

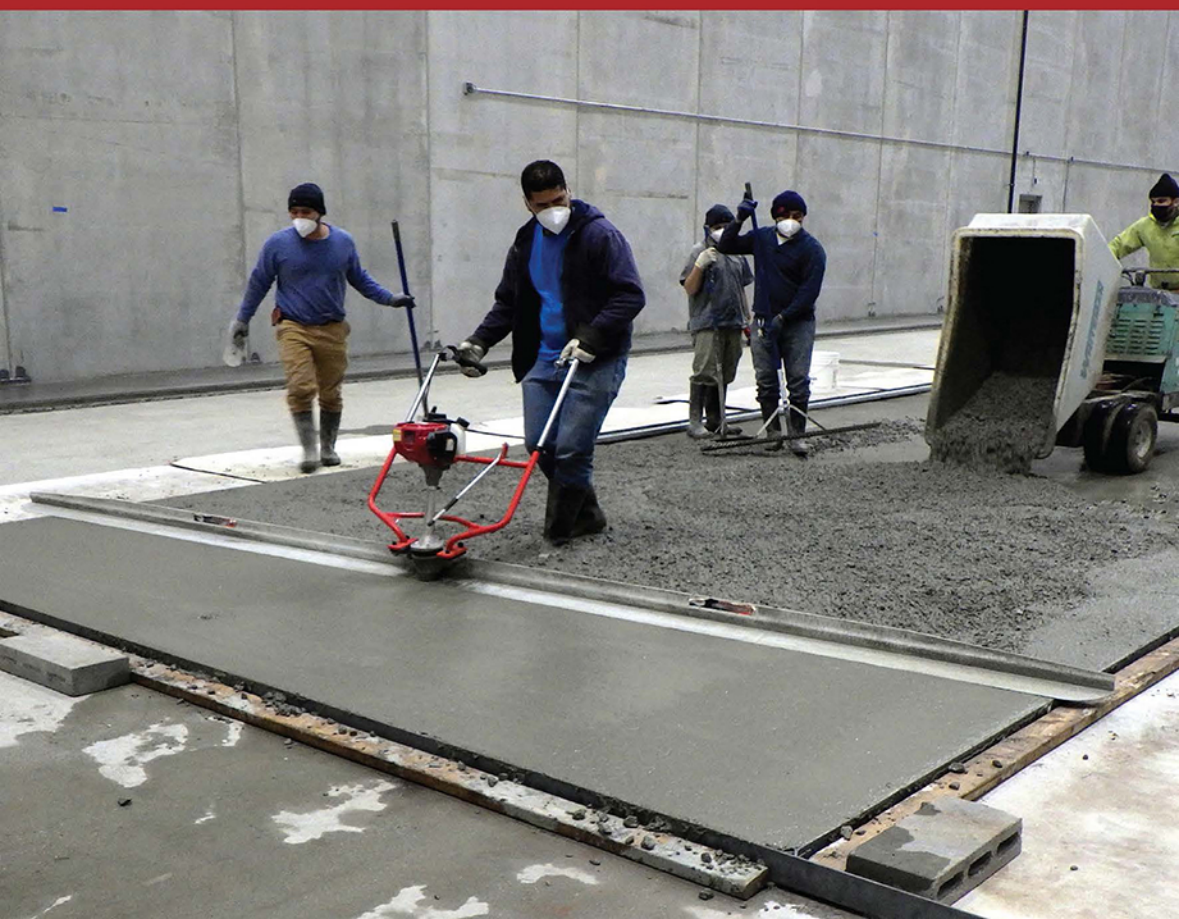


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DESIGN AND CONSTRUCTION OF CONCRETE FLOORS

THIRD EDITION

GEORGE GARBER



Design and Construction of Concrete Floors

Design and Construction of Concrete Floors recognizes that a good floor must do far more than support its intended loads. This thoroughly updated third edition provides further insight into polished concrete, limestone cement, and jointless floors for an international audience of structural engineers, architects, and building developers. This book discusses structural design, crack control, flatness, wear resistance, slip resistance, and suitability for floor coverings.

This book provides detail on different concrete floor types, including ground-supported concrete floors; suspended concrete floors; office and residential floors; institutional floors, including those in hospitals and libraries; industrial floors, including those that support robotic equipment; floors over contaminated soil; superflat floors; and polished concrete. In addition, this book expands on designing floors for sustainability and reduced carbon footprint.

George Garber first got concrete on his boots in 1979 and has worked in the field of concrete floors ever since. He has lived in Canada, the USA, and the UK and has worked in 17 more countries. He took part in the seminal research that led to the F-number and TR34 systems for measuring floor surface regularity. When not involved in concrete floors, he may be found cycling a country road on his Heron touring bike, which has more miles on it than many people's cars. He lives in Lexington, Kentucky, with his wife and business partner, Sharon Hackworth.



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Design and Construction of Concrete Floors

Third Edition

George Garber



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Introduction

Thinking About Floor Design

Concrete floors lie all around us. Every building has a floor, and in most industrial and commercial buildings, that floor is made of concrete. Many houses also have concrete floors.

Regrettably, many of those floors fail to do their job. Floors are responsible for more user complaints than any other building element except roofs.

Good floors exist, but they seldom appear by accident. They require good design, which requires a philosophy, by which I mean a coherent, integrated way of looking at a subject. Too often, a floor design is a jumble: a list of national standards, some clauses borrowed from the last project manual, and a few heavily promoted, proprietary products. That is no way to do the job.

This chapter sets out the philosophy on which the rest of the book is based. The essential ideas are these:

- A floor has a dual role. It is part of a building, but it is also part of the building user's equipment.
- A floor must be designed around the user's needs and wishes.
- Floor designers should not focus narrowly on structural strength but must consider other important properties.
- Good design requires equal attention to five factors: usage, structural strength, properties of the concrete itself, cracks and joints, and properties of the floor surface.
- Performance specifications work better than method specifications, but only if there is a good, affordable test for the property being specified.
- Single-course floors usually work better than double-course floors.
- National standards should be used with care.
- We can learn a lot from the roadbuilders.
- Remedies for bad work should be specified before the bad work occurs.

Though this book is inevitably based on my own ideas, it is more, I hope, than a description of my own personal approach to floor design. I have tried to present both sides of controversial issues, of which the concrete floor industry has many. If I have failed to address a widely used idea or product, the reason is my ignorance, not my opposition to it.

THE FLOOR'S DUAL ROLE

More than any other building element, floors exist in two different worlds. On one hand, a floor is part of a building's structure. It is designed by a structural engineer, who may rely on it to support or restrain other parts of the building. It is built under a construction contract. It is bought and sold with the building and is usually expected to last the life of the building.

On the other hand, a floor is part of the user's equipment. It may be a work surface on which the user assembles products, a roadway for warehouse trucks, or a platform for storing goods.

This dual role sets floors apart from other building elements. A roof, for example, does the same job on every building. Whether it covers a garden shed or a steel mill, its task is to keep out rain and snow. In contrast, floors do vastly different jobs in different buildings. The floor that works in a house would never do in a dairy—and vice versa.

We who design and build floors spend most of our working hours in the world of building construction. We may not often think about the floor users and their needs—but we should. To those users, the floor is far more than just another building element. It is something they use and live with every day.

A USER-ORIENTED APPROACH

Because floor uses differ widely, every floor should be designed with the user's needs in mind. Almost no one would disagree with that advice, but how many designers really follow it?

In too many cases, what passes as user-oriented design is little more than finding out the floor loadings and designing the floor to support them structurally. That is an essential step, but it is only the first step. Floor users have a long list of complaints, most of which have nothing to do with structural failure. Joints break down and must be repaired again and again. Floor surfaces wear out. Warehouses are shut down for repairs because floors aren't flat enough. For nonindustrial floors, complaints about moisture probably head the list. On industrial floors, joint problems predominate.

We can prevent most problems when we design and build floors with users' needs in mind. The process starts with asking users what they want, but it does not end there. Users—and where appropriate, their equipment suppliers—should take part in many design decisions, particularly when considering costs over the life of the building. Some users short on cash will accept higher maintenance costs tomorrow in exchange for the cheapest floor today. Others will pay a little more today to reduce future troubles. A few will gladly pay a lot more today to get a floor with lowest maintenance costs. Any one of those choices may make sense, depending on the user's circumstances and desires.

Besides making floors that are better fitted to their purpose, a user-oriented approach often makes floors cheaper as well. When you design a floor for one specific job, you can eliminate features that might be needed in a multi-purpose floor. The savings can be large.

The one case where a user-oriented approach would seem impossible is the speculative warehouse, put up in the hope of attracting a tenant or buyer. The floor user could be almost anyone, doing almost anything. But even there, a solution exists. Some property developers build speculative warehouses without floors. They install a level, granular base so prospective users can walk around in their dress shoes, but they leave the floor out. Once a contract has been signed, they design and build the floor to suit the tenant or buyer, whose exact needs can then be determined.

The user-oriented approach to floor design is becoming more important as users demand more of their floors, especially in warehouses. Racks are getting taller, with loads that the average floor cannot support. Automated storage and retrieval systems are becoming popular, with unusual flatness requirements that the average floor cannot meet.

BEYOND STRUCTURAL DESIGN

Related to this user-oriented approach is the need to go beyond structural strength in designing floors.

Most commercial and industrial floors are designed by structural engineers. Not surprisingly, such engineers look first to the structural strength of the floor. There is nothing wrong with that, as long as they go on to consider other qualities. But because of their training and experience, structural engineers may pay too much attention to the floor's role as part of the building's structure, and too little attention to the specific needs of the floor user in areas other than structural strength.

In the past, many floor designers focused too narrowly on a floor's structural strength. They examined floor loads and carefully calculated the structural design. But they spent little time on other important factors such as joint details, wear resistance, and flatness. When they tried to control such factors in their specifications, they often relied on shopworn phrases that had little effect on the final product.

That was never a good way to design floors, but it may have been tolerable in the days of hand-pushed trolleys. In today's world of robot vehicles and storage racks 30 m high, it simply will not do.

I do not advocate that structural design be ignored (and there is no chance that will happen, anyway). Nor do I mean to say that structural engineers should not design floors; many of them do a good job, and nobody can replace them. But we need to see structural analysis as just one part of the design process.

In this book, I pay relatively little attention to structural design, for three reasons. First, I know that writers more qualified than I have already covered the subject. Second, a thorough treatment of structural design would have required a much longer and different book. And third, I want to offset the traditional overemphasis on structural analysis.

A BALANCED APPROACH

Instead of concentrating on structural strength, we need to consider all the properties that make a floor successful. This book is divided into six parts, each of which deals with an equally important aspect of floor design.

Part I discusses the uses of concrete floors. We cannot even begin to design good floors until we understand how people use them.

Part II deals with structural design. While it is not a design manual, it discusses the structural types, presents the main issues to be addressed, and identifies some of the more useful design guides.

Part III discusses the concrete used for floors. Floor construction makes unusual demands of concrete. Concrete that works perfectly well on footings and walls may be wrong for floors.

Part IV deals with cracks and joints. Concrete wants to crack, but most people wish it wouldn't. For that reason, crack control is an important part of almost every floor design, but the methods for controlling cracks vary greatly. Joints are included here because they are, in many cases, the floor's chief defence against cracks.

Part V discusses properties of the floor surface. They include surface finish, flatness and levelness, wear resistance, and resistance to chemical attack. Part V also deals with toppings and floorcoverings.

Part VI discusses environmental impact, with a focus on ways to reduce the carbon footprint of concrete floors. This is the shortest of the five parts, not because it is less important than the others, but because it deals with a relatively new field subject to rapid change. New ideas are sure to arise, and some of the currently popular ideas will fall by the wayside.

METHOD VERSUS PERFORMANCE SPECIFICATIONS

A method specification tells you how to build something. A performance specification describes a property that a product must possess, without telling the builder exactly how to achieve that property.

This book is biased towards performance specifications. Well-written performance specifications, if enforced, provide the best guarantee that users will get the floors they need. Another benefit is that they encourage the development of new products and techniques.

But performance specifications only work if there is a way to measure the property being specified. That is why this book talks a lot about test methods, including some not commonly used for concrete floors. But sometimes, there is no standard test for the property you want to specify, or the available tests cost too much or are not precise enough. In those cases, method specifications still have their role to play.

SINGLE-COURSE FLOORS

In the past, many floors had two layers: a structural slab plus a topping. Two-course floors are still built, but they are less popular than they used to be—for good reason.

Single-course floors have important advantages. They are cheaper and faster to lay. And they eliminate the risk of bonding failure between the base slab and the topping. (Not every two-course floor relies on a bonded topping that can fail, but many do.)

Designers should always think first of a single-course floor, adding a second course only when there is a compelling reason for it. With today's methods of placing and finishing concrete, single-course floors can satisfy almost all requirements.

STANDARDS

It is hard to imagine designing a floor without recourse to published standards. They serve two purposes, providing a common language and saving labour. Without standards, specifications and notes on drawings would have to be much longer than they are now—and some people think they are already too long.

We can, however, misuse and overuse standards. We need to recognize their limitations, of which there are at least three. First, standards are written for ordinary circumstances. Floors for special purposes often lie outside the scope of existing standards.

Second, standards are conservative. It normally takes years for a standard-writing committee to adopt a new idea. For that reason, standards do not always incorporate the best, latest technology.

Third, standards cannot replace the designer's own analysis and judgment. As the British Standards Institution warns, 'Compliance with the British Standard does not of itself confer immunity from legal obligations'. It is the designer's job to decide where and how to use standards. Along with that goes the obligation to know what those standards actually say. We all sometimes cite standards we have not read, but it's nothing to brag about. I almost never fail to find a surprise or two when I read or re-read a standard.

This book cites mainly British and American standards. That's not so limiting as it sounds because those standards have become the models for much of the world. British standards are widely used throughout the Commonwealth (though not much in Canada), while American standards dominate North and South America.

Both the British and American systems can be confusing, though for different reasons. In Britain, the confusion comes from the shift to European rules. To a large and growing extent, so-called British standards are really just the English-language versions of European standards, and Brexit has not changed that. Many venerable British standards, such as BS 12 on cement and BS 1881 on concrete testing, have vanished. Their replacements are not necessarily better on their inherent merits but are needed for uniformity across Europe.

In America, the confusion comes from the huge number of separate standards and from the existence of two standards-writing organizations. The American Concrete Institute (ACI) controls the standards that tell us how to use concrete in construction. ASTM (formerly American Society for Testing

and Materials, but now just known by the four letters) deals with test methods and specifications for materials.

British standards start with the letters BS. If a number follows right behind those letters, the standard is one of the older, strictly British documents. If the letters EN (for Euronorm) appear after BS, the standard is European. Both kinds are available from:

British Standards Institution
389 Cheswick High Road
London W4 4AL
United Kingdom
Telephone +44 20 8996 9000
Website <https://knowledge.bsigroup.com/>

American concrete standards start with the letters ACI or ASTM. ACI standards are available from:

American Concrete Institute (also known as ACI International)
P.O. Box 9094
Farmington Hills, Michigan 48333
USA
Telephone +1 248 848 3700
Website <https://www.concrete.org/publications/>

ASTM standards come from:

ASTM
100 Barr Harbor Drive
West Conshohocken, Pennsylvania 19428
USA
Telephone +1 610 832 9611
Website <https://www.astm.org/products-services/standards-and-publications.html>

LESSONS FROM ROADBUILDING

Many valuable ideas for floors stem from road construction. The Somero Laser Screed, widely used to place concrete on big industrial floors, was invented in the 1980s as an adaptation of the big concrete paving machines used on highways. Most methods for transferring load across joints originated in highway work.

Roads and floors have much in common. Both support traffic and are more or less horizontal. Concrete highways resemble ground-supported concrete floors, while concrete bridge decks resemble suspended concrete floors.

For several reasons, roadbuilding technology is often in the lead. Highway engineers are no more skilled than floor designers, but they get more money for research. The large scale of highway work makes experimentation easier to justify and arrange.

And most roads are built for governments, who encourage the publication of reports and sharing of knowledge. In contrast, most floors are built privately by firms that often wish to guard what they see as trade secrets.

The flow of knowledge from roadbuilding to floorlaying has not ended. This book presents several ideas that are well accepted in the highway industry but still controversial when applied to floors. One such idea is the unreinforced slab on ground with closely spaced, dowelled joints. Another is the use of flexural strength specifications and testing.

REMEDIES FOR BAD WORK

In a perfect world, every floor would be laid exactly as specified. In the real world, people make mistakes. What happens then? Many specifications say little or nothing about this crucial subject. When problems occur, there is no clear course of action. The designer may try to reject a whole floor for one or two minor flaws. The builder will want to repair the floor as cheaply as possible, or may argue that it is usable despite its defects. Sometimes, the two parties reach a compromise, which may or may not meet the user's needs. At other times, there is no meeting of minds, and the matter goes to court or arbitration.

Many controversies can be prevented by deciding on the remedy before the problem occurs. Some problems call for full slab replacement, but they are rare. Most floor defects can be repaired.

Wherever possible, specifications should state what will happen when a failure is detected.



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Part 1

How Floors Are Used



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1 Nonindustrial Floors

This category includes all floors except warehouse and factory floors and a few special types covered in Chapter 3. Though nonindustrial floors get little attention in the technical press, they are far more numerous than their industrial counterparts.

Nonindustrial floors are usually easier to design and build than industrial floors for three reasons. First, their loads are generally light. Second, few of them are subject to wheeled traffic. Third—and this may be the most important reason—most nonindustrial concrete floors are concealed beneath floorcoverings such as carpet, tile, or wood.

It can be a serious mistake, however, to take these floors for granted. Problems occur even on routine house slabs. And some nonindustrial floor users have special requirements that can be as demanding as those in the heavy industry. For example, some libraries use movable, motorized shelving that requires an unusually level floor surface.

And not every nonindustrial floor stays hidden under floorcoverings. Exposed concrete floors are sometimes used in shops, institution, and even houses. And in recent years, there has been an explosion in the popularity of polished concrete.

There is no generally accepted classification for nonindustrial floors. I divide them into the following categories:

- residential floors;
- office floors;
- floors for retail trade;
- institutional floors.

RESIDENTIAL FLOORS

These are found in private houses and multiple dwellings. They are characterized by short spans, light loads, and foot traffic. Nearly all residential floors are concealed under carpet, tile, sheet material, or wood.

This is the only category of floor use in which concrete faces serious competition as a structural material. Suspended timber floors are common in houses and outnumber concrete floors in many countries.

LOADING

Residential floors support a variety of loads from occupants, furniture, partition walls, and appliances. Most loads are very light compared to those found in industrial buildings.

Designers seldom even consider loads when planning ground-supported residential floors. Such floors are usually designed to a standard thickness without regard to specific loading. A 100 mm (4 in) slab is usual and will suffice almost anywhere.

Suspended residential floors are often designed for a nominal live load of about 2.0 kN/m² (40 lb/ft²). See Table 2.1. Local building regulations may require a different figure.

Sometimes, a residential floor has to support a heavy load such as a fireplace. Then, the floor, whether ground-supported or suspended, should be designed for that particular load rather than increasing the nominal live load.

JOINT AND CRACK REQUIREMENTS

Joints and cracks seldom create much trouble in residential construction because the concrete slabs are usually concealed. Crack-control joints are seldom needed, except for isolation joints to separate a ground-supported floor from fixed objects. Construction joints may be used, but many residential floors are small enough to be laid without them.

Most residential floors are covered, but there are a few exceptions—garages, for example—where the concrete slab is exposed to view. In those cases, you may want to add joints to prevent visible cracks.

Cracks in a residential floor rarely need sealing or repair unless they are faulted or grow so wide that they would show through a floorcovering.

SURFACE REQUIREMENTS

Residential use demands little of the concrete surface. Within living quarters, the concrete is almost always concealed beneath a floorcovering or an applied flooring, which greatly reduces the demands on the concrete itself.

Residential floors are seldom tested for surface regularity. And they don't need to be tested since the typical occupants are quite happy with F_F15 for flatness and F_L10 for levelness. This is a low standard, roughly equivalent to an allowable gap of 20 mm (13/16 in) under a 3-m (10-ft) straight edge. Higher F-numbers are sometimes specified in high-rise apartment buildings—not because the occupants demand them but to minimize disputes between main contractors and floorcovering subcontractors. In Toronto, Canada, flatness testing in condominium towers has become routine for that purpose.

Wear resistance doesn't matter unless the concrete slab will be exposed to wear in the finished building. In that case, the surface should meet wear-resistance class AR3.

The surface finish or texture may or may not be important depending on how the floor will be covered. Tile, carpet, or wood flooring can be laid over almost any concrete finish. But thin sheet materials require a smooth surface with no obvious ripples or ridges. A good trowel finish is suitable.

Some residential floors have recessed areas to accommodate floorcoverings of different thicknesses.

A different finish may be required in garages and utility rooms where concrete forms the wearing surface. Some builders put a float finish on such floors, but most users appreciate a smooth trowel finish because it is easier to clean. You may want to slope the floor for drainage.

SPECIAL CONSIDERATIONS

Residential floors are usually simple to design and build, but there are a few special issues to consider, including:

- damp-proofing;
- supervision;
- poor subgrade.

Damp-proofing is very important in residential floors at ground level because most residential floorcoverings are easily damaged by rising damp. Even if the original floorcovering is not highly vulnerable to moisture damage, the occupant may change it later.

Residential floors tend to get less supervision, inspection, and testing than other floors. Because of this, designs should be as simple and foolproof as possible.

Residential floors are laid on a wide variety of building sites, including many with poor soil. People regularly build houses on ground that would be avoided for some other kinds of buildings.

Expansive clay subgrades can be particularly troublesome, especially in places with marked wet and dry seasons. In the American Gulf Coast region, many homebuilders rely on post-tensioning to improve the performance of slabs on expansive clay.

OFFICE FLOORS

With a few exceptions, office floors are similar to residential floors, though they sometimes support heavier loads. Most of the preceding discussion of residential floors applies equally to office floors.

LOADING

Office floors are typically designed for live loads of about 4.0 kN/m^2 (80 lb/ft^2) (see Table 1.1). Heavier loads may be found in file rooms.

JOINT AND CRACK REQUIREMENTS

Office floors have no special requirements for joints and cracks.

SURFACE REQUIREMENTS

Office floors are usually covered, though polished concrete is increasingly popular.

TABLE 1.1
Typical Live Loads for Nonindustrial Floors

Floor Use		Live Load kN/m ²	lb/ft ²
Residential	Private quarters	2.0	40
	Public corridors and lobbies	3.0	60
Offices	Ordinary offices	4.0	80
	File rooms	6.0	125
Schools	Classrooms	2.0	40
	Corridors	5.0	100
Libraries	Reading rooms	3.0	60
	Stacks	7.0	150
Hospitals	Wards and private rooms	2.0	40
	Operating theatres	3.0	60
Prisons	Corridors	4.0	80
	Cells	2.0	40
	Corridors	4.0	80

Surface regularity is generally unimportant, but there are some exceptions. One authority (Face, 1987) says movable partitions, used in many offices, benefit from floor levelness of F_L20 or better. That degree of levelness is hard to achieve on a suspended floor, where it may require a topping. As in residential construction, floors that will be covered with thin sheet material should be smooth enough to prevent defects showing through.

FLOORS FOR THE RETAIL TRADE

This category takes in a wide range of buildings, from small local shops to hypermarkets to do-it-yourself stores.

Floors in small and medium-sized shops are usually concealed. They are similar to office floors and are designed and built in the same way. At the other extreme, floors in big do-it-yourself stores are functionally the same as warehouse floors and should be designed as such.

LOADING

Retail floors often support heavier loads than residential and office floors. Users may be able to provide specific information about shelving and racks. Lacking that, designers typically assume a live load of about 7.0 kN/m² (150 lb/ft²). Certain businesses impose much lighter loads, but it is unwise to base the design on them because future occupants may be in a completely different line.

SURFACE REQUIREMENTS

These depend on whether the floor gets a covering. Covered retail floors have requirements similar to those for residential and office floors. They need to be smooth enough so that defects do not show through the floorcoverings. Exposed retail floors

have requirements similar to those for warehouse floors, discussed in Chapter 2. They usually get a smooth, power-trowelled finish.

Designers and builders of retail floors seldom pay much attention to flatness and levelness, but occasionally that gets them into trouble. Some retail chains in America demand flat floors, with overall F_F numbers of 35 or even 50. In the UK, BS 8204 says an SR2 surface, with a maximum gap of 5 mm under a 3-m straightedge, is suitable for ‘normal commercial floors’. The average retail floor doesn’t meet that standard, a fact that doesn’t matter on most jobs because it’s not tested. But in those rare cases where it is tested, trouble can ensue.

INSTITUTIONAL FLOORS

This category includes floors in schools, libraries, hospitals, and other public buildings. They are all characterized by heavy foot traffic but may have little else in common. Many institutional floors are concealed but direct-finished concrete is also widely used.

LOADING

Table 1.1 shows typical design loads for some types of institutional floors. Local building regulations usually dictate the loads for which these floors are designed.

Libraries are a special case and can have very heavy loads.

JOINT AND CRACK REQUIREMENTS

If an institutional floor will be covered, the joint and crack requirements are the same as for residential and office floors. Some institutional floors are made of direct-finished concrete, however. Cracks in such floors rarely affect usability but may nevertheless be highly objectionable to the users. For that reason, crack control may be extremely important—even more important than in the typical industrial floor.

SURFACE REQUIREMENTS

Some institutional floors, especially those that are polished or covered with shiny vinyl tile, need a high degree of flatness so they won’t look wavy. In America, some hospital managers have specified F_F45 overall, even on suspended slabs where that is hard to achieve. Some libraries use mobile shelving that has special requirements for floor levelness.

Wear resistance matters because some institutional floors get a lot of foot traffic. Those floors should meet wear class AR2, if the concrete forms the wearing surface.

SPECIAL CONSIDERATIONS

Some institutional floors, particularly those in public buildings such as courthouses, railway stations, and airport terminals, must combine structural strength, wear resistance, and architectural effect. That is an unusual combination in a concrete floor, but it can be achieved.

There is no single solution to the problem because much depends on customer expectations. Terrazzo is a common choice. Other options include coloured concrete, stains, and polishing.

Another challenge—and I'm not quite sure how to put this—is that institutional clients can be both demanding and at the same time not very knowledgeable about the realities of concrete construction. And since many institutional buildings are both used by and paid for by the public, you may find your floor judged by everyone who walks on it. Mockups are a good idea.

REFERENCE

Face, A. (1987). Specifying floor flatness and levelness: the F-number system. *Construction Specifier*, April.

2 Warehouse Floors

A warehouse is an industrial building used for storage. Not so many years ago, warehouses were places where men (and it was almost always men in those days) stacked bags and boxes by hand. In contrast, today's warehouse might contain automatic cranes serving racks 25 m (85 ft) high. Or it might include a mix of multi-level conveyors and wire-guided turret trucks in aisles just 2 m (6 ft) wide. Even the term *warehouse* has become dated in some circles, replaced by *distribution centre*, *fulfilment house*, *truck terminal*, or *delivery station*. I plan to keep using *warehouse*, though.

Though they vary widely, warehouse floors are often characterized by heavy loads, wheeled traffic, and large scale. In some clad-rack warehouses, the floor is designed to support a concentrated load of more than 25 t (55000 lb or 27.5 US tons) at each rack leg. Almost every warehouse includes some vehicles that travel on the floor and control aspects of the floor design. And as for scale—some warehouses have over 100 000 m² (1 000 000 ft²) of floor at ground level, and some are over 30 m (100 ft) tall.

Most warehouse floors are ground-supported. Ground-level suspended floors, built on piles, are sometimes used where the subgrade is too weak for a slab. Multi-storey warehouses are built mainly where land costs are high. But some warehouses in which the main floor is ground-supported include one or more suspended floors on mezzanines. This practice is driven by usage, not land costs.

Direct-finished concrete provides the wearing surface in almost all modern warehouses. A few warehouse floors get toppings or coatings, but almost none receive floorcoverings.

Depending on usage, a warehouse floor may have to meet strict requirements for surface regularity and wear resistance. Joint details and crack control are important issues in any warehouse that supports wheeled vehicles. Resistance to chemical attack is relatively unimportant, with the limited but significant exception of battery-charging areas, where sulphuric acid spills occur. Some designers specify epoxy coatings there.

Every warehouse contains at least one storage system and one materials-handling system, and some buildings contain more than one of each. These systems impose different demands on the floor. Often the storage system controls the slab thickness because of its weight while the materials-handling system dictates floor flatness and wear resistance because of its moving vehicles.

This chapter looks at the main kinds of storage and materials-handling systems, considering floor requirements in the following areas:

- loading;
- joints and cracks;
- surface regularity;
- wear resistance.

STORAGE SYSTEMS

These can be divided into six types:

- bulk storage;
- block stacking with aisles;
- pallet racks;
- shelving;
- mezzanines;
- mobile racks;
- automated storage and retrieval systems.

BULK STORAGE

This is the storage of loose material, such as corn or gravel, stored directly on the floor. Loading is almost perfectly uniform, with no concentrated point loads and no unloaded aisles. For that reason, bulk storage creates little bending stress in the floor slab, even where the loads are heavy.

Here are the basic floor requirements for bulk storage:

- Loading varies greatly but is always easy to calculate since all you need to know is the bulk density and height of the stored material.
- Joints and cracks may need to be sealed if the warehouse holds foodstuffs.
- Surface regularity doesn't matter.
- Wear resistance doesn't matter.

BLOCK STACKING WITH AISLES

This consists of unit loads, such as goods on pallets or paper in rolls, stacked directly on the floor. The unit loads are stacked in blocks, sometimes several units deep, with aisles for vehicle access. Loads are limited by stacking height, which rarely exceeds 9 m (30 ft), even if the building is taller than that.

Loads are expressed in kN/m^2 (lb/ft^2) and can run as high as 100 kN/m^2 (2100 lb/ft^2) but are usually much less.

On ground-supported floors, block-stacked loads are treated differently from the concentrated loads imposed by most other storage systems. For one thing, the sub-base is not considered to add anything to the basic properties of the subgrade. For another, the critical stress occurs at the aisle centreline and is a negative moment. That means that if a floor is underdesigned or overloaded, the first crack appears at the floor surface and in a highly visible location (Figure 2.1).

Here are the basic floor requirements for block stacking with aisles:

- Loading varies but is typically about 25 kN/m^2 (500 lb/ft^2). On a ground-supported slab, the designer has to know the aisle width in addition to the load.
- Joints and cracks may need to be sealed if the warehouse holds foodstuffs.
- Surface regularity doesn't matter.
- Wear resistance may be critical if the loads are slid into place.



FIGURE 2.1 Block stacking on the left, pallet racks on the right.

PALLET RACKS

These are steel frames that support palletized loads. The standard configuration consists of horizontal beams spanning between vertical end frames. The beams are usually long enough to support two pallets side by side; some support three pallets between end frames (Figure 2.2).

Pallet racks impose heavy concentrated loads on the floor. In the standard configuration, each rack leg (except the end frames) supports a weight equal to one pallet load for each level of pallets, plus the dead weight of the racks themselves. (The end rack legs support only half as much.) The load is typically 2–8 t (4400–18 000 lb, or 2.2–9 US tons) per rack leg. Very tall racks can produce heavier loads. In most cases, the bottom pallets sit on the floor and do not add to the rack loads. But sometimes, even the bottom pallets rest on beams and must be considered in the design.

Extremely heavy loading can occur in a clad-rack building (called rack-supported in America) where wind, seismic, and snow loads must be added in. Some clad-rack buildings have been designed for loads of more than 25 t (55 000 lb or 27.5 US tons)



FIGURE 2.2 Pallet racks. This is a very common configuration, with beams that hold two pallets side by side, and with the bottom pallets resting on the floor.

at each rack leg. What's more, wind on a clad-rack building can create uplift on some rack legs, and the floor has to resist that.

In many places, pallet racks must be designed to resist earthquakes, and this complicates the floor design. Seismic loading creates both downpush and uplift forces on rack legs. The downpush forces are similar to normal rack loading, but uplift is something floors aren't usually designed for. In high seismic zones, rack uplift may control the floor design.

In most cases, pallet racks are erected in back-to-back pairs, separated by a narrow flue space. This pattern puts two loaded rack legs about 300 mm (12 in) apart. The double concentration of load often controls the floor's structural design (Figure 2.3).

The loads from pallet racks may require a very thick and costly floor slab. To reduce slab thickness, some designers specify broader baseplates for the rack legs. This is sound engineering—but only if the baseplate is stout enough to spread

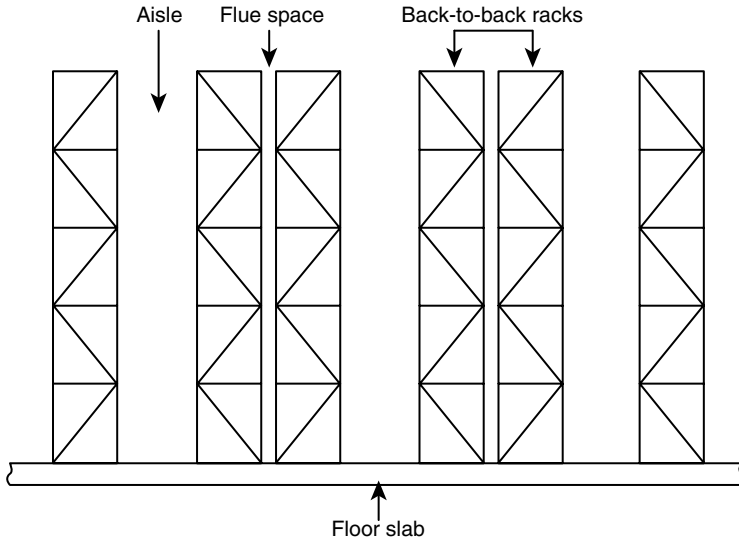


FIGURE 2.3 Pallet racks in the common back-to-back position.

the load. The typical base plate is made of thin steel and has little load-spreading ability. Thick baseplates are available, but you have to ask for them.

In some cases, the designer can reduce slab thickness just by applying a sharp pencil and some common sense to the stated rack loads. Many loads are overestimated. For example, suppose you are designing a floor for a rack system four pallets high, with all pallets supported by the racks. You ask the user the weight of the heaviest pallet load and are told it is 1.5t (3300 lb).

You then design the floor for a concentrated load 6.0 t (13 200 lb), which is the pallet load four times four, plus a bit more for the dead weight of the racks.

That would be a safe design, but almost certainly too conservative, because you based the design on the maximum pallet load. In most industries, the average pallet weighs less than the maximum—sometimes less than half as much. It makes no sense to design for a rack full of maximum loads when there is a very low probability of that situation arising.

Another way floors get oversized for pallet racks is through reliance on rack capacity rather than actual loads. Unlike floor slabs, racks cannot be fine-tuned for load capacity. They come in a few standard sizes, each capable of supporting a maximum pallet weight. If a user's actual pallet weight falls between the stated limits, the only safe option is to round up to the next higher limit. Rack designers have to do that, but floor designers don't.

Here are the floor requirements for pallet racks:

- Loading is usually 2–8 t (4400–18 000 lb, or 2.2–9 US tons) per rack leg but can be much higher in clad-rack buildings.
- Joints and cracks may need to be sealed if the warehouse holds foodstuffs. Load transfer must be considered in structural design.

- Surface regularity is not critical, but a level floor will reduce the need for shims.
- Wear resistance is not critical.

SHELVING

This is similar to pallet racking but on a smaller scale for storing nonpalletized goods. Shelving is seldom as tall or as heavily loaded as pallet racks. It is more demanding in one respect, however. The legs are closely spaced, with the back-to-back legs often in direct contact.

Here are the floor requirements for shelving:

- Loading is usually less than 3 t (6600 lb or 3.3 US tons) per leg, but back-to-back legs can be close.
- Joints and cracks are not critical, but load transfer must be considered in structural design.
- Surface regularity is not critical, but a level floor will reduce the need for shims.
- Wear resistance is not critical.

MEZZANINES

These are raised platforms supported by widely spaced posts. With mezzanine storage, there are two floors to consider: the suspended mezzanine floor and the main floor, almost always ground-supported, on which the mezzanine rests (Figure 2.4).

Mezzanine floors are typically designed for a nominal loading of 3–10 kN/m² (60–200 lb/ft²). The support posts are usually about 3–4 m (10–14 ft) apart in both

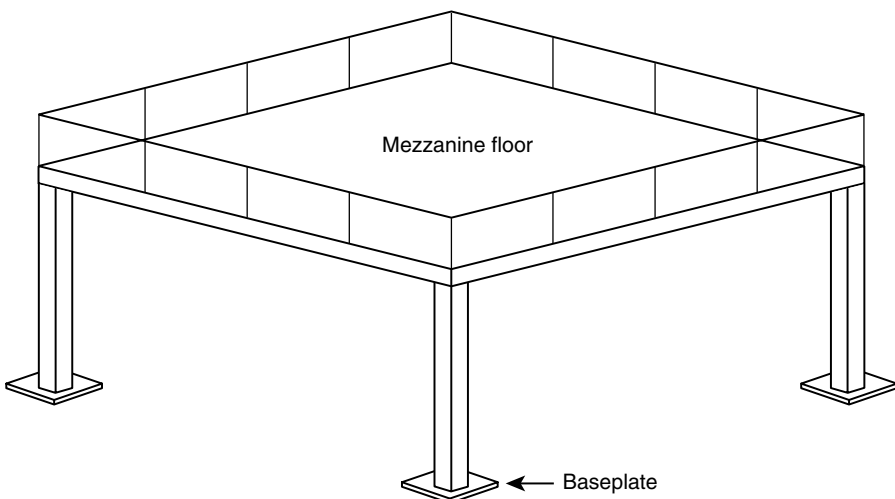


FIGURE 2.4 A mezzanine imposes widely separated loads on substantial baseplates.

directions. Not all mezzanine floors are made of concrete. Those that are almost always take the form of a composite slab, cast on a corrugated steel deck.

Mezzanines impose heavy concentrated loads on the floor below. The load at each post is typically 3.5–12 t (8000–26 000 lb, or 4–13 US tons). The legs are far enough so that each load can be considered on its own, and for this reason, a given floor can support a greater load at a mezzanine post than at a rack leg. The area beneath the mezzanine will be used for some purpose, however, and this adds loads that can complicate the structural design.

It is usually possible—and always good practice—to avoid placing a mezzanine post near a slab edge.

Unlike pallet racks, mezzanine posts come with thick baseplates that have real load-spreading ability. If the posts are very heavily loaded, it may be more practical to treat them as building columns with separate foundations. This approach is particularly useful where the other floor loads are light.

Here are the requirements for floors that support mezzanines:

- Typical loading is 3.5–12 t (8000–26 000 lb, or 4–13 tons) at each post.
- Joints and cracks need not be sealed; posts should be located away from joints.
- Surface regularity doesn't matter.
- Wear resistance doesn't matter.

MOBILE RACKS

These are pallet racks that slide horizontally on rails. Ordinary pallet racking requires at least one aisle for every pair of racks. In mobile racking, many racks can be bunched together, with the option to open an aisle at any point. There are also mobile shelving systems that work the same way; some libraries use them. Mobile racks offer unmatched storage density at the cost of lower throughput.

Here are some floor requirements for mobile racks:

Loading varies not only with product weight but also with rack design. It may be treated as a line load.

Joints and cracks don't matter, except for load transfer.

Flatness is not critical, but levelness should be F_L or higher.

Wear resistance doesn't matter because the racks move on rails.

CLAD-RACK BUILDINGS

Called rack-supported buildings in America, clad-rack buildings use pallet racks as the building's structural frame. The floor goes in first, followed by the racks, followed by the walls and roof, which attach to and are supported by the racks. Clad-rack construction imposes these special requirements on the floor:

- The floor must be laid outdoors.
- Because the floor slab forms the building's foundation, it is subject to code requirements that do not normally apply to ground-supported floors.

- The designer must consider not only the normal rack loading but also the effects of snow, wind, and earthquakes.
- The slab must resist not only the usual downpush loading but also uplift loading from wind and earthquakes.

AUTOMATED STORAGE-AND-RETRIEVAL SYSTEMS (ASRS)

These straddle the line between storage and materials-handling. A single system from a single vendor stores and moves the goods. But though they involve moving parts, they have more in common with storage systems than with traditional materials-handling vehicles.

American and British standards don't have much to say about ASR systems. For a more complete treatment, turn to the *Fédération Européenne de la Manutention* (European Warehousing Federation), which publishes two key documents: FEM 9.831 (1995) and FEM 9.832 (2001).

ASR systems are divided into two categories according to the size of the unit loads they handle. Pallet systems, covered by FEM 9.831, use racks not much different from conventional pallet racks. The stacking is done by rail-mounted cranes that work much like turret trucks but are robotic. Small-parts systems, sometimes called mini-load and covered by FEM 9.832, stock and pick individual parts and small boxes.

ASR systems have some unique floor requirements. Instead of controlling floor flatness or levelness over short dimensions, as in the F-number and TR 34 systems, FEM standards limit the overall deviation from a horizontal plane. Table 2.1 shows the FEM limits.

FEM 9.832 doesn't include the last line, presumably because mini-load systems are never over 150 m long.

Those tolerances apply to the new floor before it is loaded. FEM standards also limit long-term deformation from all sources: loading, settlement, and heaving. FEM 9.832 says vertical deformation must not exceed 1/3000 of the system length and 1/2500 of the distance between vertical supports (up to 3 m). Those aren't construction tolerances. They are instructions to the floor designer, who is supposed to take them into account when designing the floor. As far as I can tell, most designers don't pay them much attention.

Some manufacturers have their own tolerances, which may involve values and measuring techniques not found in any standard test.

TABLE 2.1
Floor Elevation Limits for ASR Systems

System Length	Maximum Overall Elevation Difference
Less than 50 m (164 ft)	20 mm (0.79 in)
50–150 m (164–492 ft)	30 mm (1.18 in)
More than 150 m (492 ft)	40 mm (1.57 in)

Source: From FEM 9.831 and 9.832.

MATERIALS-HANDLING SYSTEMS

Most materials-handling systems use wheeled vehicles that ride directly on the floor. In some warehouses, the vehicle loads control the floor's structural design. Even where that's not the case, vehicles impose requirements for joints and cracks, surface regularity, and wear resistance.

Materials-handling equipment can be divided into these types:

- conveyors;
- low vehicles;
- counterbalanced forklift trucks;
- clamp trucks;
- reach trucks;
- turret trucks;
- order pickers;
- stacker cranes;
- hybrid vehicles;
- wire-guided vehicles.

CONVEYORS

These demand little of the floor. Goods are carried on rollers or belts supported by fixed steel frames. Because there are no moving parts in contact with the floor, conveyors have more in common with storage racks than with other materials-handling equipment.

Conveyors impose concentrated loads at fixed locations, much like the loads from pallet racks. But the loads are usually lighter than rack loads and rarely control the floor design.

Here are the floor requirements for conveyors:

- Loading is seldom critical.
- Joints and cracks don't matter.
- Surface regularity doesn't matter. Even if a floor is severely sloped, conveyors can be shimmed.
- Wear resistance doesn't matter.

LOW VEHICLES

This category includes a wide range of vehicles, including hand-pushed pallet jacks, motorized pallet transporters, trolleys, and tugger-cart combinations. Their common features are low height and light loads.

Despite their light loads, some of these vehicles are hard on floors. Pallet jacks and motorized pallet transporters ride on small, hard plastic wheels that take a toll on floor joints and cracks. Some even have steel wheels (Figure 2.5).

Another issue with those pallet transporters is bottoming out on bumps. The problem is particularly acute with long-forked double pallet jacks that carry two pallets at the same time.



FIGURE 2.5 Hand-pushed pallet transporter. This may look harmless, but the small, hard tyres are hard on floor joints.

Here are the floor requirements for low vehicles:

- Loading is usually less than 700 kg (1500 lb) per wheel.
- Joints and cracks need load transfer. Joints should be filled. Cracks should also be filled if over 1 mm (1/32 in).
- Surface regularity should be F_F15/F_L13 for better, with special attention to curled joints where scraping can occur.
- Wear resistance should be AR2 or better (AR1 in areas of very heavy usage).

COUNTERBALANCED FORKLIFT TRUCKS

These are the workhorses of the warehouse world. Load-bearing forks stick out in front. The forks move up and down and may tilt but do not rotate or extend. Because the forks don't rotate or extend, counterbalanced trucks need wide aisles for manoeuvring. They can serve either block stacking or pallet racks, but either way, the minimum aisle width is about 4 m (13 ft) (Figure 2.6).

Most counterbalanced trucks ride on rubber or soft plastic tyres. These are harder than pneumatic tyres but not quite so punishing to the floor as hard plastic or steel tyres.

Counterbalanced trucks are not very sensitive to surface irregularities. But problems can arise in high-speed operations, where loads sometimes bounce off. A different problem can occur if trucks travel with the forks held very low. The forks scrape on high spots, scratching the floor.

Here are the floor requirements for counterbalanced trucks:

- Loading is usually less than 2.5 t (5500 lb) per wheel.
- Joints and cracks need load transfer. Joints should be filled. Cracks should also be filled if over 1 mm (1/32 in).



FIGURE 2.6 Counterbalanced forklifts like this are the workhorses of the modern warehouse.

- Surface regularity should be at least F_F15/F_L13 but consider higher F_F for busy warehouses or high-speed operation.
- Wear resistance should be AR2 or better (AR1 in areas of very heavy usage).

CLAMP TRUCKS

These closely resemble counterbalanced forklifts, on which they are based, but they clamp loads from the sides instead of lifting them on forks. They are used for goods that come packed in big boxes—household appliances, for example.

The floor requirements for clamp trucks are the same as those for counterbalanced forklifts.

REACH TRUCKS

These have forks that extend forward but do not rotate. Compared to a counterbalanced forklift, the reach truck can use a narrower aisle and may stack to a greater height. The typical aisle width is about 2.5 m (8 ft).

TABLE 2.2
Floor Surface Regularity for Reach Trucks

Lift Height	Recommended Surface Regularity	TR 34
	F-numbers	
Up to 5.5 m (18 ft)	F _F 20/F _L 15	FM3
5.5–8 m (18–26 ft)	F _F 30/F _L 20	FM2
Over 8 m (26 ft)	F _F 50/F _L 30	FM1

Reach trucks are sometimes called narrow-aisle trucks, but the term can cause confusion. To most people in the field of materials-handling, a narrow-aisle vehicle is one that needs an aisle about 2.5 m (8 ft) wide, and reach trucks qualify. Some people, however, use *narrow-aisle* for turret trucks and order pickers that need no steering room at all and can operate in an aisle less than 2 m (6 ft) wide.

Reach trucks roll on hard plastic tyres, which easily damage unfilled joints and cracks.

The need for surface regularity varies with lift height. Low-rise reach trucks don't need much more than counterbalanced forklifts, but a tall model is almost as demanding as a turret truck of similar height. Table 2.2 gives some recommended tolerances.

Here are the floor requirements for reach trucks:

- Loading is usually less than 2.5 t (5500 lb) per wheel.
- Joints and cracks need load transfer. Joints should be filled. Cracks should also be filled if over 1 mm (1/32 in).
- See Table 2.2 for surface regularity.
- Wear resistance should be AR2 or better (AR1 in areas of very heavy usage).

TURRET TRUCKS

These operate in an aisle only slightly wider than the truck itself. They are known as very-narrow-aisle (VNA) vehicles, a category that also includes some order pickers. The forks are mounted on a turret that lets them rotate in the horizontal plane and reach out to each side. Some turret trucks stack to great heights. Lift heights of 13 m (44 ft) are common, and some models go higher. With many designs, the operator's cab rises with the load.

Because the side clearance is so small—typically 100 mm (4 in)—VNA trucks cannot be steered manually while in the stacking aisles. They are steered automatically, either by guide rails or by wire guidance. Outside the stacking aisles, VNA trucks are usually steered manually. A few systems are totally driverless and keep the trucks on guidance even when transferring from aisle to aisle but that doesn't affect the floor requirements.

Turret trucks demand a high degree of floor surface regularity. Many people assume this is to prevent the tall mast leaning over and striking the racks, but the situation is more nuanced than that. Turret trucks have hard tyres and rigid, unsprung frames.

That combination is essential to reduce mast sway—imagine the effect if a 9-m (30 ft) mast were supported on luxury-car springs—but it makes the vehicles highly sensitive to bumps and dips. Turret trucks ride hard even on the flattest floors. On unflat floors, parts break and ride quality is unacceptable, forcing drivers to slow down.

This is the real reason turret trucks need flat floors: to go fast without undue damage or driver distress. And it's not closely related to lift height because turret trucks never go fast when at their full height. Most have speed regulators that are tied to lift height: the higher they reach, the slower they go.

This means a turret truck actually has two different needs for surface regularity. First, the floor needs to be flat and level enough so the mast does not strike the racks. That requirement depends on lift height and also on side clearance. Second, the floor needs to be flat enough to give the truck an acceptably smooth ride. I say 'flat enough' because for this purpose, levelness doesn't matter. The second requirement is independent of lift height. It depends on truck speed, traffic flow rate, and user expectations.

The second requirement (for a smooth ride) turns out to be the critical one. A floor of even average flatness and levelness is good enough to keep the mast away from the racks. But it won't give the ride quality most users want.

Unfortunately, most standard recommendations get this wrong and recommend tolerances based solely on lift height. This is what I recommend instead:

- $F_{\min} 40$ for slow, less critical VNA operations;
- $F_{\min} 60$ for typical VNA operations;
- $F_{\min} 100$ for the fastest, most demanding VNA operations.

Here are the other floor requirements for turret trucks:

- Loading can be up to 5.6 t (12 300 lb or 6.2 US tons) per wheel (the heaviest loading occurs when the truck has extended its load into the racks).
- Joints and cracks need load transfer. Joints should be filled. Cracks should also be filled if over 1 mm (1/32 in).
- Wear resistance should be AR1 or better.

ORDER PICKERS

The lift trucks described so far normally carry palletized goods or objects similar to pallets in size. Order pickers, in contrast, let workers fill orders by picking small objects from racks and shelves. The order picker may carry a pallet on which the worker can put the picked goods, but it does not place the pallet in the racks. For that reason, order pickers are rarely the only lift trucks in a warehouse. The typical warehouse using order pickers also has counterbalanced forklifts, reach trucks or turret trucks to fill the racks.

Order pickers can work in aisles of almost any width, from the 4-m (13-ft) aisles used by counterbalanced forklifts to aisles even narrower than the 2-m (6-ft) aisles served by turret trucks. Order pickers in wider aisles are steered manually. Where the aisles are less than 2.5 m (8 ft) wide, the vehicles are steered by guide rails or wire guidance.

STACKER CRANES

These are VNA stacking vehicles that ride on rails. There is usually one rail at the bottom to bear the weight and another at the top to keep the crane upright. Some models hang from overhead rails. Like a turret truck, a crane can operate in an aisle about 2 m (6 ft) wide. Cranes go higher than trucks; some stack to 30 m (100 ft).

Cranes are not easily shifted from aisle to aisle. Some users don't even try; they just buy one crane for every aisle.

Cranes are almost never manually operated. They normally form part of a computer-controlled ASR system.

Because they run on rails, stacker cranes demand little of the floor except the ability to support their weight. Here are the requirements:

- Loading is rarely critical because rack loads control the design.
- Joints and cracks don't matter.
- Surface regularity is not critical because the rail is levelled independently of the floor, but FEM standards impose overall elevation tolerances (see Table 2.1).
- Wear resistance doesn't matter.

HYBRID STACKERS

These VNA vehicles combine some features of stacker cranes and turret trucks. Like cranes, they have tall non-telescoping masts that engage a top rail while in the aisles. Like turret trucks, they ride on the floor and can travel freely from aisle to aisle. Hybrids can stack to about 20 m (66 ft).

Some models ride on a steel channel when in the aisles, but it does not greatly change the way they interact with the floor. Unlike crane rails that are made of heavy steel and levelled independently of the floor, the channels used with hybrids are thin and follow the floor's general contours. Their purpose is to guide the vehicle, not to level or support it.

Unlike turret trucks, hybrid stackers are designed to run at full speed regardless of height. For that reason, they need superflat floors.

Here are the requirements for hybrid stackers:

- Loading can be as high as several tonnes per wheel, but rack loads are almost always higher and control the floor design.
- Joints and cracks need load transfer. Joints cracks more than 1 mm (1/32 in) wide should be filled, unless all wheels ride on a steel channel.
- Surface regularity is critical: $F_{\min} 80$ to $F_{\min} 100$ in the aisles, $F_F/50/F_L 30$ in the open areas.
- Wear resistance should be AR1 or better unless all wheels ride on a steel channel.

WIRE-GUIDED VEHICLES

This category overlaps some others. It consists of vehicles that follow an electric wire embedded in the floor. Almost any vehicle could be wire-guided, but in practice, the technology is limited to VNA trucks and certain automatically controlled vehicles (AGVs).

Guidewires are installed after the concrete has hardened—sometimes long after. The installer saws a groove about 10 mm (3/8 in) deep, puts the wire in it, and seals it with hard epoxy. Some systems use several wires together, requiring a deeper cut. The result looks like a sawcut joint but generally does not act as one. Occasionally, though, a guidewire sawcut induces a crack.

Wire guidance affects floor design in two areas: embedded steel and joint movement.

Steel lying too close to the guidewire interferes with the signal. To prevent that, wire-guidance suppliers typically specify a minimum distance from wire to embedded steel, but they don't agree on what that distance should be. Recommendations have ranged from 50 mm (2 in) to an absolute prohibition on any embedded steel. That last requirement puts the floor designer in some rather tight handcuffs, as you can imagine.

In my experience, steel does not cause trouble unless it almost touches the guidewire. (A big mass of steel farther away might create a problem, but few floors contain such a mass.) And reinforcing bars that cross the wire are less likely to interfere than those that run parallel, or nearly parallel, to it. A design that keeps the steel 50 mm (2 in) from the wire is almost certainly safe, if strictly followed. Don't forget that the clearance can be horizontal as well as vertical.

Metallic dry shakes and steel fibres are usually allowed, on the assumption that the individual pieces of steel are small and evenly distributed around the guidewire. Similarly, few object to steel-armoured joints crossing the wire. However, some materials-handling consultants take a stricter view and would forbid all those things.

Slab movement at joints can break guidewires. The damaging movement can be either horizontal or vertical. Horizontal movement occurs at free contraction joints as the concrete undergoes drying shrinkage or thermal contraction. Vertical movement occurs as vehicles cross joints that lack good load transfer. If you know which joints are likely to move, you can tell the guidewire installers, who can leave slack in the wire at those spots.

ROBOTS

Compared to manufacturing, warehousing has proven resistant to automation. Most warehouses remain unautomated: forklifts have human drivers, and products are picked from shelves by human hands. But that is changing.

Automation in warehouses takes many forms that have little in common and have different implications for the floor.

Most traditional warehouse vehicles can be automated. But that barely affects floor design because the vehicles' behaviour doesn't change.

ASR systems have unusual requirements for surface regularity. We've already covered that subject under storage systems.

Perhaps the most challenging development, from the floor designer's point of view, is the growing use of autonomous mobile robots (AMRs). Hao (2021) points out that the use of AMRs got a big boost when Amazon bought Kiva Systems in 2012. Within a few years, tens of thousands of Kiva AMRs had been installed in Amazon warehouses, giving many designers and floorlayers a crash course in their requirements.

Floor requirements for AMRs have been a moving target, but they frequently involve some properties that have not traditionally been specified or measured in warehouse floors. Those properties include:

- flatness tolerances that are enforced all over, even right next to walls and columns;
- strict limits on crack width (recently relaxed, in at least some cases);
- glossiness because a shiny floor can reflect laser light and cause errors;
- slip resistance;
- surface texture (not flatness).

To make the challenge even greater, AMRs are often installed on mezzanines with composite slabs. Concrete must be pumped (usually), and flatness is harder to achieve than on ground-supported floors.

BATTERY-CHARGING AREAS

Many warehouse vehicles run on batteries, which have to be charged. The charging usually takes place in a dedicated area. People can and do charge batteries on ordinary concrete slabs, but attention to three details can improve the floor's performance in the battery-charging areas.

The first detail involves resistance to acid. Batteries contain sulphuric acid, which is highly corrosive on concrete. Over the years, acid spills are bound to occur. To help resist them, floors in battery-charging areas are often covered with epoxy coatings or epoxy toppings.

The second detail is related to the first and involves protecting the slab from subgrade moisture. Many warehouse floors are safely laid without vapour barriers to keep out subgrade moisture. But what works for the main warehouse floor may not be good enough for the battery-charging area. Moisture makes epoxy coatings and toppings peel off. If the battery-charging area will be coated or topped, the slab in that area should get a vapour barrier on all but the driest sites.

The third detail only applies to those warehouses where the batteries are stacked on racks for charging. Some battery-charging systems employ a rail-guided lift truck to remove the batteries from the warehouse vehicles and stack them on the charging racks. Some of those trucks stack four levels high and need a very level surface. One manufacturer recommends a floor specification of $F_{\min}85$ for its four-level battery stacker (Figure 2.7).

THE CHALLENGES OF THE SPECULATIVE WAREHOUSE

A speculative building is one built without a known end user. The developer hopes a buyer or tenant will come along later but doesn't know who it will be. Nobody builds a factory or a hospital 'on spec', but many warehouses are built that way. The practice creates some serious challenges for the floor designer. The challenges involve slab thickness, surface regularity, and load transfer at joints.

In a build-to-suit warehouse, you can tailor the slab thickness to the expected loads. In a speculative warehouse, you don't have that luxury. You could guess at



FIGURE 2.7 Three-level battery stacker.

the loads, but that's not how it usually works. The normal practice is for the developer to choose the slab thickness based on what the local market expects. Often, the slab thickness is tied to the building's clear height, which makes a rough kind of sense since a taller building can hold taller racks. But the result is often a gross mismatch of load capacity and actual loading. If the slab is too thin for a prospective tenant's loads, the deal falls through. If the slab is too thick, everything works—but money was wasted, and the floor's carbon footprint was bigger than it needed to be.

The surface-regularity challenge is that some warehouse systems require a degree of flatness or levelness the average floor cannot satisfy. If a prospective tenant's plans include VNA trucks, ASR systems, or AMRs, a normal floor will not do the job. The usual solution, not wholly satisfactory, is to specify the highest flatness and levelness that a good floorlayer can achieve without extraordinary effort and expense. Currently that would be F_F55/F_L35 overall. It used to be lower, and in the future, it could be higher.

The load-transfer challenge arises only with unreinforced ground-supported slabs, which are common in America. Such slabs contain many sawn joints, which can be dowelled or not. Putting dowels in every sawn joint is the safer course, but it costs a lot, and some developers resist paying for it. A popular compromise is to dowel the sawn joints only in the speed bay (the column bay next to the dock doors), trusting to aggregate interlock in the rest of the warehouse.

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3 Factory Floors and Special Cases

This chapter deals with floor in factories, along with a few special cases.

FACTORY FLOORS

Factories are industrial buildings used for manufacturing or processing. They vary widely, ranging from small engineering workshops to food-processing plants to electronics assembly buildings. Because they vary so much, it is hard to generalize about their floors. We can talk about a general-purpose floor in a warehouse or office building and have a good understanding of what that means. In contrast, the general-purpose factory floor does not exist. Every factory floor should be designed for a specific user's needs.

Most factories include some storage space and are, to that extent, warehouses. They contain storage and materials-handling systems identical to those described in Chapter 2. But factories have their own special needs in the following areas:

- loading;
- joint sealing and filling;
- crack sealing;
- surface texture;
- wear resistance;
- resistance to chemical attack;
- slope for drainage.

LOADING

Some factory equipment is very heavy, imposing concentrated loads far greater than those found in warehouses. If the load exceeds a few ton, it is often best to provide a separate foundation for it. But in some cases, it makes sense to put even very heavy equipment on the floor slab, particularly if the loads are many or if the user wishes to move the equipment from time to time.

Load safety factors for stationary loads on a factory floor can be set lower than those for moving vehicles such as forklift trucks. Floors designed for vehicle loads need a high safety factor to prevent fatigue failure, but fatigue is hardly an issue where a heavy machine stays in place for 20 years. Ringo and Anderson (1992, p. 9) suggest that safety factors can go as low as 1.3 for some stationary loads. However, higher safety factors may be needed where factory machines impart substantial vibrations to the floor slab.

JOINT SEALING AND FILLING

These are two different things. You seal joints to keep them from trapping dirt or to stop liquids from leaking through. You fill joints to protect the concrete edges from damage caused by traffic. Some factory floors need joint sealing or filling, or both, but many floors need neither.

The need for joint sealing varies from industry to industry. Companies that bash metal and saw wood rarely need sealed joints. Companies that process food and drugs usually do. In some cases, government or industry regulations require sealed joints. In other cases, users demand them because they make the facilities easier to keep clean and more likely to pass inspections. Joint sealers should be highly elastic to accommodate movement, unless the need to withstand traffic dictates a harder material.

In contrast with joint sealing, the need for which depends on the products being made, the need for joint filling depends on the kind of traffic that crosses the joints. What matters most is not the overall loading but the contact pressure, which varies with the type of tyre. Pneumatic tyres have low contact pressures, roughly equal to their inflation pressure. They do not require filled joints. Solid rubber tyres have higher contact pressures and generally require filled joints unless the traffic frequency is low. Steel tyres—not so common today as in years past—impose the highest contact pressures and can destroy a joint in short order unless it is very well filled. For steel tyres, armoured joints are better than filling.

Only those joints exposed to wheeled-vehicle traffic need to be filled.

What do you do when the usage seems to demand both joint sealing and joint filling? That is a hard question, because no product on the market combines the elasticity of a sealant with the strength and hardness of a good filler. While awaiting that perfect product, consider these options:

- Install a semirigid joint filler, but only after the concrete is at least a year old.
- Armour the joints to eliminate the need for a semirigid filler (you still need a sealant, though).
- Adopt a method of crack control that eliminates most or all of the joints.

If you choose the last option, the possible methods include continuous reinforcement, post-tensioning, shrinkage-compensating concrete, and a heavy dose of steel fibres.

CRACK SEALING

Factory users who demand sealed joints usually expect sealed cracks, too. Drug manufacturers and food processors sometimes insist that ‘all’ floor cracks be sealed.

That seems clear, but it leads to arguments because cracks come in all widths, down to the microscopic. To reduce disputes, specifications should state the critical crack width beyond which sealing is needed, and the time at which cracks are to be measured.

SURFACE TEXTURE

Most factory floors benefit from power-trowelling to a smooth, burnished finish. That produces an easy-to-clean surface with good wear resistance.

A burnished finish is wrong for some uses, however. It can become dangerously slippery if liquid or fine powder is spilled on it—a frequent occurrence in many factories. One of the slipperiest floors I ever walked on was in a cigarette factory, where almost-invisible tobacco dust covered the surface.

Consider the following methods when you want something rougher than a burnished finish:

- Give the floor a float finish.
- Give the floor a broom finish.
- Apply a slip-resistant dry shake.
- Grind the floor. You can fine-tune the results by using different grid sizes.
- Shot-blast the finished floor.
- Score the finished floor surface with shallow saw cuts.
- Apply a slip-resistant coating.

Understand that all of these measures will make the floor harder to clean and possibly less resistant to wear.

WEAR RESISTANCE

Some factory floors need a high degree of wear resistance. While a floor in wear-resistance class AR1 is good enough for almost any warehouse, some factories require more.

The need is especially great in factories where abrasive materials are present on the floor surface. Metalworking shops are notorious for this, and the condition occurs in other factories as well.

To make floors wear-resistant, designers often use special hardeners, coatings, and toppings. But plain concrete can wear surprisingly well, if well finished and well cured.

Though designers and floorlayers bear the main burden of making factory floors wear-resistant, users too have responsibility. When an industrial process produces abrasive debris, an efficient floor-cleaning programme can pay rich dividends.

RESISTANCE TO CHEMICAL ATTACK

Many industrial processes use chemicals that attack concrete. The list of troublesome chemicals includes some materials not commonly thought of as dangerous or corrosive. The food industry deals with many acids that pose not the slightest hazard to human health but attack concrete severely. Without protection, a plain concrete floor in a meat-packing plant or a vegetable cannery will not last long.

Power-trowelling helps floors resist attack by densifying the surface. But it only goes so far because the vulnerability is rooted in concrete's basic chemistry. A more complete solution is to cover the concrete with another material such as epoxy or tile.

Sulphur concrete, in which molten sulphur replaces the usual Portland cement, resists acids well.

SLOPE FOR DRAINAGE

Many factory floors are sloped so that spilled liquids or wash water will flow to drains. Laying concrete to a slope is not hard, but questions arise as to how much slope is needed, and how it's measured.

This kind of slope is normally stated in percent of rise divided by run. (In other contexts, concrete floor slopes are expressed in other terms such as elevation difference over 3 m or 10 ft.) Most authorities recommend 2.0% for positive drainage, but some recommend 1.5% or even 1.0%. I strongly recommend 2.0%.

The common specifications for surface regularity are hard to apply to sloped floors. This can result in a critical sloped area, where positive drainage is essential, going untested. To plug that loophole, I recommend specifying a minimum and maximum slope to be measured over 300 mm. This can be enforced with the same walking profilers used to measure F-numbers and TR 34 Property F.

SPECIAL CASES

The rest of this chapter looks at a few special cases:

- air-bearing vehicles;
- parking structures;
- freezer buildings;
- television studios.

AIR-BEARING VEHICLES

These work on the principle of the hovercraft, supporting a load on a cushion of compressed air. Because a hovercraft covers a large area and uses low air pressure, it can travel over rough ground. In contrast, the air bearings used on floors cover a smaller area and use higher air pressure.

Air-bearing vehicles can be designed to work on almost any floor. But if the floor is level, smooth, and airtight, then the air bearings can be smaller, the air demand lower, and the overall system more efficient. Floors that meet the following requirements have given good service in air-bearing systems:

- Seal all joint and obvious cracks to reduce air leakage. Consider post-tensioning to eliminate cracks and keep joints in compression.
- Give the floor a burnished finish.
- Specify $F_{\text{F50}}/F_{\text{L50}}$ for surface regularity. It's unusual to specify F_{L} as high as F_{L} , but it makes sense for air bearings because levelness is critical for them.

PARKING STRUCTURES (MULTI-STOREY CAR PARKS)

Some structures are built strictly for car parking while others contain a mix of parking levels and floors used for other purposes. Our concern here is with the suspended floors. Many parking structures have a ground-supported floor on the lowest level

(which is sometimes below grade), and that raises no special issues. It may even be paved with asphalt. But the upper floors demand special attention.

Car-park floors have two unusual requirements: the need for long spans, and the need to protect embedded steel from corrosion.

Long spans are important because they require maximum open space. Closely spaced columns annoy drivers and reduce the area available for parking. The need for long spans, coupled with the high loads imposed by cars that weigh 1–2 t (1–2 US tons) apiece, creates a challenge for the structural engineer. Some engineers use flat-plate floors, but often a one-way slab on beams is a better choice. Precast double tees are popular in some countries. See Chapter 5 for more information on these structural types.

Corrosion of reinforcing steel is a huge problem in car-park floors, especially in regions where salt is used to melt snow and ice. Cars drive in dripping with brine, which saturates the concrete, creating the perfect environment for corrosion of steel. The situation is even worse in a parking structure than on a road or bridge (though it can be bad there, too) because the indoor slabs are never washed clean by rain.

Designers fight corrosion in different ways, with varying degrees of success. Some try to keep the salty water away from the concrete slab with waterproof coatings. Others try to make the concrete itself more water-resistant; adding microsilica to the mix is one way to do that.

Many American designers choose post-tensioning with unbonded tendons. Tucked away inside grease-filled plastic sheaths, the steel tendons are well protected from corrosion. The anchorages remain vulnerable, however, and demand careful attention. Epoxy-coated anchors are available, but they do not eliminate the need to seal the short exposed length of steel tendon where the sheath has to be stripped.

In the future, nonmetallic rebar may offer a way to build parking structures with no corrosion risk. We aren't there yet.

FREEZER BUILDINGS

These are warehouses kept at sub-freezing temperatures, usually for storing food. In the UK, it is more often called a cold store, but that term can also describe a chilled building kept slightly above the freezing point. Such a cold but unfrozen building poses no special challenges.

Because a freezer building is a warehouse, its floor is subject to all the normal requirements for a warehouse floor (see Chapter 2). But it is also a freezer, which raises four issues:

- frost heave;
- thermal contraction;
- difficulty of repairs;
- insulation.

Frost Heave

In the early days of freezer construction, before people understood the risk, concrete slabs were cast right on the ground. The ground quickly froze, and any water present expanded as it turned to ice. As time passed, the frost went deeper and deeper,

with more and more water turning to ice. Eventually, the frozen subgrade formed a thick lens of icy soil heaving up the centre of the floor. That was frost heave, and it destroyed many a slab.

Nowadays, freezer slabs are almost always laid over a thick bed of stiff foam insulation, but insulation alone does not prevent heave. The usual solution is a sub-floor heating system, either in the sub-base or in a mud slab. A mud slab is rough, thin concrete slab laid under the main floor slab. Insulation separates the heated layer from the finish floor slab. The floor freezes, but the ground doesn't.

Not all freezer buildings need subfloor heaters. Some designers get by without them where the subgrade is dry and well drained. Eliminating the heater is not a decision to be made lightly, however, since the consequences of getting it wrong are so severe.

Thermal Contraction

A freezer floor undergoes more thermal contraction than other floors, because it's laid at a temperature much higher than it will experience in operation. Suppose we lay a freezer slab 100 m (328 ft) long with the concrete at 20°C (68°F). If we chill the building to -20°C (-4°F)—and many freezers are even colder—thermal contraction alone will make that floor about 45 mm (1-3/8 in) shorter. That shortening has to be accommodated somewhere—at joints, at cracks, or at the slab ends, depending on the floor design.

Ordinary floors also shorten over time, due mainly to drying shrinkage. But freezer floors shorten more. For that reason, freezer floors benefit from a conservative approach to crack control. Some designers choose post-tensioning or heavy continuous reinforcement.

Other designers rely on control joints but space them closely.

Because thermal contraction widens joints and cracks, they should not be filled till the building has been lowered to its final working temperature. That limits the choice of fillers since some set very slowly when cold. Cold-weather joint fillers are available.

The news with regard to thermal contraction in freezers is not all bad. Unlike most other kinds of buildings, freezers experience almost no temperature changes after they go into use. For that reason, joint and crack fillers tend to work well and last a long time in freezer floors, provided they are installed after the slab has reached equilibrium.

Difficulty of Repairs

Freezer floors are hard to repair, and that fact makes good design and good workmanship especially important. In an ordinary warehouse or factory, it sometimes makes sense to build a cheap floor and accept the need for repairs and higher maintenance costs. If joints spall, they can be patched. If the surface dusts, it can be sealed.

Applied to a freezer floor, that sort of thinking leads to disaster. Most chemicals used to patch or seal concrete do not harden or cure well at low temperatures. Even purely mechanical repairs such as grinding and sawing are hard to carry out inside a freezer, especially if they rely on water. Replacing a slab is extraordinarily hard. Though some repairs are possible, a freezer floor—more than almost any other kind—simply must be laid right the first time.

Insulation

Modern freezer floors are always laid over thermal insulation. It usually takes the form of rigid boards of closed-cell plastic foam, laid in two courses with the seams staggered.

Like the insulation used in walls and roofs, the boards used under floor slabs are specified by their insulating value. In the UK, insulating value is typically expressed as thermal conductivity, stated in watts per metre kelvin. In this system, lower values mean better insulation, and the materials used under freezer floors measure about 30 W/(mK).

Americans look at insulation the other way around, specifying resistance to heat transfer, called R-value. R-value is measured in (h)(ft²)(°F)/BTU. As you might guess, everyone just calls it R-value. When the same property is measured in SI units, it is called Rsi. To convert R to Rsi, multiply by 0.176. In this system, higher values mean better insulation, and commonly available products have an R-value of about 5 per inch (Rsi, 0.035 per mm). Insulation is usually installed at least 100 mm (4 in) thick for an R-value of 20 (Rsi, 3.5). Some designs call for more. In most cases, the engineer who designs the freezer's refrigeration system will specify the amount of insulation required under the floor.

The material used under the slab must be more than just a good insulator, however. It has to be waterproof and strong enough to support the concrete slab and loaded racks. Some closed-cell plastic foams can meet both those requirements. They come in various formulations with compressive strengths ranging from 200 to 700 KPa (30 to 100 psi).

When deciding what compressive strength to specify, it is not good enough simply to match the strength to the loading. Apply a generous safety factor. Dow Chemical, a manufacturer of freezer-floor insulation, recommends safety factors of 3 for static loads and 5 for dynamic loads.

Tall, clad-rack freezer buildings impose loads that approach the capacity of the strongest available insulation boards. Indeed, the strength of the insulation may turn out to be the limiting factor in the height of such buildings.

TELEVISION STUDIOS

Television and video recording studio floors have two special requirements: flatness and sound-proofing. In addition, some studio users like to cover their floors with epoxy, imposing a few extra steps to prevent problems with that material.

Flatness

Studio floors need flatness so cameras can roll smoothly without bumps and ripples that affect image quality. Levelness matters much less than flatness. Unfortunately, studio users do not agree on how much flatness they need.

Some just ask for the best they can get and then some. Back in the days when the flattest floors were routinely, if wrongly, specified at 3 mm (1/8 in) under a 3-m (10-ft) straightedge, some television people arbitrarily demanded a tolerance twice as strict—1.5 mm (1/16 in) under the same 3-m (10-ft) straightedge. Few if any studio floors ever met that standard, but people continued to specify it. Today, those demanding users will more likely pick the highest specification of any list provided to them or to ask whether something even better is available.

At the other extreme, some studio users make do with ordinary floors and wonder what all the fuss is about. In the face of such widely varying demands, we can hardly talk about any standard requirement for floor flatness in television studios. But a few points seem clear.

First, uniformity of flatness is essential. Users don't all require the same degree of flatness, but almost all will complain is one part of the floor—typically a joint—is markedly worse than the rest. Since floors are almost always less flat near construction joints, it's a good idea to design studio floors without such joints. If the overall flatness requirements are so high that the floor must be divided into narrow strips—likely where the flatness specification exceeds F_F70 —grinding will probably be needed near the joints.

Second, some techniques developed for superflat warehouse floors do not work on high-tolerance floors for studios. The reason is that the warehouse superflats, almost without exception, support defined traffic aisles. The floor is cast in strips, with a superflat aisle running down the centreline of each strip. Since the superflat tolerances apply only in the aisle, concrete finishers have developed techniques aimed at making the aisle flat, sometimes at the cost of flatness elsewhere. The typical superflat warehouse floor looks very flat if measured down the aisles but less flat—often far less—if measured at right angles to the aisles. That would never do in a television studio, where the users insist on equal flatness in all directions. To make a superflat floor flat in all directions for studio use, it may be necessary to make repeated passes with a hand straightedge riding on the forms, adding mortar to offset the effect of plastic settlement.

Third, any joint or crack more than about 2.0 mm (0.08 in) wide needs to be filled. Unlike a warehouse floor where the filler serves to protect the joint from damage, the goal here is to make the joint as smooth and flush as possible. Ordinary industrial joint fillers—semirigid epoxies and polyureas—work well in studios, but the standard instructions are not always good enough. To eliminate any observable bump or dip, overfill the joint or crack, let the filler harden, and then grind it flush.

Sound-proofing

This may or may not be important, depending on where the studio is located. The strictest requirements for sound-proofing exist where a single building contains more than one studio—a fairly common situation. The usual way to sound-proof a floor is to build it as a floating screed laid over acoustic insulation. The insulation should also be used at the edges of the topping.

REFERENCE

Ringo, B. C. and Anderson, R. B. (1992). *Designing Floor Slabs on Grade*. Aberdeen Group.

Part 2

Structural Design



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4 Structural Design of Ground-supported Floors

Concrete floors are divided into two main structural types. Ground-supported floors rest on the ground and are supported by it. Suspended floors are supported by other building elements.

Not all floors at ground level are ground-supported. Some are actually suspended floors, resting on piles or grade beams. Chapter 5 deals with them.

This chapter deals with:

- components;
- basic principles;
- structural types;
- design methods;
- design considerations.

COMPONENTS

Figure 4.1 shows the components of a ground-supported floor. While some components are optional, every ground-supported floor includes a subgrade and a slab.

The subgrade is the underlying ground that supports the floor and everything on it. It may be natural soil or imported fill. The quality of the subgrade is an important factor in structural design and in a floor's long-term performance.

Some subgrades support slabs directly, but in many cases, a sub-base is laid over the subgrade. Designers specify sub-bases for these reasons:

- to increase the floor's load capacity by spreading concentrated loads over a larger area of the subgrade;
- to provide a stable base for construction traffic and erection of forms;
- to create a free-draining layer beneath the slab;
- to create a capillary break so that ground moisture does not move into the slab;
- to provide a porous layer for the collection of noxious gas, as part of a vapour mitigation system.

Sub-bases most often consist of compacted granular material, typically crushed rock with a broad mix of particle sizes. Recycled crushed concrete may be suitable. Lean concrete, soil cement, and other materials are also used.

In many floors, a vapour barrier or slipsheet goes over the sub-base (or over the subgrade, where the floor lacks a sub-base). Both products are normally made of the

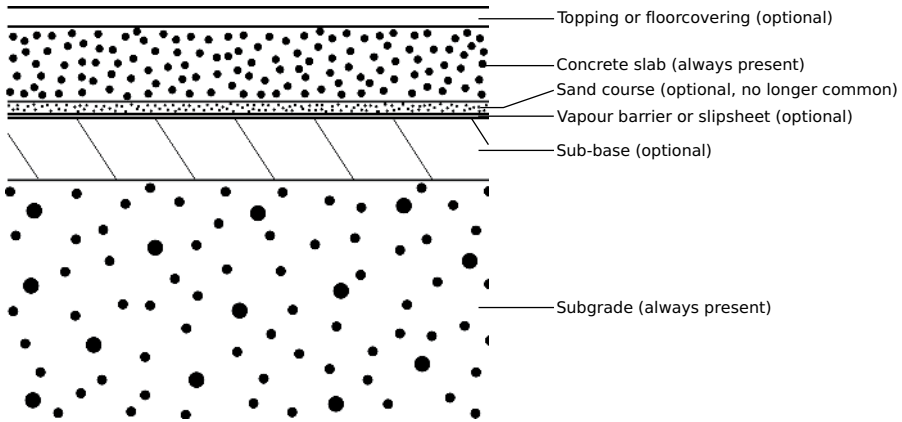


FIGURE 4.1 The components of a ground-supported floor.

same stuff—polyethylene film 0.1–0.4 mm thick—but they serve different purposes. A vapour barrier, also called a damp-proof membrane, blocks water vapour rising from the ground. A slipsheet reduces subslab friction and is essential in some designs with wide joint spacings. If a floor needs both a vapour barrier and a slipsheet, the same sheet of plastic can do double duty. Brownfield sites may need elaborate vapour mitigation systems that include polyethylene film up to 1.5 mm thick.

In some floors, a sand course lies directly under the concrete slab. The sand course smooths irregularities in the layer that lies directly below it, making slab thickness more precise and reducing subslab friction. The nominal thickness is typically 50 mm (2 in) or 75 mm (3 in), but the actual thickness varies with bumps and dips in the underlying layer.



FIGURE 4.2 Sub-base made of crusher-run stone, with a broad mix of particle sizes. This is usually the best choice because it compacts well and can be graded smooth.

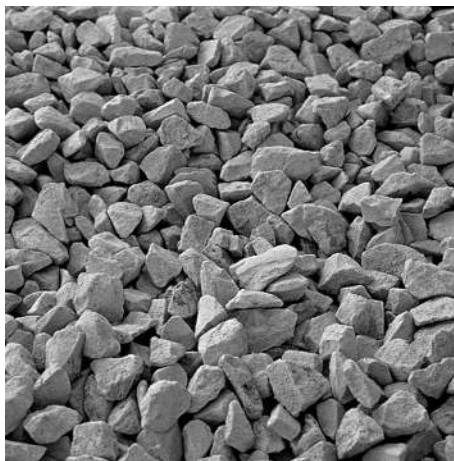


FIGURE 4.3 Sub-base made of open-graded stone with one particle size. Some designers use this to provide a capillary break.

Some designers use the sand course for another purpose—as a blotter over a vapour barrier. The idea is that the sand will soak up water from the concrete that would otherwise lead to excessive bleeding and curling. A sand course may well reduce bleeding, but its role in curling is questionable.

The slab, made of concrete, is the floor's main structural component and the one that gets the most attention. It transmits loads to the sub-base (if present) and ultimately to the subgrade, spreading them out over a big enough area that deflections are small. In many buildings, the slab also provides the wearing surface.

On floors where the slab does not provide the wearing surface, the final layer is a topping or floorcovering.

Some floors contain elements not shown in Figure 4.1, such as insulation and heating systems. Freezer floors usually have three extra components: a subfloor heating system to prevent frost heave, a mud slab, and a thick layer of foam insulation.

STRUCTURAL TYPES

Ground-supported floors can be divided into five structural types:

- unreinforced slabs;
- slabs reinforced for control of shrinkage cracks or for enhanced aggregate interlock;
- structurally reinforced slabs;
- post-tensioned slabs.

UNREINFORCED SLABS

These contain no steel reinforcement except dowels at joints. Such floors are rare in the UK but common in America. They rely wholly on the concrete's strength to support loads. The essential principle is that the load-induced stress within the slab

must not exceed the concrete's flexural strength. If properly designed and built, these slabs do not crack under load. They may crack for other reasons but not from loading.

SLABS REINFORCED ONLY FOR CRACK CONTROL OR ENHANCED AGGREGATE INTERLOCK

These contain steel reinforcement but are designed as if they did not. The reinforcement, be it steel bars, wire mesh, or steel fibres, helps with serviceability but does not add, or is assumed not to add, to the slab's structural capacity. Most floors in this category are only lightly reinforced, but exceptions exist. For example, jointless floors made with continuous reinforcement may contain as much as 0.5% reinforcing steel, by cross-sectional area, in two directions. Nevertheless, designers still treat them as unreinforced when analysing their load capacity.

This category includes most slabs made with shrinkage-compensating concrete, though some authorities put them in their own class. The small amount of prestress created by the cement's expansion, and the modest amount of reinforcing steel normally added to such slabs, do not add significantly to the floor's load capacity.

For many decades, most ground-supported floors in Europe and America were reinforced only for crack control, but that is changing. Europe has increasingly turned to steel-fibre designs in which the fibres are taken into account in determining slab thickness. At the same time, the USA has seen a contrary trend towards totally unreinforced slabs.

STRUCTURALLY REINFORCED SLABS

These contain reinforcing steel that the designer takes into account when analysing the slab's load capacity. The reinforcement can take the form of steel bars, wire mesh, or steel fibres. The analysis usually follows standard principles for reinforced-concrete design, that means that unlike the slabs in the first two categories, structurally reinforced slabs may crack under load. The designer aims not to prevent load-related cracks but to ensure the floor has enough reinforcement to resist the stresses after such cracks have occurred.

Floors for very heavy loads are often designed with top and bottom layers of steel reinforcement. Floors for lighter loads may get a single layer near the bottom.

Slabs reinforced with steel fibres fall in this category if the fibre dosage is high enough to make a real difference in the slab's post-crack behaviour and if the designer chooses a design method that takes that difference into account.

POST-TENSIONED SLABS

Post-tensioned slabs are prestressed with steel tendons. Using *post* and *pre* to describe the same slab may seem contradictory, but I can explain. The *pre* in *prestressed* means the slab is deliberately stressed before working loads are applied. The *post* in *post-tensioned* means the tendons are stretched after the concrete has set. Post-tensioning puts slabs in compression, producing an effect similar to a rise in the

concrete's flexural strength. The slab is usually designed as if unreinforced but with allowance for the higher equivalent flexural strength, taken to be the sum of the concrete's inherent flexural strength (modulus of rupture) and the residual prestress midway between slab ends. Post-tensioning allows some very efficient designs, with less steel than an equivalent structurally reinforced slab and less concrete than an equivalent unreinforced slab. Its popularity has remained strictly regional, however. Though widely used in Australia and the American Gulf Coast, it is hardly even considered in broad areas of the world.

DESIGN METHODS

Design methods for ground-supported floors fall into three types:

- finite-element analysis;
- standard methods found in design manuals;
- designs based on experience.

FINITE-ELEMENT ANALYSIS

This involves breaking down the loads and floor components into tiny elements, which are then analysed using basic principles of structural engineering. It used to be both difficult and expensive. While it still demands a high degree of engineering skill, modern computers have made it more accessible.

Finite-element analysis would seem to promise the most elegant, most efficient way to design a concrete floor. It has not, however, proven consistently superior to simpler, rougher methods, and there are two reasons for that. One reason is that the structural behaviour of a ground-supported slab is very complex and not fully understood. Engineers employing finite-element analysis have to make simplifying assumptions, the same as in the traditional methods. The other reason is that many of the variables in floor design are poorly controlled and impossible to predict with any precision.

STANDARD METHODS

While a few designers use finite-element analysis, far more choose a standard method found in a design manual. There are many to choose from. Because you cannot follow a standard method without reading the design manual that presents it, I do not explain the methods in detail here. I confine myself to general comments that may help you decide which method to use.

UK Standard Methods

In the UK, choices include:

- Chandler's *Design of Floors on Ground* (1982), which should be accompanied by Chandler and Neal's *The Design of Ground-supported Concrete Industrial Floor Slabs* (1988);

TABLE 4.1**Standard Design Methods for Ground-supported Slabs**

Method	Suitable for Unreinforced Slabs	Suitable for Slabs Reinforced for Crack Control or Enhanced Aggregate Interlock	Suitable for Structurally Reinforced Slabs	Suitable for Post-tensioned Slabs
Chandler and Neal	X	X		
Corps of Engineers	X	X		
PCA	X	X		
PTI				X
Ringo and Anderson	X	X	X	X
TR34			X	
WRI	X	X		

- the TR 34 method, set out in the Concrete Society's *Technical Report 34, Concrete Industrial Ground Floors* (2003).

Chandler and Neal offer a simple method explained with great clarity (Chandler, 1982; Chandler and Neal, 1988). It gives us the choice between working out answers from equations or looking them up in tables. The method leans heavily on old work by Westergaard (1925, 1947), Kelley (1939), and Pickett, most of which involved pavement design for vehicle loads. Despite that, it contains a clear treatment of rack and shelving loads for warehouses.

Chandler and Neal's method works well for unreinforced slabs and for slab reinforced for shrinkage crack control or enhanced aggregate interlock. If someone told me I could only use one design method, this is the one I would pick.

TR 34 (Concrete Society, 2016) provides a more complex method based on plastic analysis for concentrated loads. In contrast, most other standard methods, including Chandler and Neal's, rely on elastic analysis. The use of plastic analysis presumes that the concrete slab will crack under load and will exhibit ductile behaviour after it cracks. Plain concrete is not the least bit ductile, so the TR 34 method demands either steel reinforcement near the bottom or a substantial dosage of steel fibres. You cannot use TR 34 to design unreinforced slabs. Nor can you use it for slabs that contain reinforcement only near the top, even though that is the best location for controlling the width of shrinkage cracks.

The TR 34 method is a good choice if you are designing an industrial floor with steel fibres and wish to rely on them for post-crack ductility.

American Standard Methods

Standard design methods (see Table 5.1) in America include:

- the PCA (Portland Cement Association) method, set out in *Concrete Floors on Ground* (Tarr and Farny, 2008);

- the Corps of Engineers method, set out in *Engineering Design: Rigid Pavements for Roads Streets, Walks and Open Areas* (Corps of Engineers, 1984);
- the WRI (Wire Reinforcement Institute) method, set out in *Design Procedures for Industrial Slabs* (Wire Reinforcement Institute, 1973);
- the PTI (Post-Tensioning Institute) method, set out in *Design and Construction of Post-Tensioned Slabs on Ground* (Post-Tensioning Institute, 1980);
- Ringo and Anderson's *Designing Floor Slabs on Grade* (1992).

The PCA method is widely used for warehouse floors. In principle, it resembles Chandler and Neal's method, but the two differ greatly in presentation. The PCA method relies heavily on complex charts called nomographs rather than tables and equations. Different charts deal with wheel loading (single and dual axles), racks, and block stacking. The PCA method works for unreinforced slabs and for slabs reinforced for crack control or enhanced aggregate interlock. It used to have a serious failing in that it failed to address edge-and-corner loading, but the latest edition corrects that.

The Corps of Engineers method offers a good way to design slabs for vehicle loads. It considers edge loading and allows for the effect of load transfer at joints. It works for unreinforced slabs and for slabs reinforced for crack control or enhanced aggregate interlock.

The WRI method resembles the PCA method. Though it assumes slabs will contain crack-control reinforcement (hardly a surprise since the publisher is the Wire Reinforcement Institute), it works for unreinforced slabs, too. The WRI graphs have been reprinted in several places, but the original document is long out of print and is almost completely ignored on the Wire Reinforcement Institute's website.

The PTI method deals with post-tensioned floors. It presents a good treatment of the stresses created by swelling soil and how to resist them with post-tensioning. Ringo and Anderson (1992) point out that while the PTI manual presents post-tensioning as the solution to swelling soil, you can use it (the manual) even if you choose to resist the stresses with steel reinforcement instead of post-tensioning. The PTI method does not offer a way to calculate the slab stresses created by normal floor loading, though. For that, you need one of the other design manuals. If designing a post-tensioned warehouse floor, you would use another manual to determine the load-induced stresses and the PTI method to determine the post-tensioning needed to resist those stresses.

Ringo and Anderson's book (1992) is a design manual with a difference. It summarizes and refers to all the American design methods listed above, as well as drawing on some other less familiar sources. Ringo and Anderson present several approaches but also identify their favourites, calling them 'Authors' choice'. The result is a book that belongs on every floor designer's shelf, and not just in America. Non-American readers should be warned, however, that Ringo and Anderson concede nothing to the metric system; everything here is in US measurements. If you work in SI units, get ready to do some converting.

The Australian Option

For those willing to look beyond the UK and America, Cement Concrete and Aggregates Australia publishes the useful *Industrial Floors and Pavements*. It offers a clear explanation and the choice between simple and rigorous methods. The simple method is simple indeed: a single table in which to look up slab thickness, meant for ‘lightly loaded industrial pavements’. The rigorous method provides design equations and graphs for concentrated loads (from vehicles and racks) and block stacking with aisles.

Using a Standard Design Method

Each standard design method requires its own approach, spelled out (though not always as clearly as you might wish) in its manual. Even so, some generalizations are possible. The design process typically includes these steps:

1. Collect information on the loads. The main items of interest are the magnitude of each load, the area of loading, and the distance between loads.
2. Determine the type of load. The usual choices are concentrated loads (as from rack legs or forklift wheels), block stacking with aisles (as from stacked pallets or rolls of paper), uniformly distributed loads, and line loads (as from walls that sit on the floor). Each type calls for a different analysis.
3. Collect information on the subgrade. The main item of interest is the modulus of subgrade reaction.
4. Decide whether or not to modify the subgrade.
5. Assume a concrete strength. Flexural strength is the key property, but many design methods use compressive strength as a proxy for it.
6. Assume a slab thickness.
7. Determine the tensile stress induced in the slab by the design load plus a safety factor. If appropriate, determine stress at internal, edge-and-corner positions on the slab, with allowance for load transfer at joints.
8. Check for the effect of nearby loads, which usually add to the tensile stress but sometimes reduce it.
9. Compare the stress induced by loading to the concrete strength.
10. If the stress and strength match, the design is sound.
11. If the stress is much less than the modulus of rupture, the floor is overdesigned. Go back to Step 6 and try a thinner slab.
12. If the stress is greater than the modulus rupture, the floor is underdesigned. Go back to Step 6 and try a thicker slab. In some cases, it may make sense to change the assumptions made in Steps 4 and 5.

DESIGNS BASED ON EXPERIENCE

After reading the last few pages, you might think that most floor designs were based on a careful analysis of slab stresses. In fact, relatively few floors are so designed. For the majority of ground-supported floors around the world, structural design is based not on calculations but on experience—either the designer’s own experience or the collective experience recorded in building codes and national standards.

Most ground-supported floors in houses, offices, and shops are designed according to minimum-thickness rules, with 100 mm (4 in) being the most common value. Many light-duty and industrial floors are also designed according to these rules. BS 8204:Part 2 recommends a minimum slab thickness of 100 mm (4 in), no matter how light the loads.

In industrial buildings, a 150-mm (6 in) slab thickness has become the norm where the loadings are modest or unknown. It would not have maintained its popularity if it didn't work most of the time. Whether by coincidence or the result of trial and error, a 150-mm (6 in) slab laid on a reasonably good subgrade turns out to be just about right for the average forklift bearing the average pallet load.

Even where heavy loads dictate thicker slabs, some designers rely more on experience than on calculations. Owners may specify thickness based on what worked for them on previous projects. If a firm has a dozen similar warehouses with, say, 200 mm (8 in) slabs, it's hardly unreasonable to conclude that the thirteenth warehouse should get the same design.

In speculative warehouse construction, developers often choose the slab thickness based on what they think prospective tenants expect for a given clear height. This can lead to waste, especially in regions where normal concrete has high flexural strength. But it's common.

DESIGN CONSIDERATIONS

The rest of this chapter looks at some of the factors, major and minor, that affect the structural design of ground-supported floors. Some of the biggest factors, involving reinforcement and the material properties of concrete, get their own chapters in Section 3.

TYPE OF LOADING

When a floor is designed for specific loads, one of the early steps is to identify the type of loading. There are at least five types:

- nominal loading;
- uniformly distributed loading;
- block stacking with aisles;
- concentrated loading;
- line loading;
- horizontal loading;
- uplift.

Nominal loading is an arbitrary figure used for design purposes. It has little to do with actual, measured floor loads. It is usually expressed in terms of a uniformly distributed load, in kN/m^2 or lb/ft^2 , though the actual loads may be anything but uniformly distributed. Nominal loadings appear often in building codes and users' outline specifications. They can be useful in residential, office, and institutional buildings, where the specific loads are unknown but almost always light.

Uniformly distributed loading exerts an even force over a large area. The purest form comes from liquids in tanks and from loose bulk materials such as corn or gravel. The category can also include certain floors on which pallets or boxes are stacked. But if the goods are stacked in blocks, with aisles left open for access, the loading falls in the next category. Uniformly distributed loads are usually easy to accommodate because they create little bending stress within the slab. They are expressed in kN/m^2 or lb/ft^2 .

Block stacking with aisles exists where goods are stacked on the floor with unloaded areas (the aisles) left open for access. It is common in warehouses that lack racks and shelves. The critical stress occurs at the aisle centreline, and the amount of stress varies with the aisle width. If you know the aisle width, you can use that in the design. If the aisle width is undetermined, you design for the worst case, called the critical aisle width, which depends on the slab thickness and the subgrade modulus. Block stacking is expressed in kN/m^2 or lb/ft^2 .

Concentrated loading, also called point loading, exists where a weight bears on an area of less than 1 m^2 (10 ft^2). Loads from wheeled vehicles always fall in this category. Loads from racks and shelving usually belong here too but in a few cases are treated as line loads instead. All concentrated loads are analysed similarly, except that wheel loads often get higher safety factors than do loads from racks and other fixed equipment.

In the UK, concentrated loads are usually expressed in tons (t) and occasionally in kilonewtons (kN). Americans use US tonnes, pounds (lb), or kips ($1 \text{ kip} = 1000 \text{ lb}$).

Line loading is concentrated loading stretched out along a line. The most common source is a wall resting on the floor slab. Line loading also occurs with some rack systems and stacker-crane rails. Where line loads are substantial and far apart, typical of walls, providing separate footings for them may prove more efficient than beefing up the floor slab. Line loads are expressed in kN/m or lb/ft .

All the loads discussed so far are vertical. Floors also withstand horizontal loading from several sources. One source is vehicles that are braking, accelerating, or turning. Vehicles that travel freely on the floor impose horizontal loads through their tyres. Vehicles guided by rails impose horizontal loads through the rails. Most designers ignore such vehicle loads. Another source, harder to ignore, comes from walls and columns that are tied to the floor. In many buildings, the designer uses the floor slab to resist horizontal forces on the building frame due to wind and earthquakes. In high seismic zones, those forces can dominate the floor design, requiring substantial reinforcement in slabs that might otherwise go unreinforced. Because horizontal loads are transferred to the ground through friction, designers need to consider the subslab friction coefficient. A vapour barrier or slipsheet under the slab will reduce friction and might mean that more of the floor must be engaged to resist the horizontal load.

LOAD SAFETY FACTORS

Except in cases of reinforced slabs that are designed to crack, it would not be wise to design a floor so that it barely supported its load without cracking. We need a margin of safety to allow for errors in design or construction and, most of all, to prevent

fatigue failure. The safety factor is always greater than 1 (if it were less, the slab would be designed to fail). We can apply the safety factor to the loading, in which case we multiply the load by the safety factor, or we can apply the safety factor to the concrete strength, in which case we divide the strength by the safety factor. Some design tables have safety factors built in, while others do not. If we are not careful, we can apply the safety factor more than once, ending up with an overdesigned floor.

Choosing the safety factor is one of the most important decisions a floor designer faces. It has a huge effect on the final design and on the floor’s cost, and it lies almost wholly under the designer’s control. Rarely do owners or builders review or even know the load safety factor on which the floor design is based.

Recommended safety factors range from 1.2 to about 3.0. Low numbers are used for fixed loads where all important variables are well controlled. High numbers are used for repetitive loading and uncertain conditions. Chandler (1982, p. 7) recommends at least 1.5, even for fixed loads. Ringo and Anderson (1992, p. 9) recommend 1.4–2.0 (see Table 4.2) but say ‘When in doubt, use 2.0’. Some authorities base the safety factor to the predicted number of load cycles to prevent fatigue failure (see Table 4.3). A factor of 2.0 is supposed to suffice for unlimited load cycles.

But just what constitutes a load cycle? The answer is less clear than you might think. A traffic engineer would probably take it to be one vehicle crossing the floor one time. Chandler (1982), no doubt visualizing warehouse trucks, says it involves a vehicle travelling laden in one direction and returning unladen in the opposite direction. That seems clear enough for forklift loads, but what about a warehouse where rack loads control the design? Rack loads fluctuate but rarely make a complete swing from totally empty to fully packed. If anyone has developed a good method for counting load cycles in rack loading, I have yet to hear of it.

When evaluating load safety factors, remember that safety means different things in ground-level and elevated construction. When elevated floors fail, buildings collapse and people die. Because the consequences of underdesign are so severe, safety factors for elevated slabs are not left to the designer but are imposed by building codes.

Ground-supported floors, in contrast, cannot fall down and almost never fail catastrophically. Structural failure means the slab cracks under load and may settle to an objectionable degree. Such failure is undesirable, and we should try to prevent it, but it is clearly far less serious than structural failure in suspended, elevated floors.

TABLE 4.2
Load Safety Factors for Ground-supported Slabs

Safety Factor	Application
1.4	Non-critical and low-traffic areas with no impact loading and few load cycles
1.7	Important areas with many load cycles, where design variables are well controlled
2.0	Critical areas with many load cycles, where one or more design variables are not well controlled

Source: Adapted from Ringo and Anderson, 1992.

TABLE 4.3
Load Safety Factors to Prevent Fatigue Failure
(Chandler, 1982)

Safety Factor	Maximum Number of Load Cycles Over the Floor’s Lifespan
2.00	>400 000
1.96	400000
1.92	300000
1.87	240000
1.85	180000
1.82	130000
1.79	100000
1.75	75000
1.72	57000
1.70	42000
1.67	32000
1.64	24000
1.61	18000
1.59	13000
1.56	11000
1.54	8000
1.50	<8,000

We cannot take these comments as a license to ignore safety factors. We need them, and too high is always better than too low. But low safety factors can often be justified for ground-supported floors.

One final complication before leaving the subject: While most design methods assume you will pick a single safety factor, TR 34 recommends partial safety factors that are added to make a global safety factor (Concrete Society, 2016, 27-28). The first partial safety factor is for materials and ranges from 1.15 to 1.5. The second is for load type and ranges from 1.0 to 1.6. Thus, the global safety can be as low as 1.15 or as high as 3.1.

AREA OF LOADING

This matters in the analysis of concentrated loads. If a given weight is spread over a larger area of floor surface, it creates less tensile stress in the slab. Some design calculations use the area of loading in square millimetres or square inches. Other methods use the radius of the area of loading, which is the radius of a circle equivalent in area to the area of loading. Still others use what’s called the equivalent radius of the area of loading, which takes slab thickness into account and differs, usually by a small amount, from the actual radius.

It is easy to become confused about all this because the commonly used design methods are not consistent. Some methods use the actual area or radius and make the

necessary adjustments for the designer. Other methods use the effective radius and expect the designer to calculate it before using the equation of entering the chart.

Where the load comes from a single post on a thick, rectangular base plate, finding the area of loading is as simple as measuring the baseplate. But some situations are more complex.

In the case of wheel loading, the contact patch is hard to measure directly. If the wheel has a pneumatic tyre, the area of loading will be, almost exactly, the air pressure divided by the load. If the tyre is solid rubber or plastic—common on warehouse vehicles—the area will be smaller than for an equally loaded pneumatic tyre, but the exact size depends on the composition and thickness of the tyre material. The vehicle manufacturer may be able to provide details.

Where two concentrated loads lie close together—separated by no more than twice the slab's thickness—you can assume they both bear on a single area that includes the area between them. This condition occurs with back-to-back pallet racks and dual wheels on industrial trucks.

Rack and shelving legs normally rest on rectangular baseplates, and that fact creates both an opportunity and a risk with regard to area of loading. The opportunity is the option to specify a bigger baseplate, reducing stress within the slab. The risk is that the steel plate making up the baseplate may be too thin to do much good. To do much, the baseplate must be stiffer than the slab, but the thin sheet steel often used does not meet that requirement. Truth be told, most baseplates are designed not to spread load but to create a place for the anchor bolt. Unless you know the baseplate is stout and can justify relying on it, the safe approach is to use Equation 4.1.

$$A = (w + 2t)(d + 2t) \quad (4.1)$$

where

A = area of loading

w = width of rack leg or other upright

d = depth of rack leg or other upright

t = thickness of baseplate

Any unit of length measurement will work as long as it's the same for w , d , and t .

LOAD POSITION

Concentrated loads have different effects in different positions on the slab. A load located well away from the slab edge—called internal or interior loading—creates the least stress in the slab. The same load will produce more stress if located near the slab edge and yet more if located at a corner. The differences are substantial. Suppose we apply a 1 t load to a floor slab 150 mm thick. The sub-base is good, and the radius of the area of loading is 100 mm. According to Chandler (1982), that load in the internal position produces a flexural stress of 0.70 MPa. If we move that load to the slab's edge, the stress rises to 1.10 MPa—a 57% increase. If we move it to the corner, the stress reaches 1.28 MPa—83% higher than for internal loading.

At this point in the discussion, I should explain that the concrete floor industry has not reached a consensus on how to define *edge*. Everyone agrees that if a slab ends and there is nothing but empty space beyond, that's an edge. Almost everyone will agree that a full-depth joint within a floor, with nothing connecting the two sides, is also an edge. But what about joints that contain dowels or have reinforcement passing through them? What about sawn joints that rely on aggregate interlock to transfer load? What about cracks? Some designers treat all those as edges, while others don't. The Concrete Society, in TR 34, says 'loads at edges adjacent to joints are considered in the same way as those at true edges to be found at, for example, the perimeter of a building' (2016, p. 29). In contrast, the Australian T48 guide takes a different view:

In a jointed base, if adequate shear reinforcement (resulting in 75% joint effectiveness and ability to transfer at least 37.5% of the applied load...) is provided at the joint, the base thickness can be designed for the interior loading case.

(Cement Concrete and Aggregates Australia, 2009, p.38)
[In this context, base means concrete slab.]

You pay your money and you make your choice. As for me, I've seen enough load-related failures to make me believe that any break in a slab—joint or crack, dowelled or not—reduces the load capacity. Load transfer lessens that reduction but does not eliminate it.

Once we have defined *edge*, defining *corner* seems easy: the corner is where two edges meet. But here TR 34 introduces a surprising complication:

Although the theoretical load capacity at a true corner, as found at the perimeter of a building, is much lower than at a true edge, experience has shown that the actual capacity at a joint intersection appears to be as great as that at a joint, provided that there are the same conditions of joint opening and provision of dowels. It is therefore generally not necessary to consider potential loads at intersections provided that appropriate design considerations are applied to the single joints in the floor.

(Concrete Society, 2016, p. 29)

My own experience contradicts that. In my career, I've seen six ground-supported floors that failed under vehicle loading, and in every case, the deterioration began at corners, proceeding only later or not at all to the edges. Searching the literature for anything published that supports the TR 34 position, all I could find was an article from 1956 based on plaster models (Carlton and Berhmann, 1956). The writers reported unexpectedly low corner stresses that were only about half the edge stresses.

Uncertainty also hovers over the question of how far a load must be from an edge to qualify for the internal condition. Some people toss out an arbitrary dimension such as 1 m or 3 ft. ACI 360 says we need 4L—four times the radius of relative stiffness. TR 34 says 1L plus the radius of the loaded area. For warehouse floors, L typically ranges from 450 to 1450 mm (18–57 in). The lower number is for a 100-mm (4-in) slab on hard ground; the higher is for a 300-mm (12-in) slab on soft ground. If we apply that ACI 360 rule to the higher L value, we don't reach the internal load position till we get 5.8 m (19 ft) from the edge. That would mean that in a conventionally jointed floor, where joint spacings seldom exceed 6 m (20 ft), no part of the floor would be subject to internal loading. Everything would be edges

and corners! Even at the lower L value, a load would have to be at least 1.8 m (6 ft) from the edge to be considered internal. In contrast, the TR 34 rule gets us down to a more palatable range, from about 0.5 to about 1.5 m (20 in to 5 ft), assuming 100 mm (4 in) for the radius of the loaded area. I have no idea who's right, but I would argue that a precise answer is impossible because the edge effect must vary with the degree of slab curl, and nobody can predict that. Maybe the folks who arbitrarily pick 1 m have the right idea.

We can deal with the edge-and-corner problem in four ways:

- design the whole floor for the worst condition, which is usually corner loading but might be edge loading;
- avoid loading the slab edges and corners (hard to do where vehicle loads control the design but sometimes practical with racks and mezzanine posts);
- strengthen the slab edges by making them thicker or adding reinforcement to them;
- transfer load to adjacent slabs through dowels, tie bars, or reinforcement.

EFFECT OF NEARBY LOADS

Some concentrated loads—those from mezzanine posts, for example—are far enough apart that each one can be considered on its own. More often, however, loads must be analysed in combination.

If the distance between two loads, centre to centre, is no more than twice the slab thickness, you can treat them as one, adding the loads and including the space between them as part of the loaded area. If the loads are farther apart, normal practice is to determine the stress resulting from more demanding of the two and then adjust that figure for the effect of the second load. If both loads are identical, you start with the one in the more critical position. Edge loading is always more critical than internal loading, and corner loading is usually more critical than edge. With edge and internal loading, adjacent loads always increase stress, and the amount of increase diminishes with distance. But where the critical load occurs at a corner, adjacent loads can either raise or lower the stress, depending on their distance from the critical load, on the slab's stiffness, and on the subgrade support. The standard design methods provide ways to cater for adjacent loads, though in some cases, the treatment is more implied than explicit. Chandler (1982) is particularly clear on this subject.

SUBGRADE PROPERTIES

Because the subgrade ultimately supports all floor loads, its properties have a large effect on the structural design of the floor. You need to consider:

- subgrade modulus;
- settlement;
- heaving.

SUBGRADE MODULUS

Also called the modulus of subgrade reaction, this is a measure of the ground's ability to resist immediate elastic deformation under load. It is defined as the

TABLE 4.4
Subgrade Modulus and CBR for Typical Soils

Subgrade Quality	Description of Soil	Subgrade Modulus, MPa/m	Subgrade Modulus, lb/in ³	CBR, %
Excellent	Gravel and sandy gravel	82	300	25–80
Good	Sand, gravelly sand, silty sand, and clayey sand	54	200	10–40
Poor	Very fine sand, silt, and clay with plasticity index under 50	27	100	4–15
Very poor	Silt and clay with plasticity index over 50	14	50	3–5

pressure needed to deform the subgrade by a given unit distance and is expressed in MPa/m or pci (pounds per cubic inch).

You can measure the modulus of subgrade reaction directly by making a plate-bearing test on-site. Because no great precision is needed, many designers just estimate the value from a general description of the subgrade material. Table 4.4 shows typical values for various soil types.

Some soil engineers measure the California bearing ratio (CBR) instead of subgrade modulus. CBR values are widely used in roadbuilding and site paving. Table 4.4 shows typical CBR values alongside the values for subgrade modulus.

A higher subgrade modulus increases a floor's load capacity, but the effects are not the same for all types of loading. For block stacking, doubling the subgrade modulus will increase load capacity by about 40%. For concentrated loads, the same doubling of the modulus will increase load capacity by just 8–10%.

If the modulus of subgrade reaction is too low, the following steps can raise it:

- remove the subgrade and replace it with better material;
- stabilize the subgrade by working cement or lime into it;
- add a sub-base (see Tables 4.5 and 4.6);
- use vibrocompaction or dynamic compaction.

Where the subgrade modulus is extremely low, the only reasonable solution may be to give up on ground support and install piles.

Adding a sub-base has the same effect as raising the subgrade modulus but only for concentrated loads (see Tables 4.5 and 4.6). A sub-base does not help with uniformly distributed loads or block loading with aisles. A cement-stabilized sub-base is more effective than a granular one, but it costs more.

Vibrocompaction involves the insertion of a vibrating probe into the ground, producing columns of compacted soil. Dynamic compaction is similar in effect but is accomplished by dropping a heavy weight on the floor surface. After the columns have been compacted, the subgrade is covered with a thick sub-base called a load transfer platform. Though the system somewhat resembles a floor on piles, the slab is treated as ground-supported.

TABLE 4.5
Effect of Sub-base on Subgrade Modulus (Only for Concentrated Loads)

Sub-base Material	Sub-base Thickness	Effective Subgrade Modulus Where Original Modulus Is:				
		14 MPa/m (50 psi)	20 MPa/m (75 pci)	27 MPa/m (100 pci)	40 MPa/m (150 pci)	54 MPa/m (200 pci)
Granular	150 mm (6 in)	18 MPa/m (66 pci)	26 MPa/m (96 pci)	34 MPa/m (125 pci)	49 MPa/m (181 pci)	61 MPa/m (225 pci)
	200 mm (8 in)	22 MPa/m (81 pci)	30 MPa/m (111 pci)	38 MPa/m (140 pci)	55 MPa/m (203 pci)	66 MPa/m (243 pci)
	250 mm (10 in)	26 MPa/m (96 pci)	34 MPa/m (125 pci)	44 MPa/m (162 pci)	61 MPa/m (225 pci)	73 MPa/m (269 pci)
	300 mm (12 in)	30 MPa/m (111 pci)	38 MPa/m (140 pci)	49 MPa/m (181 pci)	66 MPa/m (243 pci)	82 MPa/m (302 pci)
	100 mm (4 in)	35 MPa/m (129 pci)	60 MPa/m (221 pci)	75 MPa/m (276 pci)	100 MPa/m (368 pci)	—
Cement-bound	150 mm (6 in)	50 MPa/m (184 pci)	80 MPa/m (295 pci)	110 MPa/m (405 pci)	—	—
	200 mm (8 in)	70 MPa/m (256 pci)	105 MPa/m (387 pci)	—	—	—
	250 mm (10 in)	90 MPa/m (332 pci)	—	—	—	—

TABLE 4.6
Subgrade Modulus Design Values

Soil	Raw Value from Plate-bearing Test	Design Value for Vehicle Loads	Design Value for Rack Loads and Block Stacking
Soft clay	30 MPa/m (110 pci)	30 MPa/m (110 pci)	14 MPa/m (50 pci)
Medium clay	62 MPa/m (230 pci)	62 MPa/m (230 pci)	22 MPa/m (80 pci)
Hard clay	127 MPa/m (470 pci)	127 MPa/m (470 pci)	38 MPa/m (140 pci)
Sandy clay	192 MPa/m (710 pci)	192 MPa/m (710 pci)	54 MPa/m (200 pci)
Silty sand	24 MPa/m (90 pci)	24 MPa/m (90 pci)	19 MPa/m (70 pci)
Loose sand	32 MPa/m (120 pci)	32 MPa/m (120 pci)	22 MPa/m (80 pci)
Dense sand	124 MPa/m (460 pci)	124 MPa/m (460 pci)	65 MPa/m (240 pci)

Source: Adapted from Walker and Holland (2016).

Up to now, this discussion has treated subgrade modulus as a single, unchanging property for any particular piece of ground, unaffected by the type of loading. And that is exactly how most design methods handle it. In a recent paper, Walker and Holland (2016) argue that this is not correct. They accept that a plate-bearing test will give a valid subgrade modulus for vehicle loading, which is short term. But for long-term loading, whether from racks or block stacking, they reduce the raw modulus to allow for soil consolidation below the surface layer. The adjustment depends

on the soil type, with clays treated differently from sands. Clays fare worse, with reductions of 55–72% (see Table 4.6). The first four soil types in the table are clays, and the last three are sands.

SETTLEMENT

The modulus of subgrade reaction describes the soil's short-term, elastic response to loading. That is the subgrade property we need to know to determine slab thickness in most design methods.

A subgrade under load also experiences long-term, plastic deformation called settlement. Slab movement caused by settlement is often many times as great as the short-term elastic deformation predicted by the modulus of subgrade reaction.

By its nature, long-term settlement is hard to predict from tests. Even geotechnical engineers with local experience can predict it only within broad limits.

Settlement is not hard to live with if it is uniform over the whole floor. Some floors have settled by more than 40 mm (1½ in) without causing any problems. The trouble-maker is differential settlement, either within the floor or between the floor and other parts of the building. It can cause wide cracks and faulting at joints and cracks. Good isolation joints minimize damage caused by differential settlement between the floor and other building elements. Differential settlement within the floor slab is a harder nut to crack. Heavy reinforcement or post-tensioning will reduce the distress but may not be a complete solution.

Though we can never eliminate settlement, these measures can reduce its ill effects:

- choose a site where little settlement is expected;
- remove the subgrade and replace it with better material;
- pre-load the subgrade for several months before laying the floor.

HEAVING

This is a serious problem with certain subgrade materials known as expansive clays. Many soils expand slightly when they get wet and shrink when they dry out, but expansive clays show this property in extreme form. In bad cases, the ground surface moves vertically by as much as 1m (3 ft). The problem is most acute in climates with marked dry and wet seasons. In places where expansive clay is widespread, geotechnical reports include a prediction of potential vertical rise (PVR) in millimetres or inches.

No easy solution exists, but all of the following have proven successful in some cases, either alone or in combination:

- two-way post-tensioning;
- reducing moisture changes;
- replacing the expansive soil;
- supporting the slab on piles and carton forms.

Two-way post-tensioning does not stop the movement but helps the slab keep its integrity as it moves up and down. Post-tensioned house slabs have become popular in

parts of the southern USA where expansive clays are widespread. The Post-Tensioning Institute publishes a guide, *Design of Post-Tensioned Slabs-on-Ground* (1980) with good information on expansive soil and the use of post-tensioning to deal with it.

Another approach, popular in Australia, is to minimize moisture changes under the floor. Wide roof overhangs help keep rain away from the building's foundation, while careful attention to landscape planting reduces drying caused by roots and wetting caused by irrigation. The Cement and Concrete Association of Australia (2003), in its recommendations for houses built on expansive soil, suggests keeping all plants at least 1.2 m (4 ft) from the floor slab. Lightly watered lawns are allowed beyond 1.2 m (4 ft). Trees and shrubs should be planted no closer to the house than 1.5 times their mature height (see Figure 4.2).

Other steps to minimize moisture changes include fixing any plumbing leaks right away and making sure that roof drains carry rainwater away from the building.

Removing the expansive clay is another possible solution—and a highly effective one, if you go deep enough. But, in many cases, huge amounts of material must be replaced.

Another highly effective solution, where money is plentiful, is to abandon ground-supported construction and replace it with a suspended floor on piles. Provided the piles go below the expansive layer, you can design this sort of floor just like any other slab on piles. You cannot build it like any other, however. Most pile-supported slabs are cast directly on the ground, even though they do not rely on the ground for long-term structural support. That will not work on expansive clay because swelling soil would lift the slab.

The answer is to pour concrete on corrugated paper forms, also called carton forms and void forms. When dry, the paper forms are strong enough to support the concrete's weight, but after they become damp, they disintegrate, leaving a void between the slab and the soil.

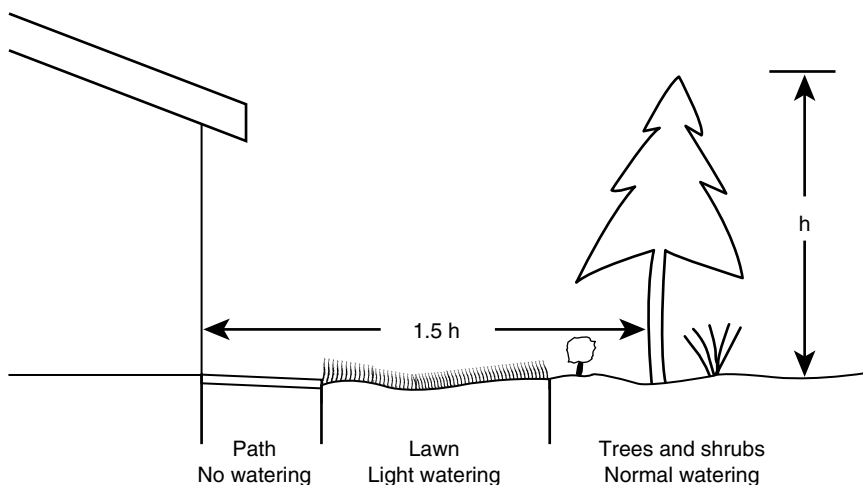


FIGURE 4.4 One way to deal with expansive clay is to control the landscaping near the floor.

Expansive clay is not the only cause of subgrade swelling. Frost heave is another. If you build a freezer without a ground heating system, the subgrade will freeze and an ice lens will form. The lens will grow year after year, eventually destroying the floor. Occupied buildings that are not freezers rarely suffer from this, but problems occur in vacant buildings, including buildings under construction.

A third, less common cause of subgrade heave is pyritic shale. This is a rock that swells not from moisture but from exposure to oxygen. As long as it stays intact under the ground, it does no harm. But when disturbed by construction activities, it starts to swell. The moisture-control measures that work against expansive clay are useless against pyritic shale.

SUB-BASES

Many floor designs include a sub-base between the subgrade and the slab. It can serve at least three purposes.

First, it reduces slab stresses by spreading concentrated loads over a larger area of the subgrade. In effect, the sub-base raises the modulus of subgrade reaction (see Table 4.5). But this only works for concentrated loads.

Second, a sub-base can provide a stable platform for construction traffic and for the erection of forms. This purpose often justifies a sub-base even where the working loads will be light.

Third, a sub-base can provide a free-draining layer and capillary break beneath the slab. Some designers choose a coarse, open-graded granular sub-base as a substitute for a vapour barrier, but there are risks to that approach. No granular sub-base will stop water vapour.

The most common sub-base material is compacted granular fill. Coarse, open-graded stone works well for drainage. All-in granular material, containing a mix of coarse and fine particles, is usually a better choice because it compacts well and can be graded smooth. All-in material goes by many different names: dense-graded aggregate (abbreviated DGA), aggregate base coarse (abbreviated ABC), road base, and crusher-run.

A few American designers specify a sub-base of rounded river gravel. This offers unsurpassed drainage and improved structural support because it conforms better to curled slabs. It is useless, though, as a base for construction traffic.

Lean concrete makes an excellent sub-base for all purposes except drainage. It contains much less cement and water than everyday concrete. The cement content is typically about 100 kg/m^3 (170 lb/yd^3). The mix is compacted and levelled with a vibrating roller. Lean concrete costs more than other sub-base materials but may allow an offsetting reduction in slab thickness.

SLAB THICKNESS

On most jobs, specifying the slab thickness is the most important structural decision. Of all the variables affecting a floor's structural capacity, thickness is the most powerful. If you double the subgrade modulus, structural capacity barely rises. If you double the concrete strength, the capacity also doubles, almost exactly. But if you double the thickness, we increase the capacity by a factor of about four.

Thicker slabs support more, but they also cost more and increase a floor's carbon footprint. If calculations lead to a slab thickness that seems excessive, consider the following changes to reduce thickness:

- improve the subgrade;
- thicken the sub-base (only effective for concentrated loads, and good for only modest gains);
- use stronger concrete;
- use post-tensioning to increase the concrete's effective flexural strength;
- use bigger baseplates under concentrated loads;
- add reinforcement and design for post-crack strength using rebar, wire mesh, or steel fibres.

CONTROLLING SLAB THICKNESS

Given the critical nature of slab thickness, you might expect it to be tightly controlled. You would be wrong. Most thickness specifications are unrealistic, and most floors are never tested for thickness. The few floors that are tested are usually found to be out of tolerance.

Some specifications set a minimum thickness while others set a target along with plus and minus tolerances, or just a minus tolerance with no upper limit. Both approaches have problems.

The problem with minimum-thickness specifications is that nobody takes them seriously. To meet a minimum thickness, a contractor must aim for a target value well above the minimum—about 40 mm (1½ in) higher. (I'll explain in a moment where that figure came from.) If the minimum thickness is specified at, say, 150 mm (6 in), a prudent contractor would need to plan for, and pay for, 190 mm (7½ in) of concrete. I have yet to see that happen. Often contractors will accept a minimum-thickness rule without complaint, but if you want to find out what they really intend to do, ask them how much concrete they plan on ordering. The answer is likely to reveal that their minimum and target thicknesses are the same, which cannot work.

The problem with target specifications is that the tolerances applied to them are too strict. They reflect what designers and owners would like to believe and not what floorlayers actually achieve.

BS 5606 allows plus or minus 10 mm (¾ in). ACI 117 is more generous, allowing minus 20 mm (¾ in) with no upper limit. ACI 117 also specifies that the mean thickness must not fall short of the target by more than 10 mm (¾ in) but that one appears achievable. Plus or minus 6 mm (¼ in) is another common tolerance.

Normal floors do not meet any of those specifications. In 1989, Armand Gustaferrero reported slab thickness results for seven ground-supported floors based on 2,111 cores (Gustaferrero, 1989; see. Table 4.7). Every floor had a mean thickness well shy of its specified target, with shortfalls ranging from 3 to 14 mm (0.10–0.55 in). Standard deviations ranged from 12 to 23 mm (0.47–0.90 in). The same year, Luke Snell and Robert Rutledge (1989) reported on a floor where 60 thickness readings gave very similar results: a mean 9 mm (0.34 in) short of the target, and a standard deviation of 19 mm (0.73 in)

TABLE 4.7

Slab Thickness Results from Seven Ground-supported Floors (Gustaferro, 1989), Listed in Order of Increasing Standard Deviation

Number of Cores	Target	Mean	Mean - target	Standard Deviation
75	152 mm (6.00 in)	140 mm (5.50)	-13 mm (-0.50 in)	12 mm (0.47 in)
153	152 mm (6.00 in)	143 mm (5.62)	-10 mm (-0.38 in)	14 mm (0.57 in)
427	152 mm (6.00 in)	145 mm (5.72)	-7 mm (-0.28 in)	15 mm (0.60 in)
862	102 mm (4.00 in)	99 mm (3.90)	-3 mm (-0.10 in)	15 mm (0.60 in)
404	152 mm (6.00 in)	138 mm (5.45)	-14 mm (-0.55 in)	18 mm (0.70 in)
111	102 mm (4.00 in)	93 mm (3.68)	-8 mm (-0.32 in)	20 mm (0.77 in)
79	102 mm (4.00 in)	92 mm (3.64)	-9 mm (-0.36 in)	23 mm (0.90 in)

Let that sink in. The average floor in Gustaferro's survey had a mean thickness 9 mm (0.36 in) below its target value and a standard deviation of 17 mm (0.66 in). If the thickness readings follow a normal distribution, we can make the following predictions about that average floor:

- 61% of its area will violate the BS 5606 specification of plus or minus 10 mm; 48% will be too thin, and 13% will be too thick.
- 26% of its area will violate the ACI 117 tolerance of minus 20 mm—all on the thin side since ACI 117 does not impose an upper limit.
- 7% of its area will be more than 25 mm below the target thickness.
- 5% of its area will be more than 37 mm below the target thickness.

That last prediction is significant because in construction a property is often considered in tolerance if no more than 5% of the readings exceed the specified limit. It's why I said, when discussing minimum-thickness specifications, that a prudent floorlayer would have to aim about 40 mm (1½ in) above the minimum thickness to be confident of success.

Gustaferro, Snell, and Rutledge wrote their articles over 30 years ago, and some people argue that practices have improved since then. Maybe so, but my own experience suggests that the improvements have been modest. In 2013, I was involved in a large warehouse project where the floor was tested for thickness at 105 locations. The floorlayer had a good reputation and used the latest laser-controlled tools to grade the sub-base and screed the concrete. The target thickness was 254 mm (10 in). The test results gave a mean of 256 mm (10.08 in), slightly higher than the target and better than any floor in Gustaferro's survey. But the standard deviation was 12 mm (0.48 in), practically the same as Gustaferro's best result and not nearly good enough to satisfy BS 5606 or ACI 117.

Where do we go with this information? For a start, we should stop writing specifications that no normal floor can satisfy. But what do we replace them with? This is what I do:

- Target thickness shall be x (fill in the design value, in mm or in).
- Mean thickness shall be at least $x - 10$ mm ($x - \frac{3}{8}$ in).

- Standard deviation shall be at most 14 mm (0.55 in).
- Mean and standard deviation shall be determined by core drilling or impact echo device as described in ACI 117.

My recommendations for mean thickness and standard deviation are based on what typical floorlayers actually achieve. Whether those limits are good enough for the design methods we now use is another question, which I have no answer for. Here is how an American organization of concrete contractors addresses that question:

Based on current practices and an analysis of as-built data, designers are cautioned that specifying a nominal 4 in slab thickness means the Average will be about 3¾ in with the lowest value at 2½ in. If this is not acceptable, the specified slab thickness should be increased.

(American Society of Concrete Contractors, 2012)

BUILDING LOADS

Many authorities recommend that ground-supported floors be structurally isolated from all other building elements. ACI 360 says ‘It is important to isolate the slab from anything that could restrain contraction or expansion’. That is good advice because a floor so built is easier to analyse and behaves more predictably.

It is not always practical, however. By necessity or choice, designers often rely on a ground-supported floor to resist stresses from other building elements. Examples include but are not limited to:

- horizontal forces from columns and perimeter walls;
- forces, both downpush and uplift, on raft foundations;
- uplift from column footings;
- horizontal forces from retaining walls.

HORIZONTAL FORCES FROM COLUMNS AND PERIMETER WALLS

In most buildings, the upright supports, whether columns or bearing walls, rest on their own footings and exert almost all their force in the downward direction. But horizontal forces also exist from wind and earthquakes. The floor offers a convenient anchor to resist those horizontal forces, but using the floor in this way can increase the likelihood of shrinkage cracks and unusually wide joints.

In portal-frame buildings, it’s normal to use the floor as tension tie to stop the legs’ spreading. This practice can lead to extremely wide joints unless the floor is continuously reinforced across its whole width.

RAFT FOUNDATIONS

Also called mat foundations, these are ground-supported floors that support the whole building. In most buildings, each column rests on its own footing, which is separate from the floor. But if the column loads are heavy enough, or the soil is weak

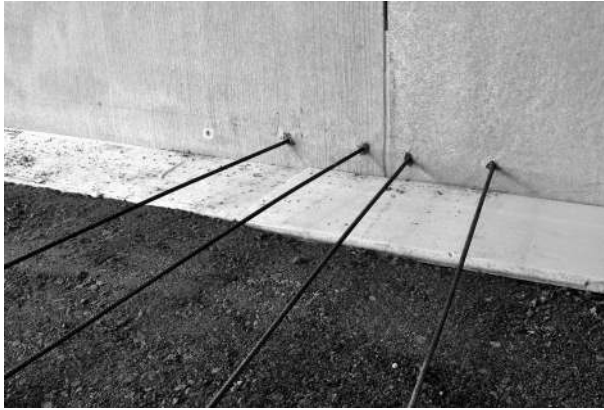


FIGURE 4.5 Wall ties. The reinforcing bars will anchor the precast concrete wall to the floor slab. This practice allows a cheaper, lighter wall panel but can cause cracks in the floor.

enough, it can become economically viable to combine all the footings into one big raft. The raft foundation usually does double duty as the ground-level floor.

The floor in a clad-rack building is a raft foundation, unless designed as a suspended slab on piles.

Raft foundations can be designed along the same lines as other ground-supported slabs, with a few differences. Unlike ordinary floors, rafts are normally subject to all the code requirements for foundations. Those requirements may include rules for minimum reinforcement and clearance between ground and reinforcing steel. The use of calcium chloride as an accelerator is usually off the table due to strict limits on chlorides in the concrete. Wind, snow, and seismic loads need to be allowed for, and some of those loads may create uplift.

UPLIFT FROM COLUMN FOOTINGS

This is unique to regions that get extremely high winds. Wind loading on a warehouse can lift the interior columns. In most places, the normal column footings are adequate to resist such uplift. But in and around Miami, USA, a recent change in the building code increased the design wind load so much that huge, costly footings would have been needed. The solution is to put a mat of rebar, called head steel, in the floor slab around each column. The slab is not structurally tied to the footing but will resist footing uplift.

RETAINING WALLS

Designers often rely on the floor slab to resist horizontal stress from the retaining walls. That practice simplifies the design of the wall and complicates the design of the floor.

In warehouses, the retaining walls around the dock leveller pits are notorious crack inducers. Some designers reduce the risk by eliminating any structural

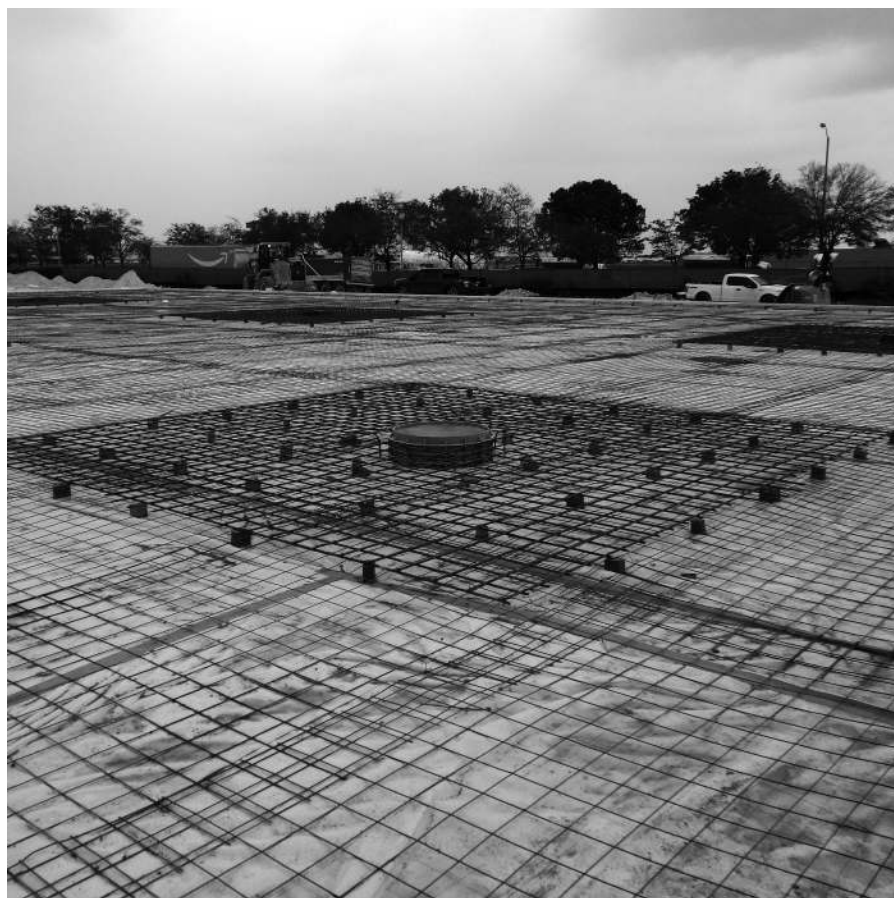


FIGURE 4.6 Head steel to resist column uplift on a job near Miami, Florida.

connection between the slab and the walls, but then, they have to find another way to restrain the walls.

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5 Structural Design of Suspended Floors

A suspended floor rests on other building elements. Most suspended floors are on the upper storeys of multi-level building and are supported by columns, beams, or walls. Other suspended floors are at ground level, supported by piles. But most floors at ground level are ground-supported, not suspended.

Suspended floors and ground-supported floors are usually designed on fundamentally different structural principles. As we saw in Chapter 4, most design methods used for ground-supported floors rely on the concrete itself to resist bending. Reinforcement is optional and serves to control cracks rather than to increase structural capacity. Suspended floors, in contrast, always include structural reinforcement or prestress. The concrete is used to resist compressive stress and shear; tensile stress is resisted by the reinforcing or prestressing steel.

Unlike most ground-supported floors (raft foundations are the chief exception), suspended floors are an integral part of the building structure. For that reason, they are covered by the structural codes: Eurocode 2 in Europe and ACI 318 in America. Anyone who wants to design a suspended floor must understand the applicable code.

This chapter is no more than a brief introduction to the structural design of suspended floors. A full treatment would call for a lengthy book of its own and a more qualified writer. What I try to do here is present the basic ideas for readers who are not themselves structural engineers and discuss some issues that the building codes don't.

TYPES OF SUSPENDED FLOORS

Suspended slabs vary more widely than ground-supported floors. The most basic division is between one-way and two-way floors. A one-way floor transfers load to its supports in one direction only. A two-way floor transfers load in two perpendicular directions. According to the structural codes, any slab with a high enough aspect ratio (length divided by width) must be treated as one-way. But even a square panel is one-way if it contains structural reinforcement or prestress in one direction only.

Two-way floors can be built with less material, but one-way floors offer two advantages. Their length perpendicular to the span is unlimited. And in residential and light commercial construction where floors normally rest on walls rather than columns, one-way floors require fewer bearing walls. The nonbearing walls can be lighter and cheaper and are more easily provided with doors and windows.

Going beyond that basic division, we can consider the following structural types:

- one-way slabs;
- one-way joist floors;

- one-way precast floors;
- two-way beamless floors (subdivided into flat plates and flat slabs);
- two-way floors on beams;
- composite steel-deck floors;
- other composite floors;
- ground-level floors on piles.

ONE-WAY FLOORS

In a one-way concrete floor, each suspended span, normally rectangular in plan, is supported on two opposing sides by beams or walls (see Figure 5.1). The slab spans in one direction between the two beams or walls.

The simplest one-way floor, common in residential construction, consists of a slab supported on each end by bearing walls. A slightly more complicated system puts the slab on beams that are supported in turn by columns or walls. In beam–girder systems, the slab transfers its load to beams, which in turn transfer the load to girders perpendicular to the beams.

The primary reinforcement or prestress in a one-way slab runs only in the direction of the span. Most one-way slabs contain secondary reinforcement that runs perpendicular to the span to control nonstructural cracks.

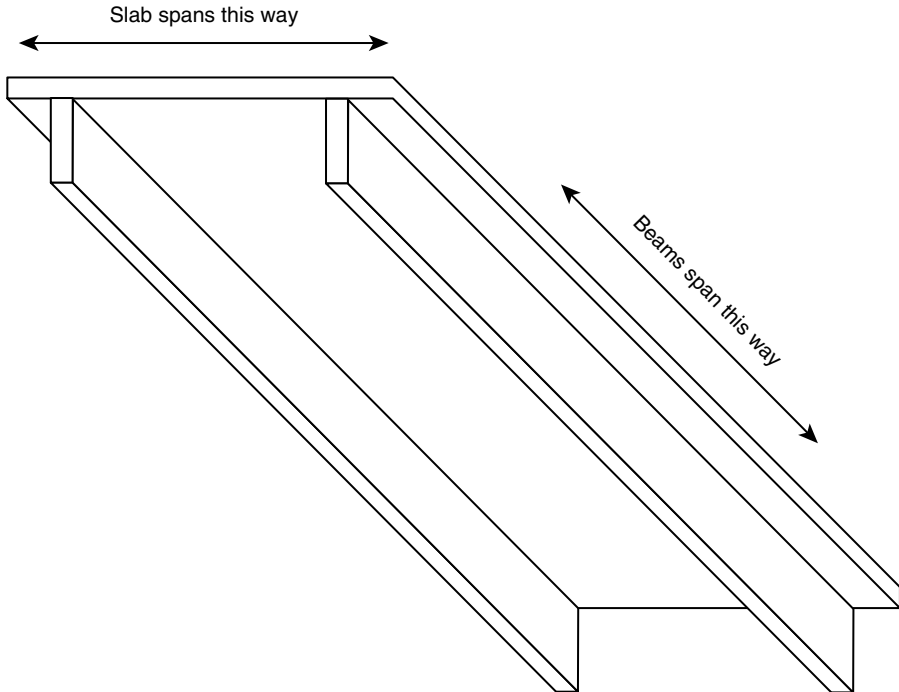


FIGURE 5.1 One-way suspended slab on beams.

Some one-way slabs, particularly in slab–beam–girder systems, get structural reinforcement in the secondary direction to resist bending in that direction. But the amount of reinforcement is always less than that in the span direction, and it is not considered to add to the load-carrying capacity of the slab.

One-way slabs can be designed efficiently for spans of up to 6 m (20 ft) between beams. There is no limit to the slab's length in the other direction, at right angles to the span.

ONE-WAY JOIST FLOORS

If the beams supporting a one-way slab are close—less than about 3 m (10 ft) apart—they are known as joists. Joists can be separate elements, made of steel, timber, or precast concrete, but they are often cast monolithically with the floor slab (see Figure 5.2). Some slabs with monolithic joists are called pan-joist floors because they are cast on steel forms called pans.

The load capacity of a joist floor is determined mainly by the depth and spacing of the joists. Joists are typically 150–500 mm (6–20 in) deep and about 600 mm (2 ft) apart. To keep costs down, it makes sense to base the design on ready-made forming systems wherever possible, and that limits the dimensions.

Joist floors can span up to 14 m (45 ft) in the direction of the joists. They can be designed for heavy loads and small deflections, making them a good choice for many industrial applications.

ONE-WAY PRECAST FLOORS

These are made wholly or partly of precast concrete.

To understand precast floors, it helps to consider how structural engineers analyse one-way floors in general. When designing a cast-in-place one-way floor, the engineer imagines it as a series of parallel beams 1 m wide (American engineers assume a beam width of 1 ft or 1 in). A precast floor takes that concept literally, making a floor of separate beams laid side by side.

Precasting offers several advantages. The units can be mass-produced, reducing costs and possibly providing better quality control. Because the units are made in a

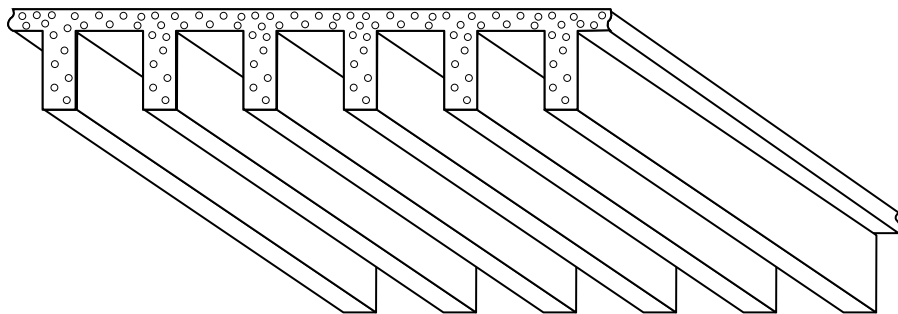


FIGURE 5.2 Suspended slab with integral joists.

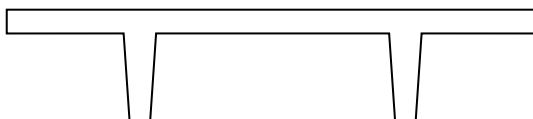


FIGURE 5.3 Section of precast double tee.

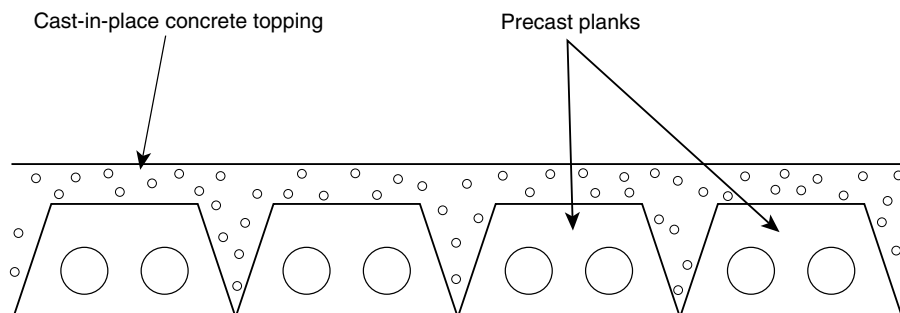


FIGURE 5.4 Precast concrete planks.

factory, manufacturers can use techniques, such as pre-tensioning and steam-curing, that are impractical on building sites.

Some precast units—tees and double tees—incorporate the finished floor surface (see Figure 5.3). They are only suitable where numerous wide joints are acceptable, which rules out many applications. Double tees are widely used in multi-storey car parks. Other precast units—planks—are meant to get a cast-in-place concrete topping (see Figure 5.4). Hollowcore planks have longitudinal holes to reduce weight. They typically come in widths of 1.2 and 2.4 m (4 or 8 ft) and thicknesses of 150–400 mm (6–16 in).

The topping over planks is typically about 60 mm (2 1/2 in) thick. It may contain light reinforcement for crack control. But if the topping will be left exposed, expect to see a crack in the topping over every seam between planks, regardless of reinforcement. Sawing joints over the seams will help control cracking.

Double-Ts can reach spans of 24 m (80 ft). Planks are more limited, with spans seldom exceeding 8 m (26 ft).

The precast industry makes a wide range of tees and planks for suspended floors. Where possible, designs should be based on standard units.

TWO-WAY BEAMLESS FLOORS

These floors rest directly on the building columns or on piles in the case of ground-level suspended floors. They are divided into two sub-types: flat plates and flat slabs.

Flat Plates

The flat plate is the simplest two-way floor, being of constant thickness throughout (see Figure 5.5). Its chief advantage is ease of construction. Formwork is easy to

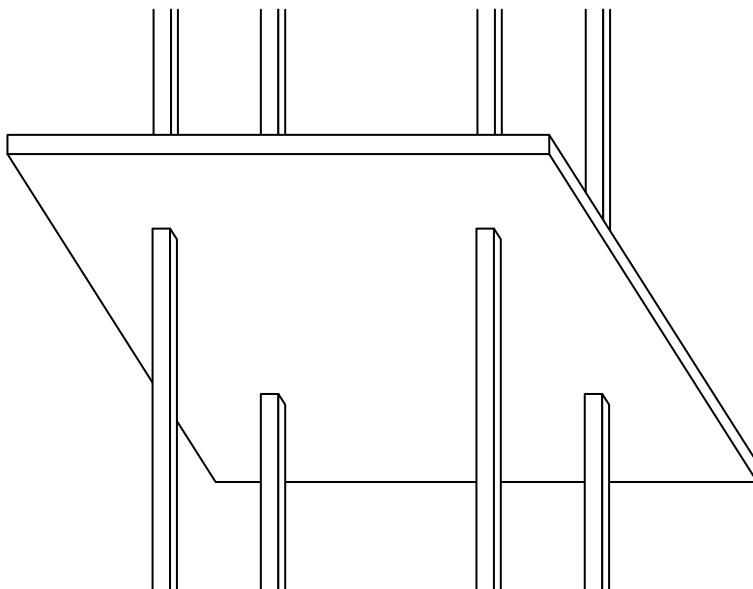


FIGURE 5.5 Flat-plate floor.

erect because the soffit (the floor's underside) is flat. Since formwork can account for more than half the cost of a floor, a design that allows simple forms has broad appeal.

Another advantage is that flat plates minimize storey height. Because there are no beams, girders, or thickened sections under a flat plate, the overall floor thickness is less than with any other type.

Drawbacks include:

- inefficient use of materials, since the whole floor must be as thick as its most highly stressed part;
- the potential for large and unpredictable deflections. Taylor and Heinman (1977) report on flat-plate floors that deflected several times the predicted amount. Flat plates are not a good choice for floors that must be very level.

Flat plates make sense for lightly loaded floors with clear spans of up to 9 m (30 ft) in both directions. They are widely used for residential, office, and institutional floors. They are usually cast in place, but in lift-slab construction, they are precast. Lift slabs are laid at ground level and then jacked up to their final elevated positions. Most lift slabs are designed as flat plates to simplify their construction.

Flat Slabs

The flat slab differs from the flat plate in having thickened sections over the columns or piles. The thickened sections resist punching shear. The flat slab is harder to build but uses materials more efficiently than the flat plate.

Compared to similar flat plates, flat slabs can support heavier loads over wider spans. They are sometimes used in factories and warehouses where the loads are

too heavy for an efficient flat-plate design. For very heavy loads, however, most designers would switch to a one-way or two-way floor on beams.

Like flat plates, flat slabs are subject to deflections that are high and hard to predict. Where the user needs a very level surface, any beamless floor is likely to disappoint.

Flat slabs can be practical for spans of up to 10 m (34 ft) in both directions.

TWO-WAY FLOORS ON BEAMS

In these designs, each suspended panel is supported on all four sides by beams or walls.

Figure 5.6 shows a basic two-way floor with beams on every column line. The supports could just as easily be bearing walls. Some designers use intermediate beams between the beams on the column lines. If the spacing between the intermediate beams is less than about 3 m (10 ft), the result is a waffle slab—similar to a one-way joist floor but with the joists running in two directions.

Two-way floors on beams generally deflect less than other suspended floors over similar spans. Waffle floors have a particularly good record for stiffness. This makes them a good choice for users who demand a high degree of floor levelness. But no suspended floor is likely to be as level as a ground-supported floor built with equal care.

Two-way floors on beams can be designed for heavy loads and long spans. Waffle slabs can economically span up to 15 m (50 ft) in both directions.

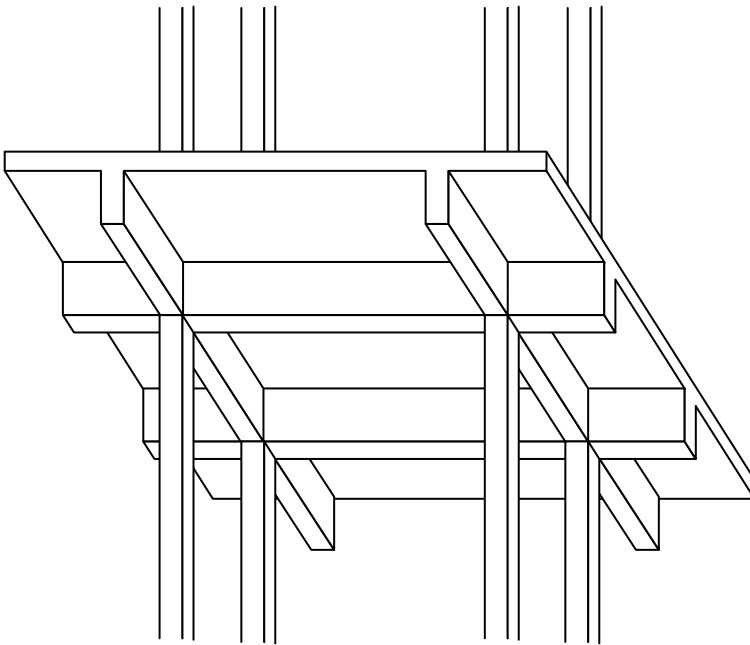


FIGURE 5.6 Two-way floor on beams.

The main drawback to these floors is that they are complicated to build. Ready-made forms can reduce the difficulty and cost.

COMPOSITE SLABS

These are one-way slabs laid on a deck made of corrugated sheet steel. The concrete doesn't just sit on top of the deck but is tightly connected to it, usually through dimples pressed into the steel. The dimples work like the deformations on rebar, connecting concrete and steel to make a composite structural element. The deck serves two purposes: it is both a leave-in-place soffit form and a layer of bottom reinforcement (Figure 5.7).

These floors go by several names. The Steel Deck Institute calls them composite steel floor deck-slabs, which is quite a mouthful. Out on the jobsite, they are often known as slabs on deck. That last term, though valid and concise, can be misleading—because not every slab on deck is composite. There are also noncomposite floors in which the steel deck serves only as a soffit form. Such floors are designed as normal slabs with internal reinforcement. The steel deck under a noncomposite slab is called a form deck, and it lacks the dimples that create composite action.

In the UK, BS EN 1994 (Eurocode 4) covers composite slabs. UK designers can get extra help from *Composite Slabs and Beams Using Steel Decking: Best Practice for Design and Construction*, published by the Metal Cladding & Roofing Manufacturers



FIGURE 5.7 Composite slab under construction in an office building. The corrugated steel deck is both soffit form and bottom reinforcement. The wire mesh will be laid in a single layer to control shrinkage cracks. Note the shear studs, like big nails, sticking up in rows. They provide composite action between the slab and the structural steel frame.

Association (Rackham et al., 2009). In America, while composite slabs remain nominally under the control of ACI 318, the American Concrete Institute has delegated responsibility to the Steel Deck Institute, which publishes the *Standard for Composite Steel Deck-Slabs* (Steel Deck Institute, 2012).

A word about slab thickness: in this book, and in most but not all discussions of composite slabs, thickness means the dimension from the top of the deck flutes to the floor surface.

Reinforcement in Composite Slabs

Composite steel-deck slabs contain three distinct kinds of reinforcement: positive, negative, and nonstructural. Positive reinforcement resists positive moments (sagging). Negative reinforcement resists negative moments (hogging). Nonstructural reinforcement is for nonstructural cracks—cracks that occur for any reason other than positive or negative moments. Most nonstructural cracks are caused by temperature changes and drying shrinkage.

Positive reinforcement consists of the steel deck, sometimes accompanied by rebar or wire mesh just above the deck.

Negative reinforcement normally consists of short lengths of rebar placed high in the slab, centred over the structural supports. Not every composite slab needs negative reinforcement. If the floor is a simply supported span—a single span with a support at each end—there is no negative moment to worry about. Floors with multiple spans experience negative moments over the supports, but the designer may choose to ignore them and design the floor as a collection of simply supported spans. Cantilevered spans always need negative reinforcement.

Nonstructural reinforcement takes several forms. In America, the Steel Deck Institute (2012, 17) allows these four options for nonstructural reinforcement:

- Wire mesh or rebar providing steel equal to $59 \text{ mm}^2/\text{m}$ ($0.028 \text{ in}^2/\text{ft}$) in two perpendicular directions, where the concrete thickness is less than 79 mm (3.1 in);
- Wire mesh or rebar providing steel equal to 0.075% of the slab's cross-sectional area (above the flutes) in two perpendicular directions, where the slab thickness is 79 mm (3.1 in) or more;
- Steel fibres at $14.8 \text{ kg}/\text{m}^3$ ($25 \text{ lb}/\text{yd}^3$), regardless of slab thickness;
- Macrosynthetic fibres at 2.4 m^3 ($4 \text{ lb}/\text{yd}^3$), regardless of slab thickness.

The requirement of $59 \text{ mm}^2/\text{m}$ ($0.028 \text{ in}^2/\text{ft}$) can be met with 6x6, W1.4xW1.4 wire mesh, which is a standard size in America. It and the other minimum requirements are probably good enough for slabs that get floorcoverings, where crack width doesn't matter much. They may not be good enough for exposed slabs, however.

UK rules are different. There the Metal Cladding & Roofing Manufacturers Association says never to use anything less than A142 wire mesh (Rackham et al., 2009, 30). On slabs less than 190 mm (7.4 in) thick, A142 wire mesh will provide more steel than the American 0.075% rule. Where slab thickness is over 190 mm (7.4 in), the American rule provides more steel.

In the special case of a multispan composite slab that is designed as if it were a collection of simply supported spans, BS EN 1994-1-1 requires 0.2% steel—rising

to 0.4% if the slab is shored during the pour. Presumably, this is meant to serve as both negative and nonstructural reinforcement.

Fibres are also used in the UK as nonstructural reinforcement in composite slabs, but guidance is hard to find beyond the recommendations of the fibre companies.

Limitations

Composite slabs are cheap and easy to build, which explains their popularity. They work well in buildings where the floors are covered, the traffic is light, and levelness doesn't matter. But they don't work everywhere due to at least three serious limitations:

- When built with code-minimum nonstructural reinforcement, they develop wide cracks that may be unacceptable in an exposed concrete floor (see Figure 5.8.).
- They are subject to deflections that are hard to predict and can be large.
- They cannot support forklifts and similar industrial vehicles.

The first two can be mitigated. Increasing the reinforcement beyond the code minimum will reduce crack width. Be warned, though, that it may take a lot of reinforcement to keep cracks at hairline width. Shorter spans and stiffer framing will reduce deflections.

The third limitation, in contrast, appears to be non-negotiable. The Steel Deck Institute (2012, 15) says this:

Composite floor deck is not recommended as the only concrete reinforcement for use in applications where the floor is loaded with repeated lift truck (forklift) or similar heavy wheeled traffic.

The problem is not the vehicle weight. It's the dynamic effects of accelerating, braking, and turning, which destroy the bond between concrete and steel deck.

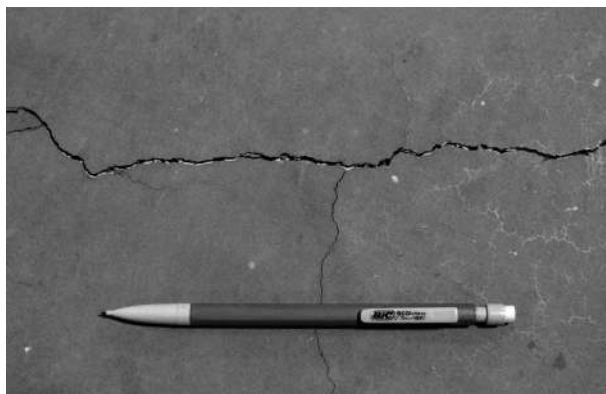


FIGURE 5.8 Typical shrinkage crack in a composite slab designed with code-minimum reinforcement.

GROUND-LEVEL FLOORS ON PILES

These do not really form a separate structural type. They are usually designed as flat plates or flat slabs, but one-way or two slabs on beams are also possible.

What distinguishes pile-supported floors from other suspended floors is their location at ground level. They are normally cast right on the ground, like ground-supported floors. They usually don't need soffit forms, and you can space the structural supports—the piles—without concern for how the space below will be used.

No one starts out wanting to build a pile-supported slab. A ground-supported slab is always preferable, and designers turn to piles only when the ground cannot adequately support the intended loads.

Floors on piles are always designed as suspended slabs, with the piles as the structural supports. Some engineers also take into account the contribution of the ground between the piles, which may give some support even if it cannot carry the whole load. That can be tricky, though, because differential settlement may alter the support conditions over time.

Most pile-supported slabs are reinforced with two mats of steel—generally bars, but sometimes wire mesh. Some are post-tensioned. Recently, more and more pile-supported floors are being reinforced with steel fibres—sometimes in combination with rebar, and sometimes on their own. This practice is still controversial, and some people say it's not allowed by the structural codes. Destrée and Mobasher (2022) offer a powerful argument in defence of the fibre-only approach, which they call the Belgian design.

It is usual to install the piles on a square grid, with piles spaced about 3 m (10 ft) apart. That keeps the spans short, simplifying the design and limiting deflection. Other patterns are possible and often make sense where fixed, concentrated loads control the design. Some pallet-rack warehouses are designed with rows of piles directly under the back-to-back rack legs, where the heaviest loads occur.

CHOOSING A FLOOR TYPE

Choosing a floor type is one of the most important decisions in designing a suspended floor. The choice depends on many factors, including:

- span (see Table 5.1);
- loading;
- need to control deflections;
- availability of formwork.

Designers must strike a balance between material and labour costs. Some elegant designs use little material but require complicated forms that are costly to build. Simple one-way slabs, flat plates, flat slabs, and slabs on metal decks are the workhorses of the suspended-floor world, largely because they are easy to build. When a more complicated floor type is needed, it should be based on ready-made formwork if possible.

Local custom plays a big part in the choice of floor type. If a design is unfamiliar to the local builders, it often costs more to build.

THE DESIGN PROCESS

Designers of ground-supported floors can choose between many design methods, or just choose a design based on experience. In contrast, designers of suspended floors are practically obligated to follow their country's structural code. In America, the national code for reinforced concrete structures, including suspended floors, is ACI 318. The UK equivalent used to be BS 8110, but BS EN 1992-Eurocode 2 has replaced it. Unlike the evolutionary changes that occurred from time to time in BS 8110 (and ACI 318), the switch to Eurocode 2 marked a sharp break in many ways. That's something to keep in mind when reading books and articles that predate the switch.

A few general comments apply to all the design methods commonly used for suspended floors. These are the main considerations:

- the floor's flexural strength, which is different from the concrete's inherent flexural strength;
- shear strength;
- control of deflection;
- control of nonstructural cracks from thermal contraction and drying shrinkage.

Most structural engineers start by designing for flexural strength—the floor's ability to support its loads. They then check the design for shear strength, deflection, and crack control.

The last two considerations—control of deflection and cracks—typically fall under the heading of 'serviceability' in books on structural engineering. I prefer to avoid that term in floor design, however, because it takes far more than control over deflection and cracks to make a floor serviceable. Real serviceability depends on flatness, wear resistance, and other factors that have little to do with structural design.

The process of structural design typically goes like this:

1. Collect information on the floor's live load.
2. Decide on the floor span, which may be controlled by the general building layout, or by the need to use the space under the floor.
3. Decide on the structural type (flat plate, waffle slab, etc.).
4. Design the floor for flexural strength, with a safety factor at least as great as required by the structural code.
5. Check the design for shear strength. Laminar shear is very unlikely to be a problem but punching shear at columns can be.
6. Calculate deflections and ensure that they are within allowed limits.
7. Ensure that the floor has enough reinforcing steel to control drying-shrinkage and thermal-contraction cracks.

Sometimes, there are shortcuts after step 3. Where the design relies on standardized products such as precast planks, the manufacturer normally supplies information on what size units to order for the desired combination of load and span. Designers of composite slabs can get help from the makers of steel decks who have design tables based on load tests.

DESIGN CONSIDERATIONS

In the rest of this chapter, we look at some of the more important factors affecting the structural design of suspended floors:

- flexural strength;
- shear strength;
- deflections;
- drying-shrinkage and thermal-contraction cracks;
- loading;
- spans;
- concrete strength;
- reinforcing steel;
- prestress;
- formwork.

FLEXURAL STRENGTH

The primary requirement for any suspended floor is flexural strength—the ability to resist bending stress. Every suspended floor needs flexural strength to support its own weight and all applied loads, along with a safety factor.

Bending induces both compressive and tensile stresses in various parts of the floor. Because of this, flexural strength involves both compressive strength and tensile strength.

Plain concrete has some inherent flexural strength (see Chapter 7), but the designers of suspended floors rarely give it much thought. (It does matter in ground-supported floors, which are designed on different principles.) The important thing is the flexural strength of the whole floor, which consists of concrete and steel working together. The concrete resists the compressive stresses and the steel resists the flexural stresses. This means that for concrete, the critical property is compressive strength, while for steel, it is tensile strength.

The structural codes allow several methods for determining flexural strength. But with any method, these are the main variables to consider:

- the type of floor (flat plate, one-way, etc.);
- the span or distance between structural supports;
- continuity across structural supports;
- compressive strength of the concrete;
- tensile strength of the reinforcing steel;
- slab thickness;
- location and amount of reinforcing steel.

A good design combines these variables in a way that is safe, economic, and in conformity with the applicable structural code.

SHEAR STRENGTH

The structural codes require designers to check suspended floors for shear. There are two forms to consider, laminar and punching. Laminar shear occurs when an upper layer of the floor slab tries to slide relative to a lower layer. Imagine a floor made of sheets of paper piled high. As you press down on the floor, each sheet would slide slightly on the one beneath it. That sliding is laminar shear.

Floor slabs almost never fail in laminar shear because they are so thin. Shear stress develops, but the concrete is strong enough to resist it. In contrast, the thick beams that support some floors can develop shear stress that exceeds concrete's modest shear strength. The usual solution is vertical reinforcing bars called stirrups.

Punching shear is a different matter and sometimes controls the floor design. The worst case occurs near the columns in a flat-plate floor. Designers deal with punching shear by adding reinforcement or by thickening the slab over the columns (turning a flat plate into a flat slab, for example). Thickened sections over columns are sometimes called shear panels.

DEFLECTION

This is the bending of a suspended floor under load. It is usually expressed as the ratio of greatest vertical displacement to span. Downward bending occurs between structural supports and is called sagging. Upward bending occurs over supports and is called hogging. We limit deflection, or try to, for two reasons.

The first reason involves surface levelness. In an industrial building, a badly deflected floor may not be level enough for some materials-handling systems, especially those developed for ground-supported slabs, where deflections are negligible. In an office, it may be hard to set up movable partitions on a floor with large deflections.

The second reason involves psychology: users lose confidence in a floor with large, obvious deflections. They may be right to worry, for severe and growing deflection can be a sign of imminent collapse. But even when a structural engineer certifies that a sagging floor will not fall down, people may not trust it.

How much deflection is too much? The traditional rule states that deflection from live load should not exceed $1/360$ of the span. By this rule, a floor spanning 10 m (33 ft) could deflect by 28 mm (1.1 in). That much deflection would not be acceptable in some modern warehouses and offices. Some floors have been designed for deflections as small as $1/2000$. On the other hand, deflections greater than $1/360$ are tolerable for some applications.

Structural codes provide guides for predicting deflection. For some standard designs, the structural engineer is allowed to specify a minimum thickness instead of calculating the deflection. Following the code does not guarantee success, however. One problem is that some users require a more level floor than the codes aim for.

A more fundamental problem is that deflections vary hugely and cannot be predicted with much accuracy.

Cracking is the main reason we cannot accurately predict deflection. Uncracked concrete deflects predictably, but we can rarely count on getting it. Reinforced concrete design is based on the premise that concrete has negligible tensile strength and will crack in zones of tension. But in fact concrete has some tensile strength. Sometimes, it cracks in tension, and sometimes, it does not. The location and number of the cracks affect how the slab deflects.

Suppose two floors are built to the same design for the same usage but under different conditions. The first job takes place in cool weather. It is ahead of schedule, so forms and shores stay in place for several weeks. The concrete ages for many months before any substantial loads are put on it. The second job takes place amidst a heat wave. It is behind schedule, so forms and shores are snatched away at the earliest moment allowed under the contract. Building materials are stacked on the floor, and the user moves in as soon as possible.

The first floor would almost certainly have fewer cracks and less deflection than the second. Both floors would have the same ultimate strength. If loaded to the point of collapse, both would have cracked and their tensile strength would be controlled by the reinforcing steel. But in normal use, the first floor, with fewer cracks, would be stiffer.

If adherence to the structural codes does not always protect against excessive deflection, what can we do? For some floor uses, nothing needs to be done because large deflections cause no trouble. No one is likely to notice deflection in a multistorey car park. For floors where large deflections would be objectionable, there are several ways to improve the odds.

The choice of structural type affects deflection. Two-way beamless floors and composite slabs are generally not good choices where deflection must be tightly controlled. Slabs on beams work better. One-way joist systems and two-way waffle slabs have the best record for small deflections.

Another way to control deflection is to use prestress instead of steel reinforcement. Prestressed floors do not necessarily deflect less; they can be designed for large or small deflections. But they deflect more predictably because they crack less.

We can also reduce deflections by overdesigning a floor—making it thicker or using more reinforcement than required by the structural code.

One almost painless way to reduce deflections is to protect the floor from early stresses that cause cracks. It helps to keep the forms and shores in place for as long as possible and to prohibit or limit early construction loads.

NONSTRUCTURAL CRACKS

The structural codes contain minimum steel requirements to control nonstructural cracks, which are cracks that form from any cause other than positive and negative moments. Most nonstructural cracks result from some combination of thermal contraction and drying shrinkage, so they are also called shrinkage cracks. The minimum steel requirements apply both parallel and perpendicular to the span. A one-way slab might be reinforced in only one direction for flexural strength, but it must meet the minimum requirements in both directions.

The code requirements do not suffice for every floor. Where good control of cracks is important, some designers use more reinforcement than the code requires. Others choose prestressed floors, which have very few cracks if properly designed and built.

The stress-relief joints commonly used to control cracks in ground-supported floors do not work with most suspended slab designs. Exceptions exist, however. Some precast floors get toppings, and in those cases, you can reduce cracking by sawing joints in the topping directly over the joints between the precast units. Some people saw joints in composite slabs, but the practice is controversial. Rackham et al. (2009, 35–36) suggest that sawn joints ‘may’ be added over the beams in composite slabs, but they are less than enthusiastic, warning that ‘where cracking has to be controlled, a more reliable measure is to use additional crack control reinforcement at the support’.

LOADING

Chapter 4 defines the types of floor loading, which are the same for ground-supported and suspended floors.

Most suspended floors are designed for nominal live loads expressed in kN/m^2 (lb/ft^2). This is a practical, if imprecise, way to describe the light loads most suspended floors are called to support. When a suspended floor must support heavy industrial loads, it should be designed for the specific loading pattern and not for a nominal loading.

SPAN

The span, or distance between structural supports, has a big effect on the floor’s structural design. Sometimes, it dictates the slab type. Table 5.1 shows maximum practical spans for various slab types.

The maximum spans listed here are not absolute limits. Longer spans are possible with every floor type but may not be economically viable.

Spans are usually determined by factors independent of the floor. For many upper-storey floors, the spacing of structural supports is controlled by the need to use the space under the floor. Closely spaced columns in a warehouse or factory might simplify floor design but would make the room below harder to use.

The situation is completely different for ground-level suspended floors built on piles. Because designers have complete control over the pile spacing, they often design these floors with short spans of only 3 m (10 ft) or so. And if a floor on piles must support heavy concentrated loads, it is sometimes practical to put the piles directly under the loads.

CONCRETE STRENGTH

Chapter 7 covers this subject in more detail. For a suspended floor, the critical property is the concrete’s compressive strength, which is usually between 10 MPa and 40 MPa (2500 psi and 5000 psi). Though much stronger concrete can be made, it is little used in suspended floors. Working in Canada, Salinas (1980) showed that

TABLE 5.1
Maximum Practical Spans for Various Floor Types

Floor Type	Maximum Span
Unshored composite slab	4.5 m (15 ft)
One-way slab	6 m (20 ft)
Shored composite slab	6 m (20 ft)
Precast planks	8 m (26 ft)
Flat plate	9 m (30 ft)
Flat slab	10 m (34 ft)
One-way joist slab	14 m (45 ft)
Waffle slab	15 m (50 ft)
Precast double-Ts	24 m (80 ft)

the cheapest floor designs had the lowest strength concrete and the highest strength reinforcing steel.

Concrete’s shear strength also matters but is never specified or measured directly. The structural codes contain empirical rules for dealing with shear. Where the calculated shear stress exceeds the concrete’s estimated shear strength, the solution is never to make the concrete stronger (though that might work) but to add reinforcing steel perpendicular to the direction of shear.

For some floors, concrete strength is controlled by factors unrelated to structural design. Designers may specify high strength to achieve other goals such as good surface finish and resistance to wear, chemical attack, and freeze-thaw damage.

FORMWORK

Formwork is the temporary structure that contains and supports the fresh concrete. It is the mould into which a suspended floor is poured. It consists of the forms themselves, along with shore hangers and other hardware needed to hold the forms in place.

Soffit forms define the bottom of the floor slab and must support the fresh concrete’s weight. They determine how the underside of the floor will look—an important consideration in multi-storey car parks and other buildings where the soffit is left exposed to view. Composite slabs use corrugated steel as the soffit form.

Side forms define the sides of the floor slab and are used to make construction joints. Side forms for floors need no great strength because most floors are not thick enough to develop much hydraulic pressure. But they do need to be set accurately because they have a big effect on the floor’s flatness and levelness.

In the old days, formwork was built on-site out of timber and plywood. That’s still done, but it costs a lot in labour and materials. Increasingly, builders rely on reusable, ready-made steel forms.

Formwork can account for more than half the cost of a suspended floor. A simple design that allows cheaper formwork will often reduce total cost, even if it uses more concrete than a more complicated design. Flat plates and simple one-way slabs are the easiest types to form up.

Questions are often raised as to when forms can be removed. The striking of side forms has no structural effect and can be done soon after pouring concrete—usually within 12–18 hours, according to Blackledge (1977, 13).

In contrast, the striking of soffit forms and the shores, if any, that hold them up does have structural effect and must be done with care. Specifications typically require that the soffit forms be left in place till the concrete has reached a certain strength. Where the schedule demands the earliest possible form-striking, it is essential to determine the concrete's strength from field-cured cubes or cylinders. The usual laboratory-cured samples can mislead. Where good control over deflection and cracking is needed, it helps to leave soffit forms and shores up longer.

In America, ACI 117 specifies that floor levelness tests (F_L readings) must be finished before soffit forms and shores are removed.

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Part 3

Materials



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6 Properties of Plastic Concrete

This chapter deals with those properties of plastic (not yet hardened) concrete that affect floor construction. Concrete is plastic for just a few hours, but the events of those hours determine how a floor performs over its whole lifespan. For properties of hardened concrete, see Chapter 7.

These are the properties of plastic concrete that matter most in floors:

- workability;
- finishability;
- bleeding;
- setting time;
- plastic settlement.

WORKABILITY

This is the ease with which plastic concrete can be compacted and moved. Concrete of high workability is called wet or loose. Concrete of low workability is called dry or stiff. Because the commonest measure of workability is the slump test, people often define workability in terms of slump; high slump means high workability. Some British standards use the term *consistence*, which I avoid because it also means constancy or uniformity—another desirable property for concrete to have but quite a different one.

The American Concrete Institute (ACI) defines workability as ‘that property of freshly mixed concrete ... which determines the ease and homogeneity with which it can be mixed, placed, compacted, and finished’. Implying that finishability is simply one facet of workability, the ACI definition serves well enough for much concrete work but not for floorlaying. In a floor construction, workability and finishability are distinct properties. Workable concrete is easy to place, compact, and strike off. Finishable concrete is easy to straightedge, float, and trowel. Workability is important in all kinds of concrete construction, but finishability matters only in floors and other objects with large open surfaces. While both workability and finishability are properties of plastic concrete, they apply at different times. Workability is essential when concrete is mixed and placed. Finishability comes into play later when the floor is floated and trowelled.

A CONTROVERSY

Workability generates more controversy than almost any other subject in floor construction. Its only serious competitor in controversy is the matter of crack control in ground-supported slabs.

Workability is a good thing, but you can have too much of it. To make concrete more workable, you add water or an admixture. If you buy workability by adding water, the price includes lower strength and higher drying shrinkage. If you buy workability by adding an admixture, the price consists of the monetary cost (which can be substantial, especially for superplasticizers) and an increased risk of inconsistent concrete, excessive air content, and finishing problems.

Because high workability is both desirable and costly, every concrete mix is a compromise. That alone would hardly be controversial; every floor design is full of compromises. What makes this subject different is sharp disagreement over what the compromise should be.

Many authorities and designers come down hard on the side of stiff concrete mixes. Deacon (1986, 2) says concrete slump should not exceed 50 mm (2 in.) Murdock et al. (1991, 90) recommend the same number but call it a target, not an upper limit. National standards are more generous. For most kinds of floor construction, BS 8500 recommends the S3 workability class, which allows spot slump reading to vary between 80 and 180 mm. ACI 302 allows up to 125 mm (5 in) for all floors except concrete toppings. But out in the real world, it's common for concrete to come down the chute at slumps as high as 200 mm (8 in).

Often, it comes down to a conflict between designers and floorlayers. The designers specify very stiff mixes; the floorlayers prefer wetter mixes and use them whenever they can. Designers believe that floorlayers care nothing about concrete quality, while floorlayers are equally convinced that designers know nothing about finishing concrete. The conflict often descends to outright deception, with designers specifying absurdly low slumps and expecting the floorlayers to cheat. I tend to side with the floorlayers in this dispute. While it's true some mixes are wetter than they need to be, a good floorlayer knows better than anyone else what degree of workability is right for the tools at hand. Forcing workers to use concrete that is too stiff does not make a better floor.

MEASURING WORKABILITY

No single test can handle the whole range of concrete workability. Standard tests have been developed for at least six methods, but only three are practical for the sort of concrete normally used on floors. And of those three, just one, the slump test, is used on over 99% of the floors where workability is tested.

The Slump Test

This is by far the most common test for workability. It is so common that *slump* is commonly used as a synonym for workability.

The test method is specified in BS EN 12350 and ASTM C143, with only trivial differences between the two. Here are the main steps:

1. Place a slump mould on a smooth, level surface and hold it down. The mould is a truncated cone 300 mm (12 in) high, open at both ends, with its wide end at the bottom.

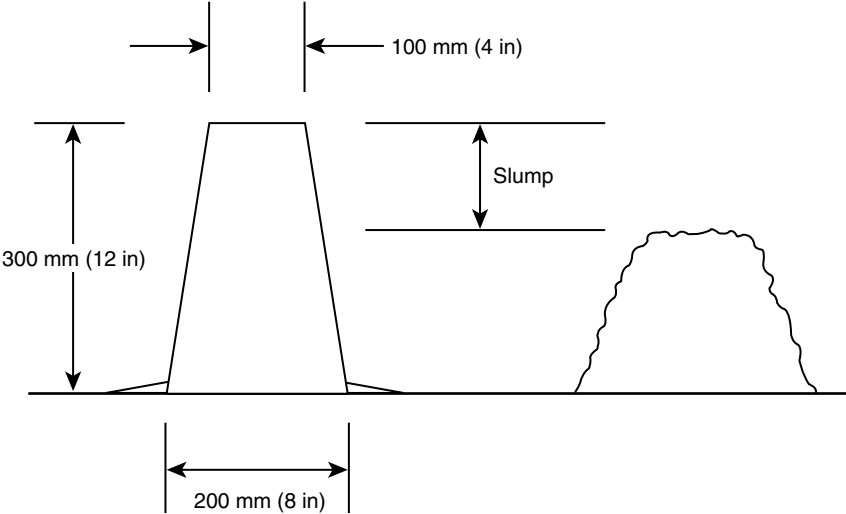


FIGURE 6.1 The slump test.

2. Fill the mould with three layers of freshly mixed concrete, compacting each layer with a steel rod.
3. Scrape the top so the concrete is flush with the top of the mould.
4. Lift the mould slowly. As you do this, the demoulded concrete slumps under its own weight.

The test result is the difference between the cone’s original height and its height after demoulding. When we say a slump is high, we mean that the cone settled by a large amount (Figure 6.1).

UK designers traditionally specified slump in multiples of 25 mm, which corresponded closely to the whole-inch values used in pre-metric days. European standards changed that, and we are now supposed to specify and report slumps in multiples of 10 mm. A system of slump classes (see Table 6.1) has come into use, with an allowed range for each class.

TABLE 6.1 Slump Classes			
Class	Application	Allowed Slump Range for Composite Sample	Allowed Range for Single Sample
S1	Floors laid with road paving machines	0–60 mm (0–2.3 in)	0–70 mm (0–2.8 in)
S2	Some floors made with lightweight aggregate	40–110 mm (1.6–4.3 in)	30–120 mm (1.2–4.7 in)
S3	Most floors	90–170 mm (3.5–6.7 in)	80–180 mm (3.1–7.1 in)
S4	Hand-screeded floors made of flowing concrete	150–230 mm (5.0–9.1 in)	140–240 mm (5.5–9.4 in)
S5	Not for floors	≥210 mm (≥8.3 in)	≥200 mm (≥7.9 in)

Source: Adapted from BS 8500.

A composite sample is made from four separate samples, taken at intervals from the same batch.

American standards offer more choices. No slump classes exist, and ACI 117 allows slump to be specified in three ways: as an absolute maximum, as a range (also absolute), or as a target. If specified as a target, slump can vary up and down by a limited amount. Where the target is 100 mm (4 in) or less, the permitted variation is ± 25 mm (± 1 in). Where the target is above 100 mm (4 in), the permitted variation grows to ± 40 mm ($\pm 1\frac{1}{2}$ in).

I recommend specifying a maximum slump rather than a range or a target, even though that departs from the latest British standards. On the job site, it is always the upper limit that people pay attention to. No one argues much about rejecting concrete that arrives too stiff, and you can always increase workability by adding some water. But everyone understands the importance of not exceeding a maximum value, and it helps to spell out that maximum value in the contract documents.

Typical slumps in floor construction range from 50 mm (2 in) to 200 mm (8 in). Slumps near the lower end are used where concrete is struck off with power equipment. Slumps near the higher end are used where concrete is struck off by hand and where concrete is pumped.

Instead of slumping, the cone of concrete sometimes breaks into two parts with the top part sliding down an inclined plane. This is called a shear slump. It may point to sloppy testing or a bad, noncohesive mix, but some perfectly serviceable mixes tend to produce shear slumps.

The slump test is both useful and widely used. On some jobs, it is the only concrete test. But we need to remember its limitations.

The slump test does not measure strength. While some correlation exists between slump and strength, it is unreliable. If two batches are identical except for water content, the wetter mix will have the higher slump and, under most conditions, the lower strength. But many factors other than water content affect slump. High-slump concrete can be strong, and low-slump concrete can be weak. Only direct strength tests on hardened concrete can tell strong concrete from weak.

Another limitation is the slump test's sensitivity to operator technique. Repeatability is none too good, even when operators follow every rule to the letter. If the operator fails to follow the standard procedure, the results can be off by as much as 75 mm (3 in). And unlike some concrete tests, slump tests are often made by untrained workers using non-standard tools. I once saw a slump cone that had been run over by a van and hammered back into shape (Figure 6.2).

As long as those limitations are understood, the slump test can provide useful information. The main value of slump testing is to detect irregularities in the concrete mix. If the concrete batcher makes a serious mistake, it usually shows up as a large change in the slump.

Arguments arise over the location and timing of slump tests. ASTM C 172 requires the taking of samples 'at two or more regularly spaced intervals during discharge of the middle portion of the batch' while forbidding samples 'from the very first or last portions of the batch discharge'. The American standard also states that the concrete shall not be tested till all the water has been added to the mix. BS EN 12350 has stricter rules, calling for the blending of four separate samples from each batch tested.

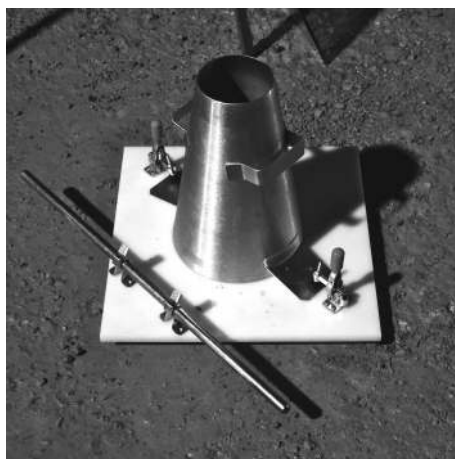


FIGURE 6.2 Brand new kit for testing slump. The slump cones on most jobs don't look this good.

Those requirements make sense if the goal is simply to get a fair sample of the concrete. But if the goal is to identify misbatched concrete in time to reject it, or to adjust workability by adding water, we need to test slump earlier. That means sampling the first part of the batch discharged from the truck or mixer. While a sample collected that way might not fairly represent the whole batch, there is simply no other way to check the mix in time to do any good.

A similar logic applies to the sampling of pumped concrete. Because concrete loses workability during pumping, builders often wish to sample the mix at the discharge end of the pipeline. Their wish is understandable, but to grant it means that a substantial volume of concrete is already in the pumping system by the time of the first slump test. It is better to sample the concrete before it enters the pump. If slump loss during pumping is a problem, the specification should allow a higher slump at the start.

The K-slump Test

The slump cone is easy to use, but that fact has not stopped people from developing even easier and faster devices for measuring workability.

The K-slump tester (see Figure 6.3) is one such device. It consists of a steel tube with a measuring rod that slides within it. The tube is perforated to let cement paste

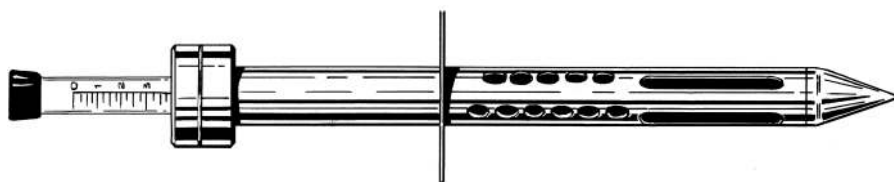


FIGURE 6.3 K-slump tester.

enter and pointed at one end, so it can be pushed into wet concrete. A flange ensures that the tester is inserted to the right depth. The measuring rod is of light plastic, calibrated in millimetres from 0 to 100.

To test K-slump, you stick the tester into fresh concrete. A hook holds the measuring rod above the concrete surface. You then wait 60 seconds, during which time mortar flows into the tester through the perforations. Higher workability means more leakage. When the minute is up, you lower the measuring rod gently till it rests on the mortar that entered the tester.

The measuring rod then shows the test result, in millimetres, on a scale that runs from 0 to 100 mm. As with the slump test, higher readings mean greater workability.

In the early days of the K-slump test, results were read in centimetres and the inventor claimed that K-slump readings in centimetres were roughly equal to regular slump readings in inches.

The K-slump tester offers three advantages over the slump cone. It is slightly easier to use; it is faster, and it can be used almost anywhere—in a bucket, in a wheelbarrow, or in the chute of a concrete truck. These advantages combine to make the K-slump test particularly useful on a fast-paced job where you want to check workability on every batch but cannot delay the pour waiting for slump tests.

The chief drawback to the K-slump tester is that people are unfamiliar with it. Despite its usefulness, it has never become popular. And the American standard for its use, ASTM C1362, has not been republished since 2010 and has been allowed to lapse. Of course, you can still find copies of it, even though it is no longer supported by ASTM. If you propose to use the K-slump test for acceptance testing, you had better expect some resistance, not least from the ready-mix supplier.

The Flow-table Test

Neither the slump test nor the K-slump test is of much use on flowing concrete made with superplasticizer. If the concrete has a design slump of more than 150 mm (6 in), it is best tested on a flow table. The test involves these steps:

1. Place a shortened slump cone in the centre of a 700 mm by 700 mm (28 in by 28 in) table.
2. Fill the cone with concrete in two layers, tamping each layer 10 times with a wooden rod.
3. Wait 30 seconds.
4. Lift the cone mould and set it aside.
5. Lift the table 40 mm and drop it. Do this 15 times in 15 seconds.
6. Measure the mean diameter of the concrete puddle.

The test result is the diameter of the puddle, with a greater diameter denoting higher workability.

HOW MUCH WORKABILITY?

We have discussed ways to measure workability, but we are not much closer to deciding how much of it we really need. No single answer will suffice, because the answer depends on many factors, including but not necessarily limited to:

- temperature (High temperatures call for high workability.);
- protection from the elements (Walls and roof allow lower workability.);
- concrete placing method (Pumping requires high workability.);
- strike-off method (Manual methods need higher workability than do vibrating screeds and laser screeds.);
- finish (Dry shakes are hard to apply on concrete of low workability.).

Since we have to start somewhere, I suggest that a maximum slump of 120 mm (5 in) is about right for the average floor laid under average conditions.

In practice, the workability is often controlled by the need for finishability. With enough effort, you can always place concrete of low workability. But you may not be able to finish it. For more on that subject, read on.

FINISHABILITY

This is the ease with which concrete can be straightedged, floated, and trowelled. In floor construction, finishability matters even more than workability. You can, with effort, place concrete of low workability. But you cannot put a good wearing surface on concrete of low finishability. For smooth trowelled floors, high finishability is an essential property.

Despite its undeniable importance, finishability has not received much study. Most of our knowledge comes not from formal research but from the experience of workers on site.

There is no standard test for finishability. In its absence, we can only rely on knowledge of those factors that make concrete finishable and on workability tests (mainly the slump test) that indirectly and imperfectly indicate finishability. Because the only true test is actual site experience, we should always be ready to change mixes that are hard to finish.

Finishability is a property of the surface mortar, and it is affected by the components of that mortar. Water, cement, and fine aggregate all appear in the surface mortar, and all affect finishability. Coarse aggregate does not matter much because it is not part of the mortar. Coarse aggregate has an indirect effect, however, in that it affects the amount of cement needed for finishability (Figure 6.4).

WATER AND FINISHABILITY

Water makes concrete finishable by lubricating the cement and aggregate particles in the surface mortar. The amount of water needed for finishability is much greater than the minimum needed to hydrate the cement.

The amount of water in the surface mortar depends largely on the water content of the original concrete mix, but that is not the only factor. Bleeding makes the surface



FIGURE 6.4 A highly finishable concrete mix.

wetter and improves finishability, up to a point. Other processes—absorption by the aggregates, chemical reaction with the cement, and evaporation—reduce the amount of water available to lubricate the mortar.

Predicting how much water a particular mix needs to ensure finishability is hard, but we have to try to get it right. Use too much water, and excessive bleeding causes trouble. Use too little, and the surface dries out and becomes impossible to finish.

If the surface mortar dries out too soon, floorlayers sprinkle it with water. Many specifications forbid the practice, but it goes on anyway. It's better to sprinkle water on a floor than to leave the surface unsealed and porous.

Though an occasional sprinkle of water is nothing to be afraid of, more than that points to a problem that needs to be corrected. If the problem is poor finishing habits, then the solution is to change those habits. In most cases, however, the solution is to use more water at batching (that is, to raise the slump) or to reduce the rate of evaporation.

Superplasticizers, though good at raising concrete's workability, are not a substitute for water where finishability is the issue. By the time finishing takes place, the effects of superplasticizer have worn off.

CEMENT AND FINISHABILITY

More cement means greater finishability, provided water is also added to maintain the water–cement ratio. To ensure a high cement content, some designers specify higher concrete strength that is required for the structural design. That may work, but

it creates the risk that a concrete supplier will develop a mix that attains high strength with relatively little cement. The safer approach is to specify strength for strength's sake, and also to specify a minimum cement content for finishability.

Deacon (1986, 2) recommends a cement content of at least 325 kg/m³ (548 lb/yd³) for concrete that forms the floor's wearing surface. ACI 302 makes a similar recommendation but tailors the minimum cement to the maximum size of the coarse aggregate. The bigger the aggregate, the less cement is needed for the same finishability.

FINE AGGREGATE AND FINISHABILITY

For a good finish, concrete must contain enough fine aggregate to cover the floor surface with mortar. An undersanded mix—one without enough fines—is always hard to finish. Most ordinary concrete mixes have enough.

The shape of the fine aggregate also matters. Rounded particles are better than angular—though angular sands may give higher concrete strength. Designers rarely specify or even consider this property, but it is worth investigating when other measures fail to produce a finishable mix.

Natural sand is usually, though not invariably, better for finishability than manufactured sand for finishability.

WAYS TO IMPROVE FINISHABILITY

When a mix proves hard to finish, one or more of the following changes may improve the situation:

- Add water, but beware of the effect on strength and drying shrinkage.
- Use more cement.
- Use more fine aggregate.
- Switch to a round-grained fine aggregate.
- Protect the fresh concrete from drying winds and sunshine.
- Use fog sprayers to keep moist air around the concrete. The goal is not to deposit liquid water but to slow the drying rate. The sprayers release a fine mist.
- Spray the concrete with an anti-evaporation film to reduce evaporation.

BLEEDING

This is the process by which water rises to the surface of a newly placed floor slab. Concrete bleeds because water is the lightest component of the mix (except for some aggregates used in lightweight concrete). The heavier components settle as the water rises (Figure 6.5).

When bleed water rises faster than it can evaporate into the air, it accumulates on the floor surface. In extreme cases, a sheet of water covers the whole floor. In milder cases, the water ponds in isolated spots.

The accumulation of bleed water on the floor surface can cause serious problems. The main risk from excessive bleeding is that concrete finishers will float or trowel the floor while bleed water is present, mixing the water back into the concrete and

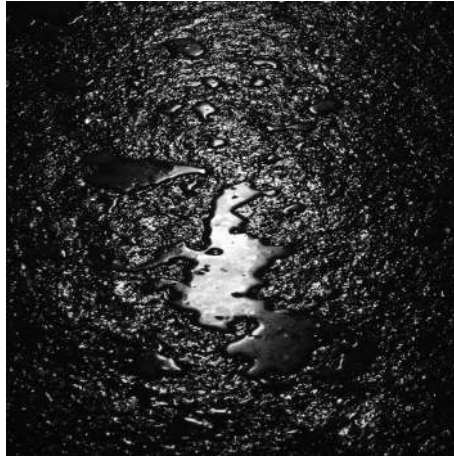


FIGURE 6.5 Bleed water ponding on a floor surface.

creating a weak layer with an abnormally high water–cement ratio. Results may include delamination and poor resistance to wear.

The standard and usually effective way to prevent those defects is to follow one simple rule: never float or trowel concrete while bleed water is visible. Wait for the water to evaporate.

While that is a good rule, it's sometimes hard to follow. In some cases, water evaporates so slowly that by the time it has disappeared, the concrete has set and is too hard to finish. In less severe cases, the floor may turn out well, but the delayed finish raises labour costs.

Here are three basic ways to deal with excessive bleeding and let finishing proceed without long delay:

- Remove bleed water mechanically.
- Raise the evaporation rate.
- Change the mix design to reduce the bleeding rate.

The traditional mechanical method is to drag the water off with a rubber hose. Nowadays, floorlayers are likely to use a highway straightedge instead of a hose, though some people believe that the straightedge, weighing more than a hose, forces too much water back into the concrete surface. Both tools work best on narrow slabs.

Another mechanical method is vacuum dewatering. A mat, consisting of a mesh layer under an impervious plastic sheet, is rolled out over the concrete surface. Vacuum is then applied under the plastic sheet, sucking out water. Finishing can usually start as soon as the mat is removed.

Yet another mechanical method relies on dry cement to absorb excess water. The cement is not applied directly to the floor because it would then bond to the wet concrete. First, dry hessian (Americans call it burlap) is laid over the floor. Then, dry cement is swept over the hessian. After the cement has become thoroughly wet, the hessian is rolled up and finishing can begin.

Increasing the evaporation rate can solve the problem of excessive bleeding but is seldom practical. On outdoor pours, the evaporation rate depends on weather and is almost wholly beyond the builder's control. On indoor pours, heat or ventilation, or both, will help get rid of bleed water. No one installs heaters just to reduce problems from bleeding, but if the building is heated anyway, it is easy, if costly, to turn up the thermostat. Ventilation may be easier to arrange than heating, but it has little effect when the humidity is very high.

A highly effective way to reduce bleeding is to change the concrete mix. In general, any change that increases the amount of very fine particles will help and so will some other changes. The following steps tend to reduce bleeding:

- Use more fine aggregate, especially at the small end of the size range (under 0.150 mm or US number 100 sieve).
- Add fly ash or slag.
- Add ground limestone.
- Use more cement (but beware of the higher cost and the risk of higher shrinkage).
- Use less water (but beware of the effect on workability and finishability).

Another effective way to reduce bleeding is to add entrained air, but I would never recommend that on any floor that gets a trowelled finish. The risk of delamination is too great.

So far, this discussion has focussed on the issue of excessive bleeding, but too little bleeding is equally bad. Some bleeding is essential in a concrete floor. If concrete did not bleed at all, finishing as we now know it would be impossible. When the bleed rate is too low, the floor surface dries out before the concrete sets. This sets the stage for a long list of problems, including plastic-shrinkage cracking, crazing, delamination, and low resistance to wear.

The issue of too little bleeding has come to the fore with the recent focus on sustainability. While there's no direct connection between bleeding and sustainability, some of the most popular measures to reduce concrete's carbon footprint also reduce bleeding. Those measures are the replacement of cement with fly ash or slag and the addition of ground limestone to Portland cement.

The trick is to match the bleed rate to the evaporation rate—a task easier said than done but not impossible. While no standard method yet exists for doing this, tools are available.

You can easily determine the evaporation rate once you know, or can guess at, the concrete's surface temperature, the air temperature, the relative humidity, and the wind speed. See Chapter 18 for more detail.

ASTM C223 describes a test for concrete's bleeding potential, which involves these steps:

1. Fill a 14-L cylinder with freshly mixed concrete. The concrete can be mixed in a lab or in the field.
2. Trowel the concrete surface three times.

3. Place the filled cylinder in a controlled-temperature room and cover it to prevent evaporation. Keep it covered for the duration of the test, except for brief exposure to carry out step 4.
4. At regular intervals, draw off the bleed water that accumulates on the concrete surface. Do this at 10-minute intervals for the first 40 minutes and at 30 minutes after that, till the bleeding stops.
5. Transfer the drawn-off bleed water to a graduated cylinder and note the accumulated volume of water after each draw.
6. Use Equation 6.1 to determine the bleeding percentage.

$$\text{Bleeding, \%} = (D/C) \times 100 \quad (6.1)$$

Where

D = accumulated mass of the bleed water drawn off, g

C = mass of net mixing water in the test specimen, g
 $= (w/W) \times S$

W = total mass of the concrete batch (not just the concrete in the specimen), kg

w = mass of net mixing water in the batch (total water content less the water absorbed by the aggregates), kg

S = mass of the concrete in the test specimen, g

The bleeding test is not common, but perhaps it should be. As for what the bleeding rate should be, information is scarce. The right number will depend not just on the evaporation rate but also on set time and possible other factors. Peter Killeen, a concrete consultant in Australia, suggests 16% as a starting point.

SETTING TIME

This is defined as the elapsed time between the introduction of water to the concrete mix and the concrete's setting—that is, its hardening. Setting time affects floor quality because it determines the time available for finishing. When concrete sets too fast, floorlayers lack the time to do their job right. When concrete sets too slow, overtime costs rise and floorlayers may be tempted to skimp on the final steps.

The rate of setting depends on many factors, but most of all on temperature and admixtures.

One factor that, perhaps surprisingly, does not matter much is the choice of cement. All kinds of cement commonly used for floors (see Chapter 8) set at similar rates, though they differ widely in the rate at which they gain long-term strength. While some cements are called rapid-hardening, the term does not mean quick setting but refers instead to the rate of strength gain after setting.

TEMPERATURE

Like other chemical reactions, the hydration of cement goes faster at higher temperatures. Heat shortens the setting time; cold extends it. Extreme heat and extreme cold both cause trouble.

It is the concrete temperature, not the air temperature, that controls the setting time. But of course the air temperature affects the concrete temperature, and only the most massive floors can long maintain an internal temperature much different from the ambient. Measures to control concrete temperature include those that cool or heat the concrete directly, and those that cool or heat the air. The latter tend to be more effective.

When heat makes setting times too short, consider these steps:

- Shade the floor from the sun's rays, either by erecting the building or by putting up a temporary shelter.
- Place concrete in the cool of the night.
- Keep aggregates cool.
- Chill the mixing water.
- Add ice to the concrete, but don't forget to include it when calculating the total water content.
- Chill the concrete with liquid nitrogen.

When cold makes setting times too long, consider these steps:

- Heat the building, taking care not to use unvented heaters that discharge carbon dioxide indoors.
- Heat the space under a suspended floor.
- Heat the mixing water.

ADMIXTURES

Some admixtures change setting time as their primary effect. Others affect setting time as a side effect.

Accelerators shorten setting time; retarders extend it. Many low-range water reducers have a slight retarding effect, which can be used to advantage in hot weather. But other low-range water reducers are mild accelerators, so it pays to read the manufacturers' information sheets.

An admixture overdose, or the use of two admixtures together, may cause a very long delay in setting. Certain impurities have a similar effect. A few kilogrammes of sugar in the mixing drum will completely prevent the concrete's setting. See Chapter 8 for more on admixtures.

ACCEPTING SHORT AND LONG SETTING TIMES

One way to deal with short or long setting times is to live with them, adjusting working methods to finish the concrete well no matter how long it takes. Fast setting in hot weather causes little trouble if you have enough workers and tools to finish the concrete in the time available. You might expect concrete contractors in the hot climate of the American Southwest to use large quantities of retarders but most do not. They just accept a short setting time and make sure they have enough workers on site to handle it. Similarly, slow setting in cold weather causes no harm if workers are prepared to stay late. Concrete contractors in some cold regions work split shifts

to limit overtime costs. The main crew starts in the morning and stays for a normal workday. The second crew—sometimes just two or three workers—shows up in the afternoon and stays till the bitter end, which may not arrive till the small hours.

PLASTIC SETTLEMENT

This is the sinking of the floor surface caused by a reduction in volume of the fresh concrete. Most concrete loses volume from the time it is mixed through loss of water and entrapped air. There may also be some leakage through the forms and, in ground-floor slabs, into the sub-base or subgrade.

Plastic settlement is distinct from drying shrinkage. Both involve reductions in volume, but settlement is a property of plastic concrete while drying shrinkage is a property of hardened concrete. Drying shrinkage occurs in all directions. Plastic settlement occurs only in the vertical direction because plastic concrete flows horizontally to fill up the forms.

Plastic settlement appears to be proportional to slab thickness. Slabs thinner than 150 mm (6 in) seldom settle enough to cause trouble. The biggest problems occur in slabs thicker than 300 mm (12 in) and in slabs cast monolithically with thick supporting beams.

Plastic settlement causes trouble in at least two ways: by causing cracks and by making the floor surface less flat.

Plastic-settlement cracks appear in fresh concrete directly over embedded objects such as reinforcing bars or post-tensioning tendons. They occur because the concrete settles and the embedded objects don't. In extreme cases, the whole reinforcing grid appears as cracks on the floor surface. Plastic-settlement cracks are more likely where reinforcing bars or post-tensioning tendons are large in diameter and close to the surface.

Plastic settlement makes a floor less flat because the settlement is not always uniform. If the whole floor surface sank by the same amount, there would be no effect on flatness. But settlement varies from batch to batch and even within each batch, leaving bumps and dips in the surface. Because of plastic settlement, it is very hard to achieve close surface tolerances on thick slabs. If slab thickness exceeds 400 mm (16 in) and the floor needs a superflat or near-superflat finish, the solution may be a floor topping.

A different flatness problem occurs at slab edges. As the surface settles, the finishers often build up the edge with mortar to keep it flush with the side form. The result is a ridge along the edge. This mimics curling and is sometimes mistaken for it.

Where plastic settlement causes or is likely to cause trouble, one or more of the following steps may be worth a try:

- Use the largest possible coarse aggregate.
- Ensure the coarse aggregate is evenly graded.
- Use less water in the concrete mix but beware of the effect on workability and finishability.
- Leave a generous surcharge when striking off.

- Place deep sections in two or more lifts. This is especially useful when casting a slab monolithically with deep joists or beams.
- Add microsynthetic fibres.

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7 Properties of Hardened Concrete

This chapter deals with the material properties of concrete in its hardened state:

- strength;
- impact resistance;
- modulus of elasticity;
- drying shrinkage;
- thermal coefficient.

STRENGTH

Because concrete is a structural material, its strength matters. But because the concrete in a floor is more than just a structural material, we should not consider its strength in isolation from its other properties.

Strength can be defined as the stress needed to make the concrete break in a particular way. The basic SI unit for stress, and thus for concrete strength, is the pascal. Concrete strengths fall in the millions of pascals, so the normal unit for concrete strength is the megapascal, abbreviated MPa. The UK uses megapascals but often calls them newtons per square millimetre (N/mm²). Two names for the exact same unit of measure. Some countries measure concrete strength in kilogrammes per square centimetre (Kg/cm² or Kgf/cm²), an old metric unit not recognized by SI. Americans use pounds per square inch (psi). Here are the conversion factors:

$$\begin{aligned} 1 \text{ MPa} &= 1 \text{ N/mm}^2 \\ &= 10.20 \text{ Kgf/cm}^2 \\ &= 145 \text{ psi} \\ 1 \text{ Kgf/cm}^2 &= 14.22 \text{ psi} \end{aligned}$$

Floor designers pay attention to these kinds of concrete strength:

- compressive strength;
- flexural strength;
- tensile strength;
- shear strength.

Designers who work with steel fibres sometimes use a strength-related property called residual strength or ductility.

TABLE 7.1
Standard Tests for Concrete Strength

Kind of Strength	Standard Test Method	
	British	American
Compressive (cube)	BS EN 12390-4	None
Compressive (cylinder)	BS EN 12390-4	ASTM C39
Flexural (beam)	BS EN 12390-5	ASTM C78
Tensile (split cylinder)	BS EN 12390-6	ASTM C496
Residual (beam with fibres)	BS EN 14651	ASTM C1609

COMPRESSIVE STRENGTH

The commonest, though not always the most useful, gauge of concrete quality is compressive strength—resistance to crushing. The UK standard test (found in BS EN 12390) measures the force needed to crush a 150-mm (6 in) cube of hardened concrete. Americans, along with most of continental Europe, replace the cube with a cylinder 150 mm (6 in) in diameter and 300 mm (12 in) high. The American standard is ASTM C 39; BS EN 12390 also includes a test method for cylinders. Because a tall cylinder offers less resistance to crushing than a cube made of the same stuff, American compressive-strength test results are lower than British. The exact relationship between cylinder and cube strengths is complex, but in general, cylinder breaks are about 20% lower (Figure 7.1).

In this book, I take a divided approach to reporting compressive strength. Strengths that appear in MPa are British cube strengths. Strengths in psi are American cylinder strengths. I apologize to readers in continental Europe and elsewhere who are used to



FIGURE 7.1 This sample includes cylinders for compressive strength and beams for flexural. Most of the world uses cylinders for compressive strength, but the UK uses cubes.

TABLE 7.2
Compressive-strength Classes for Normal-weight Concrete

Class	Characteristic Compressive	
	Strength 150-mm Cubes	150×300 Cylinders
C8/10	10 MPa	8 MPa (1200 psi)
C12/15	15 MPa	12 MPa (1700 psi)
C16/20	20 MPa	16 MPa (2300 psi)
C20/25	25 MPa	20 MPa (2900 psi)
C25/30	30 MPa	25 MPa (3600 psi)
C28/35	35 MPa	28 MPa (4100 psi)
C30/37	37 MPa	30 MPa (4400 psi)
C32/40	40 MPa	32 MPa (4600 psi)
C35/45	45 MPa	35 MPa (5100 psi)
C40/50	50 MPa	40 MPa (5800 psi)
C45/55	55 MPa	45 MPa (6500 psi)
C50/60	60 MPa	50 MPa (7200 psi)

cylinder strengths measured in MPa. You can divide the American cylinder results by 145 or reduce the British cube strengths by about 20%.

The arrival of European standards has complicated matters in the UK. British testing laboratories will keep on breaking cubes for the foreseeable future, but the European structural code is based on cylinder strengths. The compromise is to define concrete strength by both methods. British practice divides concrete mixes into strength classes, each bearing two numbers separated by a solidus (Table 7.2). The lower number represents the cylinder strength, in MPa. The higher number represents the cube strength. The letter C tells us this concrete is made with normal or heavy-weight aggregates. The other choice is LC for lightweight concrete.

In American specifications, compressive strength is almost always stated in a multiple of 500 psi, but measurements are reported in multiples of 10 psi.

Most concrete for floors has a 28-day compressive strength of 20–40 MPa (2500–5000 psi). Strengths above 40 MPa (5000 psi) are seldom used in full-thickness slabs because of high cost and drying shrinkage. Mixes for monolithic and bonded toppings sometimes show compressive strength of 50 MPa (6000 psi) or more.

Though important and easy to test, compressive strength is overused as a measure of concrete quality. In everyday speech at the building site, people often speak of compressive strength (sometimes called concrete grade or concrete quality) as if it were the only important thing to know about a mix. But concrete has many other properties that matter in floor construction. Some of those properties have no connection with compressive strength, while others—most notably drying shrinkage—can get worse with higher compressive strength.

Within the field of floor design, compressive strength matters most in suspended slabs. The principles of suspended-slab design call for the concrete to resist compression, relying on steel reinforcement or prestressing tendons to resist tension. Compressive strength is thus essential.

It plays a much smaller role in ground-supported slabs, which normally rely on the concrete's flexural strength to resist bending. The concrete in a ground-supported floor also resists compression, but flexural strength controls the design because concrete's flexural strength is always much lower than its compressive strength.

Compressive strength often stands in for other properties such as flexural strength, shear strength, modulus of elasticity, and even wear resistance. Such substitution sometimes makes sense, given that compressive strength is easy to test. But the relationship between compressive strength and other properties varies greatly. If a property truly matters, it usually deserves to be specified and tested directly.

FLEXURAL STRENGTH

This is concrete's ability to resist bending. Some people call it tensile strength in flexure because while bending creates both compressive and tensile stresses, it is always the latter that causes the concrete to fail (Figure 7.2).

The usual test for flexural strength measures the force needed to break a beam under third-point loading (see Figure 8.2). Standard test methods appear in ASTM C78 and BS EN 12390-5. The beam is a prism 150 mm by 150 mm by at least 500 mm (6 in by 6 in by at least 20 in), but other sizes are sometimes used. Flexural strength is expressed as the modulus of rupture, taken from Equation 7.1.

$$f_r = Pl/bd^2 \quad (7.1)$$

where

- f_r = modulus of rupture, in MPa (or psi);
- P = force needed to break the beam, in N (or lb);
- l = length of span (not length of beam), in mm (or in);
- b = mean width of beam, in mm (or in);
- d = mean depth of beam, in mm (or in).

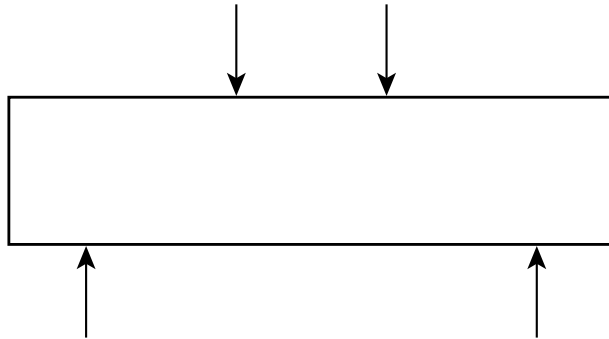


FIGURE 7.2 To test concrete's flexural strength, also called modulus of rupture, a beam is broken under third-point loading.

This equation applies only if the beam breaks within the middle third of the span, as it usually does.

Another test method, called centre-point loading and described in ASTM C293, breaks the beam by applying force only at mid-span. It gives strength results about 15% higher than those from third-point loading. Since the standard design methods are based on third-point loading, you should reduce test results from centre-point loading before using them in design calculations.

Flexural strengths for concrete used in floors range from 3 to 7 MPa (400–1000 psi).

Flexural strength is essential in ground-supported slabs. Unlike suspended slabs that are always designed as reinforced or prestressed members, many ground-supported slabs rely on the concrete alone to support loads.

Despite the importance of flexural strength, most floor designers do not specify it directly. They specify compressive strength instead and assume a relationship between the two kinds of strengths. Designers in the UK often use Equation 7.2, while Americans often rely on Equation 7.3. Sometimes, Americans will replace the ‘7.5’ value in Equation 7.3 with a higher number. Ringo and Anderson (1992, 9) recommend 9.0.

$$f_r = 0.393(f_{cu}^{2/3}) \quad (7.2)$$

where

f_r = modulus of rupture, in MPa
 $f_{cu}^{2/3}$ = cube compressive strength, in MPa

$$f_r = 7.5\sqrt{f_c} \quad (7.3)$$

where

f_r = modulus of rupture, in psi
 f_c = cylinder compressive strength, in psi

Unfortunately, both equations imply a precision that does not exist. There is no fixed relationship between compressive and flexural strengths. For any given compressive strength, flexural strength varies widely. It will usually be higher than the standard formulae suggest, but you cannot count on that unless you test it directly.

Where flexural strength is critical—as in heavily loaded ground-supported slabs—designers should specify it directly and enforce it with beam tests. This is more accurate and, in the long run, more economical than using any assumed relationship between compressive and flexural strength. Where precise control over flexural strength is unimportant—as in most suspended slabs and in lightly loaded ground-supported slabs—it makes sense to test for compressive strength and to estimate flexural strength, if necessary, from one of the standard equations.

TENSILE STRENGTH

This is concrete's ability to resist being pulled apart. Concrete is rarely tested in pure axial tension because accurate results are hard to get. According to Raphael (1984), test results from pure tension can be off by half unless the concrete samples are treated with extraordinary care.

More commonly, tensile strength is defined by the split-cylinder test. The standard tests (ASTM C 496 and BS EN 12390-6) use a concrete cylinder 150 mm (6 in) in diameter and 300 mm (12 in) long—the same as in the American test for compressive strength. Compression is applied along the side of the cylinder till the cylinder splits. Tensile strength is calculated from Equation 7.4.

$$f_{st} = 2P/(\pi dl) \quad (7.4)$$

where

f_{st} = splitting tensile strength, in MPa (or psi)

P = force needed to split the cylinder, in N (or lb)

d = cylinder diameter, in mm (or in)

l = cylinder length, in mm (or in)

Most concrete used in floors has a split-cylinder tensile strength of 2–3 MPa (300–450 psi). Concrete made with lightweight coarse aggregate is typically about 15% weaker in tension than normal-weight concrete of the same compressive strength.

Split-cylinder tensile strength is specified and tested even less often than flexural strength. It can, however, be useful as a proxy for flexural strength. Some designers are reluctant to demand beam testing for flexural strength because the testing is costly and the heavy beams are often mishandled. In contrast, split-cylinder testing costs only slightly more than compressive-strength testing and uses the same moulds. (If you are in the UK, you are probably using cube moulds and not cylinders for compressive strength, but even there, cylinder moulds are not hard to find.) To use split-cylinder data in this way, you need to determine the relationship between them and beam data using a particular set of materials.

SHEAR STRENGTH

This is concrete's ability to resist shear failure, which occurs when concrete cracks in a direction parallel to stress. Shear strength is not easy to measure, and no good standard test for it exists. Some design methods assume that shear strength is closely related to tensile strength, and that both are proportional to the square root of the compressive strength. The second part of that assumption is probably wrong but not so far wrong that it causes trouble.

Shear strength matters little in ground-supported slabs. If a ground-supported slab has the flexural strength to support its loads, it is unlikely to fail in shear.

The structural codes do require designers to check shear in suspended slabs. In most cases, shear does not control the design. Where it does, the almost universal solution is to add reinforcement or increase slab thickness, not to make the concrete stronger.

RESIDUAL STRENGTH

This applies only to concrete containing steel fibres. Some people call it ductility or flexural toughness. It is concrete's capacity to resist bending after it has cracked. Plain concrete has no such capacity, but steel-fibre concrete does. So does ordinary reinforced concrete containing rebar or wire mesh, though the term is rarely used in that context.

In the UK, residual strength is defined in terms of the notched-beam test, BS EN 14651. The test starts out much like the BS EN 12390-5 test for flexural strength, except that the beam has a notch, 25 mm deep, cut into its tension side. The notch ensures (usually) that the crack forms where it's supposed to and makes it easier to measure crack width. The beam is loaded till it cracks. In a test for straight flexural strength, the process would end there: the load at first crack would be the test result. But in a test for residual strength, the loading goes on. Under this continued loading, the crack widens and the beam deflects. The load is measured at crack widths of 0.5, 1.5, 2.5, and 3.5 mm. Alternatively, the load can be measured at deflections of 0.47, 1.32, 2.37, and 3.02 mm.

Americans use two other tests for residual strength, ASTM C1609 and ASTM C1550. ASTM C1609 is a beam test like BS EN 14651, but the beam has no notch, and there is no measuring of crack widths. Load is measured at first crack and at deflections of $L/600$ and $L/150$. ASTM C1550 replaces the beam with a concrete disc, 75 mm thick and 800 mm across.

Once you get the residual strength values from one of those tests, you have to figure out how to use them. That is where the road gets bumpy because most design manuals make no mention of residual strength and provide no way to take advantage of it. The chief exception is TR 34 (Concrete Society, 2016), which presents a method for designing ground-supported and pile-supported floors that relies on residual strength. Engineers disagree on how, or even whether, residual strength should be used in floor design. Some won't accept it all. Others will use it only for positive moments (tensile stress at the bottom of the slab) in ground-supported floors, an approach that limits its application to floors where fixed concentrated loads (think rack legs) control the design. And then there are those who would use it for all kinds of loading, even in elevated slabs.

CHARACTERISTIC STRENGTH

Floor designs are based neither on minimum strength (an almost meaningless term) nor on mean strength (which could seriously mislead) but on characteristic strength. Americans call it design strength. It's the value below which only a small percentage of readings can be expected to fall. In the UK, that percentage is 5, but American rules allow 10.

Characteristic strength is related to the mean strength as determined by tests but is always lower than the mean by an amount that depends both on the variability of the test results and on the percentage of readings allowed to fall short. Variability is

TABLE 7.3
Difference Between Characteristic and Mean Strength

Number of Strength Test Readings Allowed to Fall Below the Characteristic Value	Amount by Which Mean Strength Must Exceed Characteristic Strength
0.1%	3.00 standard deviations
0.5%	2.58 standard deviations
1%	2.33 standard deviations
5% (standard in UK)	1.64 standard deviations
10% (standard in America)	1.28 standard deviations
15%	1.04 standard deviations
20%	0.84 standard deviations

expressed as the standard deviation. Table 7.3 shows the amounts, expressed as multiples of the standard deviation, by which mean strength must exceed characteristic strength for various allowable percentages of short readings.

For most concrete mixes, the standard deviation ranges from 5 to 12% of the mean strength. A well-controlled mix will have a smaller standard deviation; therefore, its characteristic strength will be closer to its mean strength.

Where the test results are too few to determine a meaningful standard deviation, standard and very conservative rules apply.

Any strength property for which a standard test exists can have a characteristic value. The concept is not limited to compressive strength but can also apply to flexural strength, tensile strength, and residual strength.

STRENGTH GAIN

Concrete grows stronger with time. The process goes on for decades—perhaps even longer—though at an ever-diminishing rate.

By convention, we specify concrete strength at 28 days, but this is arbitrary, and the reason for it has been lost to history. There’s nothing special about 28 days. For some purposes, such as analysing a warehouse floor’s load capacity, what really matters is the strength after several months. The floor will be that old before it is fully loaded. For other purposes, such as knowing when to remove forms or stretch post-tensioning tendons, the strength at 7 days or less may be critical.

If you need a minimum strength at, say, 5 days, you can test it at 5 days. And if it doesn’t pass at 5 days, you can test it again at 7 days, or whenever you like, as long as—and this is an important condition—you made enough cylinders or cubes on the day of the pour. And if you want to know the concrete’s 90-day strength to determine long-term load capacity, you can test it at 90 days. That’s straightforward and effective.

Problems arise when you try to estimate early or late strength from 28-day test results because not all mixes gain strength at the same rate. Consider three mixes all designed to achieve the same strength at 28 days. The normal mix is made with ordinary Portland cement (American Type I or II) and no admixtures that affect

strength gain. The accelerated mix is made with rapid-hardening cement (American Type III), and the retarded mix is made with low-heat Portland cement (American Type IV). Compared to the normal mix, the accelerated mix will be stronger before 28 days and weaker after 28 days. The retarded mix will reverse that: weaker early on, stronger later.

In that example, different cement types caused the changes. Other factors include admixtures and pozzolans. True to their names, accelerating admixtures speed up strength gain, and retarding admixtures slow it down. Pozzolans such as fly ash and slag also act as retarders.

People often measure concrete strength at three days or seven days, or both—not for contract enforcement but to determine when to remove formwork or for an early sign as to whether the mix will meet its specified 28-day strength. In post-tensioned floors, concrete strength is sometimes tested at one day or even less to determine when to apply the initial stress.

DRAWBACKS OF HIGHER STRENGTH

Stronger does not necessarily mean better. Concrete needs to be strong enough to resist the stresses applied to it, with a reasonable safety factor, but beyond that higher strength can cause more harm than good. The drawbacks of higher concrete strength in floors include monetary cost, increased drying shrinkage, and increased curling.

Stronger concrete usually costs more because it contains more cement, which is concrete's most expensive basic component. According to Canadian research (Salinas, 1980) into the cost of reinforced, one-way suspended slabs, the cheapest designs are those with the weakest concrete and the strongest reinforcing steel. The savings produced by using weaker concrete more than offset the cost of the stronger steel.

Stronger concrete shrinks more on drying because it contains more cement. The added cement causes a small increase in shrinkage on its own, but the main effect comes from the extra water that accompanies the extra cement. Other drawbacks of high concrete strength are the consequences of the increased drying shrinkage. More shrinkage means more cracks, more curl, and wider joints.

IMPACT RESISTANCE

This is concrete's ability to withstand sharp blows. All the strength tests described above apply loads slowly and steadily. Many real floor loads are also applied in that way but not all.

Some concrete floors must withstand sudden blows from dropped objects or from certain industrial processes.

Though not in wide use, tests are available to determine concrete's impact resistance. Schrader (1981) describes a test that uses a 4.5-kg (10-lb) drop hammer. The hammer falls 460 mm (18 in) to strike a steel ball resting on a standard concrete test cylinder of 150 mm (6 in) diameter. The cylinder is struck repeatedly till it comes apart. The operator records the number of blows to the first visible crack and the number of blows to complete failure.

ELASTIC MODULUS

Also called Young's modulus, this is a measure of how much concrete stretches or compresses in response to a force. It's needed for some structural calculations, but designers almost never specify or test it directly. They normally estimate it from the compressive strength.

Most concrete used in floors has an elastic modulus between 25 and 33 GPa (3.6×10^6 and 4.8×10^6 psi). Elastic modulus correlates fairly well, though not perfectly, with compressive strength.

A related property, Poisson's ratio, is also used in structural calculations. When you squeeze a piece of concrete, it becomes both shorter and wider. The ratio of widening to shortening is called Poisson's ratio. It can be tested (ASTM C 469 offers a standard method), but most designers and design manuals simply assume it to be about 0.2.

DRYING SHRINKAGE

Concrete starts its life saturated with water. If the concrete is well cured, it stays saturated till the end of the curing period. It then starts to dry out and as it dries, it shrinks.

The usual shrinkage tests (ASTM C157 and BS EN 12390-16) involve casting a beam, similar to the beams used for testing flexural strength but about half the size, and storing it in a chamber where temperature and humidity are tightly controlled. The length of the beam is measured at the start of air storage and at 7, 14, 21, and 28 days after that. Testing may go on longer, but the 28-day result is what usually counts for contract enforcement. The test result is the length change divided by the beam's length, expressed in percent or microstrains: $0.05\% = 500$ microstrains.

Specifications normally limit the 28-day shrinkage, which is what you measure after 28 days of air storage. The test takes longer than 28 days because the prism is soaked in lime water first. ASTM C157 calls for keeping the prism in its mould for one day, then immersing it in lime water for 27 days, and only then starting the air storage. With that schedule, a 28-day test really takes 56 days. It has become common in America to cut the six-day soak in lime water from 27 to 6 days. That change is often called 'modified ASTM C157' and has actually been codified in Canadian standards. Some people go further and eliminate the soaking period altogether.

Twenty-eight-day test results, for the concrete regularly used in floors, range from 200 to 600 microstrains. Ultimate shrinkage is a lot more. According to Equation 7.5, which comes from ACI 209, ultimate shrinkage is 2.25 times the 28-day reading, though that may not be true for all mixes.

$$(\epsilon_{sh})_u = (\epsilon_{sh})_d (35 + d) / d \quad (7.5)$$

where

$(\epsilon_{sh})_u$ = ultimate shrinkage

$(\epsilon_{sh})_d$ = shrinkage after d days in air storage

d = number of days in air storage

Drying shrinkage has a huge effect on ground-supported slabs, where it causes cracks, curling, and loose joints. Cracks form when the floor slab is restrained from sliding freely as it shrinks—and every slab is restrained to some extent, if only by friction. Curling is caused by differential drying shrinkage from the top of the slab to the bottom. The top dries out first because it is exposed to the air. Joints become loose as drying shrinkage widens them, reducing the effectiveness of aggregate interlock, keyways, and joint filler.

Suspended slabs shrink too, but the effects there are less marked. Most suspended slabs contain enough reinforcement or prestress to handle shrinkage cracks and keep joints tight. Curling is less likely because most suspended slabs dry out from both top and bottom. Even so, a suspended slab—indeed, any concrete structure you can think of—performs better when shrinkage is lower.

Specifications typically limit the 28-day shrinkage to 350 or 400 microstrains. Lower limits are achievable but will probably require a shrinkage-reducing or shrinkage-compensating admixture.

Even if you choose not to enforce a shrinkage limit, testing is useful because it tells you what to expect. Some regions are notorious for very high shrinkage due to the quality of the available aggregates. Standard floor designs do not work well in those regions, but you can still have a successful outcome if you know the shrinkage in advance and adopt a more conservative design.

The following steps can reduce drying shrinkage:

- Increase the top size of the coarse aggregate.
- Use a coarser aggregate gradation with more retained on the bigger sieves.
- Avoid aggregates made of stone with high shrinkage. Stone shrinks too.
- Use less water in the concrete mix (but beware of the effect on workability and finishability).
- Use less cement (but beware of the effect on strength and finishability).
- Use a shrinkage-reducing admixture (but beware of the cost).

THERMAL COEFFICIENT

Like most materials, concrete expands as it heats up and contracts as it cools down. The rate of expansion and contraction is called the thermal coefficient, and it does not vary much. For concretes made with normal-weight aggregates, the thermal coefficient ranges from 10 to 13×10^{-6} per Celsius degree (5.6 to 7.2×10^{-6} per Fahrenheit degree). Lightweight concrete shrinks and expands less, with a thermal coefficient of about 8×10^{-6} per Celsius degree (4.4×10^{-6} per Fahrenheit degree).

Because we cannot do much to change concrete's thermal coefficient, there is a temptation to ignore it. That can be a mistake, however. Thermal changes have a big effect on concrete floors, especially ground-supported industrial slabs and freezer floors.

The main issue here is thermal contraction, not expansion. Expansion rarely causes trouble in concrete floors (though it does in some other concrete structures) because only in the rarest circumstances does it make the floor bigger than its original, as-cast size.

In its effects, thermal contraction mimics drying shrinkage. Both involve reductions in volume, and both cause cracks and lead to loss of load transfer at cracks and joints. Many of the problems that afflict concrete floors come from the combined effects of drying shrinkage and thermal contraction.

One important difference between thermal change and drying shrinkage is that the former never ends. Drying shrinkage is a one-way street. It goes on for a long time but at an ever-diminishing rate, and after a few years, it is, for all practical purposes, over. In contrast, thermal changes go on forever as the floor warms and cools. The only exceptions occur in buildings that are maintained at the same temperature year-round.

Lacking any way to reduce concrete's thermal coefficient, how can you deal with its effects? The first step is to make sure the floor design accommodates all expected volume changes—those from temperature change and those from drying shrinkage. Many techniques used against drying shrinkage work equally well against thermal contraction. Those techniques include control joints, reinforcing steel, steel fibres, post-tensioning, and shrinkage-compensating concrete.

The second step is to repair joints and cracks in wintertime when the concrete is at the point of greatest thermal contraction. A joint or crack filled in midwinter will normally hold up better than one filled in midsummer. In heated buildings, the end of a floor's first winter is a good time to fill joints and cracks. Thermal contraction is near its maximum, and because the concrete has undergone several months of drying in the very low humidity caused by artificial heat, you can be confident that much of the total drying shrinkage has already occurred. In freezers and cold-storage buildings, floor joints and cracks should never be filled till the floor has stabilized at its design temperature.

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8 The Components of Concrete

Ordinary concrete has three essential components:

- cement;
- aggregates (usually divided into coarse and fine);
- water.

Most concrete also contains one or more admixtures.

CEMENT

Cement is the glue that holds concrete together. If you tried to make concrete without cement, the result would be a loose collection of wet aggregates.

What we commonly call cement is, strictly speaking, hydraulic cement—a powder that hardens in the presence of water. Several types are used in floors.

NOMENCLATURE

Though cements are similar around the world, they go by different names in different countries. What's more, UK nomenclature completely changed around the turn of the century with the adoption of European standards. Canadians use the same kinds of cement as Americans but use different names.

The new system, set out in BS EN 197-1, divides Portland cements into five main categories identified by Roman numerals—CEM I to CEM V (see Table 8.1). CEM I is plain old Portland cement. The other four CEM categories describe blended cements containing Portland cement mixed with other materials, mostly limestone powder and assorted pozzolans. All categories except CEM I are subdivided, using a complex notation that can show the proportion of Portland cement, the other components (i.e., other than Portland cement), the strength class, and how fast it gains strength. For example, the identifier CEM II/B-S 42.5 N reveals all the following:

- Roman numeral II tells us this is a blended cement with at least 65% Portland cement and one other ingredient.
- The letter B tells us this cement contains a medium proportion of Portland cement, within the range allowed for Type II. (A or C here would mean higher or lower proportion of Portland, respectively.)
- The letter S tells us the other ingredient is blast furnace slag. (V here would mean fly ash, D would mean silica fume, and L or LL would mean limestone powder.)

TABLE 8.1
Main European Cement Types (BS EN 197-1)

Type	Description
CEM I	Portland cement with no more than 5% of other material
CEM II	Portland cement with up to 35% one other constituent
CEM III	Slag cement—Portland cement blended with more than 35% slag
CEM IV	Portland cement blended with a natural pozzolan
CEM V	Portland cement blended with slab and natural pozzolan or fly ash

TABLE 8.2
UK Cement Types Suitable for Floors

Type	Description	Use
CEM I	Ordinary Portland cement	Most floors
CEM II/A-LL	Portland-limestone cement with 6–20% limestone powder	Most floors
CEM II/B-S	Slag cement with 21–35% slag	Most floors, except in cold weather
CEM II/B-V	Fly-ash cement with 21–35% fly ash	Most floors, except in cold weather
CEM III-A	Slag cement with 36–65% slag	Very thick slabs

- The number 42.5 identifies the strength class.
- The letter N tells us this cement gains strength at the normal rate. (R here would denote a cement producing high early strength.)

Though BS EN 197-1 divides cements into dozens of subcategories, only a few are actually available in any particular market. Table 8.2 lists five UK cements that make reasonable candidates for floor construction.

Just to keep things interesting, American standards also divide Portland cement into five categories identified by the Roman numerals I–V, but the definitions are completely different—except for Type I, which includes ordinary Portland cement in both systems. Table 8.3 lists the American types.

PORTLAND CEMENT

The great majority of concrete floors contain Portland cement, either on its own or blended with other powders. The British standard for Portland cements, including blended cements, is BS EN 197-1. Americans have ASTM C 150 for Portland cement and ASTM C 595 for blended cements that contain limestone powder or pozzolans.

Portland cement is made by heating a mixture of limestone and clay to partial melting at about 1400°C (2600°F). After it cools, the material is ground with a little

TABLE 8.3
American Portland Cement Types (ASTM C 150)

Type	Canadian Designation*	Description	Use
I	GU	Ordinary Portland cement	Most floors
II	MS	Ordinary Portland cement with slightly lower heat of hydration than Type I	Most floors, with special value where moderate resistance to sulphate is needed
III	HE	High-early-strength Portland cement	Floor repairs, tight construction schedules, and pours in cold weather
CSA A3000 IV	—	Low-heat Portland cement	Very thick slabs
V	HS	Sulphate-resisting Portland cement	Floors with severe exposure to sulphate

* From CSA A3000.

gypsum into a powder. By changing the proportions of the raw materials, and by adjusting the manufacturing process, different kinds of Portland cement are made. Varieties include:

- ordinary Portland cement;
- high-early-strength Portland cement;
- low-heat Portland cement;
- sulphate-resisting Portland cement;
- white Portland cement.

Ordinary Portland cement—CEM I in the UK, Type I in America—is a general-purpose product suitable for most floors under most conditions. Americans have the added choice of Type II, very similar to Type I but with a slightly lower heat of hydration and better resistance to sulphates. Actually, Americans do not always have that choice because in many parts of the USA, only one type, I or II, is available. The specifications for Types I and II overlap, with the result that some manufacturers supply a product called Type I-II.

High-early-strength cement is used where the concrete must achieve high strength at an early age. This is what British standards used to call rapid-hardening cement. Now, BS EN 197-1 identifies it by the letter R at the end of the name. Americans call it Type III, and Canadians call it HE. High-early cement does not set much faster than ordinary Portland, but the hardened concrete gains strength rapidly over the next few days. Seldom needed in ground-supported floors, this cement finds occasional use in multi-storey construction when a fast schedule calls for forms and shores to be removed as soon as possible. It is also used in floor repairs. It has drawbacks: an increased risk of thermal-contraction cracks and higher drying shrinkage. Alternatives to high-early-strength cement include adding an accelerator or just using more ordinary Portland cement.

Low-heat Portland cement (American Type IV cement) gains strength more slowly and generates less heat than other types. Mainly used to limit heat build-up in massive structures like dams, it is seldom needed in floor slabs, which are usually thin enough to avoid damaging heat build-up. If you can find it, it may be worth considering for very thick slabs—400 mm (16 in) or more—especially in hot weather. An alternative to low-heat cement is to combine ordinary cement with a pozzolan such as fly ash or slag.

Sulphate-resisting Portland cement (American Type V, Canadian HS) is sometimes used in ground-floor or basement slabs that come into contact with sulphate-rich soil. American Type II cement also resists sulphate, though not so well as Type V.

White Portland cement closely resembles ordinary Portland in performance and composition, but it contains almost none of the iron compounds that give other cements their characteristic grey hue. Though the cement is indeed white, floors made with it may not be. The finished product tends towards light grey, influenced by the colour of the fine aggregate and the amount of trowelling. White cement has been used to make light-coloured floors, but nowadays, a light-reflective dry shake is more common for that purpose.

PORTLAND-LIMESTONE CEMENT (AMERICAN TYPE II, CANADIAN TYPE GUL)

This is ordinary Portland cement blended with limestone powder. Limestone powder is not cementitious on its own, but it provides nucleation sites that enhance the hardening of Portland cement. Advocates say it can replace Portland cement one-to-one, up to about 15% by mass, without reducing concrete strength. The main reason to use Portland-limestone cement is its lower carbon footprint.

British and American standards allow up to 5% limestone powder in ordinary Portland cement, and the resulting blend is still called Portland cement. The term *Portland-limestone cement* is reserved for blends with over 5% limestone powder. In the UK, CEM II/A-LL can have up to 20% limestone powder. In America, Type II cement (ASTM C595) is capped at 15%. Even higher limestone contents are possible but are rarely seen in floors.

Portland-limestone cement is increasingly popular and, in many places, has replaced Portland as the normal, everyday cement. There has been some opposition to the change—and that's putting it mildly. Proponents say that Portland-limestone cement matches the performance of Portland in every important way. Opponents say it causes crazing, plastic-shrinkage cracking, and delamination. The complaints centre on increased water demand and reduced bleeding.

The problems are likely to diminish as cement makers, ready-mix suppliers, and floorlayers gain a better understanding of this product.

POZZOLANS

These are cement-like powders blended with Portland cement or with Portland-limestone cement. They are not cements and have little or no cementing ability on their own, but they form cementitious compounds when mixed with Portland cement and water. They are sometimes called cement-replacement materials because they can replace some (never all) of the cement in a concrete mix.

The original pozzolan was volcanic ash. Today, three pozzolans are widely used in concrete floors, and all are industrial byproducts. They are:

- slag (also called ground granulated blast furnace slag or ggbs), a byproduct of steel making;
- fly ash (also called pulverized fuel ash or pfa), which is extracted from the smokestacks of coal-fired power stations;
- microsilica (also called silica fume), which comes from the silicon industry.

Pozzolans have these effects:

- They reduce concrete's carbon footprint by replacing Portland cement, which is concrete's more carbon-intensive component.
- They reduce bleeding, a change that may or may not be desirable depending on the mix design and the weather.
- They reduce the heat of hydration, a change that is beneficial in very thick slabs.
- They lengthen setting time.
- They cause concrete to gain strength more slowly in its early days.
- They make curing more important.

The effect on curing is not well known and takes some explaining. Curing can be seen as a race between strength gain and drying. We want the concrete to grow strong enough before drying stops the chemical processes that make concrete stronger. Good curing handicaps the race in favour of strength gain, slowing the rate at which concrete dries. Pozzolans work in the opposite direction by slowing the rate at which concrete gains strength. For that reason, concrete floors made with pozzolans benefit from the best possible curing methods and possibly from curing periods longer than normal. Chaplin (1990) suggests that pozzolanic concrete can match ordinary concrete in wear resistance, provided it is wet-cured for at least 7 days or cured with a high-solids resin compound.

In their effect on heat of hydration and strength gain, pozzolans closely resemble low-heat Portland cement (American Type IV) and offer a good alternative to that hard-to-find material.

How much pozzolan can we safely use in floor construction? Opinions differ. One study (Lotha et al., 1976) on the effect of fly ash shows an increase in concrete creep when that particular pozzolan exceeds 15% of the total cementitious content. Chaplin (1986) reports that quite high levels of pozzolans—up to 35% fly ash and up to 50% slag—do not reduce a floor's wear resistance, provided the concrete is cured well. The Concrete Society (2003, p. 74) recommends limiting fly ash to 30% and slag to 35%, though it doesn't say why.

NONHYDRAULIC CEMENTS

Most concrete floors are made with hydraulic cement—either Portland cement or a near relative, sometimes blended with a pozzolan. A cement is called hydraulic when it hardens by chemical reaction with water. When people use the word *cement* with no modifier, they almost always mean hydraulic cement. Nonhydraulic

cements exist, however, and are used for some special purposes. Three examples are epoxy, sulphur, and bitumen (asphalt).

Epoxy cement makes a very strong concrete with extraordinary resistance to chemical attack. No one makes whole slabs of epoxy concrete—they would cost too much—but it finds use in floor toppings and repairs. Epoxy concrete is hard to finish because the epoxy resin sticks to almost everything, including tools.

Sulphur works as a cement if heated to its melting point of 113°C (235°F). Unlike Portland cement and epoxy, sulphur hardens not by chemical reaction but by cooling. The finished product resembles Portland-cement concrete in strength but has better resistance to some chemicals. It stands up well to acids, which are hard on normal concrete. It can be finished with the same tools used on Portland-cement concrete, including power trowels. Some people think sulphur concrete will turn out to be an economic building material on the Moon (Casanova, 1997)

Bitumen, a thick petroleum product also called asphalt, is the cement in bituminous concrete, used all over the world to pave roads and car parks. It is also used indoors for ground-supported industrial floors and floor toppings, though this is less common than it used to be. Because bituminous concrete flows under sustained heavy loads, it's not a good choice for floors that support fixed equipment. The few builders who lay floors of bituminous concrete typically use road-paving machines, including heavy rollers. However, some special formulations are finished more like Portland-cement concrete, using power trowels.

AGGREGATES

Aggregates are the rock particles that make up the main part of almost every concrete mix. If you tried to make concrete without aggregates, you would get cement paste—a strong material but one with a high price, very high shrinkage, and a propensity to crack.

In the UK, BS EN 12620 is the main standard for concrete aggregates. The American equivalent is ASTM C 33.

Aggregates are inert; that is, they do not enter into the chemical reactions that harden concrete. That does not mean, however, that they are unimportant. They play a large role in determining concrete's workability, finishability, plastic shrinkage, and drying shrinkage. They also affect load transfer at cracks and induced joints.

Convention divides aggregates into coarse and fine. Coarse aggregate, also called stone or gravel, consists of particles at least 5 mm (3/16 in) across. Fine aggregate, also called sand or fines, consists of particles less than 5 mm (3/16 in) across.

Though useful, the distinction between coarse and fine aggregates is arbitrary. While particles of different sizes affect concrete's behaviour in different ways, there is no special dividing line at the 5 mm (3/16 in) mark. The conventional distinction between coarse and fine aggregates makes sense mainly because the two usually come from different pits and are stored separately. A few lucky concrete plants lie near a source of sandy gravel that provides all the particle sizes needed for good concrete, and in those cases, the distinction between coarse and fine aggregates ceases to exist. BS EN 12620 recognizes this material as *all-in* aggregate. Even where coarse and fine aggregates come separately, it makes sense to consider them together when analysing the gradation.

COARSE AGGREGATE

This consists of rock particles at least 5 mm (3/16 in) across, and it forms the biggest part of most concrete mixes. Its role is to provide bulk, reduce drying shrinkage, and help transfer load across cracks and induced joints. If you tried to make concrete without coarse aggregate, you would get grout or mortar—a material that would cost too much and shrink too much to use in floors.

Coarse aggregate may consist of natural gravel or man-made crushed rock. Both can do the job, but there are some differences between them. Gravel particles tend to be smooth and rounded, making concrete that is easy to pump and strike off. Crushed-rock particles tend to be rougher and more angular, making concrete stronger and improving aggregate interlock at cracks and induced joints.

Coarse aggregate plays a vital role in controlling concrete shrinkage, which is of great concern in floor construction. It also helps transfer loads across cracks and induced joints, a factor of great importance in unreinforced and lightly reinforced floor slabs. Because coarse aggregate is almost always the most voluminous component of a concrete mix, its weight has a big effect on the weight of the finished product. When a design calls for lightweight or heavyweight concrete, the goal is achieved, at least in part, by choosing unusually light or heavy coarse aggregates.

Coarse aggregate has little to do with the properties of the floor surface because it is usually hidden beneath a layer of mortar. But sometimes, the stones are so near the surface that affect the floor's appearance. This is called aggregate shadowing.

Gradation of Coarse Aggregate

The coarse aggregates used in concrete floors contain a range of particle sizes. The bigger particles keep the concrete dimensionally stable, reducing both plastic and drying shrinkage. The smaller particles fill the gaps between the bigger particles. Without those smaller particles, the mix would need more fine aggregate and more cement and would cost more.

Gradation is the division of aggregate into categories defined by particle size. The usual method is sieve analysis, in which the aggregate passes through a set of standard sieves, each finer than the last. The amount of material retained on each sieve is weighed, and the weights are then used to calculate the percentage of material that passes each standard sieve.

UK sieve sizes are straightforward, measured in millimetres. American sizes are more complicated. The bigger sizes, like their UK counterparts, are identified by a dimension that shows the width of each square hole in the sieve. That is simple enough, but sizes below $\frac{3}{8}$ in are identified by numbers that bear no clear relationship to any dimension in millimetres or inches. Higher numbers denote smaller sieves.

Making the situation more complex still, Americans use a second system to define aggregate gradation. ASTM C 33 identifies coarse aggregates by 'size numbers' that range from 1 to 8. In this system, a single batch of aggregate may bear two or three numbers if it contains a mix of sizes. For example, the widely used number 57 aggregate includes sizes 5 and 7, while number 467 includes sizes 4, 6, and 7. (They should be pronounced 'five seven' and 'four six seven', by the way.)

Most authorities favour a broad, even gradation, with a wide variety of particle sizes and with similar amounts retained on each standard sieve. Advocates argue that such a gradation produces a highly finishable mix with low drying shrinkage. In America, some floor specifications require that coarse aggregate meet the 8-18 rule—at least 8% and no more than 18% retained on each standard sieve between 19.0 mm (3/4 in) and 4.75 mm (Number 4). That is stricter than the normal limits imposed by ASTM C 33. But this is not always achievable.

Maximum Particle Size

Whether the gradation is even or not, it has to top out somewhere. Ordinary structural concrete typically contains nothing bigger than 20 mm (3/4 in) or at most 25 mm (1 in). Although such concrete is widely used in floors, there are good arguments for going bigger. Adding bigger stones offers these benefits:

- reduced drying shrinkage, which in turn means less curling, fewer cracks, and more stable joints;
- better aggregate interlock at cracks and induced joints;
- less plastic settlement (particularly valuable in thick slabs);
- a reduction in the amount of cement needed to achieve the same concrete strength.

Drawbacks include:

- difficulties in pumping;
- problems placing and compacting concrete around dense reinforcement;
- higher cost in some markets.

On most projects, the benefits outweigh the drawbacks, at least in ground-supported floors. It usually makes sense to use the biggest maximum particle size available, subject to these limits:

The size must not exceed one half the minimum distance between reinforcing bars and wires.

- The size must not exceed one-half (some say one-third) the slab or topping thickness.

Lightweight Coarse Aggregate

Ordinary coarse aggregate has a bulk density of about 1500 kg/m³ (90 lb/ft³). Lighter materials are available, however. Coarse aggregates weighing less than 1120 kg/m³ (70 lb/ft³) are called lightweight or low-density. Lightweight aggregates include pumice (a volcanic rock) as well as man-made products.

In the UK, BS EN 13055 covers lightweight aggregate. In America, ASTM C330 covers the material properties while ACI 213 covers usage.

Because coarse aggregate is the most plentiful component of the mix, a change to lightweight coarse aggregate makes concrete much lighter. Concrete with ordinary aggregates has a density of about 2400 kg/m³ (150 lb/ft³). If you replace the coarse

aggregate with lightweight material, the density falls to about 1700 kg/m^3 (105 lb/ft^3)—a 29% reduction. Even lower densities, down to about 960 kg/m^3 (60 lb/ft^3), are possible if you use lightweight fine aggregate too, but that makes concrete hard to finish and is rarely done in floor construction.

Almost never used in ground-supported floors, lightweight aggregate offers at least two benefits in suspended floors. It improves the floor's structural capacity by reducing dead weight, and it makes the floor more resistant to fire damage.

The main drawbacks to using lightweight concrete in floors are cost and finishing difficulties. Lightweight concrete can cost half as much again as ordinary-weight concrete.

Deleterious Ingredients

The perfect coarse aggregate would consist of nothing but sound, solid particles of rock. Real-world aggregates all fall short of that ideal—sometimes very far indeed. They contain pieces of wood and rubber, lumps of clay, chunks of coal, and other materials that do concrete no good. Sea-dredged aggregates can even be contaminated with fish.

Those deleterious materials don't often appear at the floor surface because the finishing process covers them with cement paste. They sometimes end up just below the surface, however, and that is where they cause trouble. The thin layer of cement paste above them may break up under traffic, leaving a hole. Or worse, the offending particle may expand from absorbing water or from chemical reaction, bursting the surface and creating a popout.

Standards limit the amount of deleterious material in coarse aggregate, but the amounts allowed are greater than you might suppose. ASTM C 33 allows 'clay lumps and friable particles' to make up 5% of the total mass. You probably wouldn't buy a bag of rice or a box of cornflakes knowing that up to one-twentieth of it might be inedible. But when you buy coarse aggregate specified to meet ASTM C 33, you might have to accept that much undesirable material. (The standard actually allows up to 6.5% deleterious ingredients if we add up all possible kinds.)

Of course, not every coarse aggregate tests the limits. But all contain some impurities, and for that reason, we should never be surprised when a concrete floor develops a few small holes or popouts.

Alkali-aggregate Reaction

Certain aggregates react chemically with the alkalis present in Portland cement. They expand over time, causing popouts.

The obvious solution is to avoid such aggregates. But that's not always practical because in some regions, all available aggregates are reactive. Builders in those regions have learned ways to reduce the risk. One trick is to minimize the amount of time the aggregates remain damp because the damaging chemical reaction occurs only in the presence of water. Techniques include pouring indoors so the slab never receives rain and using a curing compound instead of a wet cure.

ASTM C 33 says the use of low-alkali cement or the addition of pozzolans can reduce the damaging expansion from alkali-aggregate reaction.

FINE AGGREGATE

This consists of rock particles less than 5 mm (3/16 in) across. Its role is to fill the voids between the pieces of large aggregate. It also contributes to the mortar paste that makes a concrete floor finishable. You can make concrete without fine aggregate, but the result—called no-fines concrete or pervious concrete—is almost never used in floors.

Gradation of Fine Aggregate

Fine aggregates are graded by sieve analysis in much the same way as coarse aggregates, but the results are interpreted differently. British practice (see Table 8.4) divides fine aggregates into three gradation categories called grades C, M, and F. While all three have been used successfully in floors, Chaplin (1990) recommends only grades M and F for floors that need high resistance to wear. The Concrete Society (2016, 46) warns that we should not build industrial floors with fine aggregate ‘at the coarse end of grade C or the fine end of grade F’.

American practice (see Table 8.5) does not divide fine aggregates into categories by gradation. Americans do, however, add a refinement called the fineness modulus.

TABLE 8.4
British Gradation Limits for Fine Aggregate

Sieve	Amount Passing, by Mass		
	Grade C	Grade M	Grade F
10.0 mm	100%	100%	100%
5.00 mm	89–100%	89–100%	89–100%
2.36 mm	60–100%	65–100%	80–100%
1.18 mm	30–90%	45–100%	70–100%
0.60 mm	15–54%	25–80%	55–100%
0.30 mm	5–40%	5–48%	5–70%
0.15 mm	0–15%	0–15%	0–15%

TABLE 8.5
American Gradation Limits for
Fine Aggregate

Sieve	Amount Passing, by Mass
9.5 mm (3/8 in)	100%
4.75 mm (No. 4)	95–100%
2.36 mm (No. 8)	80–100%
1.18 mm (No. 16)	50–85%
0.60 mm (No. 30)	25–60%
0.30 mm (No. 50)	5–30%
0.15 mm (No. 100)	0–10%

To calculate it from a sieve analysis, add the percentages retained on each of the following sieves: 0.15 mm (Number 100), 0.30 mm (Number 50), 0.60 mm (Number 30), 1.18 mm (Number 16), 2.36 mm (Number 8), and 4.75 mm (Number 4). Divide that sum by 100 to get the fineness modulus. To satisfy ASTM C 33, the fineness modulus must not be lower than 2.30 nor higher than 3.10. A high fineness modulus means the aggregate is deficient in smaller particles.

Natural Sand versus Crushed-rock Fines

Like coarse aggregates, fine aggregates may be either natural or man-made. In the case of coarse aggregates, neither source is consistently superior. But in the case of fine aggregates, natural sand is almost always the better choice. The man-made product, called manufactured sand or crushed-rock fines, often contains too much dust and has a particle shape that makes it hard to finish.

Some designers allow nothing but natural sand, especially for industrial floors. The British standard for concrete wearing surfaces, BS 8204: Part 2, calls for natural sand in floors that need high resistance to wear. On the other hand, the Concrete Society (2016, 46) says manufactured sand is acceptable as long as it doesn't have more than 9% passing the 63- μ m sieve.

In the face of these conflicting recommendations and the absence of any good research results, should we still prefer natural sand? I say yes but with some flexibility. Where high-quality natural sand is available at a reasonable price, use it. But where it costs far more than manufactured sand, or is of low quality, consider the man-made alternative.

WATER

Water is an essential ingredient of every concrete mix, except those few mixes made with nonhydraulic cements. The properties of the water get little attention because they do not vary much. Almost any water safe to drink is safe for concrete, and much non-potable water will work as well.

Decisions involving water centre on the amount added to the mix. Concrete (more precisely, hydraulic-cement concrete) needs water for the chemical reactions, called hydration, that make concrete hard and strong. All concrete mixes contain more water than the minimum needed to hydrate the cement. The extra water, sometimes called water of convenience, lubricates the mix, making it easier to place and finish. On the other hand, extra water reduces the concrete's strength and increases its drying shrinkage.

SEA WATER

In a few parts of the world, scarcity of fresh water demands that concrete be made with sea water or other salt water. The main drawback to that practice is that the finished product will contain more chloride ions than national codes allow for reinforced or prestressed concrete. Salt water is safe to use in plain, unreinforced concrete, however. And it may be usable in reinforced or prestressed concrete if the embedded steel is protected from corrosion.

A less important drawback to sea water is that it causes efflorescence—salt deposits on the floor surface. The problem is mainly one of appearance.

WATER TEMPERATURE

The temperature of the mixing water has a big effect on the temperature of the fresh concrete because water has a much higher specific heat (heat capacity per unit of mass) than cement or aggregates. When concrete needs to be made cooler or hotter, adjusting the water temperature is generally more effective than trying to change the temperature of the other components. In many parts of the world, ready-mix plants heat their water in winter. Chilled water, though less common, is available in some markets.

Where ice is used to cool concrete, its mass must be counted in the mix's total water content.

ADMIXTURES

Plain concrete consists of cement, aggregates, and water. An admixture is any other material, except fibres, deliberately added to the concrete mix for a specific purpose. Some admixtures are liquid and others are dry. The latter are sometimes called additions.

Admixtures are often useful, sometimes essential, and widely overused. Thanks to manufacturers' sales efforts, we hear a lot about the benefits of admixtures. We hear less about their unwanted side effects. For example, some admixtures increase drying shrinkage. ASTM C 494 allows that as long as the increase does not exceed 35% (20% in the case of air entrainers). Given that drying shrinkage causes some of the most troublesome floor problems, you might not wish to specify or buy an admixture that causes even a 5% increase in that property, much less 35%. But if tests showed a product causing, say, a 34% increase, you might never hear the news. You would only be told the product 'meets ASTM C 494'.

Admixtures always cost money, but at least two kinds—accelerators and low-range water reducers—produce offsetting savings that sometimes reduce their net cost to zero or less. Accelerators save labour because they shorten setting times. That property is particularly valuable in cold weather, where without them, the floorlayers would have to work overtime. Low-range water reducers save money because they allow a reduction in the amount of cement to achieve a given strength.

Admixtures are classified by their effects, not their chemistry. A category may contain widely different chemicals, but their intended effects will be similar. Some chemicals affect concrete in more than one way and thus are present in more than one category. The following kinds of admixtures are used in floors:

- air entrainers;
- accelerators;
- retarders;
- low-range water reducers (plasticizers);
- mid-range water reducers;

- high-range water reducers (superplasticizers);
- pigments;
- shrinkage reducers;
- expansive admixtures.

AIR ENTRAINERS

These admixtures create air bubbles in the cement paste. Entrainment is the deliberate creation of tiny voids in the concrete, while entrapment is the incidental creation of much bigger voids during the mixing and placing of the concrete. Entrained air bubbles are round and have a diameter of 0.02–0.50 mm (0.0008–0.02 in). Entrapped air voids are less regular in shape and are usually bigger. Entrained air is usually expressed as a percentage of the total concrete volume. Typical values range from 3 to 7%.

The main reason, and the only really good one, to entrain air is to help hardened concrete resist frost damage. The air spaces provide room into which water can expand as it freezes. For good frost resistance, designers specify entrained-air contents of 4–6%, depending on the size of the biggest stones in the mix. Coarser aggregates allow lower air contents.

In addition to its effect on frost resistance, entrained air also makes the mix more workable and reduces bleeding. To achieve those goals on floors where frost resistance is not an issue, designers sometimes specify air contents around 3%.

Entrained air's main drawback—a huge one—is an increased risk of delamination. Finishing tends to trap the air under a thin surface layer, which then fails to bond properly to the main mass of the concrete below. The risk rises with the smoothness of the finish. The use of dry-shake finishes greatly increases the risk, and for that reason, the American Concrete Institute recommends against any entrained air on slabs that get such dry shakes.

A lesser drawback is reduced concrete strength. Each percentage point of entrained air lowers the concrete's compressive strength by about 5%.

Most concrete floors need no entrained air to resist frost. Two conditions must be met for frost to damage mature concrete. First, the concrete must undergo repeated freezing and thawing. A one-time fall below the freezing point, as occurs in a freezer building, rarely does noticeable harm. Second, the concrete must be saturated with water when freezing occurs. Almost no interior floor slabs meet both those conditions after the building is completed. Some floors do meet both conditions during construction, however, and in those cases, people argue whether the benefit of entrained air outweighs the risk.

Please note that entrained air does not protect newly placed concrete from frost damage. It works only on mature concrete that already gained substantial strength.

ACCELERATORS

Accelerators make concrete set earlier, and they cause the hardened concrete to gain strength faster. They may reduce long-term strength, though.

ASTM C 494 requires that accelerators produce certain effects relative to an unaccelerated control mix. They must shorten setting time by at least 1 hour and at most 31/2 hours. Their effect on compressive strength varies with time (see Table 8.6).

TABLE 8.6
Potential Effect of Accelerating
Admixtures on Compressive Strength

Concrete age	Minimum Compressive Strength, Compared to Unaccelerated Control Mix
3 days	125%
7 days	100%
28 days	100%
6 months	90%
1 year	90%

Source: From ASTM C494.

At three days, the accelerated mix is supposed to be at least 25% stronger than the control mix. After six months, the accelerated mix can be as much as 10% weaker.

Accelerators are used in cold weather to reduce late-night work and overtime expense. They also allow earlier removal of forms and shores, an important factor in some multi-storey projects.

The traditional accelerator is calcium chloride. It is cheap and effective, but in a damp environment, it (or any other chemical that releases chloride ions) promotes the corrosion of steel embedded in the concrete. For that reason, structural codes prohibit the use of calcium chloride in reinforced and prestressed (including post-tensioned) concrete.

That might seem the end of the story for calcium chloride, but the chemical still has a place in unreinforced floors. And some designers allow it in reinforced ground-supported slabs, most of which lie beyond the restrictions imposed by the structural codes. The truth is that calcium chloride is not nearly so dangerous in floor slabs as the warnings suggest because it only promotes corrosion while the concrete is damp. Most concrete floors are dry almost all the time, and in such floors, calcium chloride is harmless.

For those who need an accelerator but cannot or will not use calcium chloride, nonchloride accelerators are available at a higher cost.

Whatever accelerator is used, the dosage should stay the same throughout each pour. It's tempting to save money by dosing just the last batch or two, but that practice causes the last batches to set before the others, interfering with the orderly sequence of finishing steps.

RETARDERS

Retarders delay the setting of concrete. They have little effect on strength gain after setting.

Retarders are used mainly in hot weather. High temperatures make concrete set faster, leaving less time for finishing. Retarders offset that. They are worth considering when air temperatures exceed 30°C (86°F).

Retarders are sometimes used in cooler weather if a long delay between concrete mixing and placing cannot be avoided. This happens where the job site lies far from the concrete plant.

Retarders are rarely essential. Many builders working in hot climates have developed other ways to deal with short setting times. They pour at night, or they just make sure they have enough labour on hand to finish the concrete in the short time available.

LOW-RANGE WATER REDUCERS (PLASTICIZERS)

These admixtures increase concrete's workability. They are called water reducers because they reduce the amount of water needed for a workable mix. The 'low-range' part of the name distinguishes them from mid-range and high-range water reducers, which do the same thing but in greater measure.

Low-range water reducers let us reduce water content by 5–12% while keeping the same workability. That makes concrete stronger and may reduce drying shrinkage. Alternatively, they are used to increase workability while leaving water content unchanged.

Many water reducers have mild retarding effects, which may or may not be wanted.

Though a few people still don't like them, low-range water reducers are as safe as any admixtures can be, and they are very widely used.

MID-RANGE WATER REDUCERS

These increase workability, with effects between those of low-range and high-range water reducers. Or to put it more precisely, they produce a range of water reduction that overlaps that of the other two categories. By definition, low-range water reducers let us reduce water by 5–12% while retaining the same workability. High-range water reducers allow a reduction of more than 12% in water content. Mid-range water reducers straddle that 12% dividing line. At low doses, they serve as low-range water reducers, and at high doses, they serve as high-range water reducers.

Unlike some high-range water reducers, mid-range products do not lose effect after 40 minutes or so.

HIGH-RANGE WATER REDUCERS (SUPERPLASTICIZERS)

These let us reduce water content by at least 12% while keeping the same workability.

They allow the use of very low water–cement ratios that would otherwise make concrete almost impossible to mix and place. Such mixes have only a small role in floor construction, however, because they lack the free water needed for floating and trowelling.

In floors, high-range water reducers are more often used with normal water–cement ratios to make high-slump, so-called flowing concrete. Slumps of 200 mm (8 in) are possible. Such concrete is easy to place and strike off, but there is a price. Floor flatness may suffer because the concrete changes shape so readily before it has set.

Some floorlayers rely on flowing concrete to make huge pours using wet screeds. That technique has dwindled in popularity as powered laser screeds have come into wide use. Laser screeding allows, and indeed works better on, stiffer mixes.

Some concrete finishers dislike high-range water reducers for at least two reasons. First, they complain of uneven setting in the form of ‘mushy spots’—small areas that set much slower than the rest of the floor. Poor mixing would seem the likely culprit, but longer mixing times have not always eliminated the problem. Second, they have to deal with the way some (not all) high-range water reducers stop working after about 40 minutes. The resulting near-instant stiffening of the concrete can interfere with floor finishing.

PIGMENTS

Various pigments are available as admixtures (see Table 8.7).

Pigmented concrete is hard to get right, particularly in floors. Results often disappoint for at least three reasons. One problem is that pigments affect only the cement paste, leaving the aggregates to show their natural hues. Because of this, the colours are never very intense. Anyone expecting the colour intensity of, say, injection-moulded plastic is sure to be disappointed.

A second reason for disappointing results is efflorescence. Efflorescence is the deposition of whitish salts on the concrete surface. Pigments don't cause efflorescence, but they make it stand out.

A third problem is the difficulty of getting consistent colour from batch to batch. Small variations, which might be unobjectionable in uncoloured concrete, are painfully obvious on a coloured floor.

If you use pigments despite these problems, always provide a test slab so the customer can judge the results.

Remember, too, that there are other ways to colour a concrete floor. Coloured dry shakes may provide greater intensity, though they still face problems of efflorescence and colour variation. If a user demands a very bright, consistent colour, the best answer is probably a floor coating.

TABLE 8.7

Pigments

Colour	Pigment
Grey and black	Iron oxide Mineral black Carbon black
Blue	Ultramarine blue
Red	Iron oxide
Brown	Iron oxide Raw and burnt umber
Ivory and cream	Yellow iron oxide
Green	Chromium oxide Phthalocyanine green
White	Titanium dioxide

SHRINKAGE REDUCERS

These reduce concrete's drying shrinkage by changing the way moisture migrates through concrete. With a high dosage, 28-day shrinkage readings below 200 microstrains are possible.

Since drying shrinkage lies at the root of the most intractable floor problems—cracking, curling, and loss of load transfer at joints—the availability of an admixture that substantially reduces drying shrinkage seems too good to be true. Alas, it may be just that. Shrinkage reducers have the following drawbacks:

- They are dear, especially at the dosage needed for large reductions in shrinkage.
- They reduce bleeding, leading to a dry surface that is hard to finish.

What's more, there is some question about their long-term effect. They dramatically reduce shrinkage in the first few weeks, but after that, a floor with a shrinkage reducer will shrink more than one without. It seems that shrinkage reducers provide some benefit even after a year, but that benefit is less than the 28-day test results would suggest.

EXPANSIVE ADMIXTURES

Shrinkage reducers (discussed above) reduce shrinkage. Expansive admixtures offset it. They make concrete swell in its early days. After that, the concrete shrinks normally.

Expansive admixtures are the key ingredient in shrinkage-compensated concrete. Older books and articles often speak of making shrinkage-compensated concrete with expansive cement, but that product has all but vanished from the market, at least in the UK and America. Shrinkage-compensated concrete is still around, but it's made with admixtures.

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9 Mix Design and Mixing

MIX DESIGN

In modern construction, the person who designs the floor is rarely the person who designs the concrete mix. Most concrete comes from ready-mix companies, who hire specialists to design their mixes. Nevertheless, floor designers—and builders, too—need to know something about the subject so they can ask the right questions and comment intelligently on mix designs prepared by others.

There are three basic kinds of concrete mixes:

- ratio mixes (also called nominal mixes);
- prescribed and designated mixes;
- designed mixes.

Almost all concrete from ready-mix plants falls in the last category. Ratio mixes and prescribed mixes still appear on small jobs where concrete is mixed on site.

RATIO MIXES

Also called nominal mixes, these are described by the ratio of cement to fine aggregate to coarse aggregate, either by volume or weight. The amount of water is not defined under the assumption that the batcher will add just enough water to attain the desired workability. This used to be the standard way to describe all concrete mixes, but prescribed and designed mixes have superseded it for most purposes.

Cement–sand screeds take a slightly different method because they lack coarse aggregate. Here, the specification consists of just two numbers, expressing the ratio of cement to sand. The most common screed mixes are 1:3 and 1:4 by volume.

PRESCRIBED AND DESIGNATED MIXES

In the UK, these occupy the middle ground between crude ratio mixes and finely tuned design mixes. Both are standard recipes and are covered by BS 8500-2. They avoid the extra work needed to prepare and review a designed mix.

Prescribed mixes are meant for small projects where concrete is mixed on site and no one tests the concrete for strength. The prescribed mixes most likely to be used in floors are ST3 and ST4 with typical 28-day compressive strengths of 15 and 20 MPa, respectively (2200 and 2900 psi).

Designated mixes are similar to prescribed mixes but are meant for ready-mix plants and larger site-mixing operations with third-party certification.

DESIGNED MIXES

These are tailor-made for specific requirements and specific materials. Most are prepared by ready-mix concrete firms, though a few floor designers do the job themselves. Good mix design demands not only an understanding of the principles involved but also knowledge of how those principles apply to the available materials, which vary greatly from place to place. There is no substitute for local experience and good judgement.

If you wish to learn the general principles, Murdock, Brook, and Dewar's *Concrete Materials and Practice* (1991) is a good place to start and is unusual in that it deals clearly with both British and American procedures. Beyond that, most mix designers use a standard method. In the UK, the choices include the BRMCA (for British Ready Mixed Concrete Association) and the DoE (for Department of the Environment) methods. In America, the most popular method appears in ACI 211, *Standard Practice for Selecting Proportions for Normal, Heavyweight and Mass Concrete*.

With any method, mix design requires a high level of skill. Fortunately, it is not a skill floor designers must possess. You can design a concrete floor without knowing how to design a concrete mix (people do it every day), provided you know what questions to ask. The usual approach is that the floor designer specifies the properties the concrete must meet and then the concrete-mix designer (often an employee at a ready-mix firm) proposes a recipe that will meet those requirements. Floor designers typically specify some of the following properties:

- compressive strength;
- flexural strength;
- drying shrinkage;
- maximum or target slump;
- water–cement ratio;
- entrained air;
- minimum cement content;
- cement type;
- gradation of coarse aggregate;
- allowability of admixtures.

When a designed mix is submitted for review, it normally includes a list of ingredients showing the amounts contained in each cubic metre (or cubic yard) of concrete. It often includes test results that show that the mix is likely to achieve the specified strength. It may not contain much more unless someone insists, and on important jobs, someone should. To allow proper evaluation, a mix-design submittal may need to include some or all of the following information beyond the basics:

- coarse-aggregate gradation showing the amount retained on each standard sieve;
- fine-aggregate gradation showing the amount retained on each standard sieve;
- combined aggregate gradation showing the amount that would be retained on each standard sieve if both coarse and fine aggregates were sieved together;

- composition of the coarse aggregate—type of rock, and whether natural gravel or crushed rock;
- composition of the fine aggregate—whether natural sand or crushed rock fines;
- test results for drying shrinkage.

In most places, as of 2024, you can still get all that information if you ask for it, but that could change. Some in the ready-mix industry are promoting a system in which the buyer gets to specify the concrete's performance, but the details of the mix design are a trade secret, not subject to review. Such a system is already in place in the Canadian province of Ontario. Not everybody likes it.

KEEPING AN OPEN MIND

Some key concrete properties are hard to predict. Few of us can look at a mix design on paper and know for sure the concrete will be finishable or pumpable.

For that reason, we should keep an open mind about every mix design. If a mix proves hard to finish or turns out to have other bad properties, we should be ready to change it, even if the job schedule does not leave time for full testing of the changed mix design.

When a new mix design is used in a demanding floor, it is wise to start with a trial slab in a noncritical part of the building.

MIXING

We have two choices here: ready-mix or site-mixed concrete.

READY-MIX CONCRETE

This is batched in a concrete plant and delivered to the site in trucks. Ready-mix concrete has become the norm for almost all floor construction, at least in the industrialized world, except for the very smallest and very biggest jobs.

Ready-mix plants come in two types: central-mix and dry-batch. A central-mix plant combines all the components (except certain admixtures that are put in at the last minute) in a stationary mixer. After mixing is complete, the concrete is discharged into trucks for delivery to the job site.

A dry-batch plant puts the dry ingredients into concrete trucks. Water is then added, and the truck serves as the mixer. Dry-batching comes into its own on long hauls; the driver can wait till the right moment to add water, making sure the concrete arrives fresh at the job site. But that advantage turns into a minor drawback if the job site lies near the plant. Then, the drive may be too short for complete mixing, and you may have to let the truck mix for a few minutes after arrival on site.

For proper mixing of dry-batched concrete, the truck's mixing drum has to turn at high speed—faster than the so-called agitating speed used after mixing is complete. ASTM C 94 recommends 70–100 revolutions at mixing speed. In the

UK, Blackledge (1980, p. 3) recommends at least 100 revolutions. You can overdo it, though. The concrete should be discharged before the drum has turned 300 times.

ACI C 94, which uses the term truck-mixing instead of dry-batching, recognizes a third category of ready-mixed concrete called shrink-mixed. Shrink-mixed concrete is partially blended in a stationary mixer and then put into a truck where the mixing is completed.

Whatever the mixing method, no concrete maker has perfect control over the process. Even if the dry ingredients are batched with great accuracy, variations in the moisture content of the aggregates cause workability to vary from batch to batch. Wash water left in the mixing drum has a similar effect. The resulting changes in workability can cause problems in concrete finishing, with wetter batches setting up later than drier ones. Some floors, especially those with tight flatness tolerances, require closer control over water content and workability than the typical ready-mix plant can achieve.

One solution to that problem is to order the concrete slightly stiffer than desired and then adjust it on site by adding water. Some specifications forbid the addition of water on site but such that it can be counterproductive. Site-added water is safe as long as the following rules are followed:

- The addition of water must be under the control of one responsible person.
- The batch ticket must show the amount of water that can be added without jeopardizing strength and other specified properties.
- The amount of added water must be recorded.
- The concrete must be well mixed after the water is added.

A common mistake is to add water without mixing it properly. After water is added, the drum should make at least 30 revolutions at mixing speed.

MIXING ON SITE

Site-mixed concrete used to be common, but ready-mixed concrete has largely replaced it throughout the industrialized world. Nowadays, even the builders of small house and garage slabs are likely to order their concrete from the local ready-mix plant.

Still, site mixing hangs on at both ends of the project-size scale. It makes sense for very small jobs where the quantity of concrete needed is less than a truckload. It can also work well on jobs where concrete is used so slowly that it would take an hour or more to pour out a standard concrete truck. Some thin toppings and repair projects fall into that category.

At the other extreme, some contractors set up mobile batch plants on huge jobs. These plants have much the same equipment as fixed plants but are made to be dismantled and moved from job to job. They are often used in rural areas where local concrete suppliers don't exist or cannot supply the quantity or quality needed. They



FIGURE 9.1 This mobile batch plant has all the capabilities of a fixed plant but can be taken apart and moved between jobs.

are also used in cities so that a big, fast-paced job will have its own guaranteed concrete supply (Figure 9.1).

On small jobs, site-mixing is often associated with rough batching and a casual attitude towards quality, but it does not have to be. Some builders set up scales and weigh the components with as much care as any ready-mix producer. Others batch by volume. Though some authorities deprecate the practice, careful volume-batching can produce perfectly satisfactory floors. Batching by volume is the norm for sand–cement screeds.

Ready-mix plants and mobile batch plants use bulk cement, but smaller site-mixing operations generally get cement in bags. Each batch should contain a whole number of bags. In the UK, the standard bag has long been 50 kg, but nowadays, 25 kg is more common.

The American standard is 42.6 kg (94 lb), which seems a strange amount unless you consider its volume: exactly 1 ft³.

Almost any mixer in good condition will serve for the highly workable concrete normally used in floors. Cement–sand screed mixes are much stiffer, however, and require a forced-action mixer.

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10 Transporting and Placing Concrete

After concrete has been mixed, it must be transported and placed. Transportation is the moving of concrete from the mixer to the point of pour. Placement is the putting of concrete in its final location, ready for the next step, finishing.

In some ways, placing concrete is easier in floors than in columns or walls. Floors are usually thin, so horizontal cold joints rarely occur. Reinforcement is usually simple, and some floors lack it completely. Driven by the need for finishability, concrete for floors is usually highly workable.

In other ways, floor construction imposes unusual demands on concrete placement. This chapter looks at:

- transporting concrete;
- pour layout;
- side forms;
- tools for placing concrete;
- compaction.

TRANSPORTING CONCRETE

The following methods are commonly used to transport concrete to and across the job site:

- ready-mix trucks;
- tipper (dump) trucks;
- dumpers;
- wheelbarrows and handcarts;
- pumps;
- cranes;
- telescoping belt conveyors.

READY-MIX TRUCKS

These transport concrete from ready-mix plants and are also used with on-site batch plants. The typical model holds between 5 and 10 m³ (6 and 13 yd³), with the upper limit controlled by how much weight the local authorities will allow

on the public roads. It has a rotating drum with spiralling internal fins. When the drum rotates one way, the fins push the concrete down, mixing it. When the drum reverses its direction, the fins push the concrete up and out for discharge. The drum should never stop rotating for more than a few seconds as long as it contains concrete.

Rotation can be fast or slow. Fast rotation is called mixing speed and is used to mix the concrete and to blend in extra water and admixtures. Mixing speed is typically from 12 to 18 rpm. Slow rotation is called agitating speed and keeps the concrete mixed. Agitating speed is less than 6 rpm.

At dry-batch plants, the concrete is actually mixed in the truck's drum, requiring about 100 revolutions at mixing speed. At central-mix plants, the concrete is mixed before it enters the truck, eliminating the need for mixing speed unless something is added later. According to ASTM C 94, Standard Specification for Ready-mixed Concrete, the number of revolutions should not exceed 300, regardless of speed. If extra water is added on site, the drum should spin at least 30 times at mixing speed.

Wherever possible, ready-mix trucks should discharge their loads directly into the forms. This saves so much time and money that it often justifies major efforts to accommodate it, such as leaving out walls and building ramps (Figure 10.1).

Ready-mix trucks are heavy and easily tear up subgrades and sub-bases, especially where they have to make tight turns. Some sites require a layer of gravel or crushed rock to support concrete trucks.

On big pours, you need enough trucks, properly spaced, to maintain a steady supply of concrete. It is no good having three or four trucks queue up because they are arriving faster than the concrete can be placed. On the other hand, it is equally bad to run out of concrete and have to wait as the trucks go back for reloading. The timing of concrete delivery is more critical in floor construction than in most other concrete work.

Most suppliers will, for reasons of economy, send their trucks loaded to capacity, whether that capacity is imposed by the truck's size or the weight limits for public roads. Generally, you want full loads, except for day's last make-up load. But in a few cases, smaller loads are preferable, even if you have to pay extra for them. When laying a thin topping or making certain repairs, you may use concrete so slowly that a full truckload would take two hours or more to pour out. Ordering partial loads, well spaced, helps ensure the concrete is still fresh when it comes out of the truck.

If a job is too small or too slow to justify a ready-mix truck, ready-mix concrete may still be available. Some suppliers offer small ready-mix trailers that can be towed behind a car.

TIPPER TRUCKS

Called dump trucks in America, these can deliver large quantities of concrete and discharge it fast. But they are severely limited compared to ready-mix trucks, because they do not agitate, much less mix, the concrete. Their use is confined to very short hauls of site-batched concrete and slightly longer hauls of very stiff mixes. Using them under any other conditions invites segregation.



FIGURE 10.1 Tailgating, or pouring directly from the concrete truck into the forms, is the simplest way to place concrete.

DUMPERS

Called buggies in America, these miniature tipper trucks are useful for short distances. The typical dumper holds $0.3\text{--}0.8\text{ m}^3$ ($0.4\text{--}1\text{ yd}^3$). Some discharge their loads by gravity. Others rely on hydraulics to tip the load and offer a more controlled discharge.

Dumpers are often a good choice for moving site-mixed concrete from the mixer to its final location. They are also used to transport ready-mixed concrete from the truck to the slab, on sites where the big trucks cannot go and you don't want to use a pump or belt conveyor.

Because they do not agitate the concrete, dumpers should not be used for long hauls.

WHEELBARROWS AND HANDCARTS

These are common where labour is cheap. Even in high-wage areas, wheelbarrows and handcarts find use on small jobs and in congested areas.

The typical wheelbarrow has an effective capacity of only 0.03 m^3 (1 ft^3), which severely limits its efficiency. In contrast, a handcart holds about 0.2 m^3 (7 ft^3). That is much more than a wheelbarrow can carry, but it makes the handcart correspondingly harder to push. Handcarts are all but useless on sloped ground.

When using wheelbarrows and handcarts, pay attention to access, travel distance, and the smoothness of the travel path. Efficiency falls drastically if workers have to negotiate potholes, muddy patches, and narrow doorways.

PUMPS

None of the methods discussed so far will deliver concrete to an elevated slab. Upper-storey pours usually require a pump or crane. Pumps (though not cranes) are also widely used for floors at ground level.

A pump delivers concrete through either a pipeline or a placing boom. A pipeline consists of short lengths of metal pipe that are assembled on site before the pour begins. Each section is about 3 m (10 ft) long. Common diameters are 100 and 125 mm (4 and 5 in). The 125-mm (5-in) size may be needed where the concrete contains 40-mm ($1\frac{1}{2}$ -in) aggregate. The last section (the elephant's trunk) is made of rubber so it can be moved from side to side. The pour starts at the point farthest from the pump. As the pour proceeds, workers remove sections of pipe. While a pipeline can be used on almost any site, it restricts the work somewhat. Wide-bay pours are difficult, and work has to stop every few minutes as the line is shortened.

The alternative to a pipeline is a boom pump, consisting of permanently assembled pipes that are folded and unfolded by hydraulic power. Booms use less labour than pipelines and allow greater flexibility in pour size and shape. Many sites lack the room for them, however. They work best on outdoor pours (Figure 10.2).

Builders like to brag about how far and how high they pump concrete. Nevertheless, it is always a good idea to keep the distance as short as possible.

Most pumps need to be primed with cement-rich grout. Some builders use cement and water mixed right at the pump mouth. Others order about 1 m^3 (1 yd^3) of grout from the ready-mix supplier. Either way, the grout should be thrown away after it has passed through the pump and pipeline. It should never be incorporated into the floor slab because it has properties much different from those of the specified concrete.

Pumping sometimes requires a slightly different concrete mix than would otherwise be used. A pump mix often contains a bit more fine aggregate (3–5% more) and sometimes more cement. The properties that make concrete easy to pump also make it easy to finish, so a mix designed for pumpability usually works well in a floor.



FIGURE 10.2 Boom pumps work well outdoors and can be used indoors too on some warehouse jobs.

Pumping causes concrete to lose workability. The loss in workability varies and is less than some people suppose. For most mixes in most pumps, the loss of slump does not exceed 20 mm (1 in). But it can be much more.

Because pumping affects workability, arguments often arise over where to take slump tests. Some floorlayers request, and some specifications demand, that tests be made where the concrete leaves the pipeline. That is risky, however, because a bad batch may go undetected till a substantial quantity of it is already in the pump. It is better to specify a slightly higher slump and test it where the concrete enters the pump.

CRANES

These are used to transport concrete on multistorey buildings. They are almost never used on ground-level pours. The crane lifts a dump-bucket that typically holds about 3 m³ (4 yd³). Provided the space above the floor is clear, cranes can put concrete exactly where it is needed and work well no matter what the size or shape of the pour. Unlike pumps, cranes work with any concrete mix and do not affect workability (Figure 10.3).



FIGURE 10.3 Telescoping belt conveyor.

TELESCOPING BELT CONVEYORS

Ordinary belt conveyors are not very useful for moving concrete on site because their length is fixed. The telescoping belt conveyor eliminates that restriction in exchange for higher cost and greater complexity. Some can reach out 61 m (200 ft). Telescoping belt conveyors make a good alternative to boom pumps when pouring ground-supported slabs because they work with any concrete mix and do not affect workability.

POUR LAYOUT

A small floor can be placed in one go but bigger floors are divided into multiple pours. The pours take place on different days and are separated by construction joints. Some designers control the pour layout while others leave it to the floorlayer. Either way, it is an important part of the job because it affects all these properties:

- cost;
- schedule;
- ease of construction;
- crack control;
- curling;
- surface regularity.

The four basic choices for slab layout include the following:

- chequerboard;
- narrow strips;

- wide strips;
- large bays.

CHEQUERBOARD CONSTRUCTION

This is almost obsolete, but a few specifications still call for it. The floor is divided into small squares. Every other slab is cast first (think of the dark squares on a chequerboard), and the infill slabs are cast later.

Chequerboard construction had some merit back in the days when concrete was placed by hand and concrete saws were rare. There is little to recommend it today, however. Modern practice leans towards longer and wider slabs, fewer construction joints, and crack-control joints that are sawn rather than formed (Figure 10.4).

NARROW-STRIP CONSTRUCTION

This divides the floor into long narrow strips, each up to 6 m (20 ft) wide. Most builders lay every other strip first, and the intermediate strips, called infills, later. But there is nothing wrong with laying the strips consecutively if that proves more convenient.

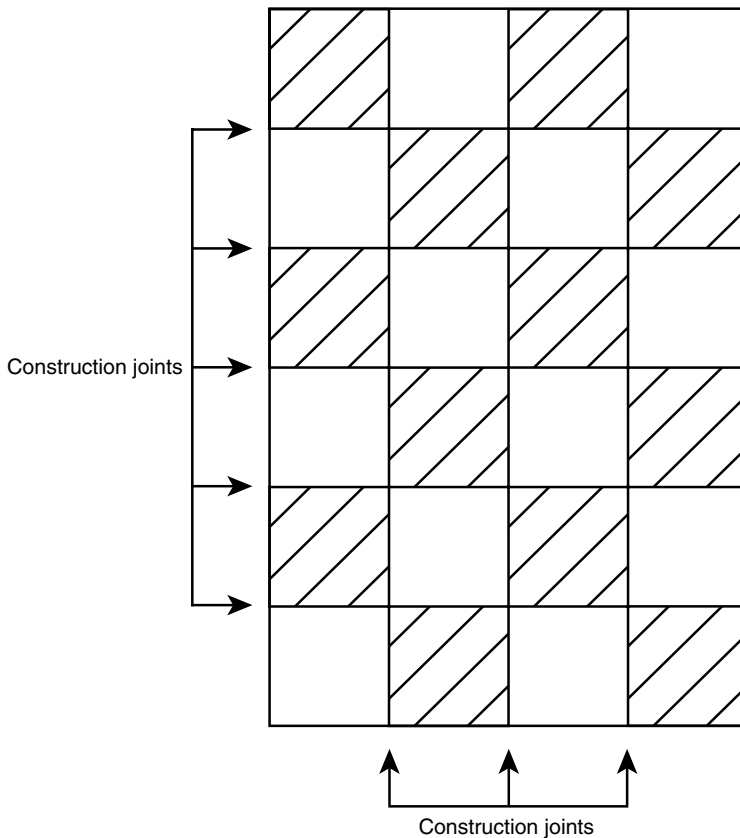


FIGURE 10.4 Chequerboard construction.

Thanks to its narrow width, each strip is well protected from longitudinal cracks. Transverse cracks can occur, though, and most designs employ sawn joints, reinforcement, or post-tensioning to control them.

It's common to cast an edge strip 0.6–1 m (2–3 ft) wide next to each side wall. No edge strips are needed at the slab end walls unless the floor is post-tensioned. In that case, a temporary gap at one or both ends leaves the anchors accessible for stressing.

Narrow-strip floors can be struck off with a wide range of tools: hand straightedges, twin-beam vibrators, and truss vibrators. Never common in America, narrow-strip construction was the norm in the UK in the 1980s and early 1990s. The industry there standardized on a slab width of 4.5 m (15 ft) and made vibrating screeds and wire mesh to suit that dimension.

That has all changed. The growing use of laser screeds and large-bay construction has relegated narrow-strip construction to a shrinking subset of the UK market. There is, however, one area where this method still reigns all over the world. Superflat floors are almost always laid in narrow strips (Figure 10.5).

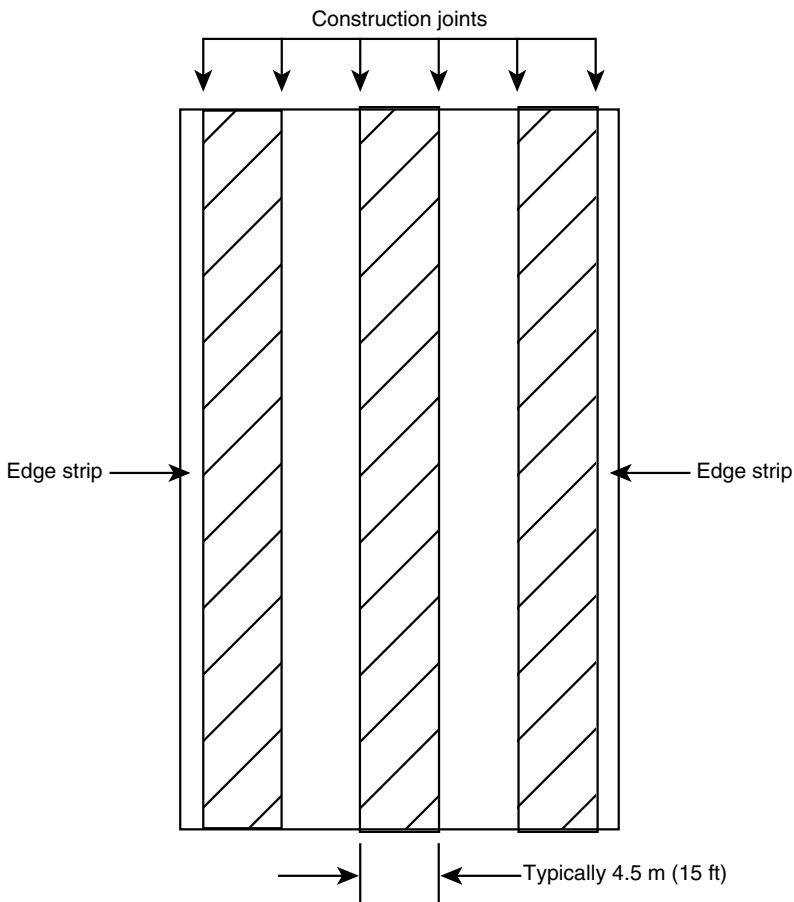


FIGURE 10.5 Narrow-strip construction, not much used today except for superflat floors.

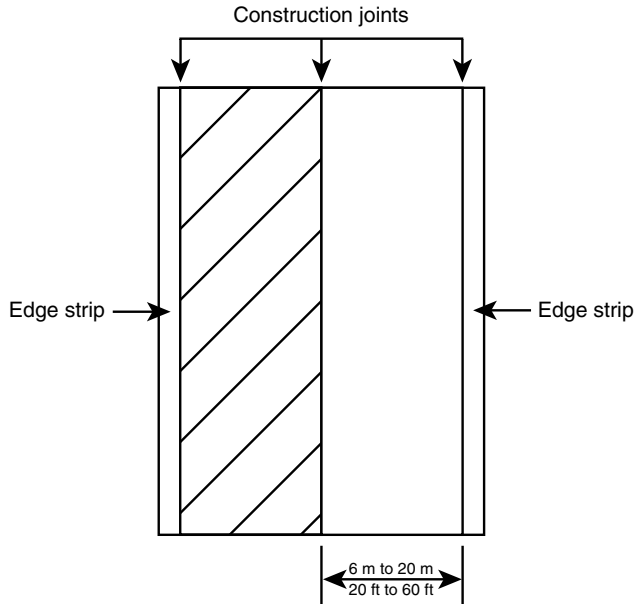


FIGURE 10.6 Wide-strip construction.

WIDE-STRIP CONSTRUCTION

This method divides the floor into long strips over 6 m (20 ft) wide. Strips vary in width, but each typically takes one whole column bay and does not exceed 18 m (60 ft) wide. Compared to narrow-strip construction, the wide-strip method costs less and goes faster, mainly because it needs less formwork. On the downside, it provides less control over surface regularity. While narrow strips can be laid to almost any tolerances (not that all are), wide strips should not be specified much higher than FF50/FL30. But that is good enough for most purposes.

Too wide for hand tools, the slabs are usually placed with a truss vibrator. Nowadays, some floorlayers use laser screeds to place wide strips. But the laser screed really comes into its own on even wider placements, discussed next (Figure 10.6).

LARGE-BAY CONSTRUCTION

This term encompasses several different techniques for laying big floors with few construction joints. The pour dimensions are limited only by the availability of concrete and the time needed to place and finish it. Some floorlayers routinely place over 4000 m² (44 000 ft²) in a day's work. Single pours have exceeded 10 000 m² (100 000 ft²).

Techniques for large-bay construction include:

- wet screeding;
- floating strike-off;
- screed rails;
- laser screeding.

Wet Screeding

This is popular in America, where it is very common in elevated-slab work. It used to be widely used on ground-supported industrial floors, but laser screeding has taken over that market. While each floorlaying crew develops its own style, the following steps are typical:

1. Set grade stakes on 5-m (15-ft) centres in two directions. These are stakes driven into the ground so that their tops lie at the specified finish-floor elevation.
2. As soon as concrete arrives on site, lay narrow strips of concrete along the lines connecting the grade stakes. These strips are the wet screeds.
3. They generally run in just one direction.
4. Use a straightedge (sometimes timber, but preferably extruded metal tubing) to level the wet screeds with the grade stakes.
5. Before the wet screeds harden, pour concrete between them and strike off using the wet screeds as side forms.
6. Remove the grade stakes.

Wet screeding is cheap and fast—attractive properties—but it has at least two drawbacks. First, it requires much skill. An inexperienced crew can get into deep trouble. Second, it offers little control over surface regularity. Exceptions exist, but the typical contractor laying to wet screeds is hard pressed to beat F_F30/F_L20 on ground-supported floors, or F_F25 on elevated slabs.

Floating Strike-off

This resembles wet screeding but without the grade stakes or the wet screeds. A worker continually checks the elevation of the strike-off with an optical level or a laser. Some specialists do a good job with this method, but it is not for beginners. As practised in the UK, floating strike-off normally relied on flowing concrete made with superplasticizer. That method has largely given way to laser screeding, however.

Advantages and drawbacks are the same as for wet screeding.

Screed Rails

These allow large bays to be placed like narrow strips. The screed rails—beams or tubes set at finish-floor elevation—support the striking-off tools as the side forms do in narrow-strip construction. Most screed rails are temporary. Timber strips or metal tubes are chaired up above the ground (for ground-level floors) or soffit form (for elevated floors). Once they have served their purpose and before the concrete has fully set, the screed rails are pulled up, and the voids are filled with fresh concrete.

Some screed rails are permanent. One type is the metal screed key, a thin steel stamping that creates a keyed joint. Though its main purpose is to form the joint, it can also serve as a screed rail for lightweight strike-off tools. Metzger (1983) warns against screed keys where the floor supports industrial traffic, and my experience confirms that.

Another type is the precast concrete screed rail, set in patties of wet concrete much as bricks are laid in mortar. Unlike screed keys, concrete rails are suitable for industrial traffic as long as the joints contain dowels or tie bars to transfer load.

Laser Screeding

Since its introduction in the late 1980s, this has become the standard method for large-bay placement in many parts of the world. The technique depends on a device called a laser screed, a term almost synonymous with the patented and trademarked Somero Laser Screed. A laser screed—or, as we might as well say, the Laser Screed™—is a heavy machine that strikes off concrete with a horizontal auger. As the auger passes over the fresh concrete, sensors and motors keep it at a fixed distance below the plane established by a laser level. Each pass levels a patch of about 20 m² (200 ft²). Then, the self-propelled machine rolls on to the next patch.

Laser screeding gives excellent control over floor levelness without the need for narrow slabs and accurate side forms. It has enabled floorlayers to make huge pours while maintaining a degree of surface regularity that used to demand narrow-strip construction. Flatness and levelness numbers of FF50/FL35 are routinely achieved, and some floorlayers regularly meet FF60/FL40 on pours that exceed 3000 m² (30 000 ft²).

As useful and popular as laser screeding has proven to be, it has a few drawbacks. It requires costly equipment and a trained operator. The standard machine weighs too much to use on most elevated floors, and the lighter models that work almost anywhere cannot match the standard machine in productivity or surface regularity. Perhaps the most far-reaching limitation is the difficulty of laser screeding floors that contain reinforcement or post-tensioning tendons. There are ways to do it—light reinforcement can be installed at the last minute, or bridges can be set up to let the laser screed ride above the steel—but most laser-screeding contractors prefer floor designs that do not require them to work around embedded steel. This preference goes a long way towards explaining the growing popularity of unreinforced and steel-fibre reinforced floors.

SIDE FORMS

Some floors are cast right up to the walls on all sides. All other cast-in-place floors need side forms, which must meet two requirements.

First, they must be strong enough to support the lateral pressure of the fresh concrete and the weight of the tools used for striking-off. Strike-off tools vary widely in wide-strip construction; the main tool is likely to be a truss-type vibrating screed with a mass of several hundred kilogrammes (several hundred pounds). Narrow-strip construction relies on lighter tools—either short vibrating screeds or hand straight-edges. Laser screeding is easy on forms because the screed machine, though very heavy, never rests on the form. It stops short, leaving the edge to be worked with lightweight hand tools.

Second, the side forms must be accurate in elevation because they help determine slab thickness and affect surface regularity. Even in laser screeding, where the screed

machine does not rely on the forms to level the floor, form elevations determine surface regularity at the construction joints. The need for accuracy varies according to the flatness and levelness requirements for the finish floor.

Deacon (1986, p. 12) recommends a tolerance of ± 2 mm (± 0.08 in) from datum for general work and ± 1.0 mm (± 0.04 in) or less for superflat floors. But those are seldom achieved in actual site practice. They represent the best work, not the typical.

Most builders set forms to grade using an optical level or laser. It's hard to do much better than ± 3 mm ($\pm 1/8$ in) with such instruments, but that's good enough for most floors.

Forms for superflat floors are often set with the same tools but get a second check from a different tool—either a long straightedge or a self-contained electronic level.

Side forms are made of steel, wood, or concrete. Steel forms are rugged but not always straight. They can be reused many times. One drawback to them is their short length—some are only 2 m (6 ft) long. Another drawback is the lack of flexibility for installation of dowels and tie bars.

Wood forms are very common in America. They offer great flexibility since they can be sawn to length and width and are easily drilled for dowels or tie bars at any spacing. Some floorlayers bevel the top of the form to create a sharp, straight edge.

Leave-in-place concrete rails can serve as edge forms as well as screed rails within a pour. They are particularly useful on sites where staking of forms is not allowed.

HAND TOOLS FOR PLACING CONCRETE

Human muscle still moves concrete into its final position in most floors. The best tools for this job are square-ended shovels and come-alongs. A come-along is similar to a garden hoe but with a wider blade. Some workers place concrete with rakes, but this practice can cause segregation.

COMPACTION

After concrete has been placed in the forms, it is still not quite ready to be finished. It needs to be compacted first. Compaction eliminates air pockets.

When concrete is poured, it contains large amounts of entrapped air. This differs from the entrained air that is deliberately introduced to help concrete resist frost. Entrained air consists of millions of microscopic bubbles, each between 0.01 and 1 mm (0.004 and 0.04 in) across. Entrapped air voids are less regular and typically more than 1 mm (0.04 in) across.

The amount of entrapped air varies with the concrete's workability. Blackledge (1980, p. 5) says concrete placed at a 75-mm (3-in) slump contains about 5% air by volume. But if you reduce the slump to 25 mm (1 in), the air content rises to about 20%. At the other extreme, high-slump flowing concrete, made with superplasticizer, entraps little air and is considered, at least by some, to be self-compacting.

You need to reduce the entrapped air to about 1% of the concrete's volume, for these reasons:

- Entrapped air weakens concrete. The rule of thumb is that each 1% of entrapped air causes a 5% reduction in concrete strength.

- Entrapped air causes fresh concrete to settle by a large and highly variable amount. This leads to plastic-settlement cracks and poor surface regularity.
- Entrapped air reduces the bond between concrete and reinforcing steel.

The most effective way to compact concrete and reduce entrapped air is vibration. Hand-tamping is still used on some jobs, but vibration works better. Two kinds of vibrators are used on floors: pokers and vibrating screeds.

The poker vibrator, also called an immersion or internal vibrator, gets its name from the fact that the business end of the tool is stuck into the fresh concrete. It consists of a vibrating cylinder 25–75 mm (1–3 in) in diameter and 300–600 mm (12–24 in) long. Floorlayers tend to favour the smaller versions, but big ones can be effective in thick slabs. Some guides say to keep the poker vertical when in use, but you can hardly follow that rule in a thin slab. The right way to use a poker vibrator is to lower it quickly into the concrete at points spaced 450–750 mm (18–30 in) apart. Leave the poker at each spot till the concrete around it is fully compacted and then pull it out slowly and move on to the next spot. You can tell the concrete is fully compacted because mortar shows at the floor surface and bubbles stop appearing. Try to avoid over-vibration because it causes segregation, but if in doubt, always err on the side of more vibration because under-vibration causes more harm than its opposite.

Unlike pokers, vibrating screeds stay on top of the concrete and compact it from the top down. They are strike-off tools first and vibrators second. Vibrating screeds can compact concrete to a considerable depth—up to 300 mm (12 in), according to some claims. It is not easy to gauge the depth of vibration, however. The surface always looks well vibrated because the action is greatest there. But if the screed moves forward too fast, lower depths may go uncompacted. The solution is to go slow.

Laser screeds, though often put in a separate category from vibrating screeds, work the same way when it comes to compaction.

All the concrete in a floor should be compacted, but the edges call for special attention. The concrete there needs all the strength and density it can get. And if the slab edges hold post-tensioning anchors, compaction is essential to prevent the anchors from breaking free when the tendons are stretched (Figure 10.7).



FIGURE 10.7 This concrete was not compacted.

SPECIFYING COMPACTION

Designers usually specify compaction by description. A typical specification requires that all concrete be thoroughly compacted by vibration and goes on to list the acceptable kinds of vibrators. Routine compliance testing almost never occurs, though suspect concrete can be cored and examined for voids.

A performance specification for compaction is within reach, however, even if rarely used. It comes from highway construction, where poor compaction is a serious risk because of the stiff concrete mixes used. *Concrete Construction* (1989) describes a method for measuring compaction with a nuclear density gauge.

THE NEXT STEP

After concrete has been transported, placed, and compacted, the next step is finishing. But because finishing is closely tied to the properties of the concrete surface, I discuss it in Part V. The next chapter jumps to curing, which takes place after the concrete has been finished.

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11 Curing

This is the process of keeping concrete damp so that hydration, the reaction of cement with water, can continue. Though concrete sets in a few hours, it continues to gain strength for a long time if kept moist. The strength gain is rapid at first but slows over time. If concrete dries out too soon, it will not achieve its potential strength and durability.

Curing is simple and often neglected—but of huge importance. All concrete structures benefit from good curing, but floors are especially demanding because they have a large area exposed to drying, and also because that exposed area becomes, in many cases, the wearing surface. A poorly cured floor may experience any of the following defects:

- crazing;
- dusting;
- low resistance to wear;
- premature spalling at joints;
- low resistance to chemical attack;
- low resistance to frost damage.

Despite curing's great importance, it sometimes gets more credit than it deserves. Some people believe curing reduces the cracking and curling caused by long-term drying shrinkage, but the evidence does not support that belief. Unless a slab stays moist forever—an impossibility in most buildings—curing only delays and does not reduce drying shrinkage.

CURING METHODS

The many methods fall into four broad categories:

- flooding;
- absorbent materials kept moist;
- waterproof sheet materials;
- curing compounds.

WET CURING

You might have noticed that *wet curing* does not appear on the preceding list. People talk about wet curing and some specifications call for it by name, but the term has been applied to so many different methods as to rob it of all effective meaning. To some, it encompasses almost every method other than the use of a curing compound. Others

reserve the term for methods that involve the addition of water during the curing period—a definition that rules out waterproof sheet materials and curing compounds. A few strict constructionists equate wet curing with flooding. But in one sense, all effective curing is wet curing, since the whole point is to keep the concrete moist.

Those whose definitions call for added water often regard wet curing as superior to other means—such as waterproof sheet materials and curing compounds—that introduce no water but merely hold in the water the concrete started out with. The theory is that added water replaces the water consumed in the hydration process, eliminating the risk of a water deficit. That sounds reasonable on first hearing, but in truth, the concrete used in floors almost always contains a water surplus, except for certain mixes made with expansive cements and expansive admixtures. There is usually plenty of water in the concrete, provided we keep it there.

FLOODING

This method cures concrete by keeping the surface covered with water. One way is ponding, which involves building a short dam on all sides of the floor. Another way is spraying, but that is rarely practical except on the smallest slabs. For good results, the spray must cover the whole floor and be kept on continuously for the duration of the cure. Flooding can do a superb job, but it is rarely seen these days in the UK and America.

ABSORBENT MATERIALS KEPT MOIST

This method relies on materials that absorb large quantities of water. The absorbent material is spread over the new floor and soaked with water. Under most conditions, water must be added frequently throughout the curing period.

Loose absorbent materials such as sand, sawdust, or straw are seldom used these days in the industrialized world, but they still appear elsewhere. They tend to dry out fast and need to be sprayed with water often.

Absorbent sheet materials include hessian (Americans call it burlap) and building paper. Specialist floorlayers traditionally used them for high-end industrial floors, but the practice had declined by the end of the twentieth century. They do a good job if kept moist, and are almost useless if allowed to dry out. For that reason, it's risky to specify an absorbent sheet material without providing close supervision and labour to keep it wet.

Absorbent sheet materials are sometimes combined with waterproof sheet materials. In that case, the absorbent material goes on the bottom and the waterproof sheet goes on top to keep it from drying out. You can buy two-part curing blankets that consist of a cloth-like fabric bonded to a sheet of polyethylene. Some builders make their own by covering the floor first with hessian and then covering that with polyethylene.

WATERPROOF SHEET MATERIALS

These work by reducing moisture loss from the floor surface. By far, the most common sheet material for curing is polyethylene film, which comes in clear, white, or black. Any colour will do indoors, but white is best for slabs cast outdoors in hot

weather because it keeps the concrete cooler. ASTM C171 recommends a nominal thickness of at least 0.10 mm (0.004 in or 4 mils), with an absolute minimum of 0.075 mm (0.003 in or 3 mils). Some floorlayers prefer thinner film—nominal 0.05 mm (0.002 in)—on the grounds that it conforms more closely to the concrete surface. But the thinner film tears more readily (Figure 11.1).

The chief complaint about polyethylene is that it leaves light and dark streaks on the floor surface. Though they fade over time, the streaks are sometimes obvious enough to make polyethylene a poor choice for floors that must present the best possible appearance. Coloured concrete, which is never used except where looks count, should never be cured under polyethylene. You can reduce streaking by keeping the polyethylene in full contact with the concrete; this takes extra care when rolling out the sheets.

If streaks are unacceptable but you still want to use sheet material, waterproof paper is another option. In America, the standard curing paper consists of two layers of reinforced kraft paper bonded with bituminous resin and reinforced with filaments.

To do their job, sheet materials must cover the whole slab and must stay in place throughout the curing period. Some specifications call for taping the seams, but hardly anyone does that. The usual practice is to lap the seams. Unless the floor is fully sheltered from the wind, the laps should be weighted down with timber or rebar. If the cover is peeled back for any reason, it should be replaced as soon as possible (Figure 11.2).



FIGURE 11.1 Curing with impervious sheet material.



FIGURE 11.2 Dry spots like this should be soaked and recovered right away.

Some floorlayers drench the floor with water before applying a waterproof sheet material. That can't hurt but is probably not strictly necessary, provided the curing starts as soon as possible.

CURING COMPOUNDS

These are liquids that dry or harden to form a water-retaining membrane on the floor surface. They are usually sprayed on, but most can also be applied by roller, brush, or mop.

Economy is the main reason to use them, but they have some practical advantages as well. You can apply them once and then forget about them. In contrast, all other methods require attention throughout the curing period to make sure the concrete stays moist. The ability to spray something on and walk away makes curing compounds attractive, where schedules are short or supervision scarce. And some curing compounds do more than cure. They serve as long-term sealers, too.

Curing compounds have at least three drawbacks. First, the cheaper, lighter products just do not cure as effectively as other methods. You cannot expect an 18%-solids acrylic resin to retain water nearly as effectively as a sheet of polyethylene or water-soaked hessian. Second, curing compounds can interfere with coatings and floor coverings. To reduce that risk, some compounds, called dissipating resins, are designed to degrade and vanish over time.

Third—and this applies only to industrial floors—some compounds show tyre marks more readily than bare concrete.

The chemical industry makes a wide variety of curing compounds. Most of those used on floors fall into one or more of these categories:

- polymer resins;
- waxes;
- dual-purpose bondbreaker-curing compounds;
- liquid hardeners.

Polymer Resins

The most widely used curing compounds consist of polymer resins in solvents. The traditional solvent was one or more aromatic hydrocarbons, but nowadays many products rely on water instead. Water-based compounds create less odour and are required by law in some places to keep down air pollution. Some of the resins used in higher-grade curing compounds are:

- styrene acrylate (often called acrylic);
- styrene-butadiene copolymer;
- chlorinated rubber (rare in the UK but an old favourite in America).

The resin contents vary from about 15 to 40%. Compounds at the higher end retain moisture better but cost more. Compounds at the lower end may not suffice where the concrete forms the wearing surface. Industrial-floor specifications sometimes require that the curing compound contains at least 30% solids. Compounds with lots of solids are often marketed as curing-sealing compounds, since they provide a membrane that lasts far beyond the usual curing period.

Some resin compounds include a fugitive dye to confirm the coverage. The dye fades over time. Other compounds contain white pigment to keep the concrete cool in hot sunshine. Unlike fugitive dye, the white can stick around for a long time and should not be used where people might object to its look.

Waxes

These are the curing compounds of choice for coloured concrete. The wax is dyed to match the concrete. A wax curing compound on its own cannot reliably colour the floor but works well in conjunction with pigmented concrete or a coloured dry shake.

Colourless waxes can be used on ordinary concrete floors.

Dual-purpose Bondbreaker-curing Compounds

These are unique to tilt-wall (also called tilt-up) buildings, in which the concrete floor forms the casting bed for the concrete wall panels. Tilt-wall construction creates several challenges with regard to curing. Slabs are cast outdoors, exposed to sun and drying winds. That creates the need for a highly effective curing method. But tilt-wall floors also need a bondbreaker so the wall panels will not stick.

That has led to the development of dual-purpose products meant to prevent bonding and cure the floor slab. Those products fall far short of the ideal, however. They all work fine as bondbreakers, because failure in that area is intolerable. They do not work so well as curing compounds.

No bondbreaker currently on the market in America meets either of the ASTM standards for curing compounds, ASTM C309 or ASTM C1315. Some manufacturers claim their bondbreakers meet the evaporation limits of ASTM C309, but the fine print reveals that this is true only when they drastically modify the ASTM C156 evaporation test. See the discussion on testing below.

Liquid Hardeners

These are not true curing compounds because they do not form a membrane that retains moisture. However, we need to consider them because they are widely advertised as curing compounds and many floorlayers use them for that purpose.

Liquid hardeners are salts dissolved in water. The salts consist of silicate ions combined with one of the metals from the left side of the periodic table: lithium, sodium, potassium, or magnesium. Sodium silicate is the most common. These chemicals are supposed to react with free lime at the floor surface, filling the pores with C-S-H gel. I say 'supposed to' because several conditions have to be met for this to work. You need free lime; you need pores; and you need a floor dry enough to absorb the solution. A newly laid concrete floor with a burnished finish is not likely to meet all those conditions.

Whether liquid hardeners actually harden concrete is debatable. What is not debatable, or shouldn't be, is whether they work as curing compounds. They don't. They don't form a membrane, and they don't meet either of the ASTM standards for curing compounds. ASTM is clear about this:

Solutions of silicate salts are chemically reactive in concrete rather than membrane-forming; therefore, they do not meet the intent of this specification.

Testing the Efficiency of Curing Compounds

Two tests are commonly used to measure how effectively curing compounds retain moisture.

ASTM C156 describes a test for 'water loss...through liquid membrane-forming curing compounds for concrete'. Three mortar specimens (not concrete) are cast in special moulds and finished with a wood float. The top of each specimen is treated with a curing compound and sealed so evaporation can take place only from that surface. The specimens are then stored under controlled temperature and humidity. The test result is the mass of the water lost in 72 hours, divided by the area of exposed surface. Lower numbers are better.

ASTM C309 (Standard Specification for Liquid Membrane-Forming Compounds for Curing Concrete) considers a compound acceptable if the ASTM C156 moisture loss does not exceed 0.55 kg/m^2 (0.11 lb/ft^2) in 72 hours. Another standard, ASTM C1315 (Standard Specification for Liquid Membrane-Forming Compounds Having Special Properties for Curing and Sealing Concrete) imposes a tighter limit: 0.40 kg/m^2 (0.08 lb/ft^2).

CEN/TS 14754-1 (2007) describes another test for curing compounds. Like ASTM C156, it involves samples that are treated with curing compounds and stored under controlled temperature and humidity. But beyond that, there are important differences between the two methods. In the CEN test, the specimens are made of concrete, not mortar. They are finished with a steel trowel, not a wood float, so they have a smoother

surface. Instead of three specimens all treated with curing compound, there are six specimens—three with curing compound and three without, as a control.

The test result, calculated from Equation 11.1, is called the efficiency index.

$$E = [100(W - W_1)]/W \quad (11.1)$$

where

E = efficiency index

W = percent loss of waste from bare specimen

W_1 = percent loss of water from cured specimens

A test result of 100% would mean the cured specimens lost no water at all. A result of 50% would mean the cured specimens lost half as much water as bare concrete. In this test, unlike ASTM C156, higher numbers are better.

British chemical suppliers typically offer curing compounds in two grades: a run-of-the-mill compound with an efficiency index of 75% and a premium product, more suitable for floors, measuring at least 90%.

We have, then, two ways to specify moisture loss through a curing compound. Use ASTM C156 and specify a maximum value in kg/m², or use CEN/TS 14754-1 and specify a minimum efficiency index. I recommend 0.40 kg/m² in 72 hours for ASTM C156, or 90% for the efficiency index.

Some people mix the two test methods, leading to misunderstandings. They prepare the specimens according to CEN/TS 14754-1, using a steel trowel to smooth the surface. But then they test moisture loss according to ASTM C156. The result is unusually low (i.e., good) readings, because a smooth surface always loses less moisture to evaporation than a rough one, when other factors stay the same. The rationale for this mixed approach is that real floors usually have a smooth, trowelled finish like the CEN/TS 14754-1 specimens, not a float finish like the ASTM C156 specimens. That's true, but it misses the point. ASTM C156 wasn't written to mimic the conditions of a real floor. The goal was to create a standard, repeatable set of conditions that would allow curing compounds to be evaluated and compared. And when ASTM C1315 limits moisture loss to 0.40 kg/m² in 72 hours, that applies only in the context of the ASTM C156 test method, as written.

It is possible, though, that neither CEN/TS 14754-1 nor ASTM C156 is the best test for the effectiveness of curing compounds. Suran et al. (2017) suggest that the oxygen permeability index (OPI) may be a better way. The test for OPI is set out in a South African standard, SANS 3001-003-2.

CHOOSING A CURE

With so many options, choosing a curing method can be hard. It helps to ask a few questions.

Is low cost important? If so, the choice will probably come down to a polyethylene sheet versus a polymer-resin curing compound.

Will the floor get a coating or topping? If so, stay away from curing compounds unless you confirm they will not interfere with bonding.

Does appearance matter? If so, an absorbent sheet material kept moist may be the best choice. Polyethylene sheets leave streaks. Curing compounds may show tyre marks.

Will the floor have to resist heavy industrial traffic? If so, this is not the job on which to compromise curing effectiveness. Choose flooding, sheet materials, or top-grade curing compounds.

Will the job get close supervision? If not, a curing compound may be the safest choice. It needs attention just once at the time of application.

Will the floor be exposed to extreme drying? If so, use waterproof sheet materials or a top-grade curing compound. Methods that rely on adding water are risky here unless someone pays very close attention to make sure the floor does not dry out. Note that extreme drying conditions are not limited to hot, dry climates. They also occur inside artificially-heated buildings.

TIMING

There is little dispute about when curing should begin. The sooner, the better. On floors with no sawn joints, curing materials should go down right after the final trowel pass. Sawn joints complicate the issue, because no one wants to remove curing materials for sawing. If the sawing can be done within an hour or two of final trowelling—as is often the case with early-entry saws—it is usual and reasonably safe to saw the floor first. But if the sawing must wait hours or overnight, then curing should start first.

No consensus exists on how long curing should last, but one fact is clear: you cannot possibly cure a slab too long. When in doubt, longer always beats shorter. Beyond that, recommendations range from a few days to a few weeks. Murdock et al. (1991, pp. 212–213) suggest that a period as short as 3 days will suffice provided the concrete contains straight Portland cement (no pozzolans) and stays above 10°C (50°F). They may not have been thinking about floors when they wrote that, however. Some authorities writing specifically about floors recommend a 7-day cure, and that is the closest thing we have to a standard duration.

There is evidence, however, that curing for longer periods offers benefits. Chaplin (1986) reports an experiment in which stretching the cure from 7 to 21 days improved a slab's wear resistance by almost 10%. Longer curing is especially beneficial where concrete gains strength slowly. That applies where the concrete contains a high proportion of slag or fly ash, and where low-heat Portland cement is used. It can also apply to any concrete placed in cold weather—but in that case the evaporation rate is generally low, making a long cure less essential to success.

In short, a 7-day cure appears to be a reasonable choice under most conditions. But if you can stretch that to 14 or 21 days without wrecking the job schedule, do so. It cannot hurt and may help.

LATE CURING

The right time to cure a concrete floor is at the start of its life, when the concrete is still saturated with its original mixing water. But if you miss that opportunity, late curing may be better than none. Chaplin (1986) describes an experiment in

which curing was restarted after a 28-day interruption. The dry slabs were soaked with water and covered with polyethylene for 7 days, during which time their wear resistance rose substantially.

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12 Reinforcement

Most concrete floors contain reinforcement. There are only two exceptions: ground-supported floors that rely solely on the concrete's inherent strength to resist all loads, and post-tensioned floors.

Reinforcement can be structural or nonstructural. Structural reinforcement is a key part of the structural design. It resists bending stresses after a slab has cracked under load. All suspended slabs have structural reinforcement, unless they are post-tensioned. Ground-supported slabs may also have structural reinforcement, but most don't. Nonstructural reinforcement limits the width of cracks that were caused by drying shrinkage or thermal contraction. It is also called secondary reinforcement.

Steel reinforcement takes four forms: bars, wire mesh, steel deck, and steel fibres.

BARS

These are steel bars, circular in cross-section. They are often called rebars, short for reinforcing bars. Nowadays, practically all of them are deformed, which means they have bumps that engage the concrete. Smooth bars are used for dowelling but not for reinforcement (Figure 12.1).

In the United Kingdom, most reinforcing bars are made of Grade 500 steel, which has a yield strength, in tension, of 500 MPa (72.5 ksi). Bars are sized by diameter, in millimetres. The bar sizes commonly used in floors are 8, 10, 12, 16, and 20 mm.

In America, most bars are made of similar steel but it's called Grade 60 and has a yield strength of 414 MPa (60 ksi). Grade 75 and Grade 80 bars are also used. Bars are sized by number, usually preceded by a hash mark (which some Americans and most Canadians call the number sign). The number denotes the bar diameter in eighths of an inch. Common sizes are #3, #4, #5, and #6.

Bars are supported on concrete bricks, or individual stands called chairs, or on long bolsters. Bars are usually laid out in two perpendicular directions, with the bar crossings tied with steel wire. But some applications, such as trim reinforcement at re-entrant corners, call for bars running in just one direction. Chairs are the only good option there.

For most purposes, bars and wire mesh are interchangeable. The main advantage of bars is flexibility. They allow any spacing, and the spacing can be adjusted in the field as needed to avoid obstacles. On the downside, bars require more labour.

NONMETALLIC BARS

The great majority of reinforcing bars worldwide are made of steel, but other materials are also used. Glass-fibre rebar is the one you are most likely to encounter in floor construction. It is strong enough to replace steel where ultimate tensile strength

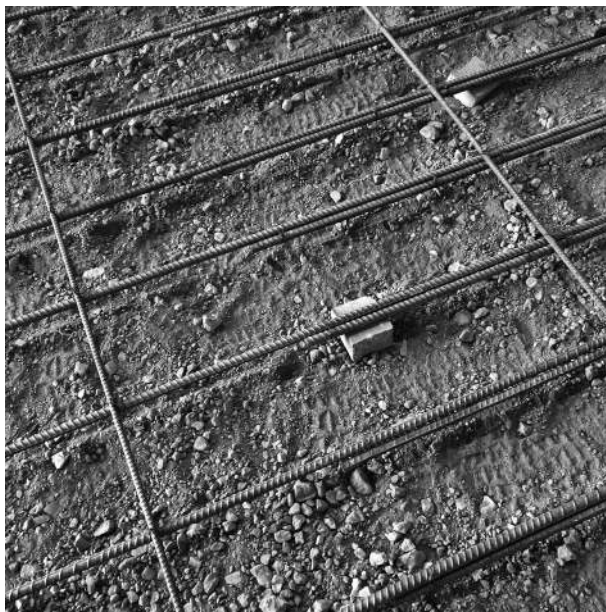


FIGURE 12.1 Reinforcing bars tie with wire to form a grid, supported on concrete bricks.

controls the design. Its proponents say it has a lower carbon footprint. It has a much lower elastic modulus, though, which makes it less effective at limiting crack width.

Glass-fibre bars may be good for certain seismic applications, where ultimate strength is what counts and crack width is irrelevant.

WIRE MESH

I call it wire mesh because I find that name the least likely to be misunderstood around the world. You probably call it something else, because it goes by many other names: welded-wire fabric, steel fabric, fabric reinforcement, welded-wire reinforcement, and WWR. Whatever you call it, it consists of steel wires laid in two perpendicular directions and welded at all the intersections (Figure 12.2).

UK WIRE MESH

In the United Kingdom, each pattern of wire mesh is identified by a letter (A, B, or C) and a number. The letter tells you the wire spacing and whether the grid is square or rectangular. *A* denotes a square grid with 200 mm spacing in both directions. It is called square mesh. *B* denotes a rectangular grid with spacings of 100 by 200 mm. It is called structural mesh. *C* denotes a rectangular grid with spacings of 100 by 400 mm. It is called long mesh. The number is the cross-sectional area of the primary or main wires, in mm^2/m .

Long mesh was popular in the heyday of narrow-strip construction. Nowadays, square mesh is the norm.



FIGURE 12.2 Wire mesh in a composite slab. Note the sagging caused by excessive distance between supports.

TABLE 12.1
Square Mesh Patterns Commonly Used in the United Kingdom

Designation	Wire Diameter	Wire Spacing	Steel Cross-sectional Area
A142	6 mm	200 mm	142 mm ² /ft (0.067 in ² /ft)
A193	7 mm	200 mm	193 mm ² /ft (0.091 in ² /ft)
A252	8 mm	200 mm	252 mm ² /ft (0.119 in ² /ft)
A393	10 mm	200 mm	393 mm ² /ft (0.186 in ² /ft)

The steel is normally Grade 460, the same as used in reinforcing bars. UK mesh normally comes in flat sheets, 2.4 m × 4.8 m. There is also a so-called merchant size, 2.0 m × 3.6 m (Table 12.1).

AMERICAN WIRE MESH

American mesh designations are completely different. The pattern is identified by four numbers, like this:

$6 \times 6, W4.0 \times W4.0$

The first two numbers show the wire spacing in inches, centre to centre. In this case, we have a square pattern and the spacing is 6 in each way. The last two numbers show the cross-sectional area of steel, in hundredths of a square inch per foot. In this case, the steel cross-sectional area is 0.040 in²/ft, and it's the same in both directions. The *W* means the wires are smooth. The only other option is *D* for deformed wires. Almost all the wire mesh used in American floors is square, with the same wire spacing and size in both directions.

TABLE 12.2
American Wire-mesh Patterns in Wide Use

Current Designation by W-number	Old Designation by Wire Gauge	Wire Diameter	Wire Spacing	Steel Cross- sectional Area
6 × 6, W1.4 × W1.4	6 × 6, 10 × 10	0.102 in	6 in	0.028 in ² /ft (59 mm ² /m)
6 × 6, W2.0 × W2.0	6 × 6, 8 × 8	0.128 in	6 in	0.040 in ² /ft (85 mm ² /m)
6 × 6, W2.9 × W2.9	6 × 6, 6 × 6	0.192 in	6 in	0.058 in ² /ft (123 mm ² /m)
6 × 6, W4.0 × W4.0	6 × 6, 4 × 4	0.225 in	6 in	0.080 in ² /ft (169 mm ² /m)
4 × 4, W1.4 × W1.4	4 × 4, 10 × 10	0.102 in	4 in	0.042 in ² /ft (89 mm ² /m)
4 × 4, W2.0 × W2.0	4 × 4, 8 × 8	0.128 in	4 in	0.060 in ² /ft (127 mm ² /m)
4 × 4, W2.9 × W2.9	4 × 4, 6 × 6	0.192 in	4 in	0.087 in ² /ft (184 mm ² /m)
4 × 4, W4.0 × W4.0	4 × 4, 4 × 4	0.225 in	4 in	0.120 in ² /ft (254 mm ² /m)

That's the official way to specify wire mesh in America. On the job site, some people still use an older system in which wire size is identified by gauge number instead of cross-sectional area. A W2.9 wire is 6-gauge, and a W1.4 wire is 10-gauge. If somebody on the job site mentions 6-gauge mesh, they probably mean 6 × 6, W2.9 × W2.9 (Table 12.2).

Most American wire mesh is made of Grade 65 steel, with a tensile strength of 450 MPa (65 ksi). This is very similar to the steel used in UK mesh. Grade 80 is also common, especially in the bigger wire sizes.

The standard flat sheet is 8 ft × 20 ft. Lighter mesh sizes also come in rolls, but rolled mesh is hard to use. The American Society of Concrete Contractors (2012) takes a firm position against rolled mesh in floor slabs:

Use of rolled welded-wire reinforcement is even more problematic. Rolls are straightened before use, but the resulting shape is a wavy profile that means WWR location is variable even if it isn't moved out of location by workers' foot traffic.

In recent years, Americans have increasingly turned to patterns with bigger wires and wider spacings, usually with deformed (*D*) wires and often using Grade 80 steel. This is called bigfoot mesh because the spacing is wide enough that workers can step between the wires and stand on the ground. This is a popular choice when ground-supported slabs are reinforced for enhanced aggregate interlock.

LAPS

For continuous reinforcement, sheets of wire mesh must be lapped. ACI 318 and ACI 439 require an overlap of one mesh square plus 50 mm (2 in). The same overlap is common in the United Kingdom, but technically BS EN 1992-2 requires that laps be determined from a complicated formula.

Laps complicate the challenge of keeping mesh at the right elevation. At the corners, you can wind up with four layers of mesh in the same vertical space. That can result in wires getting too close to the surface or even sticking up above the surface.

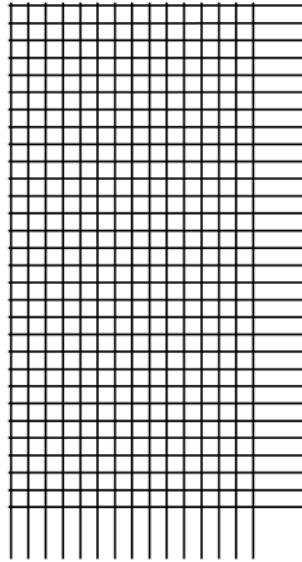


FIGURE 12.3 A sheet of wire mesh with flying ends for better laps.

A partial solution is to stagger the sheets like bricks in running bond. That way, the stacking is limited to three layers of mesh. Sometimes that's good enough, but a more thorough solution is to order wire mesh with flying ends. Cross wires are left out on two sides of each sheet, allowing the sheets to lap while staying flat (Figure 12.3).

WIRE-MESH SUPPORTS

In years past, it was common to place wire mesh on the ground or the soffit form, pour concrete over it, and pull it up into the wet concrete with hooks. This worked about as well as you would expect. Often the wire mesh ended up on the bottom. While this practice still goes on, it is less common now and no authorities endorse it.

Wire mesh needs support. The concrete bricks, chairs, and bolster used to support bars also work with mesh, but they may need closer spacing because the mesh is more flexible.

In the United Kingdom, the Concrete Society (2016, 20) is clear on the support spacing: 800 mm (four squares) for A142 or A193 mesh, and 1 m (five squares) for A252 and A393.

American guidelines are less clear but reflect a growing recognition that spacings need to be much closer than they used to be, especially with the lighter mesh patterns. ACI 302 says 'supports should be close enough that the welded-wire reinforcement cannot be forced out of location by construction foot traffic', but doesn't give any dimensions. ACI 301 requires 305 mm (12 in) or less, for wires with diameters under 5.7 mm (0.225 in). But maybe even that is not good enough. Neuber (2006) reports an experiment in which he measured the deflection of wire mesh under the weight of a 180-lb (82-kg) man, for various combinations

of wire size and support spacings. He concludes that even a close spacing of 300 mm (12 in) allows too much deflection for most common mesh patterns.

It is hard to say where this will end up, but this much is clear: if you are serious about keeping wire mesh at the right elevation, you need very close supports. Following that rule raises the cost of wire mesh and makes it less competitive with bars.

STEEL DECK

Decking made of corrugated sheet steel serves as the positive reinforcement in composite suspended floors. In this context, *positive* means the deck is there to resist positive (sagging) moments. Most composite floors also contain rebar, wire mesh, or fibres. But the deck has the starring role.

Not all steel deck steel is suitable for reinforcement. It has to engage the concrete to create a composite structure. Most deck designs achieve composite action through dimples pressed into the steel. Some do it through the shape of the flutes instead. A form steel deck, which does not create composite action, can be used as a leave-in-place soffit form but is not considered reinforcement.

STEEL FIBRES

These are short steel wires that are added to the concrete mix. They are used in ground-supported floors to limit crack width and stop invisible microcracks from growing into visible macrocracks. They are used in composite floors as nonstructural reinforcement. They are sometimes used as primary reinforcement in suspended slabs on piles, though this practice is controversial. They are not much used in other suspended slabs.

When specifying steel fibres, you need to consider the following properties:

- type (method of manufacture);
- length;
- effective diameter;
- dosage;
- deformations.

And if you are counting on the fibres to contribute to the slab's load capacity, you also need to consider their effect on the concrete's residual strength (Figures 12.4 and 12.5).

TYPE

ASTM A820 divides steel fibres into five types according to how they are made. Only the following three are currently being used in concrete floors:

- Type I—cold-drawn wire;
- Type II—sheet steel cut into strips;
- Type V—cold-drawn wire, shaved into fibres.

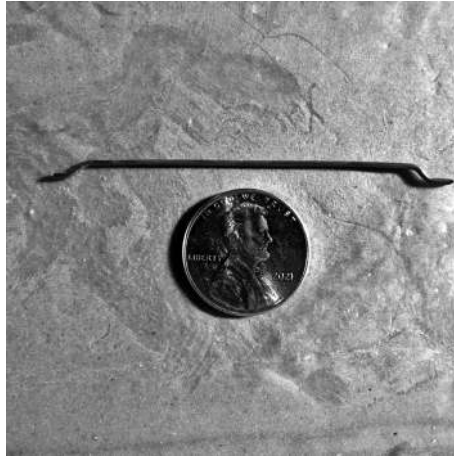


FIGURE 12.4 Type I steel fibre, 60 mm long with hooked ends. The coin has a diameter of 19 mm.

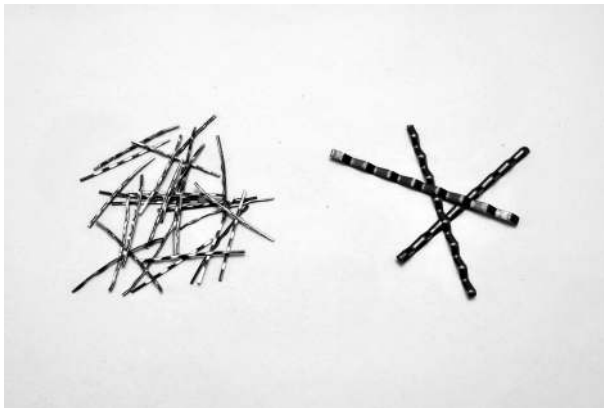


FIGURE 12.5 Type II steel fibres on the left, and Type V on the right. Both have continuous deformations.

LENGTH

Fibre lengths range from 25 to 65 mm (1 to 1½ in).

Longer is better if you are looking for high residual strength, but fibres can only get so long before they tangle and become unusable. The practical limit seems to be about 65 mm (2½ in). Even at that length tangling can occur, especially if the fibres are thin. To fight tangling, some manufacturers glue their long, thin fibres into pads, using a water-soluble glue. The pads stay together just long enough to mix without tangling, and then the glue dissolves and the fibres disperse. Fibres under 50 mm long generally do not need glue.

Shorter is better if you are trying to prevent visible cracks, and the reason for that takes some explaining. What really matters for crack prevention is not fibre length,

but fibre spacing—the distance between fibres within the concrete. And fibre spacing is inversely proportional to the cross-sectional area of the fibres, provided dosage stays constant. So what you really need, for crack prevention, is the thinnest possible fibre. But there's a catch: when you make fibres thinner, you also have to make them shorter, lest they tangle. That means the thinnest fibres are also the shortest.

If you care about both residual strength and crack prevention, you may have to compromise on fibre length.

EFFECTIVE DIAMETER

This property ranges from 0.55 to 1.3 mm (0.022 to 0.051 in). I say *effective diameter* because some steel fibres are round in cross-section and others are rectangular. The effective diameter of a rectangular-section fibre is the diameter of a circle having the same area as the rectangle.

Some manufacturers quote aspect ratio instead of effective diameter. The aspect ratio is the length divided by the effective diameter.

Thinner fibres are better at preventing visible cracks because they reduce the fibre spacing. But they are more likely to tangle, and the tangling risk goes up with the aspect ratio. If you want a very thin fibre, it needs to be short.

Thicker fibres are cheaper to make and less likely to tangle. They do not have any other benefits that I am aware of.

DOSAGE

This is usually specified by the mass of fibres per unit volume of concrete—kg/m³ or lb/yd³. An alternative is to specify the fibre volume as a percentage of the concrete volume. This makes a lot of sense, especially during the design stage. A volume percentage is easier to visualize, and it stays the same across all measurement systems (see Table 12.3).

TABLE 12.3
Equivalent Steel-fibre Dosage Rates

Kg/m ³	lb/ft ³	Volume
12	20	0.15%
15	25	0.19%
18	30	0.23%
20	33	0.25%
21	35	0.26%
24	40	0.30%
30	50	0.38%
36	60	0.45%
39	66	0.50%
42	70	0.53%
78	132	1.00%

Fibre dosages generally range from 0.15% to 0.53% (by volume). ACI 360 recommends a minimum of 0.25% for ground-supported floors, rising to 0.45% where the goal is a wider joint spacing. The Steel Deck Institute (2012) recommends at least 0.19% as nonstructural reinforcement in composite floors.

DEFORMATIONS

The first steel fibres were straight, smooth pins, and ASTM A820 still recognizes that shape as an option. Today, though, all steel fibres are deformed so the concrete will grip them better. There are three kinds of deformation: continuous, hooked ends, and flat ends.

A continuously deformed fibre has bumps down its whole length, like a miniature version of rebar. A hooked-end fibre has a bend, or sometimes multiple bends, at each end. A flat-end fibre has its ends squashed flat, looking like a kayaker's double-ended paddle. For high residual strength, hooked ends seem to work best. For crack prevention, continuous deformations may be superior.

POLYPROPYLENE FIBRES

Not all fibres used in concrete are made of steel. Over the years, people have tried other materials, including natural fibres, glass, and various plastics. Today, the main rival to steel as a fibre material is polypropylene.

Polypropylene fibres are often called synthetic. That's not wrong, but it can be misleading because the term *synthetic* category includes a vast range of fibre materials with different properties. It could even be applied to steel fibres.

Polypropylene fibres are often divided into two categories: microsynthetic and macrosynthetic, according to their width. Microsynthetic fibres have an effective diameter below 0.3 mm (0.012 in) (Figure 12.6).



FIGURE 12.6 These polypropylene fibres (macrosynthetic) tangled and formed a ball. Any type of fibre can tangle, but the risk is higher when the fibres are long and thin.

Polypropylene fibres are widely promoted as an alternative to steel fibres and other steel reinforcing, but fall short in two important ways. First, they have a low elastic modulus—much lower than hardened concrete or steel. Second, they can stretch and pull out when subjected to sustained tension.

This does not mean polypropylene fibres have no value. They help prevent plastic shrinkage and plastic settlement cracks, and they have a role to play in controlling drying shrinkage cracks.

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Part 4

Joints and Cracks



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13 Cracks

Concrete floors often crack. A crack occurs when the tensile stress on the concrete exceeds the concrete's tensile strength. While many cracks are harmless, some cause serious problems.

Designers and builders cannot guarantee crack-free floors. Some cracks can be prevented, however, and many cracks not prevented can be controlled so they do not cause trouble for the floor user.

Because it costs money to prevent and control cracks, designers need to decide how far to go in dealing with each type of crack. Not every crack causes trouble, and the elimination of cracks is not always worth the cost.

This chapter discusses the following types of cracks, with ideas on how to prevent or control each type:

Cracks in plastic concrete:

- Plastic shrinkage cracks;
- plastic-settlement cracks;
- crazing.

Cracks in hardened concrete:

- drying-shrinkage cracks;
- thermal-contraction cracks;
- structural cracks.

PLASTIC SHRINKAGE CRACKS

These occur when newly placed, still-plastic concrete undergoes severe drying. They are widest at the top and seldom penetrate the full depth or extend the full width of the slab. Though most common in dry climates, they can occur in generally humid areas like the UK, especially in high winds (Figure 13.1).

Most plastic shrinkage cracks are harmless, but some are associated with delamination and some grow into big drying-shrinkage cracks after the concrete has hardened.

Here are ways to reduce the risk of plastic shrinkage cracks.

- Lay the floor indoors, where it is protected from wind and sunshine.
- When laying floors outdoors, use curtains or tents to shield the concrete from wind.
- Avoid placing concrete when the evaporation rate is high.
- Use misters upwind of the fresh concrete to raise humidity.
- Spray the fresh concrete with a monomolecular film to slow evaporation.

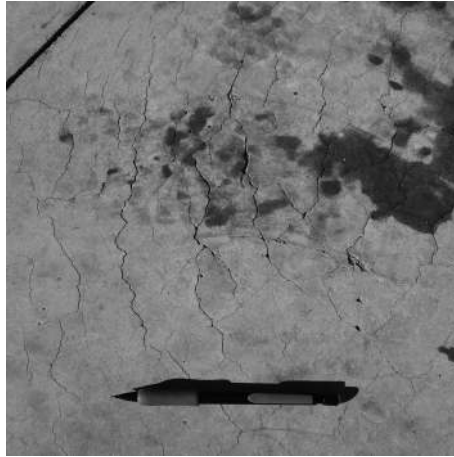


FIGURE 13.1 Plastic shrinkage cracks form before the concrete has set.

PLASTIC-SETTLEMENT CRACKS

These occur when plastic concrete settles relative to fixed objects such as reinforcing bars. The crack appears directly over the fixed object. In bad cases a crack appears over every bar, resulting in a near-perfect grid of cracks. Plastic-settlement cracks are most common where reinforcing bars are thick and close to the surface. Thick slabs crack more than thin ones, because they settle more.

Here are some ways to reduce the risk of plastic-settlement cracks.

- Increase the cover—the distance from the floor surface to the reinforcing steel. Make sure this does not compromise the structural design.
- Use smaller reinforcing bars. By using more bars of smaller diameter, you can maintain the same amount of steel.
- Take steps to reduce plastic settlement, such as increasing the size of the coarse aggregate and eliminating gaps in the aggregate gradation. Adding fibres may help.

CRAZING

This is a network of closely spaced, shallow cracks at the floor surface. Other names for it include map cracking (because it resembles the pattern of roads on a map) and alligator or crocodile cracking (because it vaguely resembles the fissures in the skins of those two reptiles). In American practice, crazing describes a network with less than 50 mm (2 in) between cracks, while map cracks are separated by greater distances.

Crazing occurs when the floor surface shrinks relative to the concrete below it. This often happens just as the concrete is setting or shortly afterwards. Contributing factors are a high evaporation rate and a smooth, burnished finish. Crazing often accompanies plastic shrinkage cracking, and it can be hard to tell where one ends and the other begins.



FIGURE 13.2 Crazing as mild as this is harmless and should be ignored. But see Figure 13.3.

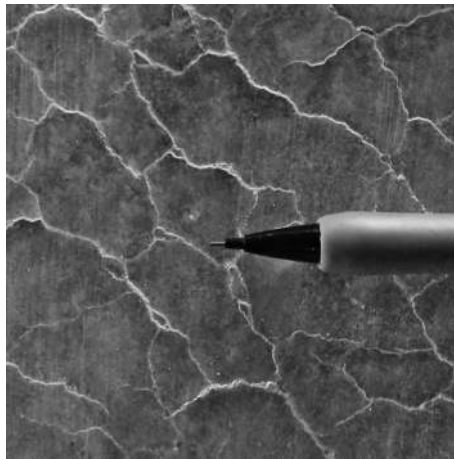


FIGURE 13.3 This degree of crazing is unacceptable to some floor users.

Crazing is usually harmless. The narrower the craze cracks, the less likely they are to cause trouble. Narrower craze cracks are often associated with closer crack spacing. This means a floor with a lot of craze cracks (i.e., with a close crack spacing) may actually fare better than one with a few.

Crazing needs no repair unless the cracks are unusually wide or accompanied by delamination (Figures 13.2 and 13.3).

Here are some ways to lower the risk of crazing.

- Don't float or trowel the floor surface while bleed water is present.
- Give the floor a broom or float finish (not a good choice, though, for industrial floors that must resist wear).

- Lay the floor indoors, where it is protected from wind and sunshine.
- When laying floors outdoors, use curtains or tents to shield the concrete from wind.
- Avoid placing concrete when the evaporation rate is high.
- Use misters upwind of the fresh concrete to raise humidity.
- Start curing as soon as possible.

DRYING-SHRINKAGE CRACKS

These occur because concrete shrinks as it dries. If a floor slab is restrained from moving freely—every slab is restrained to some extent, if only by subslab friction—the shrinkage produces tensile stresses within the slab. If the tensile stress exceeds the concrete's tensile strength, the slab cracks.

Unlike the plastic cracks and crazing described above, drying-shrinkage cracks usually extend over the full width and depth of the slab. They tend to start near points of restraint (such as building columns) and at planes of weakness in the slab (such as cold joints). They sometimes follow the lines of reinforcing bars, but by no means always.

It is hard to tell drying-shrinkage cracks from thermal-contraction cracks, described below. Both types are caused by restrained volume changes and are identical in their effect on the floor. Some measures that control drying-shrinkage cracks work equally well against thermal-contraction cracks (Figures 13.4 and 13.5).

There are two general ways to deal with drying-shrinkage cracks: prevention and control. If prevention is the goal, the choices include:

- shrinkage-compensating concrete;
- pre-tensioning with steel tendons (mainly used in precast units);

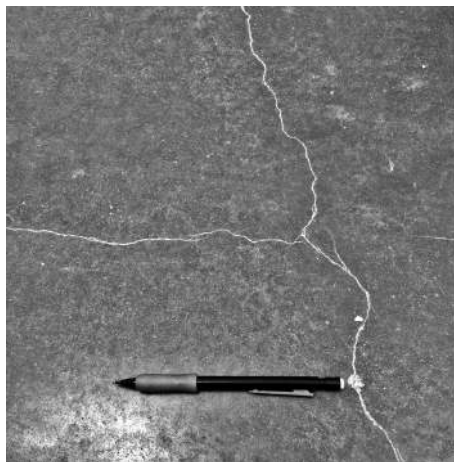


FIGURE 13.4 Hairline cracks from drying shrinkage in a floor that has been stained and polished. On a normal industrial floor, cracks like these would be almost invisible.



FIGURE 13.5 An uncontrolled drying-shrinkage crack. Few users will accept a crack like this. The coin has a diameter of 26.5 mm.

- post-tensioning with steel tendons;
- steel fibres at high dosages.

Bear in mind that none of these preventive measures is foolproof.

Most floor designers don't even try to prevent drying-shrinkage cracks. They try instead to control them with reinforcement, joints, or both. To control a crack is to manage its behaviour in such a way that it causes little harm. Suspended floors, if designed according to one of the structural codes, normally contain enough reinforcement to keep cracks narrow and trouble-free. Ground-supported floors often lack the quantity of reinforcement needed to keep cracks tight and rely instead on joints to control where the cracks will occur. For more on that subject, see Chapter 16.

Though reinforcement and jointing are the primary tools for controlling drying-shrinkage cracks, they are not the whole story. Anything that lowers drying shrinkage or eliminates restraint has the potential to reduce the width and number of cracks. Here are some ways to lower shrinkage.

- use bigger aggregate;
- avoid aggregates that show high drying shrinkage;
- use less water in the concrete mix (but beware of the effect on workability and finishability);
- use less cement (but beware the effect on strength and finishability).

And here are some ways to reduce restraint:

- isolate the floor from columns, walls, and other fixed elements;
- use a polyethylene slip sheet directly under the slab;
- make the sub-base (or subgrade, where the sub-base is absent) as flat as possible.

THERMAL-CONTRACTION CRACKS

These occur because concrete contracts as it cools. They look the same and have the same effect as drying-shrinkage cracks.

Thermal-contraction cracks can occur whenever the temperature falls, but they are most common in the early days when the concrete is weak. Some evidence suggests that thermal contraction causes many of the early cracks often attributed to drying shrinkage (Kass and Campbell-Allen, 1973).

Most methods that prevent and control drying-shrinkage cracks work equally well against thermal-contraction cracks. The exceptions are the mix-design changes that aim to reduce drying shrinkage. Adjusting the concrete mix will not substantially reduce thermal contraction.

You can prevent some thermal-contraction cracks by limiting temperature changes. Here are some measures that have proven effective.

- Lay the floor indoors, after the building envelope is complete.
- Place concrete at night. This does not reduce temperature change, but it ensures that the concrete undergoes expansion as the day warms up before contraction begins.
- Insulate the newly laid slab with blankets or straw (but not polyethylene sheets, which provide negligible insulation).

In cold weather, the use of accelerators can help reduce thermal-contraction cracks in ground-supported slabs with sawn joints. Without accelerators, the concrete might set so slowly that the joints cannot be sawn before nightfall, setting the stage for cracking. With enough accelerators, the joints get cut before the slab cracks.

STRUCTURAL CRACKS

These occur when a floor bends under load, creating tensile stresses that exceed the concrete's tensile strength. A structural crack may or may not denote a failure, depending on the floor design.

STRUCTURAL CRACKS IN SUSPENDED FLOORS

These are normal. Made of reinforced concrete, most suspended floors are meant to crack. Designers expect cracks in areas of tension and put steel there to resist the stress after the cracks have formed. A structural crack in a reinforced, suspended floor is nothing to worry about unless it grows wider than expected.

An unusually wide crack in a suspended floor may be the symptom of a serious problem, however. The floor may be underdesigned or overloaded. Or there could be construction errors such as missing or misplaced reinforcing steel.

How wide must a crack be before the alarm is raised? The answer varies with the design method. Some designers try to limit crack width to about 0.3 mm (0.01 in), but others allow more. American floors designed by the current strength-design

method are allowed wider cracks than older floors designed by the working-stress method. On the other hand, in a pre- or post-tensioned floor, any crack wider than a hairline may be cause for concern. In any case, it is the structural engineer's job to predict crack widths and let other parties know what to expect.

STRUCTURAL CRACKS IN GROUND-SUPPORTED FLOORS

Unlike suspended floors, most ground-supported floors lack structural reinforcement and are designed not to crack under load. When a structural crack appears in that kind of floor, something has gone wrong.

Ground-supported slabs crack structurally for many reasons, including:

- loads that exceed design values;
- inadequate design;
- construction errors that result in a too-thin slab;
- subgrade failure.

Overloading during construction causes many cracks. Designers tend to focus on the user's loading, but some construction equipment weighs more than anything the user will put on the floor. The way to prevent structural cracks during construction is to specify and enforce maximum loads, and to forbid any substantial loading till the concrete is strong enough to take it. The safest course is to allow nothing but foot traffic till the concrete has reached its design strength, but construction schedules don't always allow this luxury.

Though structural cracks in a ground-supported floor are evidence of failure, they are not always serious. An isolated crack seldom does real harm, especially if its cause was a temporary overload that is unlikely to recur. On the other hand, if cracks continue to form under normal loads, the floor will break up into very smaller pieces and eventually become unusable. Fortunately, this is rare.

CRACK REPAIR

The time to think about crack repair is before the floor cracks. To reduce arguments, every floor specification should include a section on crack repair. It should state the conditions under which a crack needs repair, and it should spell out the allowable method or methods of repair.

Many cracks—perhaps most—do no harm. Cracks rarely need repair if hidden under floorcoverings or exposed only to foot traffic. Even in an exposed industrial floor, a crack generally need not be repaired unless it meets one or more of these conditions.

- Its width exceeds 1 mm (1/32 in) and it is exposed to hard-wheeled traffic.
- It spalls under traffic, regardless of width.
- It shows differential movement under traffic. Readings over 0.25 mm (0.010 in.) are cause for concern.

All three conditions are related to traffic. Even in a busy warehouse or factory, cracks outside the main traffic areas can usually be left alone. Some users have special requirements, however. In a food or pharmaceutical plant, and in some electronics plants, concern for cleanliness may force the sealing of every visible crack (usually but not always excluding craze cracks). Crack sealing may also be called for in floors exposed to corrosive chemicals.

Some owners and designers insist on crack repairs solely for the sake of appearance, but that can backfire. The repair often ends up more obvious than the original crack.

Once you identify a crack as needing repair, you must decide how to do the job. Here are the four main methods:

- fill the crack with a sealant;
- fill the crack with a semirigid joint filler;
- inject glue into the crack;
- install mechanical joint stabilizers.

The choice of method depends not only on the nature of the crack but also on how the floor is used.

SEALANTS

These are described in Chapter 15 under joint sealants. Any joint sealant can also be a crack sealant. The choices include hot-poured materials and cold-poured elastomers, which come in a bewildering variety. Sealants make a good repair if the only requirement is that the crack be sealed. They do not protect a crack's edges from spalling under traffic, nor can they reduce differential movement.

Sealants require a minimum crack width—often 3 mm (1/8 in), and sometimes 6 mm (1/4 in). If the crack is not wide enough to admit the sealant, widen it with a concrete saw or an angle grinder fitted with a mason's tuck-pointing blade.

SEMRIGID JOINT FILLERS

Based on epoxy or polyurea, these are usually the best materials for cracks that have spalled, or are likely to spall, under hard-wheeled traffic. They even have some ability to stabilize cracks that show differential movement.

Because semirigids are less elastic than sealants, they will fail if cracks widen much after repair. To minimize the risk, wait as long as possible before installing them, to give the concrete time to shrink. And if the floor is subject to seasonal temperature swings, try to install semirigids in the winter when thermal contraction is greatest.

Semirigids should penetrate at least 25 mm (1 in) into the slab and may need to go deeper where the goal is to reduce differential movement.

Unless the crack is unusually neat and clean, chase it with a concrete saw or an angle grinder fitted with a mason's tuck-pointing blade. Make a groove at least 25 mm (1 in) deep and wide enough to take out all spalled edges. For the neatest repair, overfill the crack and sand or grind it flush after the filler has hardened.

GLUES

Another option is to inject the crack with a strong, hard glue. Gluing is attractive because it is the only method that restores the floor's flexural stiffness to its uncracked condition. Another benefit is that it works in very narrow cracks; some products will fit into a gap of just 0.05 mm (0.002 in) wide.

Glue's strength is also its weakness. It locks up the crack, eliminating any ability for the crack to accommodate future movement without distress. If the conditions that caused the crack continue to exist, the floor is likely to crack again. Gluing is usually safe for structural cracks caused by temporary overloading. It is not a good choice for drying-shrinkage cracks unless the floor is so old that little additional shrinkage is likely.

JOINT STABILIZERS

Some of the worst crack problems occur when cracks exposed to heavy industrial traffic lose their ability to transfer load. The two sides of the crack then move up and down relative to each other every time a vehicle passes over them. Once this starts, crack edges can break down quickly.

Sometimes you can restore load transfer with a good installation of semirigid joint filler. For this purpose, you need one of the harder fillers—either a traditional epoxy product or a high-modulus polyurea. Success is more likely if the differential movement is less than 0.5 mm (0.030 in).

If the joint filler does not work, the fix is to install a mechanical joint stabilizer.

REFERENCE

Kass, J. L. and Campbell-Allen, D (1973). Precision of early shrinkage measurements. *Journal of Testing and Evaluation*, Jan., 24–30.

14 Curling

Curling is the warping of a concrete slab so its edges are left higher than its centre. The main cause is differential drying shrinkage through the thickness of the floor. If a concrete floor dries from the top—and ground-supported floors almost always do—the top shrinks faster than the bottom. This differential shrinkage warps the slab, making it concave upwards. Thermal contraction can also curl a slab, but it plays a much smaller role than drying shrinkage—at least on interior floor slabs. It's a big issue on pavements (Figure 14.1).

Some people, especially but not exclusively in the field of highway engineering, draw a distinction between curling and warping. They use *curling* when the cause is temperature change and *warping* when the cause is drying shrinkage. That distinction is not much honoured in the concrete floor industry, and sometimes it is explicitly denied. The National Ready Mixed Concrete Association, in its white paper on the subject, says “The terms *curling* and *warping* are used interchangeably”. (NRMCA, 2018)

Curling is very common in ground-supported floors and unbonded toppings and is the main cause of failure in bonded toppings. It is a much smaller problem in suspended floors, because they are usually free to dry out from both top and bottom. Curling does show up, however, in slabs cast on steel decks.

A slab can curl up at any break—at the floor's edge, a construction joint, an induced joint, or a crack. The worst examples seem to occur at edges and construction joints, but some of that may be the result of false curling, described below.

Curling starts soon after the concrete has hardened and goes on for many months. It has been suggested that over the very long-term curled slabs settle back down due to creep. That may be true, but if so it takes years. The suggestion usually comes from someone who is trying to avoid repairing a severely curled floor.

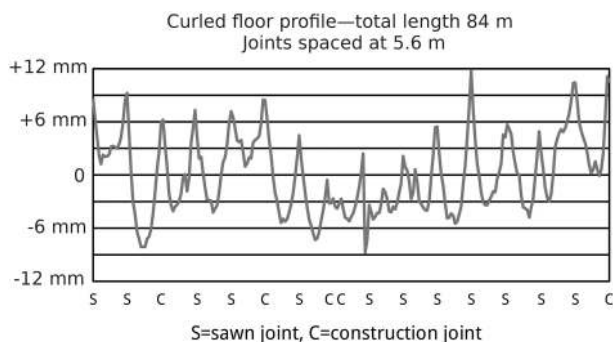


FIGURE 14.1 This is about as bad as curling gets. Curling appears at every joint, and the typical elevation difference from trough to peak is about 12 mm.

The amount of curl varies greatly from floor to floor, for reasons that are only partly understood. In general, anything that increases drying shrinkage or increases the moisture differential will make curling worse. The list of contributing factors includes but is not limited to:

- water content (Wetter mixes shrink more.);
- cement content (More cement means higher shrinkage.);
- aggregate gradation (Concrete made with coarser, well-graded aggregates shrinks less.);
- type of rock used for aggregate (Some types shrink less than others.);
- moisture content of sub-base (A wet base increases the moisture differential.);
- ambient humidity (Dry air increases the moisture differential.)

Contrary to widespread belief, curing seems to have little effect on how much a slab curls. Curing clearly affects the timing of the process, since concrete will neither shrink nor curl while it remains soaking wet. But even the best-cured slabs dry out eventually, and then they curl (Figure 14.2).

Curling is so common that we can hardly consider it a defect. We should rather think of it, like the drying shrinkage to which it is related, as a normal property of concrete floors. But curling's frequent occurrence does not mean we should ignore it. Curling profoundly affects slab behaviour, and severe curling can lead to these problems:

- debonding and break-up of concrete toppings;
- reduced structural capacity, due to loss of contact with the sub-base;
- differential movement at joints and cracks;
- reduced flatness at joints and cracks.

There are four general ways to deal with slab curl:

- resist curling stresses with post-tensioning or heavy reinforcement;
- limit curl by reducing drying shrinkage;
- design floors so curling does little harm;
- repair floors after they have curled.



FIGURE 14.2 A kitchen sponge curls as it dries. So do many floor slabs.

FALSE CURLING

Sometimes what looks like curling is really an upsweep at the slab edge, introduced during floor finishing. It results from plastic settlement, which lowers the concrete surface relative to the side forms. When concrete finishers float and trowel a surface that has settled, they tend to pull mortar towards the edge to make the finished floor flush with the top of the side form or adjacent slab. This produces a short slope that can be as high as 6 mm (1/4 in). The length of the upsweep depends on the finishing tool used (Figure 14.3).

In their effect on flatness, false and true curling are almost the same. But unlike the real thing, false curling is strictly a surface defect. It does not reduce contact between a ground-supported floor and its sub-base, nor does it cause a topping to debond.

The most reliable way to tell real curling from false is to test the floor's flatness within a day or two of construction. Real curling never shows up that soon. If the time for early testing has passed, there are still clues. Wherever curling appears confined to construction joints and is not evident at induced joints and cracks, suspect false curling.

RESISTING CURL

Prestress or reinforcement can resist and effectively prevent curling. Where even a little curling would be too much—as in a random-traffic superflat floor—prestressing and heavy reinforcement are the only safe options.

PRESTRESS

Ground-supported floors can be prestressed in two ways: shrinkage-compensated concrete and post-tensioning. Floors prestressed with shrinkage-compensating concrete generally do not curl. While the same cannot be said for post-tensioned floors, post-tensioning still prevents most curling-related problems because it eliminates most joints and cracks. A two-way post-tensioned slab curls only at its edges, which

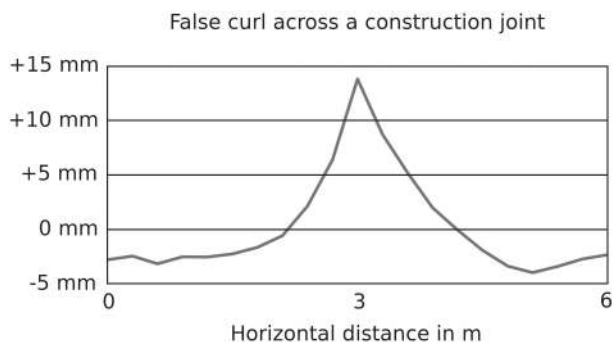


FIGURE 14.3 False curling at a construction joint.

can be 100 m (300 ft) apart. In smaller buildings the post-tensioning can go wall-to-wall, putting any curled-up edges out where they are unlikely to cause trouble.

With one-way post-tensioning—common in defined-traffic superflat floors—you should expect normal curling in the direction perpendicular to the tendons. That is acceptable in defined-traffic floors, where the critical traffic travels in just one direction.

REINFORCEMENT

Reinforcing steel can resist curling, but you have to use enough. Structurally reinforced slabs with double mats of steel almost never have problems related to curling. Jointless reinforced slabs, with 0.5% steel in both directions, have an equally good record.

On the other hand, the light reinforcement so often used in jointed slabs does not prevent curling. The best you can expect from it is some mitigation of the damages, since even light reinforcement improves load transfer across curled edges.

LIMITING CURL BY REDUCING DRYING SHRINKAGE

Anything that reduces drying shrinkage will also reduce curling. The following steps can help:

- use bigger coarse aggregate;
- avoid aggregates that have high drying shrinkage;
- use less water in the concrete mix (but beware the effect on workability and finishability);
- use less cement (but beware the effect on workability and finishability).

THE EFFECT OF POLYETHYLENE SHEET UNDER THE SLAB

For many years, it's been the received wisdom that impervious plastic under the slab made curling worse. Some authorities recommend putting the plastic under the sub-base, or covering it with a blotter layer of sand, just to help control curling.

The received wisdom appears to have been wrong. According to Tarr (2016), the assumed cause-and-effect relationship between plastic sheets and curling was a myth, based on a misreading of a 1976 article that did not even address curling. Tarr argues plausibly that plastic under the slab actually reduces curling because it blocks ground moisture, which would otherwise keep the bottom of the slab wet and increase the moisture gradient. My own experience confirms that opinion; I've seen severe curling on slabs with and without plastic.

DESIGNING AROUND CURL

The methods that prevent curl cost money, and those that limit curl do not always produce the desired effect. Fortunately, there is a third option: design the floor so it works despite curling. This is mainly a matter of getting the joints right.

JOINT LAYOUT

Since curling problems show up mainly at the joints, any design that keeps joints away from critical activities will improve the situation. In a warehouse or factory with relatively few travel paths, you can often put many of the joints in areas that get little or no traffic. Where concentrated loads control the floor design, careful layout can sometimes eliminate loading near joints.

Some people advocate very close joint spacings to reduce curling's effects. The idea is that curling tends to create an arc of uniform radius across each panel, and if you make the arc shorter the edge effects will be less severe. The logic is sound but it can backfire if some joints fail to activate.

LOAD TRANSFER AT JOINTS

Many of the bad effects of curling are related to load transfer across joints. Load-transfer devices do not prevent curling, but they maintain a connection across the joint after the floor has curled. That connection increases the floor's structural capacity and reduces differential movement—both important objectives that improve the floor's performance, especially in industrial buildings.

REPAIRING CURLED SLABS

No slab should be repaired merely because it has curled. Repair is called for only if the curling creates a problem for the floor user. The repair method depends on the nature of the problem.

If the problem is confined to poor flatness or levelness, grinding is the usual repair. It works but often has to go deeper and wider than people expect. Just running a grinder down the joint will seldom suffice. To eliminate the problem fully, the grinding swathe may have to extend as much as 1 m (3 ft) to each side of the joint. Diamond-disc grinders are best for this work; the grinders that use abrasive blocks are too slow.

Other curling-related problems may be harder to solve.

Once a thin topping has curled and begun to break up, it is beyond saving. At least part of it will have to be taken out and relaid. If a thin topping has curled and debonded but remains intact, its lifespan can sometimes be extended by injecting epoxy between the topping and its base. This is a tricky operation and does not always work.

A similar operation, using cement grout or expanding foam instead of epoxy, is sometimes performed on ground-supported slabs that have curled away from their sub-bases. Subslab subsection usually succeeds in shoring up the edge, but it does not always last. Further curling can lift the slab off the injected grout, renewing the problem.

If the problem is related to the loss of load transfer across a joint or crack, filling the gap with semirigid joint filler—epoxy or a high-modulus polyurea—sometimes saves the day. This repair works best where differential movement is less than about 0.5 mm (0.020 in). Let the filler flow into the joint as far as possible, and grind the joint flush after the filler has set.

If joint filler alone does not restore load transfer at a curled joint, consider dowel-bar retrofit or mechanical joint stabilizers.

Dowel-bar retrofit (DBR) began in the highway field but has proven equally useful, though expensive, in concrete floors. It involves cutting slots at right angles to the joint, putting smooth round dowel bars in the slots, and refilling the slots with a fast-setting mortar. For a good explanation of DBR along with clear instructions on how to do it, see the US Federal Highway Administration's *Concrete Pavement Preservation Guide* (Smith et al., 2014, 161–179). Note, however, that this guide, along with many other documents about DBR in highways, includes some details that are not needed in a floor slab. You won't need epoxy coating on the dowel bars, and you won't need expansion caps. And if your slab is less than 175 mm (7 in.) thick, you can probably get away with smaller diameter bars. There's no reason to use bigger dowels in DBR than you would in new construction.

Another way to provide load transfer at a curled joint is to install mechanical joint stabilizers.

These are aluminium cylinders with a diameter of 75 mm (3 in) and a length of 125, 150, or 175 mm (5, 6, or 7 in). Each cylinder is split in half down its length and contains a bolt, wedges, and springs. The repair involves these steps.

1. Determine the spacing needed through trial and testing. It is usually about 1.2 m (4 ft).
2. Drill holes in the floor, centred on the joint, at the spacing determined in step 1. Each hole is 75 mm in diameter and goes full depth.
3. Choose a stabilizer length based on slab thickness. Often you won't be certain of the thickness till you have drilled the hole.
4. Insert a mechanical joint stabilizer in each hole, lowering it till flush with the floor surface.
5. Tighten the bolt with a torque wrench.

Tightening the bolt forces the two halves apart with about 36 kN (8000 lb of force), locking the stabilizer to the concrete slab on both sides. The internal spring maintains the locking force as the joint opens and closes with thermal changes.

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- Smith, K., Dale Harrington, Linda Pierce, Preshant Ram, and Kelly Smith (2014). *Concrete Pavement Preservation Guide, Second Edition*. Second Edition. Federal Highway Administration.
- Tarr, S. (2016). *Concrete slab Curling Over Vapor Barriers*. Concrete International, September, 75–76.

15 Joints

These are planned breaks in the continuity of a concrete floor. Unplanned breaks are called cracks. The term *joint* is largely confined to those breaks that are more or less vertical, and not to the horizontal breaks between layers in a multicourse floor.

Joints are necessary but cause many problems. Close attention to the design and execution of joints will produce markedly better floors.

This chapter covers:

- the function of joints;
- types of joints;
- load transfer;
- how induced joints are made;
- fillers and sealants.

Chapter 16 deals with the related subject of joint spacing for crack control.

THE FUNCTION OF JOINTS

Floors have joints for two reasons: to make construction easier and to relieve stresses that would otherwise cause cracks.

To ease construction, all floors except the smallest are divided into several slabs cast on separate days. The seams between the slabs are called construction joints or day joints.

Many floors, but by no means all, contain stress-relief joints in addition to construction joints. Stress-relief joints include:

- isolation joints to separate the floor from other building elements;
- expansion joints to relieve stress from thermal expansion;
- contraction joints to relieve stress from drying shrinkage and thermal contraction;
- warping joints to relieve stress from curling.

A joint can serve more than one purpose. Many construction joints serve also as contraction and warping joints. And every contraction joint is also capable of acting as a warping joint.

GROUND-SUPPORTED AND SUSPENDED FLOORS

Joints work differently in ground-supported and suspended floors. Both kinds of floors contain construction joints, but the rules for locating them differ. In ground-supported floors, construction joints typically fall on column lines to make construction easier.

In suspended floors, structural engineers prefer to put the construction joints in areas of low moment, which normally occur away from the structural supports.

A bigger difference between ground-supported and suspended floors shows up when we consider stress-relief joints. Most suspended-floor designs omit them altogether, instead relying on reinforcing or prestressing steel to resist stresses. In contrast, most ground-supported floor designs rely heavily on joints to relieve stress. Those joints are key parts of the floor design.

The rest of this chapter deals mainly with joints in ground-supported floors.

JOINT TYPES

Joints are classified in several ways: by function, by the method of construction, and by the method of load transfer. It can get confusing. Looking at function, we can divide joints into these categories:

- isolation joints;
- construction joints;
- expansion joints;
- contraction joints;
- warping joints.

ISOLATION JOINTS

These joints separate a floor slab from other building elements, leaving the slab free to move in all directions as it responds to drying shrinkage, thermal contraction, loading, and settlement. Isolation joints also protect the slab from movements that the other building elements undergo.

Isolation joints within a floor—that is, between floor slabs—are sometimes used when a floor must meet special requirements for thermal or acoustic insulation. Examples occur in cold-storage buildings and television studios. These look like and are made in much the same way as expansion joints.

Ideally, ground-supported floors are isolated from all objects that might restrict their movement, including walls, columns, machine foundations, drain pipes, and bollards. Sometimes you have to compromise, however. Isolation is hardly possible where the structural design relies on a solid connection between the slab and other building elements—a condition that occurs at many retaining walls and in portal-frame structures.

Isolation joints at walls are made by gluing or nailing joint filler to the wall. A 20-mm ($\frac{3}{4}$ -in) thickness is standard in the UK, but 13-mm ($\frac{1}{2}$ -in) joints are common in America and seem to work as well. Wider isolation joints are used in extended-joint floor designs.

Isolation joints at columns are made in several ways. The simplest way is just to wrap the column with compressible foam, but this method is not suitable for every floor. A foam wrapping will not work where the column's support hardware sticks up above the sub-base. It also will not work on jobs where the columns go in after the slab, unless column sleeves are used (Figure 15.1) .

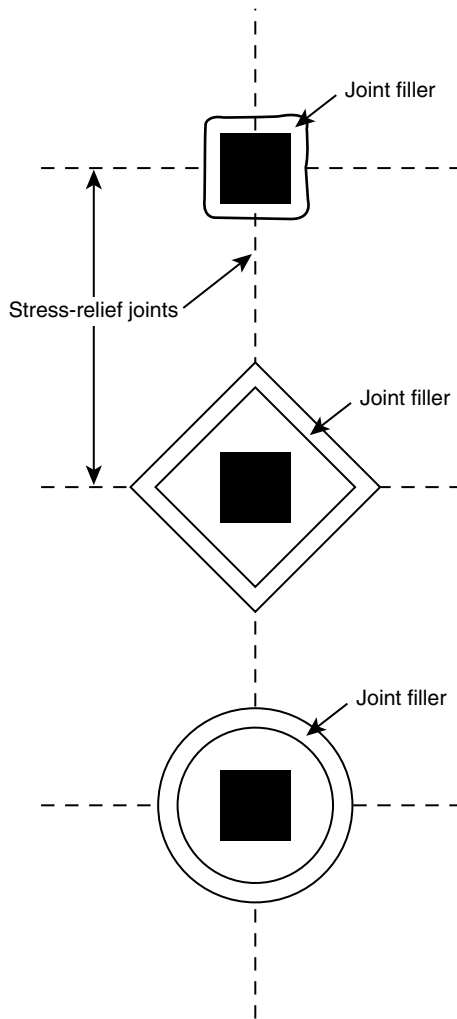


FIGURE 15.1 Three ways to isolate columns.

The alternatives for column isolation are diamond-shaped or round blockouts. Diamond blockouts are usually formed up on site, using timber. Round blockouts are usually formed with manufactured paperboard tubes. In both cases, compressible joint filler goes between the slab and blockout. Blockouts are filled with concrete, a process that may either precede or follow the laying of the main floor slab (Figure 15.2).

Isolation joints are particularly important in post-tensioned floors, which experience large horizontal movements. Long post-tensioned floors need thicker isolation joints at building columns. If a post-tensioned slab is 100 m (330 ft long), each end may pull in by as much as 40 mm (1½ in).



FIGURE 15.2 Columns of unusual shape call for special blockouts, with forms constructed on site. This type is called a hockey-rink blockout because of its shape.

CONSTRUCTION JOINTS

These divide a floor into slabs cast at separate times. They are often called formed joints, because they are made by erecting forms. Another (somewhat dated) term for them is day joints, because they define each day's work.

Their main purpose is to simplify the job by dividing the floor into pours of convenient size. However, on many floors, the construction joints also serve as stress-relief joints. Depending on details, a construction joint can serve as an expansion joint, contraction joint, or warping joint.

Construction joints often cause trouble. The floor near a construction joint is almost always less flat than the floor elsewhere—sometimes much less flat. Recognizing that fact, American standards (ASTM E 1155 and ASTM E 1155M) exclude construction joints from routine flatness testing. And the problems are not confined to poor flatness; construction joints often look bad and deteriorate quickly under traffic.

Good workmanship can go a long way towards preventing problems at construction joints. Still, the safest course is to eliminate or minimize construction joints in critical areas. Modern large-bay construction methods result in few construction joints, and this is perhaps the best argument in support of those methods. Where construction joints cannot be avoided, the following measures will improve their appearance and performance.

- Use side forms with sharp, square edges.
- When setting forms, make sure the inside edge (the edge nearest the pour) is higher than the outside edge.
- Compact the concrete well.
- When casting the second slab, keep the first one clean and do not let mortar build up on it.

Construction joints are finished in two ways. They can be tooled or trowelled flush (also called *burned in*). A tooled joint is made with an edging tool, which rounds off the slab edge. A flush joint is made by trowelling the second slab right up to the first. Tooled joints look better and are a good choice for exposed concrete floors that get light traffic. Flush joints may hold up better under industrial traffic.

But flush joints often go wrong if they are sawn out later to receive a semirigid filler or sealant. The sawer may find it hard to spot the exact location of the joint, resulting in a misplaced sawcut. Tooling prevents that problem.

If a construction joint ends up looking less than perfect, light grinding may improve it.

The important issue of load transfer at construction joints is covered later in this chapter.

EXPANSION JOINTS

These leave room for thermal expansion. Very few floors need them, because only in rare circumstances does a concrete floor expand beyond its original, as-cast size. Even on roads, which undergo greater temperature swings than do floors, modern practice eliminates expansion joints unless the concrete is cast in very cold weather. Some designers call for expansion joints in very big floors and in long buildings, where an expansion joint passes through the whole structure.

An expansion joint is made as a construction joint with a gap between the two concrete slabs. The gap is formed with joint filler, the same as used in isolation joints. Expansion joints do not fare well in areas of heavy industrial traffic, for two reasons. First, they are wider than most other joints. Second, their function demands that they be filled with soft, compressible material that has no ability to support an exposed joint edge. The best solution to this problem is to avoid expansion joints in trafficked areas. Another solution is to armour the joint edges with epoxy or steel.

If an expansion joint needs load transfer, steel dowels with expansion caps are the only option.

CONTRACTION JOINTS

These relieve tensile stresses caused by drying shrinkage and thermal contraction. They can be made either as construction joints or as induced joints.

All construction joints act naturally as contraction joints, unless restrained with reinforcement or tie bars.

Induced joints are planned cracks. The slab is weakened—usually by sawing a groove, but sometimes by casting in a piece of plastic or metal—in the hope a crack will form along the weakened plane. Any induced joint will act as a contraction joint unless restrained by reinforcement or tie bars.

If a contraction joint needs load transfer, steel dowels provide the most reliable method. Some designers depend on keyways or aggregate interlock, but those methods are less reliable.

WARPING JOINTS

These act as horizontal hinges to relieve warping (curling) stresses. All expansion and contraction joints serve also as warping joints. Construction joints also relieve warping stress, unless they contain two or more layers of reinforcing steel.

When a joint is designed to work solely as a warping joint, it usually contains tie bars or a single layer of reinforcing steel.

LOAD TRANSFER AT JOINTS

Many joints need the ability to transfer vertical loads from one side to the other. Load transfer serves two quite different purposes. It increases a slab's structural capacity by reducing stress from edge and corner loading, and it improves the performance of joints under vehicular traffic.

To improve structural capacity, the load-transfer device needs to be strong but the joint need not be tight. A modest amount of differential movement can be accepted, provided the load-transfer device eventually takes up the slack. In contrast, joints exposed to vehicular traffic need to be tight, preventing all but the most minuscule differential movement. For best performance under industrial truck traffic, differential movement should not exceed 0.25 mm (0.010 in). ACI 360 relaxes that tolerance to 0.50 mm (0.020 in.) if the vehicles travelling on the floor have soft tyres.

Here are the devices commonly used to transfer load across joints, in order of generally decreasing effectiveness:

- prestressing steel through the joint;
- continuous reinforcement through the joint;
- tie bars;
- dowels;
- semirigid joint filler;
- aggregate interlock;
- keyways.

Some joints contain more than one kind of device.

PRESTRESS

This provides near-perfect load transfer, whether the prestress comes from pre- or post-tensioning. This applies only to joints within the limits of the prestressed floor, however. Joints at the ends of a prestressed floor tend to open wide and often have problems with load transfer. Standard dowels may not suffice at the end of a very long post-tensioned floor slab, where the joint opening may exceed 25 mm (1 in).

THROUGH REINFORCEMENT

Reinforcing steel passing through a joint provides remarkably good load transfer. While the steel's shear strength plays a role here, the main benefit results from the way reinforcement keeps joints tight, maintaining concrete-to-concrete contact. It takes surprisingly little steel to do the job.

Reinforcement equal to 0.10% of the slab's cross-sectional area has been used with success on many industrial floors. You can go too low, however. Very light reinforcement, such as 6×6 , $W1.4 \times W1.4$ wire mesh popular in America, can easily stretch so much that it yields and load transfer disappears.

Because through reinforcement limits joint opening (and closing), it cannot be used in isolation, expansion, or contraction joints. It can be used in warping joints, however, provided the reinforcement is limited to a single layer.

Through reinforcement appears both in induced joints and in construction joints. Its use in induced joints creates no constructability issues, provided the steel lies far enough below the surface to allow sawing. However, its use in construction joints complicates the job considerably, because the reinforcement has to pass through the formwork. One solution is to slot or split the forms, but that makes them less rigid and harder to maintain at the right elevation. Another solution is to use threaded bar connectors, but they add cost.

TIE BARS

These are short lengths of deformed reinforcing bars. They restrict joint opening, making them unsuitable for contraction and expansion joints. They allow hinging movement, however, making them ideal for warping joints.

Tie bars resemble dowels, but the two types work on different principles. Dowels are made of smooth bar stock so they can slip, letting the joint open. At a dowelled joint, the concrete faces may be several millimetres apart; vertical loads are transferred through the dowels. In contrast, tie bars are made of deformed bar stock to limit joint opening. The tie bars may transfer some load directly, but their main purpose is to keep the concrete faces close together.

While dowels have to resist bending and shear stresses, tie bars need only resist the tensile stresses that try to pull the joint open. For this reason, tie bars can be thinner and fewer than dowel bars. They need to be longer than dowels, however, to develop a good bond with the concrete. In the UK, a common size is 12 mm ($\frac{1}{2}$ in or #4) in diameter and 900 mm (36 in) long, spaced 600 mm (24 in) on centre. Deacon (1986) recommends reducing the spacing to 300 mm (12 in) where the floor supports concentrated loads that exceed 5 t (11 000 lb).

Tie bars work well with narrow-strip construction, though that is not as common as it used to be. Back when UK floors were often laid in strips 4.5 m (15 ft) wide, many designers put tie bars in most of the longitudinal joints, switching to dowels at every third or fourth joint. That pattern still works, producing a floor with many tight joints and a few wider ones. The tight joints, containing tied bars, serve as warping joints, while the wider joints, containing dowels, serve as contraction joints.

Tie bars are also used in hybrid joints, described below.

DOWELS

These are smooth steel bars or plates. The bars can be round or square in cross-section, but they are usually round. Plates are rectangular or diamond-shaped (a square rotated 45° from the line of the joint). If installed correctly—a condition

you should never take for granted—dowels transfer load even after a joint has opened up substantially, making them unique among load-transfer devices.

Dowels have no rival as a way to transfer load across contraction and expansion joints. It is also used at warping joints, but there it faces competition from tie bars and through reinforcement.

Dowels are very widely used in construction joints, where they are easily installed by sticking them through the side forms. Their use in induced joints is less common and harder to execute. When installed at induced joints, dowels are supported on wire frames called baskets or cradles (Figures 15.3 and 15.4).



FIGURE 15.3 Round dowels at a construction joint.



FIGURE 15.4 Round dowels at sawn joints. The wire frames holding the dowels are called baskets or cradles. On this job, the contractor marked the joint lines with taut string and nailed down the baskets. Most contractors aren't that careful.

Dowel Spacing and Size

Dowel bars are usually spaced 300 mm (12 in) on centre at the slab's mid-depth. Closer spacing is rare. Wider spacing is sometimes seen, but it shouldn't exceed 600 mm (24 in) because a dowel's effectiveness goes down with distance from the applied load. To reduce restraint that can lead to cracks, some authorities recommend that no dowel be installed within 300 mm (12 in) of the point where two dowelled joints cross. Dowel plates follow different rules and are typically spaced 460 mm (18 in) on centre.

Dowel size is not yet a settled issue. Americans have long followed an old standard rule, carried over from the roadbuilders, that the dowel bar diameter should be one-eighth of the slab thickness. That made for easy calculating when using inches, because the slab thickness in inches equalled the dowel diameter in eighths. UK practice traditionally favoured thinner dowels, with Deacon (1976, 7) recommending 12-mm ($\frac{1}{2}$ -in) bars for slab thicknesses of 125–175 mm (5–7 in). As a result, American dowels often had over three times the cross-sectional area of their British counterparts in the same slab thickness, with no obvious difference in performance. Nowadays, many American designers, though by no means all, use the sizes and spacings in Tables 15.2. The bar dimensions in the tables come from ACI 360. The plate dimensions come from the manufacturers. Interestingly, the bar diameters don't stray far from the old one-eighth rule (Table 15.1).

TABLE 15.1
Dowel Size and Spacing for Construction Joints

Slab thickness	Round bars Dimensions	Spacing	Diamond plates Dimensions	Spacing
130–150 mm (5–6 in)	19 × 250 mm ($\frac{3}{4}$ × 10 in)	300 mm (12 in)	6 × 110 × 110 mm ($\frac{1}{4}$ × $4\frac{1}{2}$ × $4\frac{1}{2}$ in)	460 mm (18 in)
180–200 mm (7–8 in)	25 mm × 330 mm (1 × 13 in)	300 mm (12 in)	10 × 110 × 110 mm ($\frac{3}{8}$ × $4\frac{1}{2}$ × $4\frac{1}{2}$ in)	460 mm (18 in)
230–280 mm (9–11 in)	32 × 380 mm ($1\frac{1}{4}$ × 15 in)	300 mm (12 in)	19 × 110 × 110 mm ($\frac{3}{4}$ × $4\frac{1}{2}$ × $4\frac{1}{2}$ in)	510 mm (20 in)

Source: Adapted from ACI 360 and various plate-dowel makers.

TABLE 15.2
Dowel Size and Spacing for Sawn Joints

Slab Thickness	Round Bars Dimensions	Spacing	Rectangular Plates Dimensions	Spacing
130–150 mm (5–6 in)	19 × 330 mm ($\frac{3}{4}$ × 13 in)	300 mm (12 in)	10 × 50 × 300 mm ($\frac{3}{8}$ × 2 × 12 in)	460 mm (18 in)
180–200 mm (7–8 in)	25 mm × 410 mm (1 × 16 in)	300 mm (12 in)	12 × 64 × 300 mm ($\frac{1}{2}$ × $2\frac{1}{2}$ × 12 in)	460 mm (18 in)
230–280 mm (9–11 in)	32 × 460 mm ($1\frac{1}{4}$ × 18 in)	300 mm (12 in)	19 × 110 × 110 mm ($\frac{3}{4}$ × $2\frac{1}{2}$ × 12 in)	460 mm (18 in)

Source: Adapted from ACI 360 and various plate-dowel makers.

Most designers go by experience or a standard table. But for those who are up to the challenge, the Concrete Society (2016, 25–26) presents a way to calculate a dowel's load-transfer capacity. The method takes into account the amount of joint opening, a property ignored everywhere else, but one that undeniably affects a dowel's efficiency.

Slippage

To do its job, a dowel must be free to slip in the direction perpendicular to the joint. At the same time, it must be closely connected to the surrounding concrete so it can transfer load across the joint.

Three things are necessary for slippage. The dowel must be straight; it must be perpendicular to the joint; and it must not bond to the concrete. Failure to meet any of those conditions turns a dowel into a tie bar, making it unsuitable for a contraction or expansion joint (Figure 15.5).

Ordinary bar stock is straight enough for dowel use, but cutting it the wrong way can ruin it. Always insist that dowels be sawn to length, not sheared. Shearing costs less but puts a hook in the dowel's end, which should never be accepted.

Keeping the dowel perpendicular to the joint is the part that most often goes wrong. At construction joints, many floor layers like to leave the dowels loose during the pour, straightening them by hand after the concrete has stiffened slightly. That can work, but it depends on close attention at exactly the right time. A safer if more costly method is to support the dowels rigidly before placing concrete. Plastic mouldings called dowel aligners are available for that purpose. They work best with timber forms, to which they can be nailed. Another option, suitable for any type of form, is to erect a frame outside the form to support the dowels.

How straight do the dowels need to be? Deacon (1986, 14) recommends that the deviation from perpendicular not exceed 6 mm in 300 mm (1/4 in 1 ft). ACI 117 is more generous, allowing deviations up to 12 mm (1/2 in) over half the dowel's length. I prefer Deacon's rule and have not found it onerous.



FIGURE 15.5 Dowels should be perpendicular to the plane of the joint so the joint can open and close. These crooked dowels might as well be tie bars.

Preventing bond is a matter of putting something between the steel dowel and the surrounding concrete. That something can be grease, heavy oil, or a plastic sleeve. Oil is better than grease because it goes in a thinner layer. Plastic sleeves come in thin and thick varieties, bearing different risks. The thin sleeves are made of thin, flexible, clear polyethylene. The risk with them is that they will be dislodged during the concrete pour, since they are flimsy. The thick sleeves are made of rigid plastic, and the main risk here is that they will not fit tightly over the dowel. Because the thick sleeves are softer than steel or concrete some people worry that they may yield too much under load, resulting in a loose joint. Some of the thick plastic sleeves are meant to fit over deformed bar stock, allowing the use of ordinary reinforcing bars as dowels.

To save money and effort, debonding is usually confined to one side of the joint. When dowels are installed at sawn joints, it is good practice to debond more than half each dowel's length, to allow for the possibility the joint will not be centred on the dowels.

One extra detail is needed where dowels are used in an expansion joint. Each dowel needs a compressible cap at one end, and that end must be debonded. The cap should be at least as thick as the joint is wide.

Occasionally, dowels must be installed where a new floor abuts an old one. The usual solution is to drill holes in the old slab, glue the dowels in the holes with a strong epoxy, and debond the dowels from the new concrete.

Square Bars

While round bars and plates dominate the market, square-section bars occupy an important niche. If padded along its vertical faces, a square dowel allows some horizontal slippage parallel to the joint, while still transferring vertical loads. This can be useful where the slabs on either side of the joint are likely to shrink at different rates or in different directions, as might occur where a post-tensioned slab abuts one without post-tensioning (Figure 15.6).

SEMIRIGID JOINT FILLERS

Made of epoxy or polyurea, these were developed to help joints withstand wear and tear from warehouse trucks. They have also proven effective in improving load transfer under certain conditions. They work by eliminating the gap at the joint.

Don't expect any semirigid to work as the sole load-transfer device. For example, at a plain butt construction joint 6 mm ($\frac{1}{4}$ in) wide, no semirigid filler is likely to provide effective load transfer.

Semirigids work best in conjunction with other methods such as aggregate interlock and keyways. Those methods become much less effective as a joint widens, but a semirigid filler can reverse some of that loss. To improve the odds of success, follow these three rules:

- Wait till most of the concrete's drying shrinkage has occurred. Some authorities say to wait three months, but the only absolute rule is this: Longer is better.
- Try to fill joints when the concrete is at its point of maximum thermal contraction.

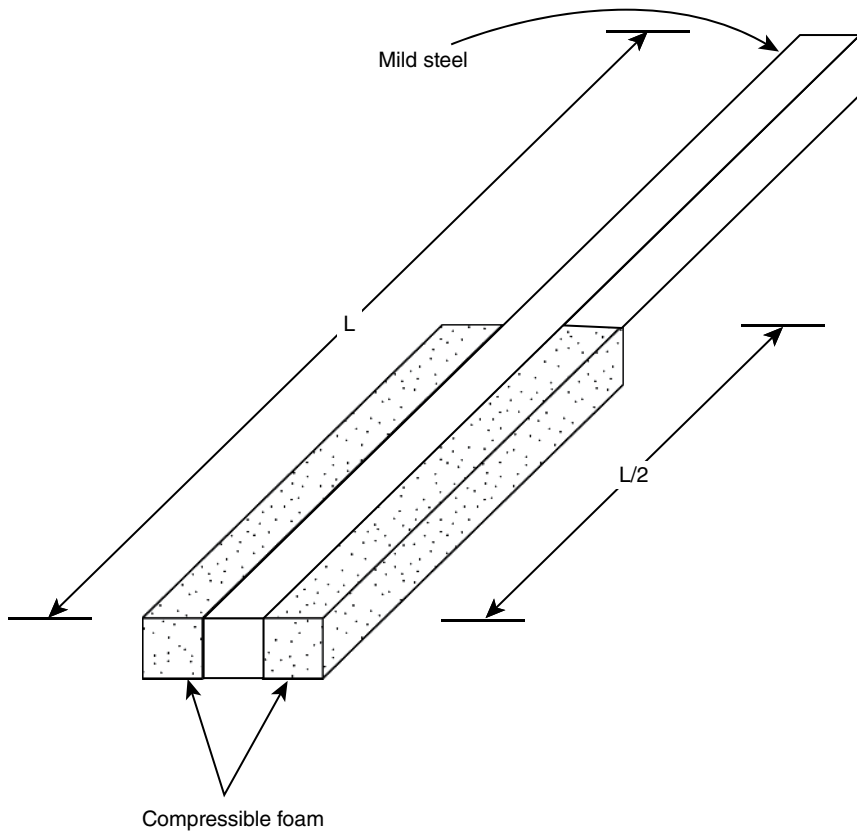


FIGURE 15.6 Square dowels with padded vertical faces allow differential movement parallel to the joint. This is useful when the two slabs being joined differ widely in age or design.

- Fill the joint as deeply as you can. You cannot always just pour filler into the joint, because in some cases it will flow right through into the ground. In those cases, you may have to put something (typically sand or a hard plastic rod) in the joint to stop leakage. But the deeper the filler goes, the better it will work.

AGGREGATE INTERLOCK

This occurs where the crack beneath an induced joint stays narrow enough so that individual particles of coarse aggregate can touch across the gap. The idea is that as one side of the joint is depressed under load, it cannot sink far before the irregular sides of the crack under the joint come into contact, transferring the load.

As I say, that is the idea. The reality is that aggregate interlock loses effectiveness dramatically as the crack beneath the joint widens, and becomes useless after the width reaches 1 mm (1/32 in) or so. ACI 302 warns us not to rely on aggregate interlock where the crack width exceeds 0.9 mm (0.035 in). That is not encouraging

advice for those who might hope to use this method as the sole method for load transfer. If an unreinforced floor has joints 4 m (13 ft) apart, and if the concrete shrinkage amounts to 500 microstrains, and if all joints activate, then we can expect a mean crack width of 2.0 mm (0.078 in)—over twice the width at which ACI 302 says aggregate interlock ceases to be reliable.

Unless the joint spacing is absurdly close—2 m (6 ft) or less—aggregate interlock is of dubious value in a floor that lacks steel at the induced joints. On the other hand, it plays an important and useful role in floors where through reinforcement or steel fibres keep joints tight.

It has been suggested, plausibly, that coarser and elongated aggregates enhance aggregate interlock.

Aggregate interlock applies only at induced joints and cracks. It does not exist at construction joints.

KEYWAYS

These are tongue-and-groove joints. Like aggregate interlock, keyways rely on concrete-to-concrete contact and lose effectiveness as the joint opens. Unlike aggregate interlock that applies only to induced joints (and cracks), keyways are installed in construction joints (Figure 15.7).

A specially shaped side form makes the key. Builders who use timber forms generally choose wood for the key former as well, nailing it on. Builders who prefer steel forms can find them with key formers already attached.

HYBRID CONSTRUCTION JOINTS

In America, many floors are now being laid with what have come to be called hybrid joints, consisting of alternating dowels and tie bars. Normally, both devices are installed on 600-mm (24-in) centres, so there is a steel device every 300 mm (12 in).

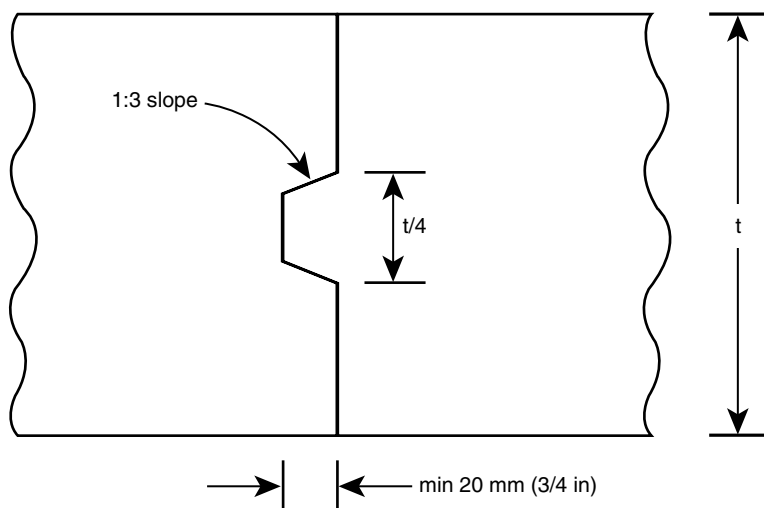


FIGURE 15.7 A keyway.

The hybrid joint was designed for floors that contain light continuous reinforcement for enhanced aggregate interlock, and it makes sense nowhere else.

The idea is that the construction joints of hybrid design will perform almost exactly like the induced joints in a floor that is reinforced for enhanced aggregate interlock. The dowels in the hybrid joints transfer load like the aggregate interlock in the induced joints. And the tie bars in the hybrid joints inhibit joint opening like the through reinforcement in the induced joints. It seems radical, but it works.

INDUCING JOINTS

Construction joints are made by casting concrete to edge forms that run the full slab depth. Other joints within a floor, whatever their function, are induced.

An induced joint is really a planned crack. The floor slab is notched or cut to create a weakened plane in hope that a crack will occur there rather than elsewhere. The notch can be made by wet forming or sawing. Wet-formed joints cost less, but sawn joints hold up better under traffic and are easier to fill.

WET FORMING

The choices here include hand tooling and plastic inserts.

Hand Tooling

With this traditional method, the floor layer uses a jointing tool to make a groove in the wet concrete. The tool leaves the joint's edges slightly rounded. Hand tooling makes a good-looking joint, but it is only practical for thin slabs because it goes, at most, 25 mm (1 in) deep. Most authorities say the joint depth should be at least one-fourth of the slab thickness, limiting hand-tooled joints to slabs not more than 100 mm (4 in) thick.

Because hand-tooled joints have rounded edges, they should not be used in areas of heavy traffic. At first thought, it might seem that rounded edges would hold up better than square ones, but the reverse is true. Under heavy traffic, any induced joint is likely to need filling, and it is hard to fill a joint that has rounded edges. The issue is usually moot, because most floors that get heavy traffic are too thick for hand tooling.

Plastic Inserts

These are strips of plastic that are pressed down into the wet concrete and left there. Many people call them Zip Strips, after the best-known brand. Some types include a top strip that is peeled away later to leave a groove for sealant.

Unlike hand tooling, plastic strips will work in thick slabs. Even so, they are seldom the best choice for floors that get heavy traffic. Sawing, described below, generally produces a more durable joint.

Inserts can be hard to install. If pushed in with too much force, they sometimes bend to the side, resulting in a wedge-shaped sliver of concrete that easily breaks up. It helps to run a trowel, with the blade held vertically, along the line of the joint. That clears away the coarse aggregate to leave a path for the insert.

SAWING

This costs more than wet forming but makes neater, more durable joints for industrial floors. Sawing is a good choice for floors that need to be flat, because it has almost no effect on surface regularity.

Joint-cutting saws fall into two categories: conventional and early-entry. Each type employs a circular blade driven by a small petrol engine or an electric motor.

Conventional saws have silicon-carbide or diamond blades and are normally used wet. Most models have a downcutting blade; that is, cutting takes place as the edge is travelling down into the slab.

Early-entry saws (Soff-Cut™ is the best-known brand) have diamond blades and are used dry. A flat plate slides along the floor surface to hold the concrete in place as the upcutting blade slices through. The bearing plate allows an early-entry saw to be used on soft, weak concrete.

Early-entry sawing grew in popularity throughout the 1990s, but it is not without its critics. Some people believe that very early sawing, made possible and encouraged by the introduction of the early-entry saw, leads to weakened joints that break down prematurely under industrial traffic. This is a question that cries out for research (Figure 15.8).

Decisions about sawing centre on two issues: depth and timing. The two are somewhat related.



FIGURE 15.8 Cutting joints with an early-entry saw. The saw cuts dry, so a vacuum tags along to collect dust.

Sawcut Depth

This is always a compromise. A deeper cut increases the likelihood that the slab will crack beneath it, activating the joint. On the other hand, a shallower cut costs less, goes faster, and leaves a thicker section below to provide aggregate interlock, possibly improving load transfer (Figure 15.9).

Traditional rules commonly called for sawing to one-fourth of the slab depth, with more conservative designers increasing that to one-third. Cutting to one-third is the norm in slabs that contain steel fibres.

Those rules have been relaxed in recent years with the introduction of the early-entry saw, which allows earlier sawing than is possible with conventional saws. The first version only cut to about 30 mm (1½ in) deep. The manufacturer claimed that was enough to force the desired crack, provided the sawing took place early enough. Today's versions go much deeper, but some designers still allow shallower joints if an early-entry saw is used.

Timing

When should you saw joints? As with sawcut depth, the answer always involves a compromise. Saw too early and you get a rough joint vulnerable to damage. Wait too long and the slab will have cracked. Some designers specify a time limit, but that can never replace careful observation and good judgement on the sawyer's part.

The general rule is that sawing should occur as soon as the concrete can stand it without ravelling. The exact timing depends on concrete mix and type of saw, and—most of all—on temperature. In hot weather, you can start sawing a few minutes after the last trowel pass. In very cool weather, you may have to wait till the next day, though that creates a risk that overnight cooling will cause thermal-contraction cracks.

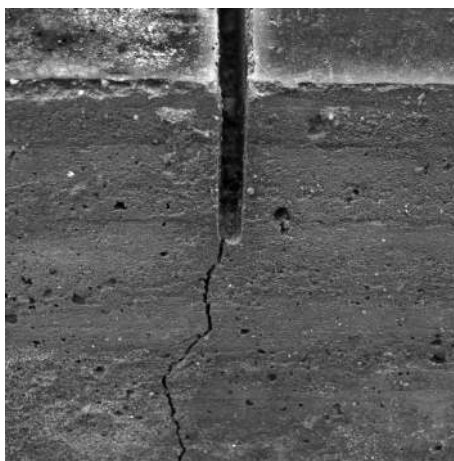


FIGURE 15.9 A sawn joint is said to have activated when a crack forms beneath it.

Early-entry saws, as their name implies, allow sawing to start earlier—though not as much earlier as you might suspect. In warm weather, there is not much difference in starting time between early-entry and conventional saws, but the spread widens in cool weather.

JOINT FILLERS

The term covers two quite different kinds of products:

- sheet fillers used in expansion and isolation joints;
- semirigid joint fillers.

SHEET FILLERS

These are solid, compressible materials used in expansion and isolation joints. A sheet filler has two functions. It defines the width of the joint and it keeps out debris. It is not meant to seal the joint against liquids.

Sheet fillers must be installed before the concrete is cast. They are almost impossible to install afterwards.

The most common type is called filler board, made of vegetable fibre bound with bitumen. Another type consists of bituminous mastic sandwiched between two layers of thin felt. A third type is made of closed-cell plastic foam, often coloured grey to match the concrete.

Sheet fillers must be easily compressed. Compressibility can be defined by the pressure needed to squeeze the material down to half its original thickness. According to American standards, vegetable-fibre (ASTM D 1751) and bitumen-sandwich (ASTM D 994) filler boards should measure between 0.7 and 5.2 MPa (100 and 750 psi). For plastic foam (ASTM D 1752), the limits are wider—0.3 and 10.4 MPa (50 and 1500 psi).

Those compressibility limits are probably good enough for expansion joints, where the effect of stiffer material is to increase compressive stress in the concrete, which can easily resist such stress. The story is different at certain isolation joints where stiffer material can increase tensile stress in the concrete, which may then crack. The solution is to make sure the compressibility lies near the soft end of the allowed range. Good results have been obtained with sheet fillers that require no more than 1 MPa (150 psi) to compress them by half.

Filler board comes in various thicknesses, normally chosen to match the specified joint width. For very wide joints, as found in post-tensioned floors, you may have to use multiple layers.

A common mistake is not to install filler board for the full depth of the slab. If the slab is designed to be 150 mm (6 in) thick, most builders will buy a filler board that is 150 mm (6 in) wide, or cut the board to that width. That seems right, but it presumes the slab will not exceed the specified thickness. But slab thickness varies. If our so-called 150-mm (6-in) slab happens to be 175 mm (7 in) thick where it abuts a building column—by no means a rare occurrence—then a 150-mm (6-in) strip of filler board will leave a substantial length of bare column sticking out, defeating the purpose of the isolation joint.

Sheet fillers keep debris out of joints, but beyond that they do not substitute for sealants. If an expansion or isolation joint needs to be sealed, the top of the filler should be cut away and the gap filled with a high-movement elastomeric sealant. Some joint fillers are scored to make this step easier.

SEMRIGID JOINT FILLERS

These help protect joints from damage caused by hard-tyred industrial vehicles. They start out liquid and are poured or injected with a caulking gun into the joint. They harden into a firm but slightly flexible solid—hence the term semirigid. After curing, they typically have a Shore A hardness of about 80–90.

Semirigids resemble joint sealants but differ from them in important ways. Semirigids protect the joint edges from mechanical damage; sealants keep liquids out of the joint. Semirigids are stiff; sealants are elastic.

Semirigids stick to concrete, but not tenaciously. One typical product has a reported tensile strength of 3.1 MPa (450 psi), but a bond strength to concrete of only 1.4 MPa (200 psi). This is deliberate, to ensure the filler does not glue the joint so tightly that the slab cracks elsewhere.

Semirigid fillers are made of epoxy or polyurea resins. Both each material has its supporters.

Epoxy has a longer history and is easier to install without special equipment. Polyurea cures faster and is less likely to change colour. Epoxies used to be consistently stiffer, but the recent introduction of high-modulus polyureas has erased that advantage.

Both products are dear, but you can minimize cost by filling only those joints that will be exposed to traffic. It is a waste to use any semirigid where it will be covered by racks or other fixed equipment.

The biggest drawback to semirigids is that they accommodate only very small joint movements. That is the price we pay for their strength and hardness. An ideal joint filler would be both strong and highly elastic, but that product does not exist. If you install a semirigid soon after laying a floor, the risk is high that some joints will reopen from continued drying shrinkage.

The imperfect solution to that problem is to wait as long as possible before filling joints. Some specifications require a 90-day delay, but that's arbitrary. You cannot wait too long, provided you fill the joints before they start to deteriorate from traffic.

Waiting only works where the joint movement is caused by drying shrinkage, which diminishes over time. If joints are subject to large cyclic movements—as in an unheated warehouse built where winters are cold—semirigids are not very effective.

Poor installation often keeps semirigids from living up to their potential. To be fully effective, these fillers need to go deep and be finished flush with the floor surface. At sawn joints, the filler should go all the way to the bottom of the kerf. At construction joints, it's good practice to chase the joint with a saw, cutting at least 25 mm (1 in) deep and creating a shelf for the filler to bear on. The most reliable way to ensure a flush joint is to overfill it, wait for the material to harden, and then sand or grind off the excess. That works better with epoxy than with polyurea, which doesn't take well to grinding. The alternative, not quite so reliable, is to overfill and shave off the excess with a blade while the material is still soft.

A dilemma occurs when a joint needs both a semirigid filler to protect against wheeled vehicles and a sealant to keep out liquids. This condition occurs often in food and pharmaceutical facilities. Semirigid fillers are too stiff to make good sealants, while sealants (described below) are too soft to protect joints from traffic. There is no practical way to use both products in the same joint, so we have to choose one and accept that it won't do the other's job.

One way around that dilemma is to get rid of the joints. Some wide-slab floor designs result in so few joints that it is economical to armour them all, eliminating any need for semirigid joint filler.

ARMoured JOINTS

Joint deterioration under traffic is a big problem in warehouses and factories. Semirigid joint fillers reduce the problem but do not eliminate it. An alternative is to gird the joint's edges with steel. Steel bars with shear studs are cast into the concrete on each side of the joint. The result is joint edges made not of concrete but of steel, which can better resist impact and wear from vehicles (Figures 15.10 and 15.11).

Armoured joints are available in both straight and wavy versions. Some versions include dowels or other load-transfer devices.

Armoured joints come into their own in extended-joint floors, where joints are few but open wide.



FIGURE 15.10 An armoured joint, ready for concrete to be poured.

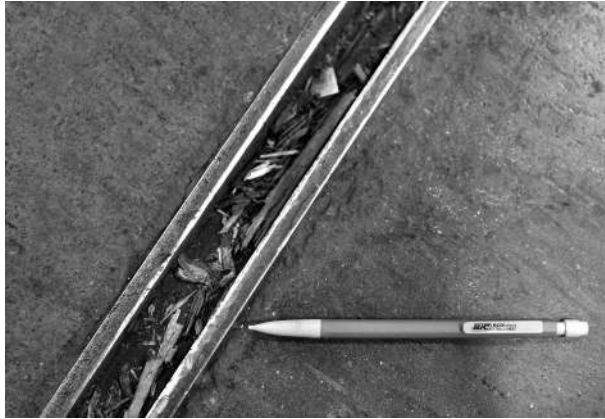


FIGURE 15.11 This armoured joint was still going strong after two decades of use in a busy grocery warehouse. The gap is 28 mm (1⅛ in) wide.

JOINT SEALANTS

People seal joints for these reasons:

- to protect floors from chemical attack;
- to keep debris out of joints;
- to make buildings easier to clean;
- to make floors look better.

Not every joint needs to be sealed. There is seldom any reason to seal joints in slabs that will get floor coverings. Even where the concrete slab forms the wearing surface, joint sealants are often unnecessary. On the other hand, some floor users—notably in the food and pharmaceutical industries—insist on the careful sealing of every joint.

Joint sealants come in two main categories: hot-poured and elastomeric.

HOT-POURED SEALANTS

A very old way to seal joints is to fill them with hot, molten bitumen or pitch. Hot-poured sealants are still in use, though cold-poured elastomers have replaced them for most applications. They are cheap but have these shortcomings.

- They cannot be applied in narrow joints.
- They do not last long, having a typical lifespan of 3 to 10 years.
- They accommodate only medium joint movement—up to about $\pm 12.5\%$ of the joint width.
- They are attacked by some common solvents.
- Coatings won't stick to them.

ELASTOMERIC SEALANTS

These find use in isolation, expansion, and contraction joints, where joints are expected to open and close. High-movement elastomers can accommodate movement greater than $\pm 12.5\%$. Medium-movement elastomers are designed to expand and contract by up to 12.5% . If there are any low-movement elastomers, no one says much about them.

Elastomers are often described as cold-poured. This just means they are installed at room temperature, in contrast to hot-poured sealants that are heated to make them flow. Some harden by chemical reaction, while others just dry out.

The category includes widely different chemical types, some of which come in two parts that are mixed just before application. Two-part sealants include polyurethanes, epoxies, and some polysulphides. One-part sealants include silicones, acrylics, and some polysulphides. Many come in both high-movement and medium-movement formulations.

INSTALLING JOINT SEALANTS

Different products require different techniques, and there is no substitute for reading the manufacturer's instructions. Nevertheless, a few general principles apply.

The joint should be clean. In some cases, cleaning is just a matter of scraping out debris or vacuuming out the joint. If the joint is very dirty, cleaning may require chasing with a concrete saw.

The joint must be wide enough. It is hard to install any sealant in a joint less than 3 mm ($\frac{1}{8}$ in) wide, and some materials need 6 mm ($\frac{1}{4}$ in). Some construction joints need to be sawn open—but if the joint is very tight, you might get away with not sealing it. Wider joints can accommodate more movement before the sealant fails.

The sealant should be installed to the right depth. In contrast to semirigid fillers, which go down at least 25 mm (1 in), most elastomeric sealants work best if their depth is about equal to their width. And some one-part elastomers have to be installed in thin layers or they won't cure properly.

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16 Crack Control in Ground-supported Floors

Concrete floors crack in many ways (see Chapter 13), but in ground-supported floors the most common are those caused by drying shrinkage and thermal contraction. In this chapter, the term *crack* refers only to that kind.

This chapter is about ground-supported floors. Suspended floors crack, too, but the structural codes dictate that those floors contain enough reinforcing or prestressing steel to keep cracks from becoming a serious problem. In contrast, many ground-supported floors are not covered by the codes and sometimes contain no steel at all.

Designers have three tools for controlling cracks: joints, reinforcement, and prestress. Joints create planned breaks in the floor, in contrast with the unplanned breaks which we call cracks. Reinforcement limits crack width. Prestress prevents cracks by putting the concrete into compression.

Each of those three tools can be used alone. In addition, the first two—joints and reinforcement—can be used together. Thus, we have four possible solutions:

- unreinforced floors with closely spaced joints;
- reinforced floors with few or no joints;
- reinforced floors with closely spaced joints;
- prestressed floors.

THE ‘LET IT CRACK’ OPTION

Well, there’s actually a fifth solution: no joints, no reinforcement. Not many floors are built that way, except some tiny ones. But it’s an option to consider, if only as a thought experiment.

Imagine two floor slabs laid side by side, both unreinforced and identical in every way except slab 1 has no joints, while slab 2 has closely spaced sawn joints in two directions. As time goes by and the concrete shrinks, slab 1 cracks. Slab 2 also cracks, but the cracks occur under the sawcuts as planned. Eventually new cracks stop forming because the shrinkage stresses have been reduced, and both slabs stabilize.

We now have two slabs that look different. Slab 1 is full of cracks and slab 2 is full of joints. Most people would prefer slab 2. But is it truly better in any fundamental way? Will slab 2 perform better or last longer? I submit that the answers to those questions are not obvious. And in at least three ways slab 1 has the edge. It costs less and its cracks are narrower than slab 2’s joints. And the number of cracks in slab 1 is almost certainly less than the number of joints in slab 2, because to control cracking with joints the distance between joints must be less than the expected distance between cracks.

I don't know where we go with this. The 'let it crack' option would be a hard sell. But even if no one actually takes it up, thinking about it may inform some decisions about crack control.

And now let's move on to the methods that are actually being used every day to control cracks in ground-supported floors.

UNREINFORCED FLOORS WITH CLOSELY SPACED JOINTS

These are cheap and easy to build—particularly if the usage does not demand load transfer or filling at the joints. Unreinforced floors have never been numerous in the UK, though they do exist there. They are far more popular in America, where the widespread use of laser screeding has encouraged the design of floors that need no reinforcing steel. Laser screeding does not require unreinforced floors, but it goes faster and costs less with no embedded steel in the way. Because so many American floors are unreinforced, the rest of this discussion will be based on American practice.

JOINT LAYOUT

Joints are normally laid out in a grid, crossing the floor in two perpendicular directions. Because there is no steel to control random cracks, joints are spaced closely to make such cracks unlikely.

But how close? That is one of the biggest questions in floor design. Everybody has an opinion, and the opinions vary widely. It seems unlikely that any definite answer will ever arise, because it depends on concrete shrinkage, site condition, and—perhaps most of all—on the floor user's tolerance for the odd random crack. The truth is that no joint spacing can totally guarantee a crack-free floor, and it comes down to probabilities. If we shorten the distance between joints, the probability of cracks goes down—always. But it never goes down to zero.

An old rule of thumb, still widely used, holds that the joint spacing measured in feet should not exceed two or three times the slab thickness measured in inches. To put it in terms that do not depend on feet and inches, the joint spacing should not exceed 24 to 36 times the slab thickness. For a 150-mm (6-in) slab, the safe maximum joint spacing would range from 3.6 to 5.4 m (12 to 18 ft). Spacings near the lower end would apply where shrinkage is not well controlled, or the designers just want to be conservative.

The current version of ACI 360 takes a more nuanced approach. Joint spacing is still based on slab thickness, but the relationship is no longer linear. And now there are three sets of recommendations for three levels of concrete shrinkage—low, typical, and high. If you don't know the concrete shrinkage, you are supposed to assume it is high. See Tables 16.1 and 16.2.

Joint spacing should be similar in both directions. Perfectly square panels aren't always possible, but the aspect ratio (length divided by width) should not exceed 1.5.

Many situations require closer joint spacing than the theoretical maximum. Any big slab penetration such as a building column acts as a crack inducer, even if isolated. In buildings with interior columns, joints should be located on all the column lines in both directions, and this requirement often controls the joint spacing, which

TABLE 16.1
ACI 360 Recommendations for Maximum Joint Spacing in Unreinforced Slabs, in SI Units

Slab Thickness, mm	Maximum Joint Spacing, m		
	Low Shrinkage	Typical Shrinkage	High Shrinkage
100	3.8	3.4	2.4
125	4.4	3.9	3.0
150	4.9	4.4	3.6
175	5.4	4.8	4.2
200	5.9	5.2	4.5

TABLE 16.2
ACI 360 Recommendations for Maximum Joint Spacing in Unreinforced Slabs, in US Customary Units

Slab Thickness, in	Maximum Joint Spacing, ft		
	Low Shrinkage	Typical Shrinkage	High Shrinkage
4	12	10	7
5	13	12	9
6	15	13	11
7	16	15	13
8	18	16	15

needs to be a fraction—typically 1/2, 1/3-, or 1/4—of the column spacing. Most designers do not add joints at minor penetrations such as drain cleanouts. But slabs sometimes crack there.

It’s usually wise to add joints at re-entrant corners, which are notorious crack inducers. Where extra joints don’t work, it’s usual to add a little reinforcement at those corners (Figure 16.1).

JOINT TYPES

The joints in an unreinforced floor can be either construction joints (formed joints) or induced joints (usually sawcuts). Most floors have a mix.

In chequerboard construction, rare these days, all joints are construction joints. In narrow-strip construction, all the joints running one way are construction joints, and all running the other way are induced. In wide-strip or large-bay construction, most joints in both directions are induced.

LOAD TRANSFER AT JOINTS

Some unreinforced floors—mainly those in warehouses and factories—need the ability to transfer load across joints.

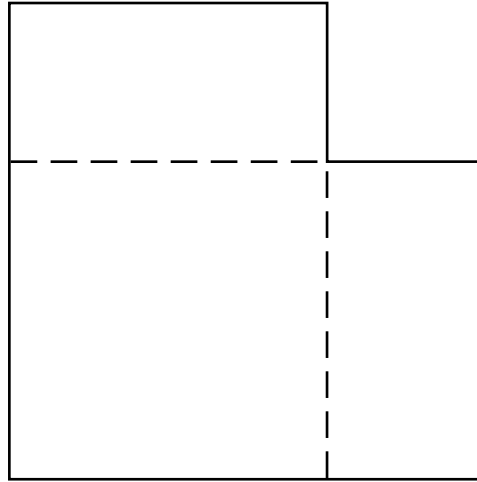


FIGURE 16.1 Cracks often form at re-entrant corners. You can control them with extra joints or reinforcement.

The construction joints pose no special problems. The usual devices for transferring load across construction joints work the same in unreinforced slabs as in other slab types. Round dowels, square dowels, plate dowels, and keyways have all been used.

Induced joints are different concern. Here you face the choice between relying solely on aggregate interlock and adding dowel baskets. Aggregate interlock comes free but is not very reliable. It works better where joint spacing is close, shrinkage is low, and aggregates are big, but it's never completely dependable. Dowel baskets perform more reliably but complicate the job. If the dowels get out of alignment they can lock up the joints, causing cracks between the joints. Even straight dowels probably increase the cracking risk a little. Some designers dowel the joints in traffic areas only.

BENEFITS AND DRAWBACKS

Unreinforced floors offer these benefits:

- lowest initial cost;
- easy access for concrete trucks and laser screeds;
- reduced risk of plastic-settlement cracks;
- no risk of steel interfering with wire-guided vehicles.

They also have drawbacks:

- Cracks, if they occur, can open wide.
- Joints are many, and this can increase maintenance costs.
- If dowel baskets are used for load transfer, construction gets more complicated and the risk of errors goes up.

In general, unreinforced floors make the most sense where traffic is light and dowel baskets aren't needed.

There is a strong prejudice in some quarters against unreinforced floors, but the evidence does not support that prejudice. Many successful floors have been built with no reinforcement whatever. Some failures have occurred, too, but that is true of every crack-control method. It is worth noting that unreinforced concrete slabs, usually with dowelled contraction joints, have been installed in thousands of miles of streets and roads all over the world.

REINFORCED FLOORS WITH FEW OR NO JOINTS (JOINTLESS FLOORS)

Though not common, these have an excellent record of success. They rely on substantial quantities of reinforcing steel to keep cracks narrow. These floors are also known as continuously reinforced concrete pavements (CRCPs), a term that comes from the highway field.

TWO-WAY AND ONE-WAY REINFORCEMENT

These floors can be heavily reinforced in one or two directions. If reinforced in two directions, they contain no joints except the usual isolation joints at columns and walls, and construction joints at the end of each day's pour.

If heavily reinforced in just one direction, they contain joints that run parallel to the reinforcement, dividing the floor into long, narrow strips. Such floors rely on different methods of crack control in the longitudinal and transverse directions. Longitudinally, each strip is designed as a reinforced jointless slab and contains a substantial amount of steel. Transversely, each strip is designed as an unreinforced jointed slab and has little or no transverse steel—typically just enough bars to support the heavy longitudinal steel (Figure 16.2).

HOW MUCH STEEL?

The reinforcement is usually stated as a percentage of the concrete's cross-sectional area, using Equation 16.1.

$$r = 100A_r / (td) \quad (16.1)$$

where

r = reinforcement, in %

A_r = cross-sectional area of reinforcing bar, in mm² or in²

t = slab thickness, in mm or in

d = bar spacing, centre to centre, in mm or in

The closest thing to a standard amount of steel for jointless construction is 0.5%, in one or two directions. Since that percentage is based on experience rather than calculations, I want to explain where it comes from.



FIGURE 16.2 One-way reinforcement in a narrow-strip superflat slab.

Long reinforced slabs with no transverse joints are common in roadbuilding, where a half century of experience has taught highway engineers how much steel they need. The Federal Highway Administration (1990) recommends at least 0.6%. The Federal Highway Administration suggests that ‘a lower percentage of steel may be acceptable; where experience has shown that [it] has performed satisfactorily’. A higher percentage, 0.7%, is recommended only in places with extreme winter cold (mean minimum monthly temperature below -12°C (10°F).)

It seems, then, that 0.6% reinforcement might be a reasonable specification for a jointless concrete floor. But what’s appropriate for a highway pavement may be more than a floor really needs. Floors are shorter than roads and are subject to less extreme temperature swings. With those mitigating factors in mind, some floor designers in the 1980s chose, somewhat arbitrarily, 0.5%. Since then many floors have been built with 0.5% reinforcement in one or both directions, and none has been known to fail in a way that suggested the amount of steel was not enough. That is the reason for the current use of 0.5% steel in jointless floors.

Some people have speculated that even less than 0.5% might suffice, especially for shorter slabs, but the research to support that remains undone.

Two-way jointless floors take 0.5% reinforcement in each direction. One-way jointless floors need the 0.5% in just one direction. They could be built with no reinforcement at all in the other direction, but typically have a few cross bars to support the longitudinal bars. Typical transverse reinforcement consists of 12-mm (1/2-in or #4) bars spaced 1.2 m (4 ft) on centre.

REINFORCEMENT DETAILS

The reinforcement usually consists of individual deformed bars. Wire mesh has also been used.

Bar spacing depends on bar size and slab thickness, but the Federal Highway Administration (1990) says it should never be less than 100 mm (4 in) or $2\frac{1}{2}$ times the biggest aggregate, or more than 225 mm (9 in). However, some floor designers break that rule at the upper limit. They specify bigger bars to allow a spacing of about 375 mm (15 in) or so, which creates a gap big enough for the workers to step through and stand on the sub-base.

Opinions vary on the ideal depth of reinforcement. In roadbuilding, steel is usually placed near mid-depth. The Federal Highway Administration (1990) recommends that the distance from floor surface to steel should be between $\frac{1}{3}$ and $\frac{1}{2}$ the slab thickness, but never less than 64 mm ($2\frac{1}{2}$ in). Some floor designers follow that recommendation, but more put the steel higher in the slab to reduce crack width at the floor surface. Interior floor slabs can use less cover (distance from surface to steel) than road pavements, because floors are not exposed to the weather. The typical design has reinforcing steel 50 mm (2 in) below the floor surface. In one-way floors, the longitudinal bars normally go on top of the less critical transverse ones.

Continuity matters. If the reinforcement is not effectively continuous for the full length of the floor, a huge crack can develop at the point of discontinuity. Bar ends should be lapped at least 25 bar diameters. The Federal Highway Administration (1990) recommends that the laps should be either staggered or skewed. In the staggered pattern, no more than a third of the bars can end in the same transverse plane, and groups of bar ends must be separated longitudinally by at least 1.2 m (4 ft). In the skewed pattern, the bar ends must lie along a line angled at least 30° from the transverse. Where welded mats replace individual bars, staggered or skewed laps become impractical. Effective laps are still possible, but require the utmost care. Failures have occurred where the laps were inadequate and also where adjacent mats were well lapped but separated vertically, allowing an uncontrolled crack to make its way through the gap between mats.

Even a so-called jointless floor contains construction joints unless it can be placed in a single pour. Some designers run the reinforcement through the construction joints. That keeps the joint tight but complicates the formwork. Others stop the reinforcement and use smooth dowels. That simplifies construction but can result in unusually wide joints that continue to open for a long time, much like the joint at the end of a post-tensioned slab.

SUBSLAB FRICTION

Reinforced jointless floors do not rely on low friction between concrete and sub-base. Some people believe high friction is good because it encourages a closer crack spacing, with correspondingly narrower cracks. These floors do not need slipsheets. However, if conditions call for a vapour barrier, there seem to be no fatal drawbacks to placing it directly under the slab, even if that results in a lower coefficient of friction.

BENEFITS AND DRAWBACKS

Reinforced floors without joints have much to offer, especially in heavily trafficked warehouses and factories. Here are the benefits:

- few or no joints to fill or seal;
- little curling;
- low maintenance costs;
- high load capacity, since almost all loading occurs in the internal position, away from slab edges and corners.

Drawbacks include these:

- widespread cracking, which some users object to even though reinforcement keeps the cracks tight;
- the cost of the reinforcing steel and the labour to install it;
- difficulty in placing concrete directly from ready-mix trucks;
- difficulty in using laser screeds.

To get around the last two drawbacks, involving ready-mix trucks and laser screeds, some floor layers leave the reinforcement on the ground till the last minute. They drive trucks and laser screeds over the steel. Then, just before the concrete hits the ground, they raise the reinforcement and support it on chairs. This can work well, but it requires careful supervision to make sure the steel ends up at the specified height.

STEEL FIBRES

Steel fibres can replace conventional reinforcement in a floor with few joints, but some details have to change. We can't look to the highway engineers for guidance this time, because steel fibres see little use in roadbuilding.

There is more than one approach to using steel fibres to eliminate joints. The usual design in America has these features:

- Joints are spaced up to 41 m (125 ft) apart.
- Slabs are placed over a slipsheet of smooth polyethylene.
- All joints are dowelled. Some may be armoured.

- Concrete shrinkage must not exceed 400 microstrains at 28 days.
- Reinforcement consists of Type II steel fibres, 25 mm (1 in) long with an effective diameter of 0.58 mm (0.023 in).
- The fibre dosage is 0.5% by volume.
- The structural design is based on an unreinforced slab, with the fibres relied on only for crack control.

Europeans have similar floors, but are more likely to use longer Type I steel fibres and base the design on residual strength. The longer fibres are less effective at preventing visible cracks, but better for residual strength.

REINFORCED FLOORS WITH CLOSELY SPACED JOINTS

These rely mainly on the joints to control cracks, but also include steel reinforcement. The reinforcement serves these purposes:

- to limit the width of any cracks that occur between the joints;
- to improve load transfer at any cracks that occur between the joints;
- to improve load transfer at joints (but only if it goes through the joints, and in some designs it does not).

Most floors nowadays fall in this category, but some of them might be more profitably designed along other lines. If a floor will get little or no traffic, why not take out the reinforcement and rely on joints alone? At the other extreme, if a floor must withstand heavy industrial traffic, why not take out the joints (the source of so many floor complaints) and rely on heavy reinforcement or steel fibres?

NOMINAL REINFORCEMENT

Some designers lay out joints in a pattern that would be suitable for an unreinforced floor, and then add very light reinforcement. This is nominal reinforcement—reinforcement in name only.

The steel usually takes the form of light wire mesh. Many American floors are made with 6 × 6, W1.4 × W1.4 mesh. In a slab 150 mm (6 in) thick, that amounts to only 0.03% steel in each direction. That seems unlikely to do much beyond reassuring those people—and they are many—who believe a concrete floor simply must contain some reinforcing steel.

LIGHT REINFORCEMENT FOR JOINT STABILITY

This is similar to nominal reinforcement, but with more steel. The joints are closely spaced. The reinforcement goes through the induced joints, usually stopping at construction joints.

The reinforcement is heavy enough to limit joint width, but light enough to allow hinging and a little opening as the steel stretches.

ACI 360 calls it reinforcement for enhanced aggregate interlock and currently recommends 0.10% steel, with a free contraction joint at intervals of 38 m (125 ft) or less. I understand the next version of ACI 360 will probably be to recommend slightly less reinforcement in slabs over 150 mm (6 in) thick and will eliminate the requirement for free contraction joints.

The reinforcement normally goes in the top half of the slab, about 50 mm (2 in) from the surface. It can take the form of either individual bars or wire mesh. Bars are easier to keep at the desired height, especially if the spacing lets workers step between the bars and stand on the ground.

This has become the dominant design for industrial floors in parts of America. A similar design is used in the United Kingdom, with similar reinforcement levels. But UK designers, following the Concrete Society's guidance (2016), put the reinforcement near the slab's bottom to increase load capacity (Figure 16.3).



FIGURE 16.3 Reinforcement for enhanced aggregate interlock, with 0.1% steel in two directions. The mat will be raised during the pour and supported on plastic chairs.

REINFORCEMENT TO ALLOW GREATER JOINT SPACING

A common use of reinforcement is to allow a wider joint spacing than would be safe in an unreinforced floor. The joint spacings are typically 6–8 m (20–25 ft), but may range up to 12 m (40 ft). What you need to remember here is that the reinforcement does not prevent cracks. Its job is to limit the width of cracks after they have occurred. If you choose this method of crack control, you accept the likelihood of visible cracks.

Some designers use the Equation 16.2, the drag factor formula, to determine how much reinforcing steel to use when extending joint spacing:

In SI units:

$$Q_s = (1.57FL)/f_y \quad (16.2)$$

where

Q_s = required steel as a percentage of the slab's cross-sectional area

F = coefficient of friction between slab and base

L = slab length (m)

f_y = characteristic strength of steel (MPa)

In US customary units:

$$Q_s = (69.5FL)/f_y$$

where

Q_s = required steel as a percentage of the slab's cross-sectional area

F = coefficient of friction between slab and base

L = slab length (ft)

f_y = characteristic strength of steel (psi)

The coefficient of friction, F , is often assumed to be 1.5. But the real value varies (see Table 16.3). Putting a polyethylene slipsheet under the slab can reduce the coefficient to 0.5.

TABLE 16.3
Subslab Friction (Post-Tensioning Institute, 1980)

Material Directly Under Slab	Coefficient of Friction
Polyethylene sheet	0.5 to 0.9
Sand	0.7 to 1.0
Granular sub-base	0.9 to 1.7
Plastic soil	1.3 to 2.1

The length of slab, L , is either the total length of the floor or the distance between free contraction joints, whichever is less. Unless the floor is square, you need to look at L in both the longitudinal and transverse directions.

Continuity of Reinforcement

Reinforcement can continue through the joints, or not. If it goes through, then the joints become tied. They still act as hinges to relieve curling stresses, but they do little to relieve straight shrinkage stresses unless the steel yields. When figuring the slab length (L) for the drag factor formula, you ignore the tied joints and measure all the way to the slab end or the first joint that is not tied. Running the reinforcement through the joints improves joint stability and reduces joint maintenance, but increases the number of cracks between the joints.

If reinforcement stops at the joints, then they become free contraction joints. They may need dowels for load transfer, depending on loads and traffic patterns. Stopping the reinforcement at the joints reduces the risk of cracks, but increases the likelihood of joint problems.

PRESTRESSED FLOORS

Prestress puts the concrete slab in compression before drying shrinkage and thermal contraction can create the tensile stresses that cause cracks. If the compressive prestress equals or exceeds the tensile stress induced later, the floor does not crack. Actually, the prestress could even be slightly less than the tensile stress, since concrete has some ability to withstand tension before cracking.

Two very different prestressing methods are widely used in floors: shrinkage-compensating concrete and post-tensioning with steel tendons. Pre-tensioning with steel tendons—the usual method for prestressing precast elements, and the process that normally comes to mind when someone mentions prestressed concrete—is rare if ever used for ground-supported floors.

SHRINKAGE-COMPENSATING CONCRETE

This is made with an expansive admixture. It can also be made with expansive cement, but that material has become scarce. The concrete expands slightly soon after setting. After that early expansion, it undergoes drying shrinkage at a normal rate.

If you restrain the expansion, it creates compressive stresses within the floor to offset the tensile stresses that come later. The usual way to provide that restraint is with reinforcing steel, though subslab friction plays a contributing role.

Shrinkage-compensating concrete is rare in the UK, and British standards say almost nothing about it. It is more common in America, so we need to look to American standards. ACI 223 provides general guidelines for the design and use of the material. ASTM C845 specifies expansive cement while ASTM C157 and ASTM C878 describe standard tests for measuring the expansion of concrete specimens.

The key to success is to make sure the expansion exceeds the shrinkage. Floorlayers who specialize in this field normally test a trial batch for expansion. That is an important step because the amount of expansion depends not only on the expansive cement

but also on the properties of the other components, which vary from job to job. If a mix shows unusually high drying shrinkage, the normal amount of expansive cement may not suffice to prevent cracks.

The standard rules call for shrinkage-compensating concrete to be laid out in slabs that are square, or nearly square. Each slab, which can be as big as 50×50 m (150×150 ft) is placed by the large-bay method and contains no joints, except isolation joints at building columns and other penetrations. A few engineers have questioned the requirement for square slabs. If they are right, it would open the possibility of narrow-strip floors, including superflat floors, made of shrinkage-compensating concrete. But for now square panels remain the norm.

Because the prestress from expansive cement is small, most designers count it as contributing to the floor's load capacity.

The main drawback to shrinkage-compensating concrete is its price. If expansive cement cost the same as ordinary Portland cement, it might have become the standard material. But expansive cement always costs more.

Shrinkage-compensating concrete finds its greatest use in busy warehouses, particularly in the grocery trade. The typical owner choosing shrinkage-compensating concrete has concluded that the reduced joint maintenance, which last for the life of the warehouse, is worth the initial cost.

POST-TENSIONING

With this method, the prestress comes from steel cables called tendons. The *post* in post-tensioning means the tendons are stretched after the concrete has set.

Post-tensioning makes possible the construction of very big slabs with no joints and few or no cracks. The longest practical dimension is about 130 m (400 ft). Unlike slabs made of shrinkage-compensating concrete, post-tensioned slabs are not strictly limited as to shape. They can be long and narrow, or L-shaped, with no compromise in performance.

Bonded and Unbonded Tendons

Tendons can be bonded (also called grouted) or unbonded. In bonded construction, you install each tendon within a rigid tube. After the tendon has been fully stretched, you pump grout into the tube, locking the tendon in place along its whole length. In unbonded construction, each tendon comes greased and encased in a plastic sheath. The tendon sticks out beyond the sheath at each end so it can be stretched and anchored. An unbonded tendon applies stress to the concrete only through the anchors at each end, like a giant clamp.

Bonded construction offers flexibility in floor usage, since the tendons can be cut later, should the need arise, without harm. Unbonded construction costs less and resists corrosion better. Regional preferences vary, with bonded construction normal in Australia and parts of Asia, while unbonded construction rules the day in America.

Tendon Details

In ground-supported floors, tendons normally run straight and lie near the slab's mid-depth. This differs from normal suspended-floor practice in which tendons are

draped—curved in the vertical plane—to resist bending moments. Tendons can run in one direction or two. If they run in one direction only, the floor needs another method—usually closely spaced joints—to control cracks in the other direction. One-way post-tensioning is used in racked warehouses where the traffic aisles all run the same way.

The typical tendon consists of seven steel wires—one down the centre, and six more spiralling around it. The steel is much stronger than that used for ordinary reinforcement; in America the standard product is Grade 270 steel, with characteristic strength of 1830 MPa (270 000 psi).

Post-tensioning steel costs more than reinforcing steel, but you need less of it.

At each end the tendon passes through a steel anchor. One type, called a barrel anchor, mounts outside the slab and is installed after the edge form has been stripped. The more common internal type mounts just inside the slab's edge and is nailed to the edge form. Wedges connect the tendon to the anchor, preventing movement toward the centre of the slab, but allowing movement in the other direction so the tendon can be stretched. Most designs include backer bars—two 12-mm (#4) deformed bars lying parallel to the tendons and close to the anchors.

Stretching the Tendons

Stress is applied with a hydraulic jack, which both stretches the tendon and sets the wedges. A gauge shows the applied force, so the operator can stop when the specified value has been reached. It's good practice to calculate the expected elongation and measure it during the stressing. If the measured elongation differs much from the prediction, it can be a sign of gauge error, or tendon slippage at the far end, or the tendon's hanging up between the anchors.

Slabs less than 15 m (50 ft) long are usually stressed in one operation after the concrete has reached about 25 MPa (3000 psi) compressive strength. But one-step stressing doesn't work so well on longer slabs, which are likely to crack before stress is applied. Two-step stressing prevents most of those early cracks. The first step is to apply one third of the ultimate stress as soon as the concrete's compressive strength reaches 10 MPa (1200 psi), determined by testing site-cured concrete cubes or cylinders. The second step is to apply full stress when the concrete strength reaches 25 MPa (3000 psi). Once in a while a crack occurs before even partial stress can be applied. If this happens, sealing the crack with sticky tape will help keep out debris and, with luck, let it close up later.

Under most conditions, the early stressing takes place the day after the pour. But in hot weather it may need to occur on the same day. The people testing the concrete strength, as well as the people doing the stressing, need to be ready whenever the concrete strength is expected to reach 10 MPa (1200 psi), even if that happens at night or on the weekend.

Shorter tendons can be stretched from one end; longer tendons should be stretched from both ends. One-end stressing not only saves time but also allows the slab to be poured right up against a wall or adjoining slab, without a gap. Aalami and Jurgens (2003) recommend two-end stressing where the length exceeds 36 m (120 ft), but they are writing about suspended floors with draped tendons. Since ground-supported floors have straight tendons, friction losses are lower and it is probably reasonable to stress from one end at much greater lengths.

Calculating the Prestress

Because post-tensioning applies force at the slab edges, the prestress is always higher there. It gradually diminishes with distance from the anchors, reaching its minimum at the slab's mid-length. Designers proportion the tendons (size and spacing) to provide a certain residual prestress at the mid-length, after allowance for friction losses. Where the post-tensioning serves only to control cracks, the minimum prestress ranges from 350 kPa (50 psi) to 1.0 MPa (150 psi). The Post-Tensioning Institute (1980) suggests 350 kPa (50 psi), but that leaves little room for error.

Prestress above 1.0 MPa (150 psi) is specified where the goal is an increase in the floor's load-bearing capacity. If you design a floor for mid-length prestress of say 2.0 MPa (290 psi), that is effectively the same raising the concrete's flexural strength by that amount. You can take advantage of that to reduce slab thickness or use lower-strength concrete, compared to a non-post-tensioned slab. In warehouse construction, post-tensioning can often save 50 or 75 mm (2 or 3 in) on slab thickness. Sometimes this pays for the post-tensioning, providing excellent crack control at no net cost. But the savings are not available on lightly loaded floors, which are usually designed to minimum thickness requirements anyway and cannot be made thinner.

Equation 16.3 determines the tendon spacing:

$$S = P / \left[(C_{mid} A_{slab}) + (W_{slab} 0.5 LF) \right] \quad (16.3)$$

where

S = tendon spacing in m (or ft)

P = design tensile stress on each tendon in N (or lb)

C_{mid} = desired mid-length compressive stress in MPa (or psi)

A_{slab} = cross-sectional area of slab per 1 m (or ft) in mm² (or in²)

W_{slab} = weight of slab per m² (or ft²) in N (or lb)

L = slab length between anchors in m (or ft)

F = coefficient of friction between slab and ground

Workmanship

More than any other method of crack control, post-tensioning requires careful workmanship. Success depends on attention to three details: isolation joints, sub-base preparation, and concrete compaction.

A post-tensioned floor must be well isolated from other building elements, so it can shrink freely. Isolation joints must be wider than usual because slab movement is large, especially near the edges. A big post-tensioned slab can shrink by 30 mm (over 1 in) at each end, and the isolation joints must be capable of accommodating that. It's good practice to isolate the slab with soft foamed plastic at least twice as thick as the predicted movement.

The sub-base should be smooth and even to reduce friction. It is particularly important to eliminate any sharp steps or ruts, because they can pin the slab and keep it from sliding.

Last, concrete must be well compacted around the anchors. Compaction matters in every concrete floor, but post-tensioning raises the stakes since poor compaction can result in a highly stressed anchorage breaking out.

Benefits and Drawbacks

Post-tensioned floors offer these benefits:

- very good crack control, with most slabs remaining free of visible cracks;
- increased load-bearing capacity (depending on the amount of prestress);
- few restrictions on slab shape or size.

They also have drawbacks that limit their use:

- lack of flexibility in floor usage, especially with unbonded tendons;
- need for gaps at slab ends, to leave access for the stressing jack;
- very wide joints where the post-tensioned slab ends, since all the concrete's shrinkage is concentrated there.

SUBSLAB FRICTION

An important factor in crack control is the friction between the concrete slab and the layer right below it. Reinforced floors without joints do not depend on low friction and may even perform better if the friction is high. But with that exception, low friction is desirable and offers these benefits:

- Unreinforced floors are less likely to develop random cracks.
- Reinforced floors with joints may need less reinforcement.
- Post-tensioned floors need fewer tendons.

Table 16.3 shows friction coefficients for materials often used under slabs. A polyethylene slipsheet provides the lowest friction.

To reduce friction further, some designers call for two layers of polyethylene, sometimes with water between them. Such double slipsheets are common under post-tensioned floors, where it is usual to assume a friction coefficient of 0.4 when they are used.

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17 Crack Control in Suspended Floors

Crack control is simpler on suspended floors than on ground-supported floors. The designer of a ground-supported floor has a bewildering range of tools for controlling cracks: joints, reinforcement, post-tensioning, shrinkage-compensating concrete, shrinkage-reducing admixtures, and more. In contrast, the designer of a suspended slab has two options: prestress and conventional steel reinforcement, with a third option of steel fibres in a few cases.

Throughout this chapter, I use the word *crack* for breaks that occur in the hardened concrete from loading, drying shrinkage, thermal contraction, or any combination of those three. Excluded are breaks that occur before the concrete has set or just as it is setting: plastic-shrinkage cracks, plastic-settlement cracks, and crazing. It's not that those early cracks don't matter. It's that they are largely independent of the floor design. For ways to deal with early cracks, see Chapter 13.

PRESTRESSED FLOORS

Most suspended floors are supposed to crack. They are made of reinforced concrete, and reinforced concrete is designed to crack under load. If it never cracked, it wouldn't need reinforcement.

Prestressed floors, a category that includes both precast units that are pre-tensioned and cast-in-place slabs that are post-tensioned, are the exceptions to that rule. Unlike reinforcement, which works only after the concrete has cracked, prestress prevents cracks by keeping the concrete in compression. A prestressed floor should not crack.

This is not to say prestressed floors never crack, or that every crack that occurring in them is a serious defect. Post-tensioned floors sometimes crack before the first tensioning, and that's usually not a problem if the crack closes up when the tensioning finally happens. But cracks in prestressed floors should be few.

FLOORS WITH CONVENTIONAL STEEL REINFORCEMENT

These will crack. The reinforcement is there not to prevent cracks but to limit their width. And that leads to two key questions: What is the maximum width we should strive for, and how much reinforcement does it take? Those questions have proven stubbornly hard to answer.

If there is anything like a standard target crack width, worldwide, it would be 0.30 mm (0.012 in). It appears in the Eurocodes and many other places. ACI 224, *Control of cracking in concrete structures*, goes into more detail, recommending the crack widths shown in Table 17.1 for 'reinforced concrete under service loads'.

TABLE 17.1
Recommendations for ‘Reasonable Crack Widths,
in Reinforced Slabs Under Service Loads’

Exposure	Crack Width
Dry air or protective membrane	0.41 mm (0.016 in)
Humidity, moist air, soil	0.30 mm (0.012 in)
Deicing chemicals	0.18 mm (0.007 in)

Source: Adapted from ACI 224.

Most suspended floors fall in the first category, with a crack-width target of 0.41 mm (0.016 in). Slabs in parking structures could fall in the last category, depending on what part of the world they are in, with a target of 0.18 mm (0.007 in).

It all seems clear and helpful, but a footnote in ACI 224 calls into question: ‘It should be expected that a portion of the cracks in the structure will exceed those values. With time, a significant portion can exceed those values’. What portion, and by how much? ACI 224 doesn’t say.

And once you have met the challenge of specifying a target crack width, you face another question: how far beyond the target width does a crack have to get before you raise the alarm? *Concrete Construction* magazine tried to answer that question in 2001 by interviewing Edward Nawy and Randall Poston (*Concrete Construction* staff, 2001). The questions centred on Table 4.1 in ACI 224, which is the source of the numbers in my Table 17.1. Nawy wrote the technical paper behind Table 4.1 and chaired the ACI 224 committee in the 1970s. Poston chaired the committee from 1991 to 1997.

I encourage you to read the whole story but will quote a few excerpts. Nawy said ‘an average of crack-width measurements that exceeds a value in the table by, say, 100% is, in all likelihood, unacceptable under any circumstance’. Poston said ‘I’ve found in practice that if a few cracks have average widths exceeding the limits in the table by less than 50%, structural implications are unlikely....’

In my experience, most structural engineers on most jobs pay little attention to all that. They specify reinforcement that meets the structural code and assume it’s good enough to control crack width.

So far, this discussion has been about structural cracks—cracks that result from bending under applied loads. When we turn to nonstructural cracks caused by drying shrinkage and thermal contraction, the situation gets even worse. Here is ACI 224 again:

The minimum amount and spacing of reinforcement to be used in structural floors, roof slabs, and walls for control of temperature and shrinkage cracking is given in ACI 318 or in ACI 350R. The minimum-reinforcement percentage, which is between 0.18 and 0.20%, does not normally control cracks to within generally acceptable design limits. To control cracks to a more acceptable level, the percentage requirement needs to exceed about 0.60%.

I find that statement astonishing. An ACI technical committee, populated by some of the brightest lights in our industry, is telling us we need 0.60% reinforcing steel, if not more, to control nonstructural cracks.

In the end, most structural engineers deal with nonstructural cracks and structural cracks the same way. They follow the structural codes and hope for the best.

COMPOSITE FLOORS

These consist of a concrete slab poured on, and working compositely with, a corrugated steel deck. They have a reputation for wide cracks.

In a composite floor, structural cracks can form on the top or the bottom. Cracks on the bottom don't matter, because the steel deck controls them and they cannot be seen. Cracks on the top occur over beams and girders and can get very wide, because engineers aren't required to provide reinforcement there unless the floor is designed with continuous spans or is cantilevered. To limit crack width in a composite floor, the first step is to provide negative reinforcement over the beams and girders, even if it is not needed for structural strength.

But structural cracking over the supports is only part of the problem. Nonstructural cracks from drying shrinkage and thermal contraction are hard to control because the steel deck provides so much restraint. Reinforcement levels that might be adequate in a flat-plate floor or a ground-supported slab can result in wide cracks if used in a composite floor.

In America, the Steel Deck Institute (2012) recommends any of the following for control of nonstructural cracks:

- wire mesh or rebar providing steel equal to $59 \text{ mm}^2/\text{m}$ ($0.028 \text{ in}^2/\text{ft}$) in two perpendicular directions, where the concrete thickness is less than 79 mm (3.1 in);
- wire mesh or rebar providing steel equal to 0.075% of the slab's cross-sectional area (above the flutes) in two perpendicular directions, where the slab thickness is 79 mm (3.1 in) or more;
- steel fibres at $14.8 \text{ kg}/\text{m}^3$ ($25 \text{ lb}/\text{yd}^3$), regardless of slab thickness;
- polypropylene fibres at $2.4 \text{ kg}/\text{m}^3$ ($4 \text{ lb}/\text{yd}^3$), regardless of slab thickness.

If you follow those rules, you can say you went by the book. But don't expect much in the way of crack control.

UK recommendations are somewhat more conservative, at least where conventional reinforcing steel is concerned. Rackham et al. (2009, 30, 35) recommend at least A142 wire mesh, adding that 0.30% steel may be needed where the slab surface will be left exposed or covered with a rigid topping such as terrazzo. But the UK rules get fuzzy where steel or polypropylene fibres are used, saying, in effect, just ask the fibre manufacturers what to do and follow their instructions.

Recent experience with composite floors that support robots with strict crack-width requirements suggests that none of the standard rules are good enough when you want to keep all cracks at hairline width. Some of those floors have been built with as much as 0.55% steel in the form of wire mesh, along with

a hefty dose of polypropylene fibres. They were successful, but that's hardly a model we can follow on composite floors for everyday use.

A few people like to saw joints in composite slabs for crack control, much as they would in a ground-supported floor. They put joints over the beams and girders, and sometimes in between. Rackham et al. (2009, 35-36) suggest this practice, but they are less than enthusiastic about it and say reinforcement is more reliable. Ryan (1994) argues strongly against sawing joints in composite slabs.

For many composite floors, perhaps most, this whole discussion is moot. They will be hidden under floor coverings, and almost any crack width is acceptable. For composite floors that will be exposed to view, be aware that the standard recommendation may result in crack widths that users will not like.

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Part 5

The Floor Surface



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18 Floor Finishing

One big difference between floors and other building elements made of concrete is that floors are finished. With walls and columns, the surfaces exposed to view are cast against forms. A floor also has forms, but its all-important top surface is unformed. Finishing is the process of making that unformed top into a usable floor surface.

Floor finishing is much more than a simple smoothing process. Though little appreciated, it is one of the hardest, most highly skilled jobs in the building trades.

This chapter covers:

- principles of finishing;
- tools;
- sequence of finishing steps;
- types of finishes;
- other finishing methods;
- how to specify finishes.

PRINCIPLES OF FINISHING

Ordinary concrete finishing consists of three basic steps: striking off, floating, and trowelling.

Striking off, also called screeding, is the process of levelling the fresh concrete. It takes place right after the placing and compacting operations described in Chapter 10. Accuracy in strike-off is the key factor in making floors level.

Floating is the process of working the concrete with wide-bladed tools held flat against the floor surface. It serves these three purposes:

- It depresses the coarse aggregate to leave a surface mortar of cement, fine aggregate and water.
- It smooths the small ridges and holes left after striking off.
- It compacts the surface mortar.

On some floors the finishing ends there. This leaves a rough surface called a float finish, with the texture of coarse sandpaper.

Trowelling further smooths and compacts the surface mortar, using steel blades (and some made of plastic) held at an angle to the floor surface. Early trowellings are done with blades held almost flat. Later trowellings are done with blades at progressively steeper angles, increasing pressure on the concrete.

TOOLS

Catalogues show dozens of tools for finishing concrete floors. To an extent the choices are arbitrary and personal. One floorlayer likes a wooden hand float; another swears by magnesium. Nevertheless, there are a few basic types that most floorlayers use. We can divide tools into these groups:

- tools for striking off;
- floats;
- trowels;
- other tools.

TOOLS FOR STRIKING OFF

These include hand straightedges, highway straightedges, vibrating screeds, roller screeds, and laser screeds.

Hand Straightedge

Also called saw rod or saw beam, the hand straightedge is the most basic tool in floor construction. It was undoubtedly used on the earliest concrete floors, and yet it plays a key role in modern superflat construction. It is nothing more than a straight (some straighter than others) beam, usually rectangular in section. Typical dimensions are 25–50 mm (1–2 in) wide, 90–150 mm (3½–6 in) deep, and up to 6 m (20 ft) long. Some straightedges have short handles at each end; most of them don't.

Timber beams are common, but extruded metal tubing is straighter and lasts longer. There is a minor controversy over the use of aluminium versus magnesium straightedges. Both metals are light and lend themselves to being extruded into precise shapes, but aluminium particles can cause a damaging reaction in fresh concrete, raising blisters on the floor surface. It's far from certain, however, that enough aluminium ever rubs off a straightedge to cause this reaction. I've never seen it (Figure 18.1).

Hand straightedges are common in narrow-strip construction, where they easily span the pour and rest on the side forms. They are also used for wet screeding on large-bay pours.

Highway Straightedge

This is a special form of hand straightedge with a long handle attached to its mid-point. The name comes from its origin in road paving. Highway straightedges make floors flatter.

Blade lengths range from 3 to 5 m (10 to 16 ft). Blade cross-sections range from 40 by 40 mm (by 1½ by 1½) to 50 by 125 mm (2 by 5 in). The thinner highway straightedges are sometimes called check rods, because they serve to check a floor's flatness but cannot move much material. Heavier straightedges are sometimes called bump cutters or scraping straightedges (Figure 18.2).

The connection between handle and blade is adjustable. With the better models, you can adjust the blade's angle by twisting the handle.



FIGURE 18.1 Striking off with a hand straightedge.



FIGURE 18.2 A lightweight highway straightedge, also called a check rod, on a large-bay pour.

The highway straightedge strikes off at right angles to the primary strike-off. Some floorlayers also use it on the diagonal. An essential tool in narrow-strip super-flat work is also used on wide laser-screeded pours to smooth out the seams between adjacent passes of the laser screed's auger.

Vibrating Screed

This strikes off the concrete and also provides compaction. The main types are wet-screed, single-beam, double-beam, and truss.

A wet-screed vibrator is a long metal plate with a vibrator and handle attached. Some models have two handles. It's mainly used on wide-bay pours as an alternative to laser screeding, but it's also used in narrow-strip construction, riding on the side forms (Figure 18.3).

A single-beam screed is just a beam—timber or metal tubing—with a vibrator bolted on. The beam is typically 50 by 150 mm (2 by 6 in) in section. A double-beam screed is similar but includes two beams, one in front of the other. Single-beam and double-beam screeds are limited in length to about 6 m (20 ft). Vibration comes from an electric motor or small internal-combustion engine. Both types are usually pulled along by hand.

A truss screed is made of steel and looks like a scale model of a truss bridge. It comes in sections that can be bolted together for different lengths. Some truss screeds span as far as 25 m (80 ft) and can be adjusted for camber. However, spans of 5 to 12 m (16 to 40 ft) are more common. Power comes from an internal-combustion engine or, less often, compressed air. Vibration is applied at several points along the screed's length. Winches—either hand-cranked or powered by the engine—pull the screed along (Figure 18.4).



FIGURE 18.3 A wet-screed vibrator, used here on a narrow-strip pour.



FIGURE 18.4 A truss screed.

All vibrating screeds are used in much the same way. They rest on the side forms, or on intermediate screed rails, or—in the case of wet screeds—on the soft concrete. They are pulled over the concrete, levelling it and compacting it. It's important to get the speed right. If the screed goes too fast, it leaves high and low spots. If it goes too slow, it may overvibrate the concrete.

Roller Screed

This is a steel tube that spins at high speed, rotating against the direction of travel. It is pulled along the tops of the side forms. Roller screeds come in lengths up to about 9 m (30 ft), making them suitable for narrow-strip pours and some wide strips. A drawback is the fixed length. To make pours of different widths, you need more than one roller.

Roller screeds work on very stiff mixes, making them a good choice for steeply sloped floors. Such floors are not common, however.

Unlike vibrating screeds and laser screeds, roller screeds do not vibrate. If you strike off with a roller screed, you need another tool, probably a poker vibrator, to compact the concrete.

Laser Screed

This levels the concrete with a vibrating auger that is adjusted automatically relative to a laser beam. In large-bay construction, the laser screed controls levelness far better than any other strike-off tool (Figure 18.5).

Since its introduction in the 1980s, the laser screed has transformed the laying of big industrial floors. Floorlayers with laser screeds achieve rates of production and



FIGURE 18.5 A laser screed on a large-bay pour.

standards of flatness and levelness that would have seemed incredible forty years ago. With laser screeding, it is now business as usual to lay 3000 m^2 ($30\,000 \text{ ft}^2$) a day and to achieve overall F-numbers of $F_F 55/5F_L 305$.

Because the laser screed does not rest on the side forms, it can be used on slabs of almost any width. Quality suffers on the widest pours, however, because of the amount of time it takes to work the screed all the way across. For good flatness in hot-weather pours, it is wise to limit pour width to about 35 m (110 ft). In cool weather, wider pours are safe.

Despite its powerful advantages, the laser screed faces some limitations. It works best on ground-level floors. The standard laser screed is too heavy for most suspended slabs, and the lighter, smaller laser screeds developed for upstairs work are both less productive and less precise.

Another limitation is the difficulty in working the laser screed around reinforcing bars and post-tensioning tendons. If the bars or tendons are chaired up before the pour, there is no place for the laser screed to stand. The usual solution is to leave the

steel on the ground till the last possible minute, but that complicates the pour and creates a risk that the bars or tendons may not end up in the right position. Another solution is to support the screed on a moveable bridge. Laser-screed operators often prefer pours with nothing in the way; this is a key but not always a recognized factor in the current popularity of unreinforced and steel-fibre-reinforced slabs.

A third limitation is the screed's inability to level a floor all the way to the edge. With every other method of striking off, when you get to the slab's edge your tool rides on the side form. A laser screed cannot do that because its spinning auger would grind against the form. Laser screeding normally stops about 0.5 m (1–2 ft) from the edge, leaving a narrow strip to be worked by hand. The result can be a floor that is very level over most of its area (where the laser screed did its job), but with severe slopes or bumps at the construction joints.

FLOATS

A float has a flat surface that is held parallel to the floor surface. Edges are rounded so they do not dig in. Floats can be divided into two groups according to when they are used. The first group consists of bull floats and darbies that are used right after striking off, before bleed water appears. The second group includes hand floats and power floats used later, after all bleed water has disappeared.

The bull float, also called skip float, is a wide tool with a long handle. The typical model is about 200 mm (8 in) wide and 1–1.5 m (3–5 ft) long. Nowadays most are made of aluminium or magnesium, but some floorlayers prefer the traditional wood. The handle consists of tubular sections that snap or screw together. By adding sections you can make the handle as long as you like, but it is hard to manoeuvre a handle over 6 m (20 ft) long.

The long handle lets the floorlayer smooth the floor without walking in the fresh concrete. At the time bull floating normally occurs—right after striking off—the concrete is too soft to support a person's weight.

A related tool is the channel radius float. Longer and stiffer than a bull float, it is somewhat harder to use but does a better job making floors flat.

A darby is a long float with a low handle. Typical dimensions range from 50 to 100 mm (2 to 4 in) wide and from 1 to 1.5 m (3 to 5 ft) long. It can be made of wood or magnesium. The handle is usually located at one end so the floorlayer can sweep the tool across the floor while kneeling at the slab's edge. Some darbies have two handles, one at each end. Darbies can replace bull floats on very narrow slabs. Some floorlayers use darbies at the slab's edges, and bull floats farther out (Figure 18.6).

The highway straightedge, while not usually considered a floating tool, often replaces bull floats and darbies. See the preceding section on tools for striking off.

The basic hand float resembles a darby, but is shorter and is used later in the sequence of finishing steps. Sizes vary greatly, but the typical float is about 90 mm (3½ in) wide and 300–600 mm (12–24 in) long. Common materials are the traditional wood, magnesium, and resin-impregnated canvas. It is possible to float a whole floor by hand, but nowadays this only occurs on the smallest jobs. Bigger floors are power floated, but even there hand floats are used at edges and in congested areas (Figures 18.7).



FIGURE 18.6 A bull float with a blade of laminated wood being used on a dry shake.



FIGURE 18.7 A hand float.

Power floats come in two types. The original type, not seen much these days, is designed strictly for floating, not trowelling. It consists of a steel disc about 460 mm (18 in) in diameter driven by an internal-combustion engine. This type incorporates vibration as well as rotary action. It is heavy and cannot be used till the concrete is quite hard.

Today the tool of choice, for most, is a power trowel machine (described below) fitted with attachments designed for floating. Any trowel machine can be turned into a power float by attaching to it either float shoes, combination blades, or pans.

Float shoes are individual steel floats that fit over the trowel blades. Each float shoe is turned up on both the leading and trailing edges. Combination blades are turned up on the leading edges only. They can be used for floating (if held flat against the floor) and for trowelling (if tipped). Combination blades represent a compromise—not quite so good at floating as float shoes or pans, nor quite so good at trowelling as dedicated trowel blades.

A pan is a steel disc with a turned-up edge all around. Pans can be fitted to almost any trowel machine, but it's not a good idea to put them on walk-behind machines with a diameter greater than 1 m (3 ft), because friction makes the bigger machines hard to control. Pans are dished, with the edge 3–10 mm (1/8–3/8 in) higher than the centre. At least one manufacturer offers pans with minimal dish for use on floors that must be very flat.

TROWELS

A trowel has a flat surface that is held at an angle to the floor surface. Trowels look a lot like floats, but there are some clear differences. Trowels have sharp edges; floats have rounded edges. Trowels are used at an angle to the floor surface; floats are held level. Trowels are made of steel; floats were traditionally made of wood, though other materials are used today.

Three kinds of trowels are in wide use: hand trowels, fresnos, and power trowel machines.

Hand Trowels

A hand trowel is a thin sheet of steel, usually spring steel or stainless, with a low handle. It is typically 75–125 mm (3–5 in) wide and 250–500 mm (10–20 in) long. Trowels for floors are almost always rectangular; pointed bricklayer's trowels have no place in floor construction. Trowel size is largely a matter of personal preference, but in general it is good practice to use the biggest practical size for the first trowel pass. Smaller trowels may be used for later passes as the concrete stiffens. Some floorlayers carry a very small hand trowel for filling in holes.

Though it is possible to produce a smooth, hard surface with hand trowels, power trowel machines do a better job. In modern industrial floor construction, most floorlayers rely heavily on trowel machines and floors are the better for it.

Fresnos

A fresno is a big trowel with a long handle. It can be thought of as the trowelling equivalent of a bull float. A typical fresno is 125 mm (5 in) wide and 600 mm–1m

(24–40 in) long. It works fairly well for a first trowelling on soft concrete but is not very effective later as the concrete hardens.

Power Trowel Machines

These are rotary devices that resemble ceiling fans. Each rotor turns several (usually four) trowel blades. Power normally comes from an internal-combustion engine, but electric machines are available for use where exhaust fumes are not acceptable. You can turn any power trowel into a power float by fitting it with float shoes, combination blades, or pans.

Walk-behind trowel machines have a single rotor and a long handle sticking out to one side. Sizes vary, but the most popular machines come in diameters of 910 and 1170 mm (36 and 46 in). Smaller machines are used at edges and in tight quarters.

Ride-on trowel machines (riders) have two rotors and the operator sits between them.

Rotor diameters range up to 1.5 m (5 ft) (Figures 18.8 and 18.9).



FIGURE 18.8 A ride-on trowel machine with finish blades.



FIGURE 18.9 A small walk-behind trowel machine used at an edge. Most walk-behinds are bigger.

Higher productivity is the main reason for using riders, but not the only one. Because they weigh more than walk-behind machines, they allow some finishing steps to take place later than would otherwise be possible, and they help achieve a dense, burnished finish.

Any trowel machine worth buying provides for changing the blade angle and speed of rotation. For floating, blades stay level and spin slowly. For the first trowelling, they are tilted slightly but do not speed up much. Blade angle is then increased for each later trowel pass. Speed is also increased as the concrete become harder.

Power trowelling has become the standard method for finishing industrial floors, with hand work relegated to edges.

OTHER TOOLS

Floorlayers use a few finishing tools that do not fit neatly into the three categories of striking off, floating, and trowelling.

The grate tamper or jitterbug is a metal sheet full of holes, mounted on a rectangular frame, with a tall handle. You push the grate into the concrete to depress the coarse aggregate. Grate tampers have a bad effect on flatness.

A roller tamper serves the same purpose, but the metal sheet is formed into a tube and the tube is rolled over the floor surface. Roller tampers don't reduce flatness as much as grate tampers do.

A finishing broom is used where a broom finish is specified. It's more common on outdoor paving than on floor slabs. The broom is 600–120 mm (24–48 in) wide and has soft, fine bristles. It needs a very long handle, so a floorlayer can drag it over the floor without walking in the concrete.

A wire broom has stiffer, coarser bristles than a finishing broom. It is used to produce a scratch finish, which is sometimes specified for slabs that will get toppings or ceramic tile.

Grinders are used both to correct defects and as finishing tools in their own right. Some builders try to repair floors with hand-held angle grinders, but such machines are useless for all but the smallest defects. A better choice for correcting curled-up joints and rough spots is a concrete grinder with a 250-mm (10-in) diamond disc. This machine is about the size of an ordinary lawn mower, and it typically powered by a 6-kW (8-hp) internal-combustion engine. Electric models are also available. Some grinders have a hose fitting, so water can be introduced at the grinding face, while others have vacuum systems to remove dust and allow dry grinding. Bigger grinders are sometimes used to repair large areas.

Early-age grinding (described below) uses a different sort of machine. The standard tool is a grinder with two rotating discs, each fitted with three abrasive blocks called stones. Stone grinders have little effect on hard, strong concrete. They work in early-age grinding because that process calls for their use while the concrete is still young and weak.

Special high-speed grinders are used to finish terrazzo.

A jointing tool is a hand tool for inducing joints. It is also called a groover, a name that describes its use perfectly. It is a small hand float, typically about 150 mm (6 in) long, with a ridge on the bottom. This tool has little application in modern floor construction; there are better ways to make joints.

An edger is a hand tool for rounding off the edge of a slab. It resembles a jointing tool (the two often come as a matched set) but with the ridge on one side instead of the centre.

FINISHING STEPS

The finishing of a concrete floor takes many separate steps. The exact number and order of steps depend on several factors, including the type of finish desired, the workability and finishability of the concrete, and the preferences of the floorlayers. Here is a typical sequence:

1. Strike off with a vibrating screed.
2. Use a 3-m (10-ft) highway straightedge at right angles to the screed. Lap each pass by 1.5 m (5 ft).

3. Wait for bleed water to appear and evaporate. This can take several hours.
4. Even after bleed water has evaporated, wait for the concrete to stiffen enough so that a footprint goes no more than 5 mm (¼ in) deep.
5. Float, using pans on a power trowel machine.
6. Use a hand float at edges and penetrations.
7. Wait till the concrete has hardened enough for trowelling. Experience is the only reliable guide here.
8. Power trowel, using trowel blades held almost level.
9. Use a hand trowel at edges and penetrations.
10. Power trowel a second time, with blades tilted.
11. Use a hand trowel again at edges and penetrations.
12. Power trowel a third time, with blades tilted higher and throttle partly opened.
13. Use a hand trowel again at edges and penetrations.
14. Power trowel a fourth time, with blades steeply tilted and the throttle wide open.
15. Start curing right away.

The sequence described here would be suitable for a direct-finished industrial floor, laid in wide or narrow strips and designed to meet these surface requirements:

- surface regularity— F_F35/F_L25 overall (ACI 117 “flat” category);
- wear resistance—AR2;
- description of surface—burnished finish;
- slip resistance—not critical.

Bear in mind that any list of steps is descriptive, not prescriptive. Some floorlaying crews achieve excellent results using methods much different from my list.

TYPES OF FINISHES

Floor finishes are usually specified by description. Here are the main types, from smoothest to roughest:

- burnished;
- haze;
- float;
- broom;
- scratch.

BURNISHED FINISH

Multiple trowel passes make a floor smooth and hard. If taken as far as it can go, trowelling produces a very dense, somewhat darkened surface; this is called a burnished or burnt finish. The sequence of finishing steps described above leads to a burnished finish. In many ways, this is the ultimate floor finish: hard-wearing, easy to clean, and good-looking. It's the best choice for most industrial floors.

It's not ideal for every job, however. If a floor will get a covering such as tile or carpet, it is a waste of effort to put a burnished finish on it. And if a floor will get a



FIGURE 18.10 Burnished finish. This is the smoothest finish achievable by trowelling. The coin, for scale, has a diameter of 19 mm.

bonded topping or coating, a smooth finish is not only unneeded but counterproductive. The hard finish will have to be removed by shot-blasting or similar means.

Even floors exposed to wear should not get a burnished finish if it could make them too slippery. This situation can arise where liquid or fine powder could be spilled on the concrete. Slipperiness is seldom a problem if the floor stays clean and dry (Figure 18.10).

HAZE FINISH

This is what you get when you stop one or two trowel passes short of a burnished finish.

Occasionally, a designer or user will want a finish just slightly rougher than a standard trowel finish, but smoother than the rough finishes described below. Be warned that it can be very hard to achieve a haze finish without leaving trowel marks.

FLOAT FINISH

In the finishing sequence described above, leaving out steps 7-14 would result in a float finish. Compared to a burnished finish, it's markedly rougher and has higher skid resistance. Sometimes it's chosen for its appearance; the floating operation leaves swirls, which some people find attractive (Figure 18.11).

On the other hand, a float finish has less resistance to wear and is harder to clean.

A float finish is usually good enough for floors that will get coverings. But if the covering will be a thin sheet material, some of the float marks might show through. In that case, it's safer to give the floor at least one trowel pass.

BROOM FINISH

This is made by dragging a finishing broom over the soft concrete. In the finishing sequence described above, brooming would take place after step 6 and would replace steps 7-14.



FIGURE 18.11 A float finish, with swirls.

A broom finish is functionally similar to a float finish. But it looks different because the broom leaves straight lines, in contrast with the swirl marks left by floating. Broom finishes are more popular on outdoor pavement than on interior floors.

SCRATCH FINISH

This is made by scoring the soft concrete with a wire broom. In the finishing sequence listed above, scratching would replace steps 5–14.

A scratch finish is never used where it would be seen in the finished building. Its only purpose is to prepare a base slab for a bonded topping or ceramic tile.

Though plenty of toppings have been laid over scratch-finish slabs, there are better ways to ensure bonding. One good method is to float the slab and later roughen the hardened concrete by shot-blasting or scabbling.

OTHER FINISHING METHODS

Most concrete floors are finished by striking off, floating, and trowelling. But there are other methods used in addition to, or in place of, the basic three. Some of them are:

- early-age grinding;
- polishing;
- dry shakes (also called sprinkle finishes);
- vacuum dewatering.

EARLY-AGE GRINDING

This alternative to floating and trowelling gets its name from the fact that the concrete is ground early on, after it has set but before it has gained much strength. The process involves these steps:

1. Strike off in the normal way.
2. Smooth with a bull float or highway straightedge.
3. Cover with polyethylene sheeting.
4. One or two days later, remove the polyethylene and grind all over to a depth of about 1 mm (1/32 in).

The result is a floor with a texture like sandpaper—a bit rougher than a burnished finish, but smoother than a float or broom finish. It is likely to have less wear resistance than a burnished floor, but as far as I know that has not been tested. Early-age grinding does a good job preparing a floor for coatings and coverings. The slightly rough texture makes for good adhesion, and the possible reduction in wear resistance hardly matters. There is debate, however, over the suitability of this finishing method for bare floors in warehouses and factories.

The normal tool for early-age grinding is a double-disc grinder with three abrasive blocks on each disc. The blocks should be made of 1.70-mm (US no. 12 sieve) grit. Though grinding takes place without added water, airborne dust is generally not a problem because the concrete is still moist.

The main benefit to early-age grinding—and the reason it was introduced—is the elimination of overtime work in cold weather. Instead of staying up all night to float and trowel a slab cast at low temperatures, floorlayers go home after a normal work-day and come back a day or two later to finish the job.

Never wildly popular, early-age grinding has fallen into almost total disuse. As far as I can tell, no one in the UK or America is actively promoting this method. Still, it remains an option worth considering.

POLISHING

This looks a lot like early-age grinding, but the timing is different and so are the results. It usually takes place long after the concrete has been placed and can even be done on old floors. The concrete is ground, and then polished, using rotary machines and progressively finer abrasives. Polishing with 400-grit makes a surface about as smooth as a burnished finish. Polishing with finer grits can produce high gloss unlike anything that can be achieved with floats and trowels (Figure 18.12).

Polishing is usually done by specialist contractors, not concrete floorlayers, and is considered more like a floorcovering than a concrete finish.

DRY SHAKES

Also called a sprinkle or dust finish, a dry shake consists of dry aggregate, coated with or mixed with dry cement, that is cast on the fresh concrete and worked in by floating. Depending on what aggregates they are made of, dry shakes can:

- hide fibres;
- increase a floor's resistance to wear;



FIGURE 18.12 Polished concrete.

- make a floor more slip-resistant;
- colour a floor;
- make a floor more electrically conductive.

Dry shakes are widely used. I will go farther and say they are widely overused. That is particularly true of wear-resistant dry shakes, which come in two basic types: non-metallic and metallic. The non-metallics consist of brittle mineral aggregate—that is, rock. The metallics consists of iron filings. Sadegzadeh and Kettle (1988), along with Scripture et al. (1953), presented persuasive evidence that non-metallic shakes have little or no effect on wear resistance. My own testing confirms that. The metallics, in contrast, clearly produce a marked improvement. But even metallics are often specified in locations where plain concrete, with a good burnished finish, would serve as well.

What's more, dry shakes have drawbacks that often go unrecognized. They can fail by delamination, with the shake peeling off in thin sheets. Good workmanship reduces the risk of delamination, but even the most careful floorlayers experience it. Another drawback is reduced flatness. The straightedge work that makes a floor very flat is not compatible with the application of a dry shake. Phelan (1989) suggests it is hard to achieve flatness better than F_F45 on a dry-shake floor. However, the use of ride-on trowel machines with big float pans may be severing the connection between dry shakes and poor flatness.

Designers should approach dry shakes as they should approach anything that raises the costs of a floor and introduces some risk: caution and a 'show me' attitude. If a dry shake meets a real need more effectively or cheaply than an alternative such as a topping or coating, use it. If it does not meet those conditions, spend the money elsewhere.

To apply a dry shake with success requires care and skill (Figure 18.13). Here are the typical steps:

1. Strike off normally and wait for bleed water to disappear.
2. Apply two thirds of the specified amount of dry-shake material. Mechanical spreaders are widely used, but some floorlayers still use shovels.



FIGURE 18.13 A metallic shake being dropped from a power spreader.

3. Work the dry shake into the concrete with a wood bull float.
4. Apply the remaining one third of the dry shake.
5. Again, work the dry shake into the concrete with a wood bull float.
6. Trowel as needed to give the desired finish.

Never use entrained air in concrete that will get a dry shake, because air greatly increases the risk of delamination.

Since the dry shake soaks up water from the concrete beneath it, that concrete must not be too dry. A dry-shake floor is not the place for stiff, low-slump concrete or low water–cement ratios. Slumps near 150 mm (6 in) are typical.

VACUUM DEWATERING

This is a technique for sucking water from fresh concrete. After the floor has been struck off, airtight mats are laid over it and vacuum is applied under the mats. Deacon (1986) suggests the vacuum should stay on for 3–5 minutes for each 25 mm (1 in) of slab thickness.

Vacuum dewatering eliminates bleed water and greatly reduces finishing time, especially in cool, damp conditions. You can usually start floating the floor right after the vacuum mats come off. As with early-age grinding, the chief benefit of vacuum dewatering is the elimination of late-night overtime in cold weather.

The process is said to improve concrete strength and wear resistance.

Because the mats are about 5 m (16 ft) square, vacuum dewatering is best suited to narrow-strip pours. The technique is hard to apply to wide-strip and large-bay pours.

HOW TO SPECIFY FINISHES

Many specifiers do a poor job on floor finishes. They rely on method specifications that try to tell the floorlayers what to do, step by step. The following language has appeared in hundreds of American specifications:

First, provide a floated finish. The finish shall next be power trowelled three times, and finally hand trowelled. The first trowelling after floating shall produce a smooth surface which is relatively free of defects but which may still show some trowel marks. Additional trowelling shall be done by hand after the surface has hardened sufficiently. The final trowelling shall be done when a ringing sound is produced as the trowel is moved over the surface.

Reading that, I can't help imagining some earnest inspector cupping his ears, listening for that telltale ringing sound. Whatever it merits as a general guide, a specification like that has at least two serious shortcomings when made part of the contract documents.

First, it clouds the issue of responsibility for poor results. If a builder follows every instruction to the letter, who is to blame if the finished floor has defects?

Second, it is counterproductive because it may force floorlayers to adopt unfamiliar methods. Either that, or they ignore the instructions, creating a different sort of problem. Good floorlayers develop their own method of working—a method suited to their own abilities, tools, and local conditions. Two crews can achieve equally good results using quite different methods.

Instead of telling floorlayers how to do their job, designers should describe the required finish and leave it to the floorlayers to sort out the details. In other words, designers should write performance specifications rather than method specifications. For most purposes, designers can control the floor finish by including these three items in their specifications:

- a requirement for surface regularity;
- a requirement for wear resistance;
- a description of the desired surface texture.

Surface regularity and wear resistance can be specified in terms of standard tests. Surface texture is trickier because no practical test exists for it, though there have been some attempts. All we can do is describe it, but in practice that works reasonably

well. Most floorlayers know what is meant by *burnished finish*, *float finish*, and *broom finish*. And if the finish is particularly important, a mock-up will ensure that all parties understand what is needed.

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19 Concrete Toppings

A concrete topping is a layer of concrete placed on top of a structural slab. Toppings are laid over both ground-supported and suspended floors. They fall into three main types: monolithic, bonded, and unbonded.

Not every floor needs a topping. In the past, it was widely accepted that high-quality floors needed toppings, but few people say that today. Well-made, direct-finished concrete slabs are as good as toppings for most purposes and almost always cost less. The modern fashion is to use direct-finished concrete, with no topping, wherever possible.

Nevertheless, toppings have their place (Figure 19.1). They are still used for these purposes:

- to provide high resistance to wear;
- to reduce material costs (but not labour) by putting strong concrete at the floor surface and weaker concrete in the base slab;
- to provide a base for other construction work, with the topping laid after the other work has ended;
- to repair defects.

MONOLITHIC TOPPINGS

Also called integral toppings, these are laid while the underlying concrete is still plastic. They are typically about 15 mm ($\frac{5}{8}$ in) thick, though there seems to be nothing special about that dimension. The coarse aggregate is usually no bigger than 10 mm ($\frac{3}{8}$ in).

Unless the base slab hardens or crusts over before the topping is laid, monolithic toppings usually live up to their name, with a strong bond between topping and base. For that reason, most designers count the topping as part of the overall floor thickness. If design calculations support a slab thickness of say 150 mm (6 in), it would be normal to make the base slab only 135 mm (5 $\frac{3}{8}$ in) thick, making up the final 15 mm ($\frac{3}{8}$ in) in topping concrete.

The usual reason to choose a monolithic topping is to make the floor surface of stronger concrete than the mass of the slab. The topping concrete is normally a high-strength mix, sometimes containing special aggregates such as traprock. The base slab can then be made of ordinary, weaker concrete. Another possible use of a monolithic topping is to create a coloured floor, without the cost of using pigment throughout a structural slab.

The drawback to a monolithic topping is higher labour cost, compared to a direct-finished slab. There is also a small risk of delamination if the builder lets the base slab sit for too long before laying the topping.

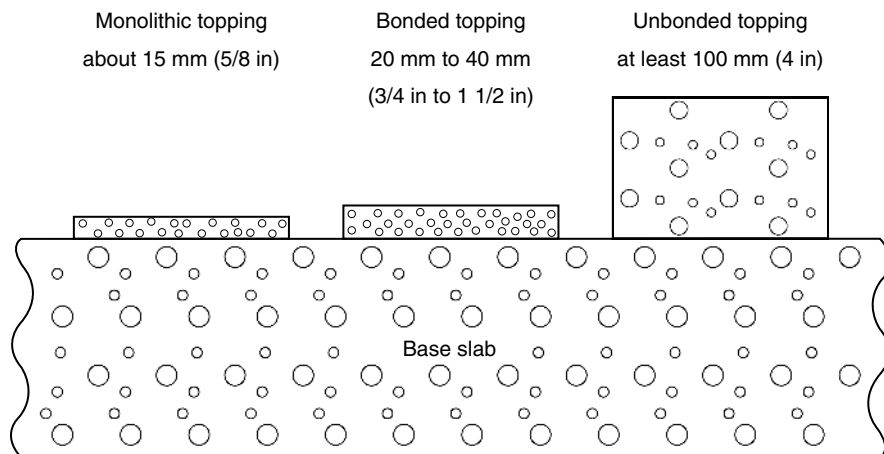


FIGURE 19.1 Topping thickness varies with type.

BONDED TOPPINGS

These are laid over a structural slab that has already hardened. Too thin to have much strength on its own, a bonded topping depends on its bond to the base slab. The coarse aggregate is usually 10 mm ($\frac{3}{8}$ in)—same as in monolithic construction. BS 8204:Part 2 recommends that bonded toppings be 20–40 mm ($\frac{3}{4}$ –1½ in) thick. It is risky to try a bonded topping much over 40 mm (1½ in) thick, because curling stresses are too likely to pull the topping off its base. If a topping must be over 40 mm (1½ in) thick, unbonded construction is the safer choice.

Because bonded toppings do not always stay bonded, structural engineers generally do not count them as part of the floor's structural thickness. There are exceptions, however. Some precast units for suspended floors rely on bonded toppings for structural strength (Figure 19.2).

IMPORTANCE OF BOND

A bonded topping is no better than its bond to the base slab. If bond fails, so does the topping.

The usual way to check for bond failure is a chain drag. ASTM D4580 describes the standard test. You drag a chain or chains over the floor and listen for a rattling sound. It works but has two weaknesses. It may find tiny delaminations that would never lead to topping failure. And it will miss areas that are on the brink of delaminating but haven't separated just yet.

Another option is to test bond strength by isolating a small section of topping with a saw or core drill, gluing a ring to its surface, and measuring the force needed to break it free. According to one expert in this field (Dennis, 1989), readings above 0.7 MPa (100 psi) denote satisfactory bond, while readings below 0.5 MPa (70 psi) reveal a problem. In contrast, concrete itself typically has tensile strength of 2–3 MPa (300–450 psi).



FIGURE 19.2 A bonded topping under construction.



FIGURE 19.3 The chain-drag tool for finding delaminations.

You could write performance specifications based on pull-off tests, but nobody I know does that. The normal approach is to specify the base-slab preparation and topping techniques known to work (Figure 19.3).

PREPARING THE BASE SLAB

Chapter 22 covers this subject, but a few points are worth noting here.

Though it's tempting to give the base slab a rough finish, you cannot count on that alone to provide a good bond. On the contrary, a rough finish may make matters worse because it traps dirt and is hard to clean. The safer course is to give the base a smooth finish (not necessarily burnished), and count on roughening it by other means just before the topping goes on.

An unusually thorough study by Wells et al. (1999) suggests that among preparation methods shot-blasting provides the most reliable bond—so good that it eliminates any dependence on bonding agents. That same study shows that polymer-modified bonding agents worked no better than plain old cement–sand paste.

People may argue about preparation methods and bonding agents, but no one disputes the need for cleanliness. Even the thinnest layer of dust will inhibit bond. If you would not eat a sandwich after dropping it on the base slab, it's not clean enough.

JOINTS IN BONDED TOPPINGS

All movement joints in the base slab should extend upward through the topping. Otherwise the topping is almost certain to crack.

For our purposes here, movement joints include all isolation, expansion, contraction, and warping joints. A construction joint may or may not be a movement joint, depending on the amount of reinforcement passing through it. Construction joints in suspended floors are usually not movement joints. If in doubt, assume the joint will move.

A topping can have more joints than its base slab. Extra joints are sometimes needed for construction convenience, or to divide the floor into narrow strips for better control over flatness.

UNBONDED TOPPINGS

Also called overslabs, these are, in effect, separate slabs laid on top of the base slab. There is no attempt to bond the topping to the base. On the contrary, the topping performs more predictably if completely unbonded. Some designers cover the base slab with polyethylene sheets or building paper to prevent random bonding.

An unbonded topping should be at least 100 mm (4 in) thick. There is no maximum thickness, as long as the base slab can support the weight. Unlike the thinner monolithic and bonded toppings, it can be made with normal-size aggregates. Because it is unbonded, it can never be counted in the structural thickness of the slab.

For crack control, unbonded toppings are treated as ground-supported slabs, even if the base slab is suspended. Any of the crack-control methods discussed in Chapter 16 can be used.

Most unbonded toppings contain light reinforcement and sawcut joints, but heavy reinforcement, steel fibres have all been used.

One big advantage of unbonded construction is that the joints in the topping need not follow the joints in the base slab. There is no need to extend base-slab joints up into the topping, unless you expect very large movements.

TABLE 19.1
Recommended Thicknesses for Concrete Toppings

Topping Type	Minimum Thickness	Maximum Thickness
Monolithic	10 mm (3⁄4 in)	20 mm (3⁄4 in)
Bonded	20 mm (3⁄4 in)	40 mm (1½ in)
Unbonded	100 mm (4 in)	No limit

Another advantage is that unbonded toppings can be laid over old surfaces that might not be suitable for bonding. An oil-contaminated slab makes a bonded topping almost impossible, but poses no problem in unbonded construction.

The main drawback is that unbonded toppings raise the finished floor elevation by at least 100 mm (4 in). In new construction, you can anticipate this by depressing the base slab. It creates problems in remedial work, however. Ramps usually have to be built, and doorways may lack needed overhead clearance (Table 19.1).

FORBIDDEN THICKNESSES

Bonded toppings should not exceed 40 mm (1½ in) in thickness, lest curling stresses cause them to debond. Unbonded toppings should be at least 100 mm (4 in), lest they lack the structural strength to support traffic. That leaves us with a forbidden range between 40 and 100 mm (1½ and 4 in). What if the topping thickness needs to fall in the forbidden range?

It happens more than you might suppose, thanks to the widespread past use of wood-block flooring 60 mm (2½ in) thick. Many industrial buildings contain such flooring, and with changing uses owners often want to replace some blocks with concrete. The only topping that will not change the finish floor elevation is one that matches the thickness of the blocks.

Some designers have successfully bent the rules by adding steel fibres at about 40 kg/m³ (70 lb/yd³). That has not been done enough to consider it tried and true, but it's worth considering if a topping simply must fall in the forbidden thickness range.

CEMENT–SAND SCREEDS

These are topping made of cement, sand, and just enough water to make the mix workable. There is no coarse aggregate.

Because screeds have poor resistance to wear, they are never used as a wearing surface. They are always covered with carpet, tile, vinyl sheets, or similar materials. Screeds are often used in houses, offices, shops, and institutions, but almost never in warehouses and factories.

Like regular concrete toppings, screeds can be either bonded or unbonded. There are no monolithic screeds, though. The rules for bonding screeds are the same as

TABLE 19.2
Recommended Thicknesses for Cement–sand Screeds

Topping Type	Minimum Thickness	Maximum Thickness
Bonded	20 mm (¾ in)	40 mm (1½ in)
Unbonded	100 mm (4 in)	No limit
Floating	65 mm (2½ in)	No limit

those for bonding toppings. The base slab must be carefully prepared, and the screed should be 20–40 mm (¾–1½ in) thick.

Unbonded screeds are similar to other unbonded toppings, but are sometimes thinner. While unbonded toppings made of ordinary concrete should be at least 100 mm (4 in) thick, unbonded screeds are sometimes half that.

The floating screed is a special type of unbonded screed separated from the base slab by a layer of insulation (thermal or acoustic). Floating screeds should be at least 65 mm (2½ in) thick (Table 19.2).

SCREDS VERSUS DIRECT-FINISHED SLABS

Though useful, screeds are rarely essential. In almost every case where a screed could be considered, the alternative of a direct-finished slab also exists.

Designers choose screeds for these reasons:

- to improve surface regularity (flatness and levelness);
- to provide slopes for drainage;
- to hide a defective floor;
- to incorporate wiring and other utilities.

All those aims can also be met with direct-finished concrete. With care, a slab can be laid as flat and level as a screed, and can be sloped. Defective concrete surfaces can be repaired by grinding and patching, instead of screeding. In-floor utilities provide perhaps the strongest argument for screeds, but even here there are alternatives.

Local fashion often determines the choice between screed and direct finish. If you build in a part of the world where screeds are common (much of Europe, for example), you can probably count on finding skilled screedlayers, but the local workers may lack the ability to put a good finish on a concrete slab. If you go to a region where screeds are rare (America, for example), you will have no trouble finding skilled concrete finishers, but screedlayers will be thin on the ground.

What about America?

Screeds are almost unknown in America, where the preference for direct-finished concrete slabs is all powerful, even in residential and office work. But Americans might well rethink that preference.

The increasing focus on floor flatness has revealed that direct-finished suspended slabs are seldom very flat. And composite slabs—popular in America—are the worst.

They often lack the flatness needed to make a floor look good when covered with thin, shiny material such as sheet vinyl or vinyl tile. The result has been disputes and many dissatisfied customers.

When an American floor in a hospital, school, or apartment block is found not to be flat enough, the usual remedy is to cover all or part of it with a cementitious levelling compound that looks a lot like a sand–cement screed. That means many American floors are in fact getting screeds. They just weren't designed that way.

SCREED MIXES

These are usually identified by ratio of cement to sand by mass, even if they end up being batched by volume. Table 19.3 shows the two mix designs most common in the UK. It also shows US equivalents, but screeds are so rare in America that no standards for them exist. The 1:4 mix is for general use, and the 1:3 mix is used in high-traffic areas. Remember, though, that even a 1:3 screed needs a floorcovering.

Murdock et al. (1991, 405) recommend the stronger 1:3 mix for any screed that supports a thin covering such as carpet, sheet vinyl, or vinyl tile, reserving the 1:4 mix for thick coverings such as ceramic tile.

The water content is typically 7–12% of the total mix, by mass—but it's normally judged by eye. If you squeeze a handful of screed mix, it should clump together without any appreciable water being squeezed out.

Components can be batched by mass or volume. Batching by mass may be technically superior, but in practice most screedlayers batch by volume and that is normally good enough. When poor batching occurs—as it does all too often—the cause is more likely to be carelessness than any inaccuracy inherent in volume batching.

Because it is stiffer than the concrete used in floor slabs, screed material should be mixed in a forced-action mixer. Pan mixers and trough-type mortar mixers are suitable. Free-fall mixers are not. Ready-mix screed material, delivered by truck, is a dependable alternative to mixing on site, but it is not available everywhere.

SCREEDLAYING TECHNIQUES

Over the years, screedlayers have developed techniques quite different from those used on concrete slabs and toppings.

TABLE 19.3
Screed Mixes, by Volume

Use	Mix ID by Dry Mass	UK Components			USA Components		
		Cement	Sand Dry	Wet	Cement	Sand Dry	Wet
Heavy traffic	1:3	1 bag (50 kg)	0.10 m ³	0.12 m ³	1 bag (94 lb)	3.0 ft ³	3.6 ft ³
General	1:4	1 bag (50 kg)	0.13 m ³	0.16 m ³	1 bag (94 lb)	3.9 ft ³	4.8 ft ³

One method is to lay the screed in strips about 3 m (10 ft) wide. Temporary forms—typically wood battens or steel angles—are fixed to the base slab. This method offers good control over flatness and levelness, but the joints sometimes show up as obvious bumps.

The other method is to lay the screed continuously, with no side forms. This is called wet screeding. It offers little control over levelness but eliminates the construction joints.

The screed is compacted either with a roller or by tamping with a flat plate. The vibrators used to compact ordinary concrete do not work well. This step is important; many screed failures have been traced to poor compaction.

Finishing is a matter of smoothing the surface with straightedges, floats, and trowels. Power tools are rarely used. There is no attempt to densify the surface with repeated trowellings, as is done with concrete.

Screeds need to be cured, and the methods are the same as for concrete slabs. See Chapter 11.

SCREED TESTING

Screed failures are both common and costly. They are common because screeds are often mixed on site and laid without much supervision or inspection. They are costly because they often go undetected till the floor is in use. Then the repair must deal not only with the screed but also with its covering, which may cost more than screed and base slab combined. Timely tests can prevent most screed failures.

Effective testing must focus on the properties that matter. Some concrete tests have little meaning when applied to screeds. The slump test is useless on screed mixes. Strength testing is possible, but not very relevant because a screed mix is not a structural material.

Most screed failures involve debonding, poor surface regularity, or local crushing. Turning that around, we can say the important properties are bond strength (only for bonded screeds), good surface regularity, and resistance to local crushing. We can test screeds for all three properties.

Bond can be checked by tapping with a hammer, steel rod, or chain drag. A hollow sound denotes debonding. Bond strength can be quantified by pull-off tests. Screeds can be tested for surface regularity using the methods described in Chapter 20. The straightedge test is the most common, but screeds can also be specified by F-number or by TR 34 category.

Resistance to local crushing is of special interest in screed construction. Regular concrete floors also need this property, but hardly ever lack it. In contrast, local crushing is a very common cause of failures in screeds. The problem shows up as a crumbling of the screed under a concentrated load such as a furniture leg or high-heeled shoe.

The UK's Building Research Establishment has developed a crushing test for screeds (Roberts, 1986). The BRE screed tester consists of a 4-kg (9-lb) drop hammer that falls 1 m (39 in) on to a circular foot covering an area of 500 mm² (0.775 in²). After four blows the depth of indentation is measured with a special gauge (Figure 19.4). Most screeds show test results between 0 and 5 mm (0 and 3/16 in).

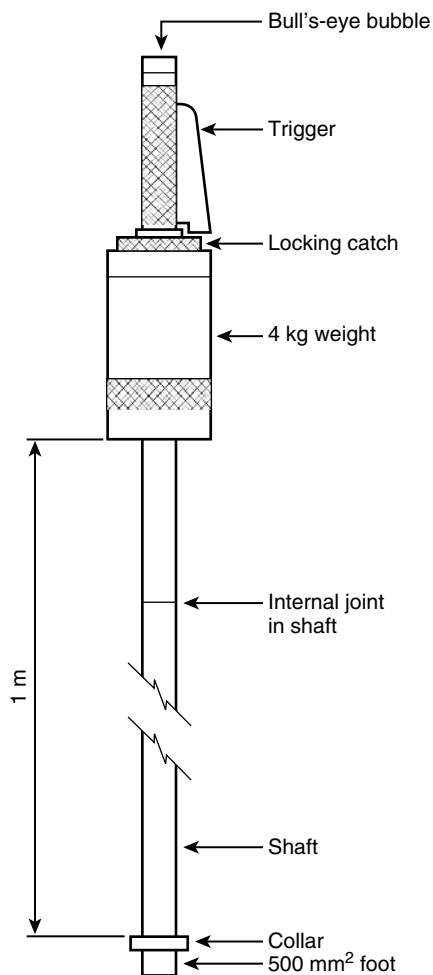


FIGURE 19.4 BRE screed tester.

Table 19.4 shows recommended values. The test is suitable for most screeds, but when used on floating screeds the hammer weight is cut in half.

TERRAZZO

This is a special type of bonded concrete topping used for its good looks. Terrazzo toppings are traditionally laid in small panels about 1 m (3 ft) square, separated by thin strips of metal or hard plastic. After the concrete has hardened, it is ground smooth and polished.

Terrazzo is concrete, but its ingredients are chosen with appearance in mind. The aggregate consists of marble chips, ranging in size from 2 to 25 mm (1/16 to 1 in). White Portland cement is the traditional binder, but ordinary Portland is also used.

TABLE 19.4**Classification of Cement–sand Screeds by BRE Screed Test**

Category	Use	Maximum Indentation From 4 Blows	
		Random Tests ¹	Grid Tests ²
A	Areas of very heavy traffic, areas where later disruption would be unacceptable, dust-free rooms	2 mm	3 mm
B	Areas of heavy traffic such as corridors, shops, and restaurants	3 mm	4 mm
C	Areas of light traffic such as offices and houses	4 mm	5 mm

¹ About one test for every 10 m², with special attention to vulnerable areas such as doorways and joints.

² Tests at point 2 m apart in both directions.

In both cases, 10% of the readings are allowed to exceed the specified maximum by up to 1 mm.

Pigments may be added. The mixes are always cement-rich, with a 1:2 or 1:2.5 ratio of cement to marble aggregate. Some terrazzo is made with epoxy or another resin as the binder, in place of cement. Most terrazzo contractors mix on site.

Terrazzo is struck off, floated, and trowelled in much the same way as other concrete toppings. It does not call for great care in trowelling, however, because the finish comes not from the trowel but from the grinders.

Grinding typically takes place about two days later. The first grinding pass uses coarse abrasive blocks of No. 20 grit. Later passes take progressively finer blocks. The final polish comes from No. 60 or 80 grit abrasive.

Terrazzo can be laid directly over the concrete slab, but some specialists prefer to lay it over a sand–cement screed. This creates a three-course floor, complicating the job but saving money on costly terrazzo material.

Terrazzo is a good choice for public areas where good appearance must be coupled with resistance to heavy foot traffic. It lasts a long time and is easy to clean. It is often seen in building entrances, airports, and railway stations. Though not suitable for industrial traffic, it holds up well under light vehicles such as luggage trolleys.

SUMMARY—CHOOSING A TOPPING

No one type of topping is best for every job.

Monolithic toppings cost less than other types and add to the slab's structural thickness. But they must be laid at the same time as the base slab.

Bonded toppings can be installed at any time, but require great care to prevent debonding. They often cost more than other types.

Unbonded toppings can also be installed at any time. They often cost less than bonded toppings, though more than monolithic. They come into their own over old floors because they can be laid without regard for joints and cracks in the base slab.

Their main drawback is the effect on finished floor elevation, which rises by at least 100 mm (4 in).

Cement–sand screeds are used only where the floor will be concealed.

Terrazzo toppings are used mainly for visual effect. They provide a good-looking floor surface that resists heavy foot traffic.

Lastly, direct-finished concrete slabs are almost always an alternative to toppings. They usually cost less.

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20 Surface Regularity

Specifications for floor surface regularity have undergone big changes since the last edition of this book, on both sides of the Atlantic. In the UK, the fourth edition of TR 34 (Concrete Society, 2016) completely rewrote its specifications, with new terminology and tolerances. Hardly any part of the old TR 34 system was left untouched. In America, the author of the F-number system (Face, 2022) introduced new equations for calculating tolerances on defined-traffic floors.

HISTORY

For most of the twentieth century, floor designers either ignored surface regularity or tried to control it with specifications based on a 3-m (10-ft) straightedge. Those straightedge tolerances were rarely enforced; indeed, effective enforcement was next to impossible because there was no standard test.

So the situation might have remained, except for a development in the materials-handling field. In the early 1970s, forklift makers introduced the very-narrow-aisle (VNA) turret truck. It differed from ordinary forklifts in having its fork mounted on a rotating turret. While ordinary forklifts needed aisles about 4 m (13 ft) wide, the new turret trucks could run in aisles only 2 m (6 ft) wide. Narrower aisles meant greater storage density—something many warehouse users sought.

The turret truck had one glaring drawback, however. It needed a flat floor. Warehouse users who tried to run turret trucks on ordinary 1970s floors soon learned that neither the 3-m (10-ft) straightedge nor the floorlaying methods then in use were good enough for the new vehicles.

To satisfy turret-truck users, floor designers and builders developed ways to build flatter and more level concrete slabs. Their efforts led to the superflat floor, discussed at the end of this chapter.

Perhaps even more importantly, the sharper focus on surface regularity led people to question the flatness and levelness of all floors, not just those that supported turret trucks and needed a superflat surface. The result was radical new ways to specify and test floor surface regularity: the F-number system in America and the TR 34 system in the UK.

But before we look at those systems, we need to consider two key distinctions: between flatness and levelness, and between random and defined traffic.

FLATNESS AND LEVELNESS

These terms have overlapping definitions in everyday speech. But within the field of concrete floors, flatness and levelness mean different things.

Flatness is defined as planarity or lack of curvature. A flat floor is smooth and free of bumps or dips. An unflat floor is bumpy or wavy.

Levelness is defined as horizontality or lack of slope. A level floor is horizontal. An unlevel floor is sloped or tilted.

Consider two examples. In normal use, a billiards table is both flat and level. If we put bricks under one end, the table will still be flat but it will no longer be level. On a calm day, the surface of a pond is both flat and level. If the wind rises the surface will cease to be flat, but it will remain level.

Some floors are designed to be unlevel. They are sloped for drainage or to minimize site grading. I never hear of any floors designed to be unflat, though many turn out that way.

Flatness and levelness are both desirable properties (except on those floors with design slopes), but they have different implications for the floor user. Flatness is critical where the main issue is the behaviour of wheeled vehicles. Flatness is also important where appearance matters—as in an institutional floor that will be covered with vinyl tile. In contrast, levelness is critical where the main issue is the installation of fixed equipment such as warehouse racks or machine tools.

While big exceptions exist, most users find flatness matters more than levelness. If a floor is unlevel, fixed equipment can be shimmed or adjusted to accommodate it. But it is not so easy to adapt a wheeled vehicle to a surface that is not flat enough for it.

Flatness and levelness also have different implications for the floorlayer. Flatness comes from finishing; it is determined mainly by the finishing methods and to a lesser extent by the finishability of the concrete mix. Levelness comes from forms and strike-off; it is determined mainly by the accuracy of the side forms and the method used to strike off the concrete.

DEFINED VERSUS RANDOM TRAFFIC

Floors get two kinds of traffic: defined and random. In the TR 34 system, the terms are *defined movement* and *free movement*. On a defined-traffic floor, vehicles are confined to fixed paths. On a random-traffic floor, vehicles or walkers are free to roam, though inevitably some traffic paths see more use than others.

The distinction matters because the two kinds of traffic call for different ways of enforcing surface regularity. On a defined-traffic floor, it's practical to measure the profile down every travel path. You can check effectively every part of the floor surface that matters to the vehicle user. In contrast, a random-traffic floor has an infinite number of possible travel paths. You could never measure them all, so you have to fall back on statistical sampling. You check selected points or lines and hope they represent the whole surface.

Historically, the highest requirements for surface regularity have been found in the defined-traffic category. The reason is that turret trucks—the vehicles that demand the flattest and most level floors—run in defined paths. It would be wrong, however, to assume that defined-traffic floors are necessarily superior in surface regularity.

Though defined-traffic floors are important, their random-traffic cousins are far more numerous. Defined-traffic floors are found in VNA warehouses, in some factories with automatically guided vehicles, and in amusement park rides—and almost nowhere else. The great majority of industrial floors, as well as practically all nonindustrial floors, fall in the random-traffic category.

F-NUMBERS

Since its adoption into ACI and ASTM standards in the late 1980s, the F-number system has become the most common way to specify and measure floor surface regularity in the United States and Canada. It is also widely used in Latin America and Australia. Europeans, in contrast, are more likely to use the TR 34 system or the German standards DIN 18 202 and DIN 15 185.

The F-number system includes three separate numbers:

- F_{min} , which encompasses both flatness and levelness and is used only on defined-traffic floors;
- F_F , which controls flatness and is used only on random-traffic floors;
- F_L , which controls levelness and is used only on random-traffic floors.

Defined-traffic floors are specified by the single number F_{min} . Random-traffic floors are specified by a pair of numbers, written as F_F/F_L , except for suspended floors, which are specified by F_F alone in most circumstances.

The three numbers have this much in common:

- A higher F-number always denotes a better floor.
- The normal scale runs from 10 to 100. Only the worst floors exhibit F-numbers below 10, and only a few of the best measure above 100.
- The scales are linear. If you double the F-number, you halve the magnitude of the allowed deviations.

F_{min} FOR DEFINED-TRAFFIC FLOORS

The F-number system controls defined-traffic floors by means of a single number called F_{min} . F_{min} defines both flatness and levelness and is measured over the wheel spacings of the vehicle that will travel on the floor. Testing is confined to the travel paths.

When you say a floor measures, say, $F_{min}50$, you are not making a general statement about the floor's flatness and levelness. You are saying that when a particular vehicle travels in a particular path, it will not encounter any slope or change in slope greater than that allowed by the F_{min} equations developed by Allen Face (Face, 2022). F_{min} controls three separate properties: longitudinal flatness, transverse levelness, and longitudinal levelness. There is a separate equation for each.

Longitudinal Flatness

This is controlled by measuring the 600-mm curvature, called q , down each wheel-path. See Figure 20.1. Depending on the vehicle involved, there can be two, three, or four wheelpaths. The tolerance comes from Equation 20.1 or 20.2.

Equation 20.1 SI units.

$$|q_{max}| = 80.1 / F_{min} \quad (20.1)$$

where

q_{max} = limit value for 600-mm curvature as defined in ASTM E1155, in mm

F_{min} = the defined-traffic F-number, dimensionless

Equation 20.2. US customary units.

$$|q_{max}| = 3.24 / F_{min} \quad (20.2)$$

where

q_{max} = limit value for 24-in curvature as defined in ASTM E1155, in inches

F_{min} = the defined-traffic F-number, dimensionless

Transverse Levelness

This is controlled by measuring the elevation difference between left and right wheelpaths. The tolerance comes from Equation 20.3 or 20.4. Some four-wheeled vehicles have different wheeltrack dimensions front and back, and in those cases the transverse levelness tolerance is calculated twice, once for the outermost wheelpaths and again for the innermost.

Equation 20.3. SI units.

$$|d_{imax}| = \left[6.55(L + 68.6)^{0.5} - 48.3 \right] / F_{min} \quad (20.3)$$

where

d_{imax} = limit value for elevation difference between corresponding points on left and right wheelpaths, in mm

L = distance between left and right wheelpaths, centre to centre, in mm

F_{min} = the defined-traffic F-number, dimensionless

Equation 20.4. US customary units.

$$|d_{imax}| = \left[1.3(L + 2.7)^{0.5} - 1.9 \right] / F_{min} \quad (20.4)$$

where

d_{imax} = limit value for elevation difference between corresponding points on left and right wheelpaths, in inches

L = distance between left and right wheelpaths, centre to centre, in inches

F_{min} = the defined-traffic F-number, dimensionless

Longitudinal Levelness

This is controlled by measuring the elevation difference over the vehicle wheelbase. The tolerance comes from Equation 20.5 or 20.6.

Equation 20.5. SI units.

$$|d_{imax}| = B \left[6.55(B + 68.6)^{0.5} - 48.3 \right] / (LF_{min}) \quad (20.5)$$

where

d_{max} = limit value for the difference between the average elevation of the outermost wheelpaths and the average elevation of the innermost wheel tracks at a distance B in either direction, in inches

B = vehicle wheelbase (distance between axles, centre to centre), in inches

L = distance between left and right wheelpaths, centre to centre, in inches

F_{min} = the defined-traffic F-number, dimensionless

Equation 20.6. US customary units.

$$|d_{max}| = B \left[1.3(B + 2.7)^{0.5} - 1.9 \right] / (LF_{min}) \quad (20.6)$$

where

d_{max} = limit value for the difference between the average elevation of the outermost wheelpaths and the average elevation of the innermost wheel tracks at a distance B in either direction, in inches

B = vehicle wheelbase (distance between axles, centre to centre), in inches

L = distance between left and right wheelpaths, centre to centre, in inches

F_{min} = the defined-traffic F-number, dimensionless

MEASURING F_{MIN}

The standard instrument used to be a differential floor profileograph set up to match the wheel and axle spacings of the critical vehicle. The profileograph is a rolling instrument that collects reading while travelling down the vehicle wheelpaths. While profileographs still exist, much F_{min} testing is now done with the same walking profilers used to measure random-traffic F-numbers. These profilers measure the elevation difference over 300 mm (12 in) (Figure 20.1 and Figure 20.4).

There is a debate over whether the 300-mm spacing is close enough to catch every significant defect. Some advocate a much closer spacing, which would make the walking profilers unusable and require a rolling instrument like the differential profileograph. A paper by Allen Face (2015) presents a well-reasoned argument for the 300-mm spacing. Since Face invented both the walking profiler and the modern differential profileograph (not to mention the F_{min} system), I'm not inclined to dispute his conclusions.

Specified F_{min} values range from 40 (rarely lower) to 100 (never higher). F_{min} 100 is the traditional superflat specification and is reserved for the busiest VNA warehouses.

In recent years, F_{min} 60 has become popular for less-demanding VNA applications. With laser screeding, contractors can lay F_{min} 60 floors in large bays, eliminating the costly narrow-strip layout needed for F_{min} 100. F_{min} 40 is sometimes specified for the least demanding VNA applications and also for low-rise automatically guided vehicles.

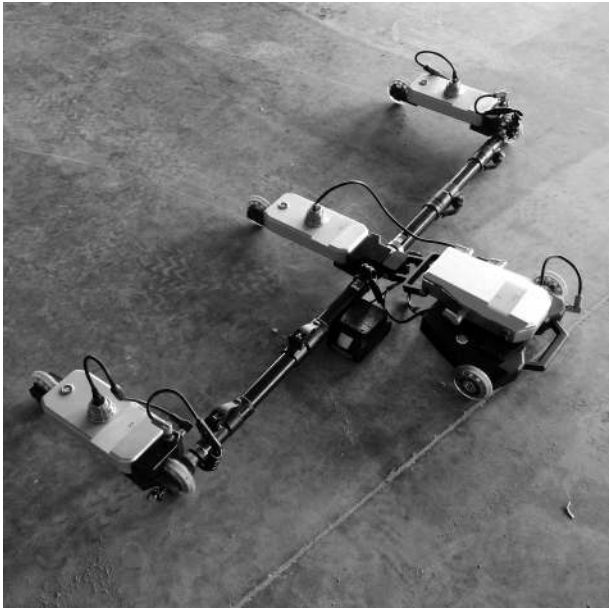


FIGURE 20.1 A differential profileograph for measuring *Fmin*.

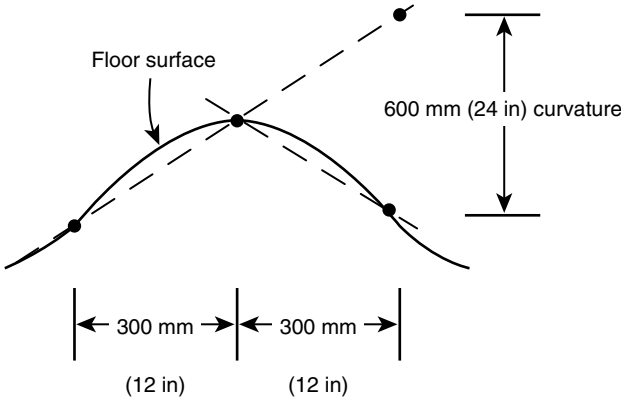


FIGURE 20.2 600-mm (24-in) curvature, the basic property of flatness for random-traffic floors in both the F-number and TR34 systems. It's called *q* in the F-number equations. TR34 used to call it Property II and now calls it Property F.

***F_F/F_L* FOR RANDOM-TRAFFIC FLOORS**

The F-number system controls random-traffic floors with a pair of numbers, *F_F* and *F_L*. The flatness number, *F_F*, is based on the floor curvature over 600 mm (24 in), a property called *q*. The levelness number, *F_L*, is based on the floor slope over 3 m (10 ft), a property called *z* (Figures 20.2 and 20.3).

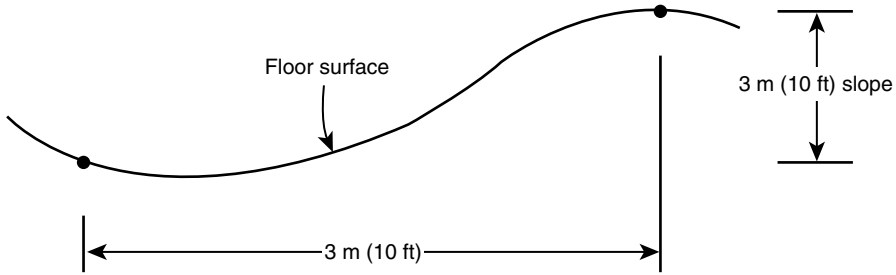


FIGURE 20.3 3-m (10-ft) slope, the basic property of levelness for random-traffic floors in both the F-number and TR34 systems. It's called q in the F-number equations. TR34 used to call it Property IV and now calls it Property E.

ASTM E1155 describes the standard test, which involves these steps:

1. Determine the test section, which could be the day's pour or a part of the pour, but cannot include more than one pour.
2. Determine the minimum number of z readings. For test sections of 150 m² or more, the minimum is the area in m² divided by 3. (In US customary units, it's the area in ft² divided by 30, for sections of 1600 ft² or more.)
3. Lay out enough straight lines on the floor to provide at least the minimum number of z -readings3-m (10-ft) slope readings. The number of z readings in each line is the length in m, minus 2.7 m, divided by 0.3 m. (In US customary units, the number of readings in each line is simply the length in ft minus 9.)
4. Make an equal number of lines, with an equal number of total readings, in both the longitudinal and transverse directions. Note that the all runs do not have to be of the same length; on some irregular slabs that would be impractical. It's also allowable to orient all lines at 45° to the test section's longest side. And if the test section is less than 7.5 m (25 ft) wide, 45° lines are obligatory.
5. Survey lines must stay at least 600 mm (2 ft) from slab edges, construction joints, and penetrations. They can cross induced joints, though.
6. Measure point elevations on 300-mm (12-in) centres down each survey line.
7. Calculate the elevation difference between each pair of adjacent points. This value is the 300-mm (12-in) slope.
8. Calculate the difference between each pair of consecutive 300-mm (12-in) slope readings. This is the 600-mm (24-in) curvature or q .
9. Calculate F_F from Equation 20.7 or 20.8.
10. Calculate the sum of each set of ten consecutive 300-mm (12-in) slopes. This is the 3-m (10-ft) slope or z .
11. Calculate F_L from Equation 20.9 or 20.10.

Equation 20.7. SI units.

$$F_F = 114 / (3S_q + \bar{q}) \quad (20.7)$$

where

F_F = the random-traffic flatness number, dimensionless

q = 600-mm curvature as defined in ASTM E1155

S_q = standard deviation of q

$\bar{q}$ = mean of $\bar{q}$

Equation 20.8. US customary units.

$$F_F = 4.57 / (3S_q + \bar{q}) \quad (20.8)$$

where

F_F = the random-traffic flatness number, dimensionless

q = 24-in curvature as defined in ASTM E1155

S_q = standard deviation of q

$\bar{q}$ = mean of $\bar{q}$

Equation 20.9. SI units.

$$F_L = 315 / (3S_z + \bar{z}) \quad (20.9)$$

where

F_L = the random-traffic flatness number, dimensionless

z = 3-m slope as defined in ASTM E1155

S_z = standard deviation of z

$\bar{z}$ = mean of $\bar{z}$

Equation 20.10. US customary units.

$$F_L = 12.5 / (3S_z + \bar{z}) \quad (20.10)$$

where

F_L = the random-traffic flatness number, dimensionless

z = 10-ft slope as defined in ASTM E1155

S_z = standard deviation of z

$\bar{z}$ = mean of $\bar{z}$

ASTM standards allow a variety of tools for measuring F_F and F_L , including optical levels, lasers and levelled straightedges with depth gauges. However, almost everybody uses a walking electronic inclinometer with feet 300 mm (12 in) apart (Figure 20.4).

While no fixed relationship exists between F_F and F_L , the former averages about 40% higher than the latter on ground-supported slabs. On suspended floors, the ratio of F_F to F_L tends to run higher—but F_L isn't enforced on most suspended floors.



FIGURE 20.4 Measuring surface regularity with a walking profiler. The operator walks it over the floor in a straight line, pivoting on the front foot after each step. The result is a connected series of elevation differences measured on 300-mm (12-in) centres. The data can be analysed to determine F_F , F_L , and F_{min} .

ACI 117 recommends a two-tiered format for random-traffic F-number specifications. The overall F-numbers apply the area-weighted mean of all the test sections in the floor. The minimum local F-numbers apply to smaller sections of the floor. Minimum local numbers are always lower than the overall numbers. If the specifier fails to call out a minimum local number, ACI 117 defaults to 0.6 times the overall value.

The two-tiered format, though sometimes criticized as needlessly complex, has proven an effective tool for improving floor flatness and levelness. It pushes floorlayers towards higher numbers, without punishing them brutally for the occasional bad day. The goal is to lay the whole floor to the overall F-numbers. But if the floorlayers do worse than that in a small area, it will still be accepted, provided it meets the minimum local F-numbers. Such an occurrence serves as a warning that the crew must do better on later slabs, to bring the overall numbers up to the specified values. If a test section fails to meet even the minimum local values, it must be repaired or replaced. But such failures are rare if the numbers are chosen with care and if all parties understand the rules from the start.

Construction Joints

ASTM E1155 forbids measuring F_F and F_L within 600 mm (24 in) of any slab edge or construction joint. There is an exception for very small slabs. Because the edges and construction joints are statistical anomalies, including them in the calculations would distort the results.

The exclusion of construction joints from testing causes some problems, because the areas close to construction joints are usually the least flat parts of a floor. Sometimes you can locate the construction joints in a noncritical area. Failing that, it's hard to justify a system that excludes the spots where bad readings are most likely to occur.

But ASTM E1155 has an answer for that. In addition to F_F and F_L you can specify a limit for q 600-mm (12-in) curvature across the construction joint. The typical tolerance is plus or minus 4.0 mm (0.150 in). The standard test calls for at least one test for each 3-m (10-ft) length of joint. The test results are not analysed statistically; it's pass or fail.

Suspended Floors

Random-traffic F-numbers apply to suspended floors, but with some restrictions.

ACI 117 applies the flatness number, F_F , to suspended floors without exception. But it prohibits the enforcement of F_L suspended floors, with the exception of fully shored slabs that are tested while the shores are still in place. Unshored floors, including most composite floors, are excluded from levelness testing.

It's hard to make suspended floors flat, and it's even harder to make them level. When a suspended floor must meet tight tolerances for surface regularity, the best choice is usually a topping or screed.

THE TR 34 SYSTEM

In the UK industrial floors are normally specified using the TR 34 system. (Concrete Society, 2016). It gets its name from the Concrete Society's *Concrete Industrial Ground Floors (Technical Report 34, Fourth Edition)*, called *TR 34* for short. The fourth edition changed the system from top to bottom, with new categories and tolerances, and totally different method to defined-traffic floors. The changes align TR 34 more closely with F-numbers.

The TR 34 system shares many features with F-numbers—a fact stemming from their common origin in research carried out by Allen Face in the late 1970s and early 1980s.

Like F-numbers, TR 34 controls both flatness and levelness. Again like F-numbers, TR 34 has different specifications for defined traffic and random traffic. The basic properties of 600-mm curvature and 3-m slope are the same in both systems, though identified by different letters. But beyond that there are important differences, and most of them favour F-numbers. Here are some shortcomings of TR 34 relative to F-numbers:

- TR 34 limits you to a small number of standard categories—three categories for defined traffic and four for random traffic. In contrast, F-numbers are continuously variable. You can choose whatever value you need, limited only by what is achievable in the field.
- On random-traffic floors, TR 34 requires separate tests with different instruments for 600-mm curvature and 3-m slope. The F-number system gets both from a single test. This means TR 34 surveys cost more and take longer.

- On defined-traffic floors for VNA trucks, TR 34 ties the specification to the lift height. This is based on a misunderstanding of why VNA trucks need flat floors. See Chapter 2. The F-number system lets the designer tailor the specification to the usage.
- TR 34 was written for industrial floors on ground level. It's not easily adapted to nonindustrial floors and elevated floors. F-numbers are more flexible and have been used on all kinds of floors.

The TR 34 system, in both its original and current forms, has been effective on many jobs. If you are designing a warehouse floor, ground-supported or pile-supported, it will meet your needs. If you are designing anything else, F-numbers are better.

STRAIGHTEDGE TOLERANCES

Some specifiers continue to specify floor flatness by reference to a 3-m (10-ft) straightedge, and this method is still found in British and American standards. The straightedge test is cheap and easy. Beyond that, there is not much to recommend it (Figure 20.5).

FACTORS THAT AFFECT SURFACE REGULARITY

These are the most important factors:

- structural deflection;
- curling;
- width of pour;
- accuracy of side forms;
- striking off and finishing methods.

STRUCTURAL DEFLECTION

Suspended floors all deflect, and their deflections are hard to control and predict.

Deflection has a huge effect on levelness and a smaller but still significant effect on flatness. Deflection is a serious problem for suspended floors that need to be level. ACI 117 recognizes this by simply eliminating the F_L levelness requirement on most

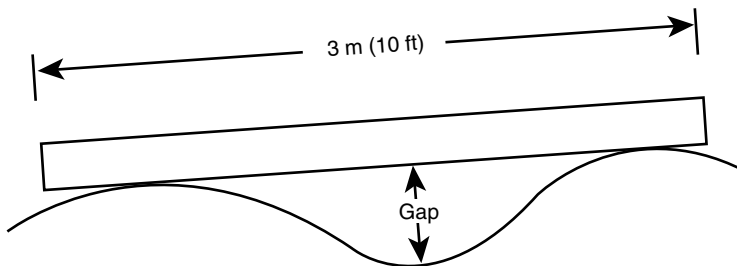


FIGURE 20.5 The straightedge test.

suspended floors. It says 'levelness tolerance shall not apply to slabs placed on unshored form surfaces and/or shored form surfaces after the removal of shores'. In effect, the ACI standard is telling us not to use ordinary suspended slabs where levelness matters.

That's good advice, to the extent we can follow it. But some suspended floors do need to be level, no matter what ACI 117 tells us. What are our options?

One answer is to overdesign the slab and its supports. Another is to lay a thin topping over the suspended structural slab. But a topping won't stop the floor deflecting under loads applied later.

Deflection is seldom a problem on ground-supported floors.

CURLING

This is a major cause of poor surface regularity on ground-supported floors. It can also occur with some toppings and some composite floors. Testing flatness and levelness during construction rarely detects curling, because the process unfolds over many months.

Chapter 14 discusses curling and presents some ways to minimize its effects.

WIDTH OF POUR

The narrower the pour, the easier is it to make the floor flat and level. The main reason is that a narrow pour allows a more accurate strike-off, at least with traditional (before the laser screed) methods. Superflat floors are almost always laid in narrow strips no more than 6 m (20 ft wide).

In wide-strip construction, where the floor is struck off with a vibrating screed, floor levelness tends to deteriorate as the pours get wider. Some vibrating screeds can span 24 m (80 ft), but you cannot expect them to maintain a very level surface over that distance.

Laser screeding reduces the connection between slab width and surface regularity. With a laser screed, some floorlayers can achieve good flatness and levelness on pours as much as 30 m (100 ft) wide.

ACCURACY OF SIDE FORMS

Side forms matter because they determine the elevation to which the floor is struck off. Forms have a big effect on levelness, but much less effect on flatness.

Laser screeding does not eliminate the importance of accurate side forms. Though the laser screed itself does not rely on the forms, its action stops about 0.5 m (2–3 ft) from the slab edges. The accuracy of the forms determines the surface regularity of that narrow strip between the slab edge and the laser-screeded surface.

With ordinary equipment, it is hard to set forms closer than ± 3 mm ($\pm 1/8$ in). But that's good enough for most floors.

Superflat floors need higher accuracy, though. Some floorlayers who specialize in superflat work use special forms with an adjustable top edge. Others use what look like ordinary steel or timber forms, but they take extra care in setting them.

It's not enough to set the forms level. They need to stay level till the concrete is finished. Forms need strong bracing to stand up to a heavy vibrating screed.

STRIKING OFF AND FINISHING METHODS

The method of strike-off has a big effect on levelness, but only a small effect on flatness. Finishing methods work the other way around, heavily affecting flatness but doing little for levelness.

Here are the main tools used for striking off, listed in order of decreasing levelness achieved:

1. hand straightedge riding on forms (narrow strips only);
2. full-size laser screed;
3. vibrating screed on narrow strips;
4. roller screed;
5. vibrating screed on wide strips;
6. lightweight laser screed;
7. hand straightedge on wet screeds.

When it comes to finishing, two things to consider are the amount of straightedge work and the use of pans for floating. Working the floor with hand straightedges, including highway straightedges, dramatically improves flatness. Floorlayers aiming for superflat tolerances normally straightedge the concrete many times in two directions, scraping and filling as the concrete grows harder. The narrow-strip layout almost universal for superflat floors makes the straightedge work more convenient.

Straightedges are less effective on wide-strip and large-bay pours. There floorlayers aiming for tight tolerances often choose pans for floating. Pans—especially the big ones used with riding trowel machines—flatten a floor better than float shoes and far better than hand floating.

Dry shakes tend to make floors less flat (but not less level) because they interfere with the finishing steps that enhance flatness. Phelan (1989) suggests that we avoid dry shakes if the required degree of flatness is higher than F_{r45} .

SUPERFLAT FLOORS

There is no universally accepted definition, but in general a superflat floor is one near the upper limit of the achievable. The first-recorded superflat floor—for Boots in Nottingham, England—was laid in very narrow strips (about 2 m or 6 ft wide), with screw-adjustable steel forms (Figure 20.6).

Modern practice is much closer to normal narrow-strip construction, but with some extra precision and straightedge work. These steps are typical:

1. Lay out the floor in strips no more than 6m (20 ft) wide, with construction joints in noncritical areas.
2. Set forms as accurately as possible with an optical level.
3. Check forms with a walking profiler.
4. Recheck forms just before pouring concrete and adjust as needed.



FIGURE 20.6 An unusual superflat floor, laid for an amusement park ride.

5. Pour concrete at a slump of 100–125mm (4–5in) with minimal variation between batches.
6. Compact concrete with poker vibrators.
7. Strike off with a hand straightedge riding on the forms.
8. Strike off again with a hand straightedge riding on the forms. See Figure 20.7.
9. Strike off with a 3-m (10-ft) highway straightedge at right angles to the forms. Lap each pass by 1.5 m (5 ft).
10. Strike off a third time with a hand straightedge riding on the forms.
11. Strike off again with a 3-m (10-ft) highway straightedge.
12. Wait for bleed water (if any) to form and then disappear.
13. Power float, making passes across the slab width.
14. Right after floating, scrape with a 3-m (10-ft) highway straightedge. Fill low spots with material scraped from high spots. See Figure 20.8.
15. Wait as long as possible.
16. Power trowel.



FIGURE 20.7 Reworking a superflat pour with a hand straightedge.



FIGURE 20.8 This worker has just scraped the floor with a highway straightedge and is about to add mortar to a low spot.

17. If possible, scrape again with a 3-m (10-ft) highway straightedge. Filling low spots will probably not be possible at this stage, but scraping high spots may be.
18. Continue power trowelling to produce the desired finish (usually burnished).
19. Survey the floor and mark out-of-tolerance spots.
20. Grind minor defects with a 250-mm (10-in) diamond disc.

As with any list of floorlaying steps, this one should be regarded as descriptive, not prescriptive. Some floorlayers get good results from somewhat different methods.

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21 Resistance to Wear and Chemical Attack

When a concrete floor is left exposed in the finished building, it needs to resist wear and chemical attack.

Wear is the erosion of a floor surface caused by solid objects rolling or sliding on it. It occurs every time a vehicle travels over a floor. Even foot traffic causes wear, as you can see on the steps of a public building.

Wear is mechanical, which distinguishes it from chemical attack. Chemical attack and wear often cause similar damage and may occur together, but they remain separate problems with separate solutions. Both issues are largely confined to industrial buildings. In nonindustrial buildings, most floors hide under floorcoverings. While that does not eliminate wear and chemical attack, it effectively transfers the problems from the concrete slab to the floorcovering. Coverings can be replaced and are not necessarily expected to last for the life of the building.

In industry, however, the concrete slab usually provides the wearing surface. A structural element, meant to last for many decades, is then subject to heavy wear and the possibility of chemical attack. That makes the industrial floor unique in building construction, challenging designers and floorlayers alike.

We in the concrete-floor industry have not always met that challenge. Wear and chemical attack cause serious problems and have resulted in the replacement of whole floors. In bad cases, the whole surface is destroyed to a depth of many millimetres (1/2 in or more), leaving the floor unusable. Even milder problems can create dust, which is unacceptable in some factories and warehouses.

The situation is so bad that some users won't accept a plain concrete floor. Believing that concrete is inherently weak, they spend fortunes on sealers and dust-proofers, some of which don't even help.

We can do better. Plain concrete floors can do amazing things, lasting for decades even under heavy industrial traffic. We just have to get a few details right.

THE TRADITIONAL APPROACH TO WEAR RESISTANCE

Though wear resistance is crucial, most floor specifications say little about it. If they address the subject at all, most designers still use method specifications rather than performance specifications. The traditional approach is to try to control wear resistance through one or more of these contributing factors:

- concrete compressive strength;
- water-cement ratio;
- curing;
- finishing methods.

This indirect approach sometimes works because those factors all matter, but it's risky. Many factors affect wear resistance and no specification can control them all directly. One floor may have good concrete strength but wear out because of poor curing. Another may have good strength and good curing and yet wear out because the main contractor used unvented heater.

Where resistance to wear is particularly important, the traditional response has been to specify surface treatments such as toppings, coating, and hardeners. Of the hundreds of products on the market, most fit into these categories:

- high-strength toppings (most often made of strong Portland-cement concrete, but sometimes of epoxy concrete or other materials);
- dry shakes (metallic or non-metallic);
- resin seals (polymer resins that coat and penetrate the floor surface);
- liquid hardeners (chemicals that are supposed to reach with concrete to harden the surface).

Surface treatments often succeed in preventing excessive wear. But they have serious drawbacks, the biggest of which is their price. Some cost as much as the slab. Another drawback is that surface treatments sometimes fail for reasons that have nothing to do with wear resistance. Toppings, dry shakes, and resin seals do not always bond to the underlying concrete.

There is a better way, which is to specify wear resistance and enforce it with performance tests on the finished floor.

CLASSIFYING WEAR RESISTANCE

British standards are miles ahead of American standards in this field. While ACI 302 addresses wear resistance, it does not tie its recommendations to any test, even though ASTM has several test methods that might have served. In contrast, BS 8204:Part 2 classifies wear resistance according to the results of a standard test that is both easy to perform and available all over the world.

Floors are divided into four classes, called AR0.5, AR1, AR2, and AR4. *AR* stands for abrasion resistance. The numerals represent the maximum wear depth in the Chaplin test, which we will get to in a moment.

The nomenclature has changed over the years. AR0.5 used to be called Special, and AR4 used to be called AR3. That's something to remember when reading older documents, including previous editions of this book. And there used to be a fifth class called Nominal, with a maximum wear depth of 0.80 mm, but it seems to have been abandoned (Table 21.1).

TESTING WEAR RESISTANCE

Over the years, researchers have built dozens of machines for measuring wear. Some abraded the floor with rolling wheels. Others used abrasive pads, dressing wheels, shot-blasting, or a combination of methods. In some tests, depth gauges determined the amount of wear. In others, a concrete sample was weighed before and after the test to reveal how much material was lost.

TABLE 21.1
British Classification of Wear Resistance

Wear Class	Degree of Wear Resistance	Maximum Wear Depth*	Typical Use	Source of Wear
AR0.5	Extremely high	0.05 mm	Very heavy-duty factories	Heavily loaded steel tyres, impact, dragging
AR1	Very high	0.10 mm	Heavy-duty factories and warehouses	Steel tyres, impact
AR2	High	0.20 mm	Medium-duty factories and warehouses	Hard plastic tyres
AR4	Good	0.40 mm	Light-duty factories and warehouses, offices, and shops	Rubber tyres, feet

* From standard test with Chaplin abrasion tester

These testers were built for research. They did not become standard instruments for enforcing performance specifications, though some of them undoubtedly could have been used for this purpose.

In America, several machines have been incorporated into standard tests. ASTM C779 describes three procedures for measuring the wear resistance of 'horizontal concrete surfaces'. Procedure A uses rotating and revolving discs with silicon carbide grit. Procedure B uses steel dressing wheels, and procedure C relies on heavily loaded ball bearings. Other ASTM tests deal with wear resistance but are less suitable for floors. ASTM C 418 describes a method for testing small concrete samples. ASTM C 944 describes another dressing-wheel test but one suited for small samples such as test cylinders. Two ASTM standards describe ways to test the wear resistance of coarse aggregates (not concrete) by tumbling them in a special drum called a Los Angeles machine. But as we shall see, coarse aggregate has little to do with wear resistance at the floor surface.

It is likely that one or more of these American tests could be used for or adapted to compliance testing as part of a performance specification for wear resistance. But that has not happened yet. The ASTM tests remain little used.

THE CHAPLIN ABRASION TESTER

In the early 1980s, the Cement and Concrete Association (now the British Cement Association) developed an instrument for measuring the wear resistance of concrete floors. Some early documents called it the accelerated abrasion apparatus, but it's now better known as the Chaplin abrasion tester after Ralph Chaplin, who worked on its development (Figure 21.1).

This device involves a spinning plate with three steel wheels. Following a circular path, the wheels simulate the wear caused by industrial vehicles. In the standard test, the plate makes 2850 revolutions; it takes about 15 minutes and makes a shallow groove in the floor. A gauge measures the depth of the groove at eight locations.



FIGURE 21.1 Chaplin abrasion tester.

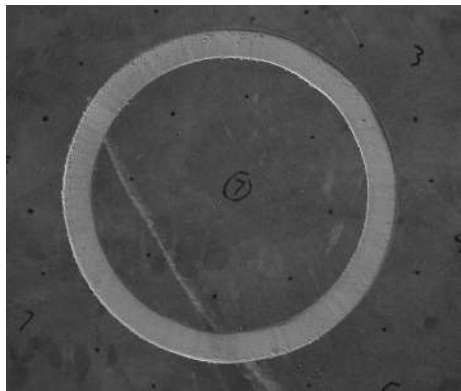


FIGURE 21.2 Wear ring made by the Chaplin test. The test result is the depth of the ring, measured at eight spots and determined by before-and-after micrometer readings.

Wear depth is reported to 0.01 mm. Most concrete floors show wear depths between 0.02 and 1.00 mm (Figure 21.2).

When a floor is tested for compliance, the Concrete Society (2016) recommends three separate Chaplin tests or one test per 4000 m² (43,000 ft²), whichever is more.

The test has some limitations. Because it uses rolling wheels, it is best suited to floors on which wheeled vehicles are the main source of wear. Chaplin results seem

to correlate reasonably with sliding wear, as well. But the Chaplin test may not be appropriate where the potential source of damage is impact, corrosive wear (wear plus chemical attack), or erosion from moving liquids.

Another limitation is that the test does not produce enough wear on extremely hard floors. Some AR0.5 floors show wear depths of only 0.01mm or so—right at the limit of accuracy of the depth gauge. For this reason, the standard does not discriminate well between highly resistant floors.

MOHS HARDNESS

Some use Mohs hardness as a measure of wear resistance. The Mohs scale, invented for use on rocks, ranks materials according to how well they resist scratching. The scale goes from 1 (talc) to 10 (diamond). A Mohs test kit includes 8 numbered picks that differ in hardness. When performing the test, you try to scratch a surface with several picks. Normally, you find that one pick makes a scratch while the pick one number down on the scale leaves a smear like a pencil mark on paper. The test result is then reported as halfway between those two pick numbers. If the 3-pick scratches and the 2-pick smears, the test result is 2.5. Readings always end in .5. I have seen readings as low as 1.5 and as high as 7.5 on concrete floors, but most range from 3.5 to 5.5.

Mohs testing of concrete floors has become popular, especially in connection with polishing. It's not hard to see why. A Mohs test takes a minute or two, and the whole kit fits in a coat pocket. There are as yet no standard guides for the Mohs numbers we can expect on concrete floors. From my own experience, I would say that readings below 4.5 sometimes indicate a problem, and readings below 3.5 always do.

FACTORS THAT AFFECT WEAR RESISTANCE

Many factors affect wear resistance. All of the following have been identified at one time or another as important factors, but it turns out that some don't matter much:

- concrete compressive strength;
- finishing methods;
- aggregates;
- dry shakes;
- liquid hardeners;
- resin seals;
- curing;
- carbonation.

CONCRETE COMPRESSIVE STRENGTH

Many people believe the concrete's compressive strength determines its resistance to wear. Some designers seem to think strength is the only factor worth worrying about.

Surprisingly, research reveals only a weak connection between concrete's measured strength and its wear resistance in a finished floor. The connection is weak

because wear occurs at the surface, which may be much stronger or much weaker than the bulk of the concrete below. Big differences in concrete strength—one study looked at 36 versus 85 MPa (4200 versus 9900 psi)—do show up in wear tests (Chaplin, 1986, 10-11; Scripture et al., 1953, 316). But within the strength range found in ordinary floors, other factors—notably finishing and curing—dominate. Concrete with compressive strength ranging from 25 to 40 MPa (3000–5000 psi) has produced floors in every wear class.

FINISHING METHODS

These matter more than concrete strength. Good floorlayers take justifiable pride in their ability to give concrete a durable finish by floating and trowelling.

A smoother finish means greater resistance to wear. This is true not just for concrete; it seems to be a general principle applicable to most if not all materials. All else being equal, a power-trowelled floor will resist wear better than a floated or broomed floor. And among trowelled finishes, it is the burnished finish produced by multiple passes that resist wear best. For floors that must meet wear class AR1 or better, it is risky to specify or allow anything less than a burnished finish produced by power trowelling (Figure 21.3).

AGGREGATES

The choice of fine aggregate affects a floor's resistance to wear. Chaplin (1986, p. 11) compares manufactured sand (crushed limestone fines) to several types of natural sand. When tested with a Chaplin machine, the slabs made with crushed limestone wore about three times as much as those made with natural sand.

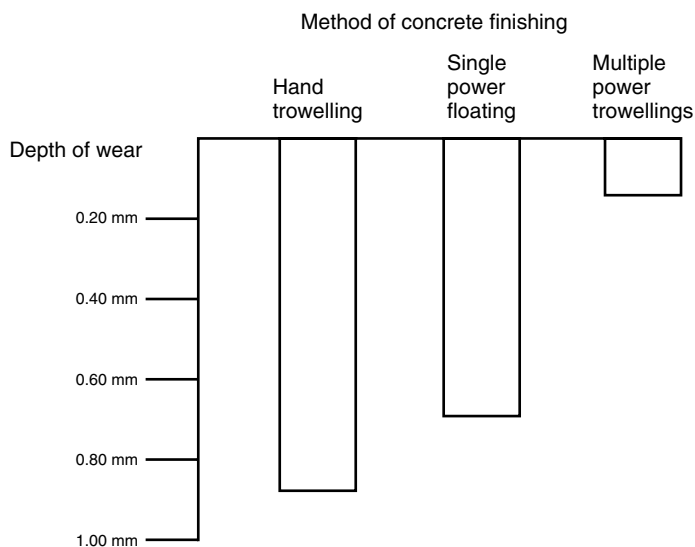


FIGURE 21.3 Effect of finishing methods on wear resistance.

In contrast to the fine aggregate and contrary to some long-held beliefs, coarse aggregate seems to have little or no effect on wear resistance. Wear tests show no significant difference between concrete made with soft and hard coarse aggregates. Even materials as different as slag and marble on the one hand and granite and trap-rock on the other give similar results (Scripture et al., 1953).

The likely explanation is that the finishing process pushes the coarse aggregate down, leaving at the surface a mortar consisting of cement and fine aggregate. It is this mortar, and not the coarse aggregate farther down, that must resist wear.

Coarse aggregate undoubtedly plays a role in resisting wear after the mortar layer has been destroyed. But by then, the floor will have already failed in the eyes of most users.

DRY SHAKES

These are often specified for the sole purpose of enhancing wear resistance. They don't always accomplish that purpose.

Shakes vary greatly in their effect on wear resistance because they come in two different forms: non-metallic and metallic. Non-metallic shakes are brittle mineral aggregates—in other words, rock. Metallics consists of iron filings.

The non-metallics cost less but are far less effective. Research reveals little benefit from dry shakes made of brittle mineral aggregates, no matter how hard the rock (Scripture et al., 1953; Sadegzadeh and Kettle, 1988). My own research confirms their findings.

In contrast, metallic dry shakes unmistakably improve a floor's resistance to wear. Tests show that a metallic shake can be several times as resistant as plain concrete (Scripture, Benedict and Bryant, 1953; Chaplin, 1986). Tested with a Chaplin machine, some metallic-shake floors show less than 0.01 mm of wear.

Such results would make a metallic shake the finish of choice for industrial floors, except for a few rather serious drawbacks. Dry shakes are costly; they sometimes delaminate; and they tend to make floors less flat.

Non-metallic dry shakes are hard to justify if their only purpose is to resist wear. They may make sense for other purposes, such as to colour a floor. Metallics are worth considering for floors that need an extraordinary degree of wear resistance.

LIQUID HARDENERS

These are silicate salts dissolved in water. They have a small but measurable effect on wear resistance. Sadegzadeh and Kettle (1987) report that silicate hardeners improved the wear resistance of poorly cured slabs by 15–38%.

Hardeners are cheap and may be useful remedies where a small improvement in wear resistance is called for. For example, if a floor shows wear depth just over the maximum allowed—say, 0.23 mm when the specification says 0.20 mm—then a liquid hardener just might bring it into compliance. You cannot expect much more than that, however.

The use of liquid hardeners on new floors, absent any problems, is hard to justify.

RESIN SEALS

These coat and impregnate the concrete surface with resins. The most common resins are polymers such as epoxy, polyurethane, and acrylic.

Some resin seals do very well in wear tests. Sadegzadeh and Kettle (1987) report one experiment in which a moisture-curing polyurethane resin shifted floor slabs from the worse than AR4 to AR2.

Some resin-based curing compounds produce extremely good test results. They seem to have a double effect. Besides keeping in moisture like any good cure, the resins fill pores in the concrete.

CURING

This has a huge effect on wear resistance. Chaplin (1986) suggests that floors cured under polyethylene can be several times more wear resistant than uncured floors. Fentress (1973), using a totally different test, reports similar improvement for floors cured under wet hessian (burlap) (Figure 21.4).

CARBONATION

This occurs when carbon dioxide in the air reacts chemically with fresh concrete. It can ruin a floor, resulting in a crumbling, friable surface layer that can, in the worst cases, go 12 mm ($\frac{1}{2}$ in) deep.

The usual culprit is an unvented heater burning fossil fuels and discharging their exhaust within the building. Internal combustion engines also contribute but rarely cause troublesome carbonation on their own.

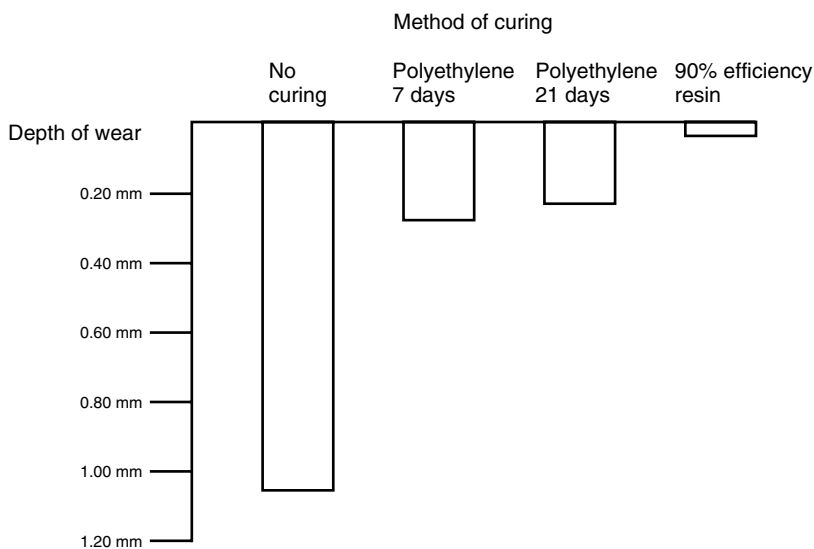


FIGURE 21.4 Effect of curing on wear resistance.

There is no safe level of carbon dioxide. Even the normal quantity of carbon dioxide found in the atmosphere makes concrete slightly weaker than would otherwise be the case. You can't do anything about that, but you can minimize the contribution from other sources.

Some curing methods block carbon dioxide and may be worth considering if no other choice exists. But the right solution is to avoid unvented heaters at all costs.

CORRECTING LOW WEAR RESISTANCE

There are several ways to improve the wear resistance of an existing floor. Since they don't all work on every floor, repair often involves trial and error. The use of a Chaplin machine or other wear tester will help determine what works. Here are some things to try:

- grinding;
- late curing;
- surface treatments;
- toppings;
- cleanliness.

GRINDING

Poor wear resistance often stems from a surface that is markedly weaker than the underlying concrete. This can result from poor finishing, lack of curing, early freezing, or carbonation.

If the weak layer is less than 3 mm ($\frac{1}{8}$ in), grinding is likely to succeed.

Large-scale grinding should not start till a trial proves it will work. Generally, you only have to grind a square metre (square yard) or two, with wear tests before and after, to find out.

You can sometimes save money by grinding only those parts of the floor that get traffic. In a warehouse, grinding would rarely be needed under racks.

Depending on usage and user expectations, you may have to follow up with polishing to match the original surface texture. Polishing with 400-grit abrasive is roughly equivalent to a burnished finish.

LATE CURING

Where poor curing is the reason for a weak surface, it is sometimes possible to restart the curing process by flooding the floor with water. Chaplin (1986) describes a test in which slabs were air-dried for 28 days and then soaked and cured under polyethylene for 7 days. The delayed curing gave the floor's wear resistance a boost. However, not even the late-cured concrete was as wear-resistant as concrete cured well from the start (Figure 21.5).

SURFACE TREATMENTS

We have already considered the effect of liquid hardeners and resin seals on new floors. Both kinds of treatments are also used on existing floors.

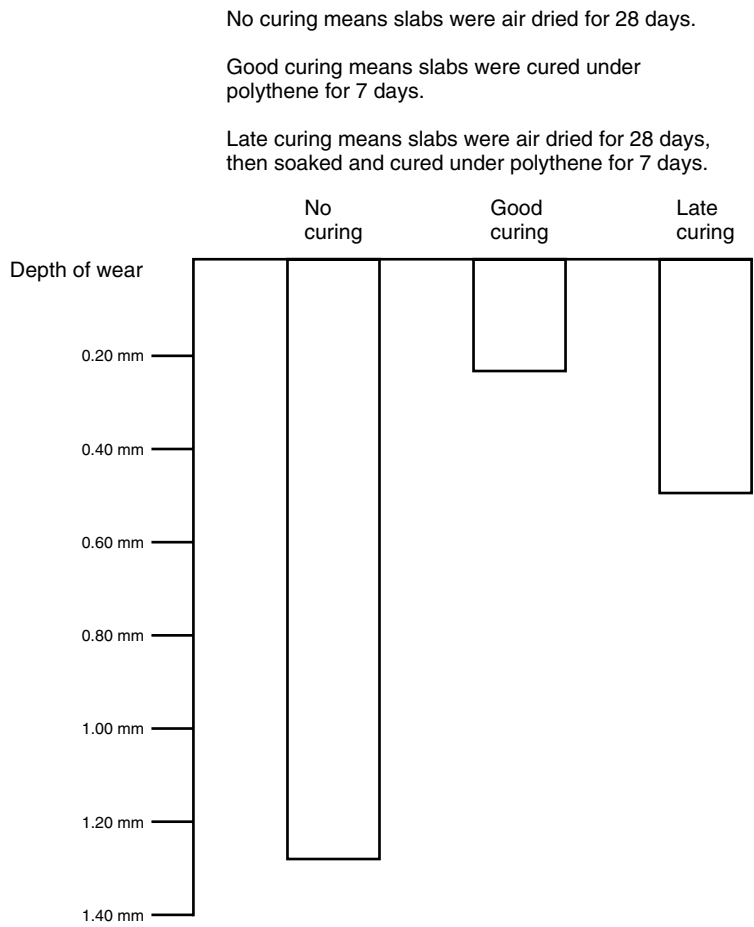


FIGURE 21.5 Effect of late curing on wear resistance.

Liquid hardeners are cheap and easy to use but give at best only a modest improvement in resistance to wear. Hardeners are most effective on concrete with a low water–cement ratio, a condition often not met on floors with poor wear resistance.

Resin seals work better and have saved many floors.

TOPPINGS

A concrete topping can be designed for any desired degree of wear resistance. This should be the method of last resort, however, due to high cost. And with bonded toppings, there is always a risk the bond will fail. An unbonded topping eliminates that risk but raises the finished floor elevation by at least 100 mm (4 in).

CLEANING

Clean floors last longer than dirty ones. Loose debris leads to what is called three-body wear, in which the debris particles roll between vehicle tyres and the floor surface.

Depending on what the debris consists of, this kind of wear can be destructive. What's more, some kinds of debris lodge in vehicle tyres, and that also increases wear.

RESISTING CHEMICAL ATTACK

Chemical attack may mimic wear, and some of the measures that help concrete resist wear also work against chemical attack. But the two processes are fundamentally different and may require different solutions.

CONCRETE'S CHEMICAL RESISTANCE

Plain concrete resists alkalis and mineral oils well. But it's readily damaged by acids, fats, and sugar solutions. All three occur in food processing plants, and acids are widely used in many other industries. Warehouse floors often come under attack from the sulphuric acid used in lift-truck batteries.

Only so much can be done to make plain concrete more resistant to chemicals because we are dealing with basic properties of the material. We are not helpless, however. These steps all help concrete resist chemical attack:

- higher cement content;
- lower water–cement ratio;
- good compaction;
- good curing;
- the smoothest possible finish.

They all work by making the concrete less porous. Dense concrete is less pervious to liquids and thus better able to resist liquid chemicals.

Another option is to make the concrete out of something beside hydraulic cement. Epoxy or sulphur can serve as cement, producing a concrete that resists some chemicals much better than ordinary concrete made with Portland cement.

Nobody makes whole slabs out of epoxy because it costs too much and generates too much heat as it cures. It works well as a topping, though, providing excellent resistance to most acids and other chemicals. Due to its extreme stickiness before it has hardened, epoxy concrete is hard to finish. Some contractors let it set and then finish it by sanding, followed by the application of a final thin coating.

Sulphur concrete, in contrast, can replace Portland-cement concrete throughout the slab. It is made by mixing dry aggregates with elemental sulphur. The batch is then heated to sulphur's melting point and placed in the forms. It hardens by cooling and can be worked with normal concrete tools. The finished product, with structural properties similar to those of ordinary concrete, resists most acids and a wide variety of salts. It has low resistance to alkalis, however.

PROTECTING THE CONCRETE

Since our ability to improve concrete's inherent resistance to chemical attack is so limited, the main defence is to put something between the concrete and the aggressive chemicals.

Toppings and Coatings

A very common method of protection is to cover the concrete slab with a chemical-resistant topping or coating. Manufacturers sell a wide range of products for that purpose, including:

- polyurethane paints;
- epoxy paints;
- epoxy-mortar toppings;
- epoxy-concrete toppings;
- polyester-mortar toppings;
- latex-modified concrete toppings;
- asphalt toppings.

No product works for every application, and standards are few. You have little choice here but to read the manufacturers' brochures and decide on one proprietary product or another. Proceed with caution because it is easy to spend a fortune on a coating or topping that does not work.

Tiles

In the food processing and some other industries, special tiles or bricks are often laid over the concrete floor. They can work very well, but only if the covering is continuous and well maintained. Even one open joint or crack can let damaging chemicals reach the concrete, where they may go undetected till the slab is ruined.

Tiles and bricks are no better than the grout or mortar that goes between them. Because ordinary grouts and mortars contain Portland cement, they are no better than concrete at resisting chemical attacks. Grouts made with epoxy or furan resin work better in aggressive environments but can be tricky to install (Aalberts et al., 1989). Furan grout comes only in black.

Sealing Joints and Cracks

It does no good to coat a concrete floor with highly resistant material if joints and cracks remain open gateways for aggressive liquids. There have been some interesting failures in which liquids got past an epoxy topping and ate away the concrete underneath.

One solution is to fill all gaps and then cover everything with a chemical-resistant coating. But that does not always work because materials tough enough to serve as a wearing surface often lack the elasticity to stay intact as joints and cracks widen over time.

The alternative solution is to carry joints and cracks through the coating or topping and then seal them, choosing a chemical-resistant caulk. The joints and cracks then remain visible, though sealed, at the floor surface.

Cleanliness

The degree of chemical attack is closely tied to how long the chemical stays in contact with the floor. Even highly aggressive spills do little harm if they are cleaned up right away.

When deciding whether a concrete floor needs a coating, topping, or floorcovering to protect it from chemical attack, ask these questions:

- Are spills rare, occasional, or continual?
- Are spills cleaned up promptly?

Where spillage is continual, the floor probably needs special protection. Where spillage is rare or occasional, it may make sense to use plain concrete and provide for cleaning. Some floors in harsh environments are sloped to drains. When the floor users detect a spill, they wash it down with water, minimizing the time the attacking chemical can act on the concrete floor.

ATTACK FROM BELOW

So far, we have looked only at attacks caused by chemicals spilled from above. Danger also comes from below, caused by chemicals dissolved in ground water. The main risk comes from sulphate-bearing ground water. It's widespread, but we have at least three defences against it:

- good, strong concrete;
- sulphate-resisting cement;
- pozzolans added to the concrete;
- a vapour barrier under the slab.

Sound, strong, well-compacted concrete can go a long way towards resisting sulphate, even when the mix contains ordinary Portland cement. According to one authority, a concrete mix designed to resist sulphates should have a cement content of at least 280 kg/m³ (470 lb/yd³) and a water–cement ratio not greater than 0.55 (Blackledge, 1980). Most concrete used in floors meets both requirements anyway, but it's a start.

For more protection, consider replacing ordinary Portland cement (American Type I) with sulphate-resisting cement (American Type V), if you can find it. Americans have the added option of using Type II cement, which resists sulphates better than Type I, though not quite so well as Type V. Fly ash also offers some protection.

Vapour barriers provide some protection against sulphates in the ground. Many designers take the position that the protection provided by a vapour barrier is effectively total and makes other measures redundant. That issue is not settled, however. Klinger et al. (2021) present a thorough discussion of the subject.

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22 Preparation for Floorcoverings

A theme of this book is that plain, direct-finished concrete slabs serve well for many purposes. Nevertheless, some floors need to be covered. In houses and offices, floorcoverings are almost universal. In warehouses and factories, some floors get coatings or toppings to give them properties hard or impossible to achieve with plain concrete.

Though some products can be put down on almost any floor, others have strict requirements. Here are the main points to consider when a concrete slab will receive a floorcovering:

- moisture;
- bond;
- surface regularity.

MOISTURE

Water lies at the root of most floorcovering failures. Damp concrete under floorcoverings leads to rot, unsightly mildew, and growth of dangerous moulds. Moisture makes toppings and coatings peel off and wrecks the glue under vinyl tile and stuck-down carpet.

Reading some books and articles on floor design and construction, you might get the idea that protecting floors from moisture is not very important. Do not make that mistake. Moisture is a problem, and controlling it is a challenge. The reason some writers say little about it is that they focus on the direct-finished, bare concrete floors used in warehouses and factories. Moisture does not harm those floors. But if you deal with residential, office, or commercial floors—or indeed with any slabs that receive floorcoverings—you need to think about moisture.

Apart from floods and roof leaks, which lie beyond the scope of this book, damaging moisture comes from two sources: the groundwater under the floor and the mixing water added to the concrete during construction.

MOISTURE FROM BELOW

The ground below the floor always contains some water. In moist climates, it can contain a lot of water, reaching the point of total water saturation—called the water table—just a metre or two below the surface. If you lay a concrete floor directly on the ground, water vapour rising through the ground will tend to accumulate on the underside of the slab. But it will not stop there because concrete is somewhat pervious to water vapour. Some water vapour will pass through.

What happens next depends on what lies on top of the concrete floor. If the concrete is bare, the water vapour will pass into the air and never be noticed. But if the concrete is covered with a material less pervious to moisture, water will collect under the covering. Or if the concrete is covered with a moisture-sensitive material, water will enter that material. Damage ensues.

To prevent that damage, some floors need protection from rising water vapour. Table 22.1 classifies floorcoverings according to their vulnerability. Coverings with no vulnerability can be laid with little or no concern for protection. Materials having

TABLE 22.1
Vulnerability of Floorcoverings to Moisture Damage

Floorcovering	Vulnerability		
	None	Moderate	High
Access flooring	X		
Anti-static vinyl			X
Asphalt topping	X		
Bitumen topping	X		
Brick	X		
Carpet			X
Cement–sand screed	X		
Ceramic tile	X		
Composite vinyl tile		X	
Concrete topping	X		
Cork			X
Epoxy coating		X	
Epoxy topping		X	
Felt-backed vinyl			X
Hardwood			X
Linoleum			X
Magnesite (magnesium oxychloride)			X
Polyester resin			X
Polyurethane coating		X	
Rubber sheet			X
Semi-flexible vinyl tile		X	
Stone	X		
Terrazzo	X		
Vinyl sheet			X
Vinyl tile		X	
Wood block (decorative, laid in cold glue)			X
Wood block (industrial, laid in hot mastic)	X		
Wood strip or plank			X

Note: Invulnerable materials may become vulnerable if stuck down with moisture-sensitive glues.

moderate vulnerability are sometimes laid without protection, especially in drier regions. Coverings with high vulnerability should always be protected.

Concrete itself—including concrete toppings—is not damaged by moisture. Bare concrete slabs normally need no protection from damp, except where the ground water contains sulphates. Rising water vapour has caused debonding of concrete toppings, however, where a latex bonding agent was used between base slab and topping.

Vapour Barriers

These provide the main defence against water vapour rising from the ground.

Some people draw a distinction between vapour barriers and vapour retarders, reserving the former term for products that totally block water vapour and the latter for products that block almost all of it. ACI 302 takes a hard line on this, saying ‘True vapour barriers are products, such as rugged multiple-reinforced membranes, that have water transmission ratings of 0.00 perms per square foot per hour when tested in accordance with ASTM E 96’. The polyethylene sheet normally used under floor slabs doesn’t meet that absolute requirement, so ACI 302 insists on calling it a vapour retarder. Well, that’s one opinion. Another ACI standard, *Concrete Terminology*, disagrees. It defines *vapour barrier* as a ‘membrane located under a concrete floor slab that is placed on the ground to retard transmission of water vapour’ and *vapour retarder* as ‘a membrane that impedes the transmission of gas molecules’. Not much difference between them. And the Australian *Guide to Industrial Floors and Pavements* (Cement Concrete and Aggregates Australia, 2009, 47) uses *vapour barrier* to describe polyethylene sheet 0.2 mm (8 mils) thick, a product that does not meet ACI 302’s definition. Most people I talk to still say *vapour barrier*, except in the UK where they call it a damp-proof membrane or DPM.

Whatever the name, the common material for that purpose is polyethylene sheet, and it comes in different thicknesses. American building codes now call for at least 0.15 mm (6 mils), though thinner material used to be common. In the UK, the standard vapour barrier is twice as thick—0.30 mm (12 mils), also called 1200-gauge. Australia goes with 0.2 mm (8 mils). All those thicknesses do fine if the sheets remain whole. The best argument for thicker material is that construction activities are less likely to damage it. Very thick vapour barriers, going up to 1.5 mm (60 mils), are used on brownfield sites to block methane and other dangerous gasses (Figure 22.1).

American codes allow the sheets to be laid with 150-mm (6-in) laps and do not require taping. Many designers specify bigger laps or taping, or both. The UK’s National House Building Council (2024) requires 300 mm (12 in) laps that must be taped. Interestingly, an Australian guide takes a contrary position, recommending 200-mm (8-in) laps and arguing against taped seams (Cement Concrete and Aggregates Australia, 2009, 47).

You can specify vapour barriers by performance instead of thickness. ACI 302 says permeability should not exceed 0.2 perm (0.3 US perm) when tested according to ASTM E96.

The vapour barrier normally goes directly under the concrete slab. Other locations are sometimes specified, but the arguments for them are not compelling. And if the vapour barrier also serves as a slipsheet, under the slab is the only possible location.



FIGURE 22.1 Heavy-duty vapour barrier with sealed seams, on a brownfield site.

What to Do When the Vapour Barrier is Missing

Sometimes, you need to lay a floorcovering where the floor has no vapour barrier. The barrier may have been forgotten, or the floor usage may be changing from one that did not need protection from water vapour. It's a challenging situation but not hopeless. Consider these remedies:

- Cover the slab with an unbonded topping or unbonded cement–sand screed, using a membrane between the slab and the topping.
- Install a vapour barrier between the slab and the floorcovering. This only works for a few kinds of coverings, such as wood flooring laid on sleepers.
- Choose a floorcovering not easily damaged by moisture. Some choices, such as ceramic tile, brick and stone, are immune to water damage.
- Test the concrete for moisture content to see if it really is damp enough to cause trouble.

If you try the last suggestion and test for moisture, use judgment when interpreting the test results. Readings change over the course of a year and from year to year.

MOISTURE FROM WITHIN

Water vapour rising from the ground is not the only source of damaging moisture. Even on the driest sites, every concrete slab, concrete topping, or cement–sand screed starts life soaking wet. The excess water eventually evaporates, but till it does, it can

interfere with moisture-sensitive floorcoverings. In some areas, it is a bigger problem than moisture rising from the ground.

The key is to let the concrete dry out before installing a floorcovering, but that's easier said than done because it takes so long. One rule of thumb says to allow four weeks for every 25 mm (1 in) of slab or screed thickness. Following that rule, you would have to wait 16 weeks before covering the typical 100 mm (4 in) house or office slab. Thick industrial slabs would need even more time.

That four-weeks-per-25-mm rule is just a rough guide, however. Slabs dry out faster in hot, dry weather and in winter when the building is heated. On the other hand, the process takes much longer in cold, damp conditions and on outdoor pours where the floor is repeatedly drenched with rain.

Instead of waiting a prescribed length of time, some floorcovering contractors prefer to test the concrete's moisture content. A simple but reasonably effective test is to tape down a small square of polyethylene sheet overnight. If you see water the next day, the concrete is probably too wet. Some contractors get instant results using hand-held testers that measure the concrete's electrical resistance, giving a simple 'pass' or 'fail'. Others use hygrometers that give a relative humidity (RH) reading in percent.

BOND

Most floorcoverings are glued or stuck down in some way to the concrete. Some coverings, such as carpet and vinyl tile, will stick well enough to any concrete surface that is clean and dry. But coverings in the following list require a strong bond:

- bonded concrete toppings;
- bonded cement–sand screeds;
- almost all paints and coatings.

For any of those, the concrete surface should be at least slightly rough, free of weak laitance and very clean. The following methods have been used with success, though not all are suitable for every kind of floorcovering:

- scabbling;
- shot-blasting;
- grinding;
- scarification;
- scratch finish;
- acid etching.

Scabbling roughens the concrete by hammering. The typical scabbler has several hardened-steel head that move up and down, driven by compressed air. Scabbling should continue till it exposes the coarse aggregate. It does a good job but makes a lot of noise and leaves a mess. The action is too violent for some suspended floors. And the resulting surface is too rough for most coatings and for very thin toppings.



FIGURE 22.2 A surface prepared by shot-blasting.

Shot-blasting erodes the concrete by driving tiny steel balls (shot) against it. The shot is recirculated, and the concrete dust is extracted by vacuum. Shot-blasting is clean and quiet, making it a good choice for a building in use (Figure 22.2).

Grinding is not common but works well, leaving the surface smoother than most other methods, though still rough enough for a good bond.

A scarifier roughens the surface with a rotating cylinder. Special washers that resemble small gears are mounted loosely on the cylinder's surface, where they bounce and rattle against the concrete, breaking off small chips.

Some builders prepare a floor by giving it a scratch finish or by leaving a rough-tamped surface. Both methods are less reliable than scabbling, shot-blasting, grinding, or scarification, all of which remove the concrete surface and can be performed immediately before the floorcovering goes on. The American Concrete Institute suggests a scratch finish may be good enough but warns it must be kept clean or cleaned later with detergent and acid. UK authorities are even less encouraging. Deacon (1976) warns us: "Preparation is simplified if the base is left smooth and not ridged with tamp marks. A heavily tamped surface alone does not provide an adequate key".

In acid etching, the floor is scrubbed with muriatic (a chemist would call it hydrochloric) acid. This is useful for cleaning but cannot really replace mechanical methods.

No matter how you prepare the surface, the effort will go to waste if the concrete is not clean when the covering is laid. Cleaning the concrete thoroughly is not good enough. It has to stay clean or be cleaned again. Many a failure has occurred because a well-prepared base slab was fouled by other construction trades. A little dust or even the overspray from nearby painting can prevent bond.

To ensure cleanliness, it's wise to apply the covering as soon as possible after the base slab is prepared. Even one day may be too long to wait on a dusty building site. Some contractors cover the prepared surface with polyethylene sheets or building paper to keep it clean.

SURFACE REGULARITY

This matters where the floorcovering is a thin sheet material such as vinyl tile. Minor irregularities show through and can become even more obvious than on bare concrete. The problem also occurs with some floor coatings, especially those that are opaque and glossy.

The objectionable defects fall into two categories.

The first category consists of bumps and dips having a wavelength of 0.3–1.2 m (1–4 ft). A standard flatness test will detect such defects, and the right flatness specification, if enforced, will prevent them. Unfortunately, it is hard to determine the right flatness specification since we are dealing here with aesthetics and personal opinion. Most users are happy with an F_F30 surface (between FM 1 and FM 2 in the British TR 34 system). Many live with worse. But some particularly demanding users have complained even where the surface measured above F_F50 (well above FM 1).

The second category consists of very short, sharp defects such as trowel marks, faulted joints and cracks, and poorly finished construction joints. Standard flatness tests usually miss such defects. The human eye is the only reasonable test device for such defects.

If detected in time (i.e., before the floorcovering is laid), surface irregularities can be corrected by these methods:

- grinding;
- covering the slab with a cement–sand screed;
- application of a proprietary smoothing compound (often but inaccurately called a levelling compound);
- use of a more forgiving floorcovering.

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Part 6

Sustainability



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23 Reducing Carbon Footprint

Worldwide, concrete has an enormous carbon footprint, and concrete floors are responsible for much of it. Cement is the main offender.

Exact numbers are hard to come by because the methods of calculating carbon footprint are complicated and don't all give the same answer. Depending on who you ask, cement could be the source of 6% of total CO₂ emissions. Or it could be 8%. But the details hardly matter because the basic facts are obvious:

- The making of cement generates a lot of CO₂.
- Concrete uses a lot of cement. The typical concrete mix is about 12% cement by mass.
- Concrete floors use a lot of concrete. The typical 50 000 m² warehouse floor contains about 24 000 tonnes of concrete.

Concrete floors are part of the problem. Can they be part of the solution?

If the goal is carbon neutrality—net zero—the path forward for concrete floors is not clear. As long as we stay tied to Portland cement, total decarbonization will be hard. According to a World Economic Forum report (2024), 35% of cement's CO₂ emissions comes from the fuel burned to heat the clinker. That could be reduced to zero with alternative heat sources. But 53% comes from the chemical processing of the limestone that goes into the cement, and nobody has a plausible plan for eliminating that. As the World Economic Forum says in a slightly different context, '50% of emissions reductions needed to achieve net-zero goals are expected to come from technologies not yet available at scale'. In other words, we need a breakthrough.

Short of a breakthrough, we still have opportunities to reduce the carbon footprint of the concrete floors we build, and that's what this chapter is about. I'll list some steps that are already available, along with a few that are not quite ready but could be soon. But I won't be addressing the really big stuff, like decarbonizing the cement manufacturing industry.

PORTLAND-LIMESTONE CEMENT

This is Portland cement blended with limestone powder. It's already available in many places. Americans call it Type IL and allow up to 15% limestone powder by mass. Canadians call it Type GUL and have the same 15% limit. In Europe, Type CEM II/A-LL can go up to 20%. Higher percentages are possible, but above 15%, the side effects make the product hard to use in floor construction.

EFFECT ON CARBON FOOTPRINT

Adding powdered limestone to cement reduces carbon footprint in two ways. First, it lets us make concrete with less Portland cement while keeping the same strength. Portland cement is the concrete's most carbon-intensive component. Second, it reduces the heat needed to make cement.

The cement companies claim that switching from straight Portland to Portland-limestone cement reduces the carbon footprint of the manufacturing process by about 5%. The reduction in the whole floor's carbon footprint will be considerably less.

OTHER BENEFITS

None that I am aware of.

DRAWBACKS

Some floorlayers report finishing problems, probably related to reduced bleeding. The risk of plastic-shrinkage cracking, crazing, and delamination may be higher. I expect these problems will fade away as floorlayers get used to the product.

Portland-limestone cement has been blamed for higher shrinkage and lower strength, but the cement industry disputes those claims.

FLY ASH

This is a fine powder recovered from the smokestacks of coal-burning power stations. Though it is not really cement, it has properties that let it replace some of the cement in a concrete mix. In floor slabs, the quantity of fly ash should not exceed 20% of the total powder content by mass. (Higher percentages are possible in some other concrete structures.) This does not mean, however, that we can replace 20% of the cement with fly ash because the replacement ratio is almost always less than 1:1.

EFFECT ON CARBON FOOTPRINT

Fly ash reduces carbon footprint by reducing the amount of cement in the floor.

There is some irony here because the process that creates fly ash, burning coal to make electricity, has a huge footprint. But presumably that would take place anyway, so we are getting a free ride.

OTHER BENEFITS

Fly ash makes concrete more resistant to sulphates in the ground and is sometimes used just for that reason. Fly ash also makes concrete set slower, which can be desirable in hot weather.

Fly ash can make a floor cheaper but only in certain places. It seems only right that fly ash would cost less than cement since it's a waste product. But increased demand,

coupled with reduced supply as less coal is burned, has changed the economics. Fly ash now costs extra in some markets.

DRAWBACKS

Fly ash makes concrete set slower. I listed that as a benefit and so it is—but only in hot weather. In cold weather, the slower set is a drawback and increases the risk of early cracking. Under some conditions, we might have to add an accelerator, which adds cost and has drawbacks of its own, to offset the retarding effect of fly ash.

Concrete with fly ash requires extra attention to curing. Without good curing, the floor will have lower resistance to wear.

Much like Portland-limestone cement, fly ash reduces bleeding and that can lead to finishing problems.

If the world is really headed towards net-zero, fly ash will become scarce as coal-fired power stations go away. It's not something to rely on for the long term.

SLAG

This is short for ground granulated blast furnace slag, a cementitious powder made from a waste product of steel manufacturing. In its effects, both good and bad, it closely resembles fly ash. But it can be used safely at higher dosages, up to 40% of the total cementitious content. And it seems to have fewer side effects.

EFFECT ON CARBON FOOTPRINT

Slag reduces carbon footprint by reducing the cement content. Compared to fly ash, slag has a greater effect because it can be used at higher cement-replacement levels—40% instead of 20%. Slag generally replaces cement 1:1.

You can use both fly ash and slag in the same mix but not at the percentages recommended above. The cement replacement material, fly ash and slag combined, should not exceed 50% of the total powder by mass.

OTHER BENEFITS

Concrete with slag sets slower. This is a benefit in hot weather.

Slag makes concrete lighter in colour. This improves light levels in the building and might allow a small reduction in lighting costs.

DRAWBACKS

Concrete with slag sets slower. I listed that as a benefit and so it is—but only in hot weather. In cold weather, the slow set is a drawback and increases the risk of early cracking. Under some conditions, we might have to add an accelerator, which adds cost and has drawbacks of its own, to offset slag's retarding effect.

Concrete with slag requires extra attention to curing. Without good curing, the floor will have lower resistance to wear.

NATURAL POZZOLANS

Fly ash and slag are called pozzolans. The original pozzolans were natural volcanic deposits, and the Romans made concrete with them.

The modern concrete industry doesn't make much use of natural pozzolans, except for a few special applications unrelated to floor construction. But that could change. Cementitious volcanic deposits are available in many parts of the world, and some require little energy to make them usable in concrete.

RECYCLED GLASS POWDER

This is waste glass, ground into a fine powder. Almost any kind of glass will do, and the result is a cementitious product that can be used to replace up to 90% of the Portland cement, according to some advocates. It's already being made, but not on a big scale, and it still costs far more than Portland cement.

As a cement-replacement material, glass powder has some clear advantages over fly ash and slag. While all three are waste products, they are not all equally available. Fly ash comes from coal-burning power stations, which are not found everywhere and are in decline. Slag comes from blast furnaces, which are even scarcer than coal-burning power stations. In contrast, recycled glass is potentially available in every city and town worldwide.

Making cement out of glass could bring benefits that go beyond the concrete industry. Besides reducing concrete's carbon footprint, it would raise demand for recycled glass, which is now in surplus. And if the demand for recycled glass exceeds the supply, it might be economic to replace some plastic containers with glass, reducing the huge problem of plastics recycling. Many products now packaged in plastic used to come in glass; perhaps that day will come again.

REDUCING SLAB THICKNESS

All the methods discussed so far work by reducing the amount of Portland cement in a concrete floor. There's a simpler, more obvious way to the carbon footprint of concrete: use less. In a floor, that usually means making the slab thinner.

We could just cut slab thickness 20% across the board and reduce the immediate carbon footprint by 20% but that would be risky. The long-term footprint might actually go up because some of those thinned-down slabs would fail and need early replacement.

We need a more measured approach. Here are some ideas for reducing the thickness of ground-supported warehouse floors:

- Get the most accurate loading information you can and design the floor for that. Ask lots of questions about pallet weights and rack configurations.
- Watch out for multiple safety factors.

- Specify and measure the concrete's flexural strength instead of assuming it from a standard formula. This step alone has been used to justify reductions of 15% in slab thickness.
- Consider adding structural reinforcement to use less concrete. But steel has a carbon footprint too, so this approach requires careful analysis.

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