Guide for Concrete Floor and Slab Construction

Reported by ACI Committee 302

Eldon Tipping
Chair

Dennis Ahal
Secretary

Robert B. Anderson	C. Rick Felder	John P. Munday
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Alphonse E. Engleman	Jerry A. Holland	Philip A. Smith
Robert A. Epifano	Arthur W. McKinney	Bruce A. Suprenant
Samuel A. Face, III	Steven N. Metzger	R. Gregory Taylor

FOREWORD

The quality of a concrete floor or slab is highly dependent on achieving a hard and durable surface that is flat, relatively free of cracks, and at the proper grade and elevation. Properties of the surface are determined by the mixture proportions and the quality of the concreting and jointing operations. The timing of concreting operations—especially finishing, jointing, and curing—is critical. Failure to address this issue can contribute to undesirable characteristics in the wearing surface such as cracking, low resistance to wear, dusting, scaling, high or low spots, poor drainage, and increasing the potential for curling.

Concrete floor slabs employing portland cement, regardless of slump, will start to experience a reduction in volume as soon as they are placed. This phenomenon will continue as long as any water, heat, or both, is being released to the surroundings. Moreover, because the drying and cooling rates at the top and bottom of the slab will never be the same, the shrinkage will vary throughout the depth, causing the as-cast shape to be distorted and reduced in volume.

This guide contains recommendations for controlling random cracking and edge curling caused by the concrete's normal volume change. Application of present technology permits only a reduction in cracking and curling, not elimination. Even with the best floor designs and proper construction, it is unrealistic to expect crack-free and curl-free floors. Consequently, every owner should be advised by both the designer and contractor that it is normal to expect some amount of cracking and curling on every project, and that such occurrence does not necessarily reflect adversely on either the adequacy of the floor's design or the quality of its construction (Ytterberg 1987; Campbell et al. 1976).

Refer to the latest edition of ACI 360R for a detailed discussion of shrinkage and curling in slabs-on-ground. Refer to the latest edition of ACI 224R for a detailed discussion of cracking in reinforced and nonreinforced concrete slabs.

This guide describes how to produce high-quality concrete slabs-on-ground and suspended floors for various classes of service. It emphasizes aspects of construction such as site preparation, concreting materials, concrete mixture proportions, concreting workmanship, joint construction, load transfer across joints, form stripping procedures, finishing methods, and curing. Flatness/levelness requirements and measurements are outlined. A thorough preconstruction meeting is critical to facilitate communication among key participants and to clearly establish expectations and procedures that will be employed during construction to achieve the floor qualities required by the project specifications. Adequate supervision and inspection are required for job operations, particularly those of finishing.

Keywords: admixture; aggregate; concrete; consolidation; contract documents; curing; curling; deflection; durability; form; fracture; joint; mixture proportioning; mortar, paste, placing; quality control; slab-on-ground; slabs; slump test; specification.

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ACI 302.1R-04 supersedes ACI 302.1R-96 and became effective March 23, 2004.

CHAPTER 1—INTRODUCTION

1.1—Purpose and scope

This guide presents state-of-the-art information relative to the construction of slab-on-ground and suspended-slab floors for industrial, commercial, and institutional buildings. It is applicable to the construction of normalweight and structural lightweight concrete floors and slabs made with conventional portland and blended cements. Slabs specifically intended for the containment of liquids are beyond the scope of this document.

The design of slabs-on-ground should conform to the recommendations of ACI 360R. Refer to ACI 223 for procedures for the design and construction of shrinkage-compensating concrete slabs-on-ground. The design of suspended floors should conform to requirements of ACI 318 and ACI 421.1R. See Section 1.2 for relevant work by these and other committees.

This guide identifies the various classes of floors as to

- Use;
- Design details as they apply to construction;
- Necessary site preparation; and
- Type of concrete and related materials.

In general, the characteristics of the concrete slab surface and the performance of joints have a powerful impact on the serviceability of floors and other slabs. Because the eventual success of a concrete floor installation depends on the mixture proportions and floor finishing techniques used, considerable attention is given to critical aspects of achieving the desired finishes and the required floor surface tolerances. This guide emphasizes choosing and proportioning of materials, design details, proper construction methods, and workmanship.

1.1.1 *Prebid meeting*—While this guide does provide a reasonable overview of concrete floor construction, it should be emphasized that every project is unique; circumstances can dictate departures from the recommendations contained herein. Accordingly, contractors and suppliers are urged to make a thorough review of contract documents before bid preparation.

The best forum for such a review is the prebid meeting. This meeting offers bidders an opportunity to ask questions and clarify their understanding of contract documents before submitting their bids. A prebid meeting also provides the owner and the owner's designer an opportunity to clarify intent where documents are unclear and to respond to last-minute questions in a manner that provides bidders an opportunity to be equally responsive to the contract documents.

1.1.2 *Preconstruction meeting*—Construction of any slab-on-ground or suspended floor or slab involves the coordinated efforts of many subcontractors and material suppliers. It is strongly recommended that the designer require a preconstruction meeting to be held to establish and to coordinate procedures that will enable key participants to produce the best possible product under the anticipated field conditions. This meeting should be attended by responsible representatives of organizations and material suppliers directly involved with either the design or construction of floors.

The preconstruction meeting should confirm and document the responsibilities and anticipated interaction of key participants involved in floor slab construction. Following is a list of agenda items appropriate for such a meeting; many of the items are those for which responsibility should be clearly established in the contract documents. The following list is not necessarily all-inclusive:

1. Site preparation;
2. Grades for drainage, if any;
3. Work associated with installation of auxiliary materials, such as vapor barriers, vapor retarders, edge insulation, electrical conduit, mechanical sleeves, drains, and embedded plates;
4. Class of floor;
5. Floor thickness;
6. Reinforcement, when required;
7. Construction tolerances: base (rough and fine grading), forms, slab thickness, surface configuration, and floor flatness and levelness requirements (including how and when measured);
8. Joints and load-transfer mechanism;
9. Materials: cements, fine aggregate, coarse aggregate, water, and admixtures (usually by reference to applicable ASTM standards);
10. Special aggregates, admixtures, or monolithic surface treatments, where applicable;
11. Concrete specifications, to include the following:
    a. Compressive strength, flexural strength, or both, and finishability (Section 6.2);
    b. Minimum cementitious material content, if applicable (Table 6.2);
    c. Maximum size, grading, and type of coarse aggregate;
    d. Grading and type of fine aggregate;
    e. Combined aggregate grading;
    f. Air content of concrete, if applicable (Section 6.2.7);
    g. Slump of concrete (Section 6.2.5);
    h. Water-cement ratio (w/c) or water-cementitious material ratio (w/cm); and
    i. Preplacement soaking requirement for lightweight aggregates.
12. Measuring, mixing, and placing procedures (usually by reference to specifications or recommended practices);
13. Strikeoff method;
14. Recommended finishing methods and tools, where required;
15. Coordination of floor finish requirements with those required for floor coverings such as vinyl, ceramic tile, or wood that are to be applied directly to the floor;
16. Curing procedures, length of curing, necessary protection, and time before opening slabs for traffic (ACI 308R);
17. Testing and inspection requirements; and
18. Acceptance criteria and remedial measures to be used, if required.

Additional issues specific to suspended slab construction are as follows:

1. Form tolerances and preplacement quality assurance survey procedures for cast-in-place construction;
2. Erection tolerances and preplacement quality assurance survey procedures for composite slab construction (see ANSI/ASCE 3 and ANSI/ASCE 9 [Section 12.1]);
3. Form stripping procedures, if applicable; and
4. Items listed in Section 3.3 that are appropriate to the structural system(s) used for the project.

1.1.3 *Quality assurance*—Adequate provisions should be made to ensure that the constructed product meets or exceeds the requirements of the project documents. Toward this end, quality control procedures should be established and maintained throughout the entire construction process.

The quality of a completed concrete slab depends on the skill of individuals who place, finish, and test the material. As an aid to ensuring a high-quality finished product, the specifier or owner should consider requiring the use of prequalified concrete contractors, concrete suppliers, accredited testing laboratories, and concrete finishers who have had their proficiency and experience evaluated through an independent third-party certification program. ACI has developed programs to train and certify concrete flatwork finishers and concrete inspectors and testing technicians throughout the United States, Mexico, and Canada.

1.2—Terminology

adjusted mix optimization indicator (MOI-Adj)—intersection of the coarseness factor value and the adjusted workability factor on the coarseness factor chart.

adjusted workability factor (W-Adj)—the workability factor adjusted for cementitious content. For each 94 lb (43 kg) of total cementitious material above 564 lb/yd^3 (335 kg/m^3), increase the workability factor by 2.5%. For each 94 lb (43 kg) of total cementitious material below 564 lb/yd^3 (335 kg/m^3), decrease the workability factor by 2.5%. (Example for a workability factor of 33% and 600 lb/yd^3 [356 kg/m^3] of cementitious material: 600 lb/yd^3 [356 kg/m^3] – 564 lb/yd^3 [335 kg/m^3] = 36 lb/yd^3 [21 kg/m^3]; 36 lb [16 kg]/94 lb [43 kg] = 0.38; 0.38 × 2.5% = 0.95%; W-Adj = 33% workability factor + 0.95% = 33.95%).

coarseness factor—the percentage of combined aggregate that is larger than the 3/8 in. (9.5 mm) sieve, divided by the percentage of combined aggregate that is larger than the No. 8 (2.36 mm) sieve, expressed as a percent. (Example: 33% retained on the 3/8 in. [9.5 mm] sieve/45% retained on the No. 8 [2.36 mm] sieve = 73.3%).

differential set time—the difference in timing of initial power floating of sequential truck loads of concrete as they are delivered to the jobsite.

dry shake—metallic or mineral hardener mixed with cement and applied dry to the surface of concrete during finishing operations.

floating—a term used to describe smoothing and subsequent compaction and consolidation of the unformed concrete surface.

mix optimization indicator (MOI)—intersection of the coarseness factor value and the workability factor on the coarseness factor chart.

pumping—the vertical displacement and rebound of the soil support system in response to applied wheel loads.

rutting—the creation of troughs in the soil support system in response to applied wheel loads.

score—the creation of lines or notches in the surface of a concrete slab.

water slump—the magnitude of slump, measured in accordance with ASTM C 143, which is directly attributed to the amount of water in the concrete mixture.

window of finishability—the time period available for finishing operations after the concrete has been placed, consolidated, and struck-off, and before final troweling.

workability factor—the percentage of combined aggregate that passes the No. 8 (2.36 mm) sieve.

1.3—Related work of other committees

1.3.1 *ACI committees*

117—Prepares and updates tolerance requirements for concrete construction.

201—Reviews research and recommendations on durability of concrete and reports recommendations for appropriate materials and methods.

211—Develops recommendations for proportioning concrete mixtures.

223—Develops and reports on the use of shrinkage-compensating concrete.

224—Studies and formulates recommendations for the prevention or control of cracking in concrete construction.

301—Develops and maintains reference specifications for structural concrete for buildings.

308—Prepares guidelines for type and amount of curing required to develop the desired properties in concrete.

309—Studies and reports on research and development in consolidation of concrete.

311—Develops guides and procedures for inspection and testing.

318—Develops and updates building code requirements for reinforced concrete and structural plain concrete, including suspended slabs.

325—Reports on the structural design, construction, maintenance, and rehabilitation of concrete pavements.

330—Reports on the design, construction, and maintenance of concrete parking lots.

332—Gathers and reports on the use of concrete in residential construction.

347—Gathers, correlates, and reports information, and prepares recommendations for formwork for concrete.

350—Develops and updates code requirements for concrete in environmental structures.

360—Develops and reports on criteria for design of slabs-on-ground, except highway and airport pavements.

421—Develops and reports on criteria for suspended slab design.

423—Develops and reports on technical status, research, innovations, and recommendations for prestressed concrete.

435—Provides recommendations for deflection control in concrete slabs.

503—Studies and reports information and recommendations on the use of adhesives for structurally joining concrete, providing a wearing surface, and other uses.

504—Studies and reports on materials, methods, and systems used for sealing joints and cracks in concrete structures.

515—Prepares recommendations for selection and application of protective systems for concrete surfaces.

544—Studies and reports information and recommendations on the use of fiber-reinforced concrete.

640—Develops, maintains, and updates programs for use in certification of concrete construction workers.

1.3.2 *The American Society of Civil Engineers*—ASCE publishes documents that can be helpful for floor and slab construction. Two publications that deal with suspended slab construction are ASCE Standard for the Structural Design of Composite Slabs (ANSI/ASCE 3) and ASCE Standard Prac-

Table 2.1—Classes of floors on the basis of intended use and the suggested final finish technique

Class	Anticipated type of traffic	Use	Special considerations	Final finish
1. Single course	Exposed surface—foot traffic	Offices, churches, commercial, institutional, multi-unit residential Decorative	Uniform finish, nonslip aggregate in specific areas, curing Colored mineral aggregate, color pigment or exposed aggregate, stamped or inlaid patterns, artistic joint layout, curing	Normal steel-troweled finish, nonslip finish where required As required
2. Single course	Covered surface—foot traffic	Offices, churches, commercial, multi-unit residential, institutional with floor coverings	Flat and level slabs suitable for applied coverings, curing. Coordinate joints with applied coverings	Light steel-troweled finish
3. Two course	Exposed or covered surface—foot traffic	Unbonded or bonded topping over base slab for commercial or non-industrial buildings where construction type or schedule dictates	*Base slab*—good uniform level surface tolerance, curing *Unbonded topping*—bondbreaker on base slab, minimum thickness 3 in. (75 mm), reinforced, curing *Bonded topping*—properly sized aggregate, 3/4 in. (19 mm) minimum thickness curing	*Base slab*—troweled finish under unbonded topping; clean, textured surface under bonded topping *Topping*—for exposed surface, normal steel-troweled finish. For covered surface, light steel-troweled finish
4. Single course	Exposed or covered surface—foot and light vehicular traffic	Institutional or commercial	Level and flat slab suitable for applied coverings, nonslip aggregate for specific areas, curing. Coordinate joints with applied coverings	Normal steel-troweled finish
5. Single course	Exposed surface—industrial vehicular traffic, that is, pneumatic wheels and moderately soft solid wheels	Industrial floors for manufacturing, processing, and warehousing	Good uniform subgrade, joint layout, abrasion resistance, curing	Hard steel-troweled finish
6. Single course	Exposed surface— heavy-duty industrial vehicular traffic, that is, hard wheels and heavy wheel loads	Industrial floors subject to heavy traffic; may be subject to impact loads	Good uniform subgrade, joint layout, load transfer, abrasion resistance, curing	Special metallic or mineral aggregate surface hardener; repeated hard steel-troweling
7. Two course	Exposed surface— heavy-duty industrial vehicular traffic, that is, hard wheels and heavy wheel loads	Bonded two-course floors subject to heavy traffic and impact	*Base slab*—good uniform subgrade, reinforcement, joint layout, level surface, curing *Topping*—composed of well-graded all-mineral or all-metallic aggregate. Minimum thickness 3/4 in. (19 mm). Mineral or metallic aggregate surface hardener applied to high-strength plain topping to toughen, curing	Clean, textured base slab surface suitable for subsequent bonded topping. Special power floats for topping are optional, hard steel-troweled finish
8. Two course	As in Classes 4, 5, or 6	Unbonded topping—on new or old floors where construction sequence or schedule dictates	Bondbreaker on base slab, minimum thickness 4 in. (100 mm), abrasion resistance, curing	As in Classes 4, 5, or 6
9. Single course or topping	Exposed surface—superflat or critical surface tolerance required. Special materials-handling vehicles or robotics requiring specific tolerances	Narrow-aisle, high-bay warehouses; television studios, ice rinks, or gymnasiums. Refer to ACI 360R for design guidance	Varying concrete quality requirements. Special application procedures and strict attention to detail are recommended when shake-on hardeners are used. F_F 50 to F_F 125 (“superflat” floor). Curing	Strictly following techniques as indicated in Section 8.9

tice for Construction and Inspection of Composite Slabs (ANSI/ASCE 9).

CHAPTER 2—CLASSES OF FLOORS

2.1—Classification of floors

Table 2.1 classifies floors on the basis of intended use, discusses special considerations, and suggests finishing techniques for each class of floor. Intended use requirements should be considered when selecting concrete properties (Section 6.2), and the step-by-step placing, consolidating, and finishing procedures in Chapter 8 should be closely followed for different classes and types of floors.

Wear resistance and impact resistance should also be considered. Currently, there are no standard criteria for evaluating the wear resistance of a floor, and it is not possible to specify concrete quality in terms of ability to resist wear. Wear resistance is directly related to the concrete-mixture proportions, types of aggregates, finishing, curing, and other construction techniques used.

2.2—Single-course monolithic floors: Classes 1, 2, 4, 5, and 6

Five classes of floors are constructed with monolithic concrete; each involves some variation in strength and final finishing techniques. If abrasion from grit or other materials is anticipated, a higher-quality floor surface may be required for satisfactory service (ASTM 1994). Under these conditions, a higher-class floor, a special mineral or metallic aggregate monolithic surface treatment, or a higher-strength concrete is recommended.

2.3—Two-course floors: Classes 3, 7, and 8

2.3.1 *Unbonded topping over base slab*—The base courses of Class 3 (unbonded, two course) floors and Class 8 floors can be either slabs-on-ground or suspended slabs, with the finish to be coordinated with the type of topping. For Class 3 floors, the concrete topping material is similar to the base slab concrete. The top courses for Class 8 floors require a hard-steel troweling and usually have a higher compressive strength than the base course. Class 8 floors can also make use of an embedded hard aggregate, a premixed (dry-shake) mineral aggregate, or metallic hardener for addition to the surface (Section 5.4.5).

Class 3 (with unbonded topping) and Class 8 floors are used when it is preferable to not bond the topping to the base course, so that the two courses can move independently (for example, with precast members as a base), or so that the top courses can be more easily replaced at a later period. Two-course floors can be used when mechanical and electrical equipment require special bases and when their use permits more expeditious construction procedures. Two-course unbonded floors can also be used to resurface worn or damaged floors when contamination prevents complete bond or when it is desirable to avoid scarifying and chipping the base course and the resultant higher floor elevation is compatible with adjoining floors. Class 3 floors are used primarily for commercial or nonindustrial applications, whereas Class 8 floors are primarily for industrial applications.

Plastic sheeting, roofing felt, or a bond-breaking compound is used to prevent bond to the base slab. Reinforcement, such as deformed bars, welded wire fabric, bar mats, or fibers, may be placed in the topping to reduce the width of shrinkage cracks. Unbonded toppings should have a minimum thickness of 3 in. (75 mm). The concrete should be proportioned to meet the requirements of Chapter 6. Joint spacing in the topping should be coordinated with joint spacing in the base slab.

Additional joints should be considered if the topping slab thickness mandates a closer spacing than the base slab to limit uncontrolled cracking and slab curl. Curl or warping will be more probable due to the effects of drying from the top surface only.

2.3.2 *Bonded topping over base slab*—Class 3 (bonded topping) and Class 7 floors use a topping bonded to the base slab. Class 3 (bonded topping) floors are used primarily for commercial or nonindustrial applications; Class 7 floors are used for heavy-duty, industrial applications subject to heavy traffic and impact. The base slabs can either be a conventional portland cement concrete mixture or shrinkage-compensating concrete. The surface of the base slab should have a rough, open pore finish and be free of any substances that would interfere with the bond of the topping to the base slab.

The topping can be either a same-day installation (before hardening of the base slab) or a deferred installation (after the base slab has hardened). The topping for a Class 3 floor is a concrete mixture similar to that used in Class 1 or 2 floors. The topping for a Class 7 floor requires a multiple-pass, hard-steel-trowel finish, and it usually has a higher strength than the base course. A bonded topping can also make use of an embedded hard aggregate or a premixed (dry-shake) mineral aggregate or metallic hardener for addition to the surface (Section 5.4.5). Bonded concrete toppings should have a minimum thickness of 3/4 in. (19 mm). Proprietary products should be applied per manufacturers' recommendations. Joint spacing in the topping should be coordinated with construction and contraction joint spacing in the base slab. Saw-cut contraction joints should penetrate into the base slab a minimum of 1 in. (25 mm).

If the topping is placed on a base slab before the joints are cut, joints in the topping should extend into the base slab and depth should be appropriate for the total thickness of the combined slab. If the topping is installed on a previously placed slab where joints have activated, additional joints in the topping are unnecessary as shrinkage relief cannot occur between the slab joints in the bonded topping. When topping slabs are placed on shrinkage-compensating base slabs, the joints in the base slab can only be reflected in the bonded topping slab if the bonded topping slab is installed shortly after the maximum expansion occurs. Maximum expansion usually occurs within seven to 14 days.

2.4—Class 9 floors

Certain materials-handling facilities (for example, high-bay, narrow-aisle warehouses) require extraordinarily level and flat floors. The construction of such superflat floors (Class 9) is discussed in Chapter 8. A superflat floor could be constructed as a single-course floor or it could be constructed as a two-course floor with a topping, either bonded (similar to a Class 7 topping) or unbonded (similar to a Class 8 topping).

2.5—Special finish floors

Floors with decorative finishes and those requiring skid resistance or electrical conductivity are covered in appropriate sections of Chapter 8.

Floors exposed to mild acids, sulfates, or other chemicals require special preparation or protection. ACI 201.2R reports on means of increasing the resistance of concrete to chemical attack. Where attack will be severe, wear-resistant protection suitable for the exposure should be used. Such environments and the methods of protecting floors against them are discussed in ACI 515.1R.

In certain chemical and food processing plants, such as slaughterhouses, exposed concrete floors are subject to slow disintegration due to organic acids. In many instances, it is preferable to protect the floor with other materials such as acid-resistant brick, tile, or resinous mortars (ACI 515.1R).

CHAPTER 3—DESIGN CONSIDERATIONS

3.1—Scope

This chapter addresses the design of concrete floors as it relates to their constructibility. Specific design requirements for concrete floor construction are found in other documents: ACI 360R for slabs-on-ground, ACI 223 for shrinkage-compensating concrete floors, ACI 421.1R for suspended floors, ANSI/ASCE 3 for structural design of composite slabs, and ANSI/ASCE 9 for construction and inspection of composite slabs. Refer to ACI 318 for requirements relating to the building code.

3.2—Slabs-on-ground

3.2.1 *Required design elements*—The following items should be specified in the contract documents prepared by the designer:

- Base and subbase materials, preparation requirements, and vapor retarder, if required;
- Concrete thickness;

- Concrete compressive strength, flexural strength, or both;
- Concrete mixture proportion requirements;
- Joint locations and details;
- Reinforcement (type, size, and location), if required;
- Surface treatment, if required;
- Surface finish;
- Tolerances (base, subbase, slab thickness, and surface);
- Concrete curing;
- Joint filling material and installation;
- Special embedments; and
- Preconstruction meeting, quality assurance, and quality control.

3.2.2 *Soil-support system*—The performance of a slab-on-ground depends on the integrity of both the soil-support system and the slab; therefore, specific attention should be given to the site preparation requirements, including proof-rolling, discussed in Section 4.1.1. In most cases, proof-rolling results are far more indicative of the ability of the soil-support system to withstand loading than the results from in-place tests of moisture content or density are. A thin layer of graded, granular, compactible material is normally used as fine grading material to better control the thickness of the concrete and to minimize friction between the base material and the slab. For detailed information on soil-support systems, refer to ACI 360R.

3.2.3 *Moisture protection*—Proper moisture protection is essential for any slab-on-ground where the floor will be covered by moisture-sensitive flooring materials such as vinyl, linoleum, wood, carpet, rubber, rubber-backed carpet tile, impermeable floor coatings, adhesives, or where moisture-sensitive equipment, products, or environments exist, such as humidity-controlled or refrigerated rooms.

A vapor retarder is a material that is intended to minimize the transmission of moisture upward through the slab from sources below. The performance requirements for plastic vapor retarder materials in contact with soil or granular fill under concrete slabs are listed in ASTM E 1745. It is generally recognized that a vapor retarder should have a permanence (water vapor transmission rate) of less than 0.3 perms, as determined by ASTM E 96.

The selection of a vapor retarder or barrier material should be made on the basis of protective requirements and the moisture-related sensitivity of the materials to be applied to the floor surface. Although conventional polyethylene film with a thickness of as little as 6 mils (0.15 mm) has been used, the committee strongly recommends that the material be in compliance with ASTM E 1745 and that the thickness be no less than 10 mils (0.25 mm). The increased thickness offers increased resistance to moisture transmission while providing greater durability during and after installation.

A number of vapor retarder materials have been incorrectly referred to and used by designers as vapor barriers. True vapor barriers are products that have a permanence (water-vapor transmission rating) of 0.00 perms when tested in accordance with ASTM E 96. The laps or seams in either a vapor retarder or barrier should be overlapped 6 in. (150 mm) (ASTM E 1643) or as instructed by the manufacturer. The joints and penetrations should be sealed with the manufacturer's recommended adhesive, pressure-sensitive tape, or both.

The decision whether to locate the vapor retarder or barrier in direct contact with the slab or beneath a layer of granular fill should be made on a case-by-case basis (Suprenant and Malisch 1998b). For moisture-sensitive flooring materials and environments, placing concrete in direct contact with the vapor retarder or barrier eliminates the potential for water from sources such as rain, saw-cutting, curing, cleaning, or compaction to become trapped within the fill course. Wet or saturated fill above the vapor retarder can significantly increase the time required for a slab to dry to levels required by the manufacturers of floor coverings, adhesives, and coatings.

Placing concrete in direct contact with the vapor retarder or barrier, however, requires additional consideration if potential slab-related problems are to be avoided. When compared with identical concrete cast on a draining base, concrete placed in direct contact with a vapor retarder or barrier has been shown to exhibit significantly larger length change in the first hour after casting, during drying shrinkage, and when subject to environmental change; there is also more settlement (Suprenant 1997). Care should be taken in design detailing to minimize restraint to such movement (Anderson and Roper 1977). Where reinforcing steel is present, settlement cracking over the steel is more likely because of the increased settlement resulting from a longer bleeding period. The potential for a greater measure of slab curl is also increased.

Concrete that does not lose water to the base does not stiffen as rapidly as concrete that does lose part of its excess water to the base. If rapid, surface drying conditions are present, the surface of concrete placed directly on a vapor retarder will have a tendency to dry and crust over while the concrete below the top fraction of an inch remains relatively less stiff or unhardened. When this occurs, it may be necessary to begin machine operations on the concrete surface before the concrete below the top surface is sufficiently set. Under such conditions, a reduction in surface flatness and some blistering or delamination can occur as air, water, or both become trapped below the finish surface.

The committee recommends that each proposed installation be independently evaluated as to the moisture sensitivity of subsequent floor finishes, anticipated project conditions, and the potential effects of slab curling, crusting, and cracking. The anticipated benefits and risks associated with the specified location of the vapor retarder should be reviewed with all appropriate parties before construction. Figure 3.1 can be used to assist this evaluation process.

3.2.4 *Reinforcement for crack-width control*—Reinforcement restrains movement resulting from slab shrinkage and can actually increase the number of random cracks experienced, particularly at wider joint spacing (Section 3.2.5.3). Reinforcement in nonstructural slab-on-ground installations is provided primarily to control the width of cracks that occur (Dakhil, Cady, and Carrier 1975; CRSI 1990). This reinforcement is normally furnished in the form of deformed steel bars, welded wire reinforcing, steel fibers, or post-

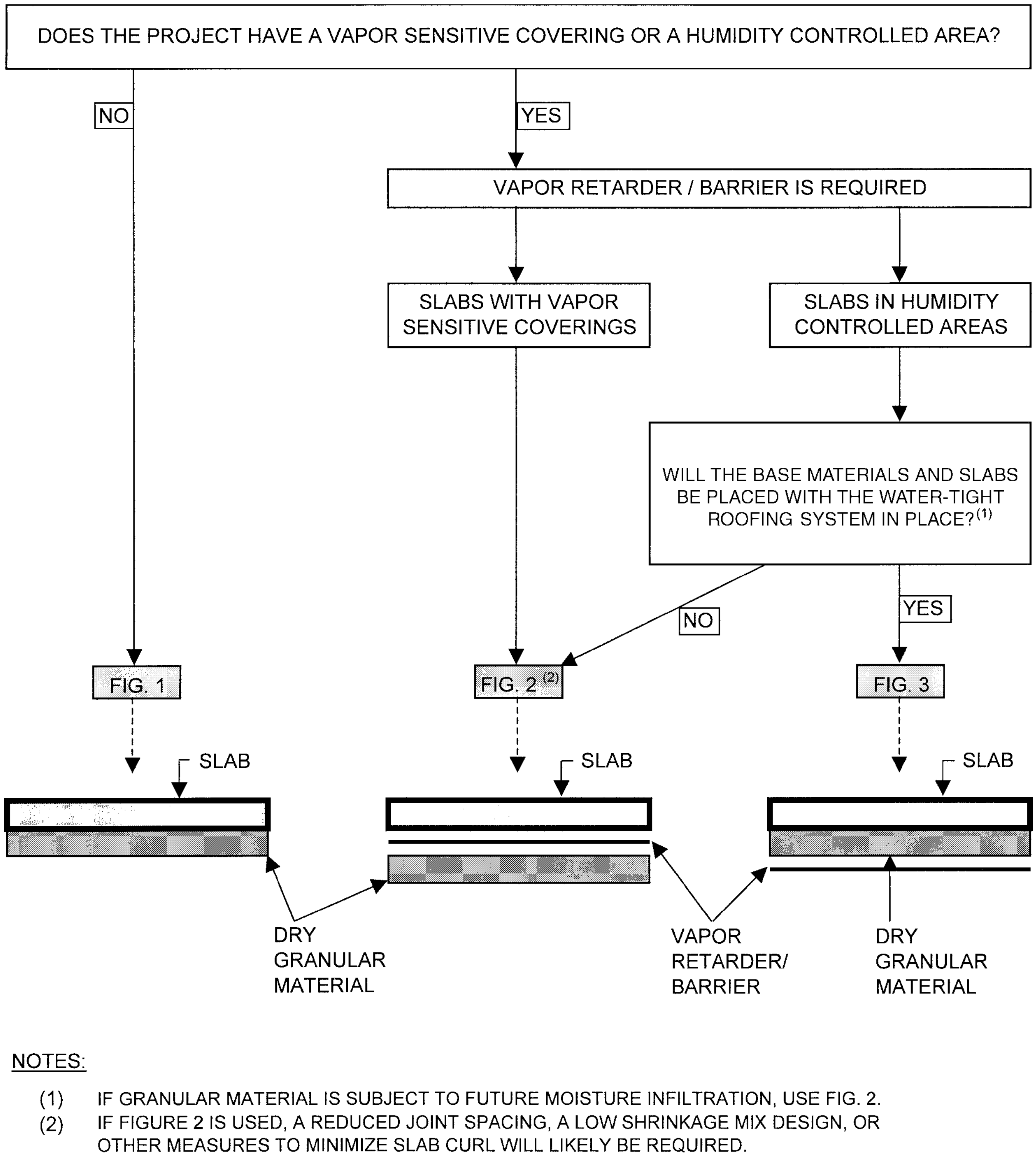


Fig. 3.1—Decision flow chart to determine if a vapor retarder/barrier is required and where it is to be placed.

tensioning tendons. Combinations of various forms of reinforcement have proved successful.

Normally, the amount of reinforcement used in nonstructural slabs is too small to have a significant influence on restraining movement resulting from volume changes. Refer to Section 3.2.5 for a detailed discussion of the relationship between joint spacing and amount of reinforcement.

Temperature and shrinkage cracks in unreinforced slabs-on-ground originate at the surface of the slab and are wider at the surface, narrowing with depth. For maximum effectiveness, temperature and shrinkage reinforcement in slabs-on-ground should be positioned in the upper third of the slab thickness. The Wire Reinforcement Institute recommends that welded wire reinforcement be placed 2 in. (50 mm) below the slab surface or within the upper third of slab thickness, whichever is closer to the surface (CRSI 2001; Snell 1997). Reinforcement should extend to within 2 in. (50 mm) of the slab side edge.

Deformed reinforcing steel or post-tensioning tendons should be supported and tied together sufficiently to minimize movement during concrete placing and finishing operations. Chairs with sand plates or precast-concrete bar supports are generally considered to be the most effective method of providing the required support. When precast-concrete bar supports are used, they should be at least 4 in. (100 mm) square at the base, have a compressive strength at least equal to the specified compressive strength of the concrete being placed, and be thick enough to support reinforcing steel or post-tensioning tendons at the proper elevation while maintaining minimum concrete cover requirements.

When welded wire reinforcement is used, its larger flexibility dictates that the contractor pay close attention to establishing and maintaining adequate support of the reinforcement during the concrete placing operations. Welded wire reinforcement should not be placed on the ground and pulled up after placement of the concrete, nor should the mats be walked in after placing the concrete. Proper support spacing is necessary to maintain welded wire reinforcement at the proper elevation; supports should be close enough that the welded wire reinforcement cannot be forced out of location by construction foot traffic. Support spacing can be increased when heavier gage wires or a double mat of small gage wires is used.

Reinforcing bars or welded wire reinforcement should be discontinued at any joints where the intent of the designer is to let the joint open and reduce the possibility of shrinkage and temperature cracks in an adjacent panel. Where the reinforcement is continued through the joint, cracks are likely to occur in adjacent panels because of restraint at the joint (WRI/CRSI 1991). When used in sufficient quantity, reinforcement will hold out-of-joint cracks tightly closed. Some designers prefer partial discontinuance of the reinforcement at contraction joints to obtain some load-transfer capacity without the use of dowel baskets. Refer to Section 3.2.7.

3.2.4.1 *Steel fibers*—In some installations, steel fibers specifically designed for such use can be used with or without conventional mild steel shrinkage and temperature reinforcement in slab-on-ground floors. As in the case of conventional reinforcement, steel fibers will not prevent cracking of the concrete. Use of steel fibers through the contraction joints reduces the width of joint openings and that increases the likelihood of cracking occurring between joints. The crack width, however, should remain narrow and, in most cases, there are nondetectible microcracks providing sufficient quantities of fibers used for the given slab joint spacing and thickness, and subgrade conditions and concrete material shrinkage properties are taken into consideration.

3.2.4.2 *Synthetic fibers*—Polypropylene, polyethylene, nylon, and other synthetic fibers can help reduce segregation of the concrete mixture and formation of shrinkage cracks while the concrete is in the plastic state and during the first few hours of curing. As the modulus of elasticity of concrete increases with hardening of concrete, however, most synthetic fibers at typical dosage rates recommended by the fiber manufacturers will not provide sufficient restraint to inhibit cracking.

3.2.4.3 *Post-tensioning reinforcement*—The use of high-strength steel tendons as reinforcement instead of conventional mild steel temperature and shrinkage reinforcement allows the contractor to introduce a relatively high compressive stress in the concrete by means of post-tensioning. This compressive stress provides a balance for the crack-producing tensile stresses that develop as the concrete shrinks during the curing process. Stage stressing, or partial tensioning, of the slab on the day following placement can result in a significant reduction of shrinkage cracks. Construction loads on the concrete should be minimized until the slabs are fully stressed (PTI 1990; PTI 1996). For guidelines on installation details, contact a concrete floor specialty contractor who is thoroughly experienced with this type of installation.

3.2.4.4 *Causes of cracking over reinforcement*—Plastic settlement cracking over reinforcement is caused by inadequate consolidation of concrete, inadequate concrete cover over the reinforcement, use of large diameter bars (Dakhil, Cady, and Carrier 1975), higher temperature of reinforcing bars exposed to direct sunlight, higher-than-required slump in concrete, revibration of the concrete, inadequate curing of the concrete, or a combination of these items.

3.2.5 *Joint design*—Joints are used in slab-on-ground construction to limit the frequency and width of random cracks caused by volume changes and to reduce the magnitude of slab curling. Generally, if limiting the number of joints by increasing the joint spacing can be accomplished without increasing the number of random cracks, floor maintenance will be reduced. The layout of joints and joint details should be provided by the designer. If the joint layout is not provided, the contractor should submit a detailed joint layout and placing sequence for approval of the designer before proceeding.

As stated in ACI 360R, every effort should be made to isolate the slab from restraint that might be provided by any other element of the structure. Restraint from any source, whether internal or external, will increase the potential for random cracking.

Three types of joints are commonly used in concrete slabs-on-ground: isolation joints, contraction joints, and construction joints. Appropriate locations for isolation joints and contraction joints are shown in Fig. 3.2. With the designer's approval, construction joint and contraction joint details can be interchanged. Refer to ACI 360R for a detailed discussion of joints. Joints in topping slabs should be located directly over joints in the base slab.

3.2.5.1 *Isolation joints*—Isolation joints should be used wherever complete freedom of vertical and horizontal movement is required between the floor and adjoining building members. Isolation joints should be used at junctions with walls (not requiring lateral restraint from the slab), columns, equipment foundations, footings, or other points of restraint such as drains, manholes, sumps, and stairways. Isolation joints are formed by inserting preformed joint filler

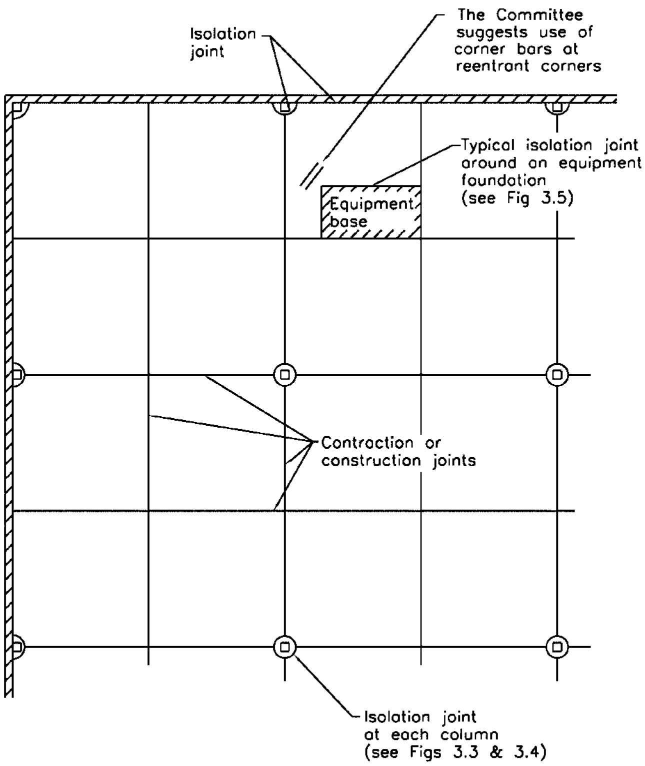


Fig. 3.2—Appropriate locations for joints.

between the floor and the adjacent member. The joint material should extend the full depth of the slab and not protrude above it. The joint filler will be objectionably visible where there are wet conditions, or hygienic or dust-control requirements. Two methods of producing a relatively uniform depth of joint sealant are as follows:

1) Score both sides of the preformed filler at the depth to be removed by using a saw. Insert the scored filler in the proper location and remove the top section after the concrete hardens by using a screwdriver or similar tool.

2) Cut a strip of wood equal to the desired depth of the joint sealant. Nail the wood strip to the preformed filler and install the assembly in the proper location. Remove the wood strip after the concrete has hardened.

Alternatively, a premolded joint filler with a removable top portion can be used. Refer to Fig. 3.3 and 3.4 for typical isolation joints around columns. Figure 3.5 shows an isolation joint at an equipment foundation.

Isolation joints for slabs using shrinkage-compensating concrete should be dealt with as recommended in ACI 223.

3.2.5.2 *Construction joints*—Construction joints are placed in a slab to define the extent of the individual concrete placements, generally in conformity with a predetermined joint layout. If concreting is ever interrupted long enough for the placed concrete to harden, a construction joint should be used. If possible, construction joints should be located 5 ft (1.5 m) or more from any other joint to which they are parallel.

In areas not subjected to traffic, a butt joint is usually adequate. In areas subjected to hard-wheeled traffic, heavy loadings, or both, joints with dowels are recommended (Fig. 3.6). Refer to Section 3.2.7 for a detailed discussion on

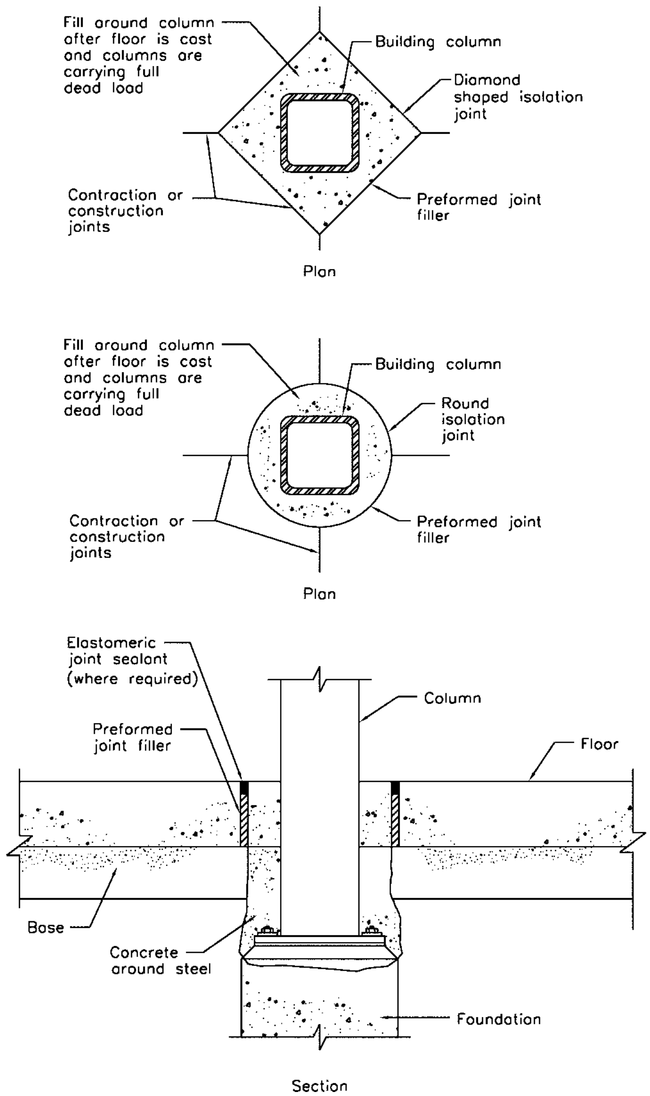


Fig. 3.3—Typical isolation joints at tube columns.

dowel joints. Keyed joints are not recommended where load transfer is required because the two sides of the keyway lose contact when the joint opens due to drying shrinkage (Section 3.2.7).

3.2.5.3 *Contraction joints*—Contraction joints are usually located on column lines with intermediate joints located at equal spaces between column lines as shown in Fig. 3.2. The following factors are normally considered when selecting spacing of contraction joints:

- Method of slab design (ACI 360R);
- Thickness of slab;
- Type, amount, and location of reinforcement;
- Shrinkage potential of the concrete (cement type and quantity; aggregate size, quantity, and quality; *w/cm*; type of admixtures; and concrete temperature);
- Base friction;
- Floor slab restraints;
- Layout of foundations, racks, pits, equipment pads, trenches, and similar floor discontinuities;
- Environmental factors such as temperature, wind, and humidity; and

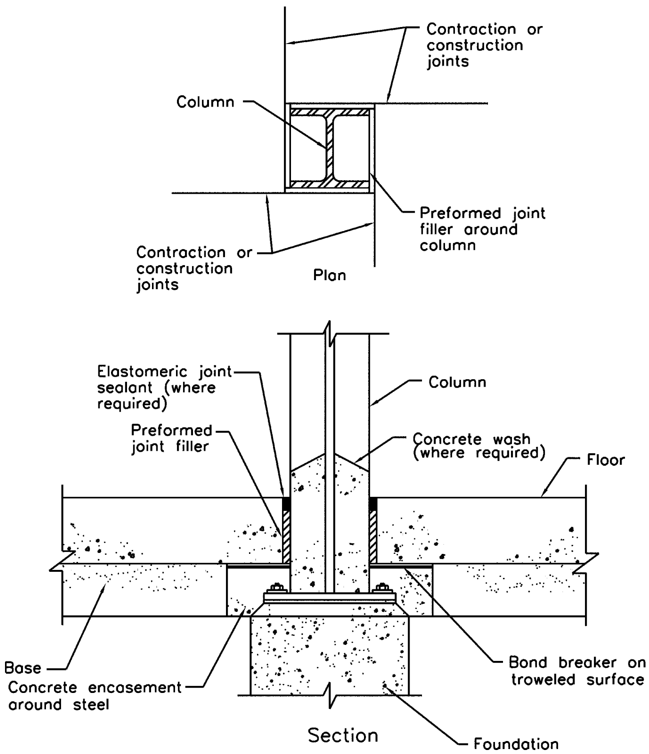


Fig. 3.4—Typical isolation joint at wide flange column.

- Methods and quality of concrete curing.

As previously indicated, establishing slab joint spacing, thickness, and reinforcement requirements is the responsibility of the designer. The specified joint spacing will be a principal factor dictating both the amount and the character of random cracking to be experienced, so joint spacing should always be carefully selected.

Curling of the floor surface at joints is a normal consequence of volume change resulting from differential moisture loss from concrete slab to the surrounding environment. This distortion can result in conflict with respect to installation of some floor coverings in the months after concrete placement. Current national standards for ceramic tile and wood flooring, such as gymnasium floors, are two instances that require the concrete slab surface to comply with stringent surface tolerances that cannot be met under typical slab curling behavior. The designer should consider the requirements for successful installation of floor coverings contained in Division 9 of the project specifications when performing the concrete slab design (ACI 360R).

For unreinforced, plain concrete slabs, joint spacings of 24 to 36 times the slab thickness, up to a maximum spacing of 18 ft (5.5 m), have produced acceptable results. Some random cracking should be expected; a reasonable level might be random visible cracks to occur in 0 to 3% of the floor slab panels formed by saw-cutting, construction joints, or a combination of both. If slab curl is of greater concern than usual, joint spacing, mixture proportion, and joint details should be carefully analyzed.

Joint spacing in nominally reinforced slabs (approximately 0.2% steel placed within 2 in. [50 mm] of the top of the slab) can be increased somewhat beyond that recommended for

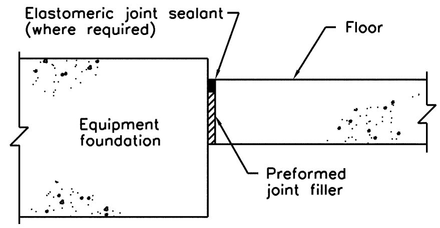


Fig. 3.5—Typical isolation joint around an equipment foundation.

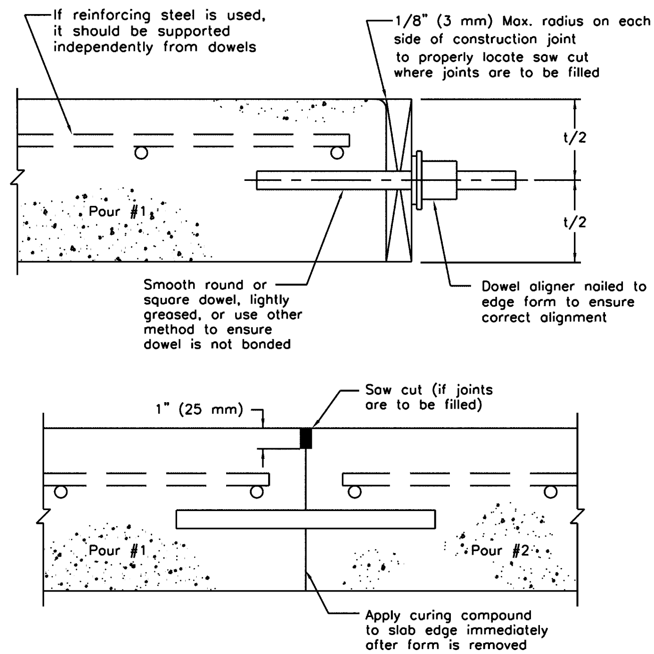


Fig. 3.6—Typical doweled construction joint.

unreinforced, plain concrete slabs, but the incidence of random cracking and curling will increase. Reinforcement will not prevent cracking. If the reinforcement is properly sized and located, cracks that do occur should remain tightly closed.

Contraction joints can be reduced or eliminated in slabs reinforced with at least 0.5% continuous reinforcing steel placed within 2 in. (50 mm) of the top of the slab or upper one-third of slab thickness, whichever is closer to the slab top surface. This will typically produce a larger number of closely spaced fine cracks throughout the slab.

Joints in either direction can be reduced or eliminated by post-tensioning that introduces a net compressive force in the slab after all tensioning losses.

The number of joints can also be reduced with the use of shrinkage-compensating concrete; however, the recommendations of ACI 223 should be carefully followed.

Contraction joints should be continuous, not staggered or offset. The aspect ratio of slab panels that are unreinforced, reinforced only for shrinkage and temperature, or made with shrinkage-compensating concrete should be a maximum of 1.5 to 1; however, a ratio of 1 to 1 is preferred. L- and T-shaped panels should be avoided. Figure 3.7 shows various types of contraction joints. Floors around loading docks have a tendency to crack due to their configuration and restraints.

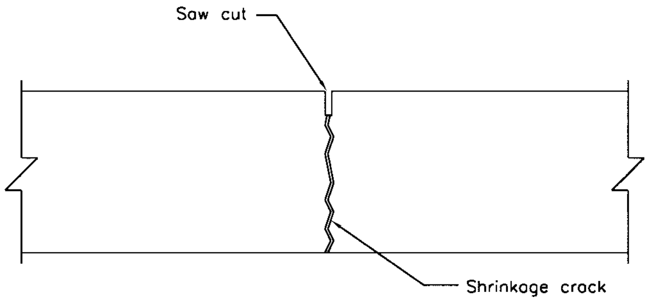


Fig. 3.7—Saw-cut contraction joint.

Figure 3.8 shows two methods that can be used to minimize slab cracking at reentrant corners of loading docks.

Plastic or metal inserts are not recommended for constructing or forming a contraction joint in any exposed floor surface that will be subjected to wheeled traffic.

3.2.5.4 *Saw cutting joints*—Contraction joints in industrial and commercial floors are usually formed by sawing a continuous slot in the slab to result in a weakened plane, below which a crack will form (Fig. 3.7). Further details on saw cutting of joints are given in Section 8.3.12

3.2.6 *Joint filling*—Contraction and construction joints in floor areas subject to the hard wheels of material handling vehicle traffic should be filled with a semirigid filler to minimize wear and damage to joint edges. Construction joints should be saw-cut 1 in. (25 mm) deep before filling. Joints should be as narrow as possible to minimize damage due to wheels loads while still being wide enough to be properly filled.

Where wet conditions or hygienic requirements exist, joints should be sealed with an elastomeric liquid sealant or a preformed elastomeric device. If there is also industrial vehicular traffic in these areas, consideration should be given to strengthening the edge of the joint through alternative means.

Refer to Section 5.12 for a discussion of joint materials, Section 9.10 for installation of joint fillers, and ACI 504R for joint sealants.

3.2.7 *Load-transfer mechanisms*—Doweled construction and contraction joints (Fig. 3.6 and 3.9) are recommended when load transfer is required, unless a sufficient post-tensioning force is provided across the joint to transfer the shear. Dowels force the concrete sections on both sides of a joint to undergo approximately equal vertical displacements subjected to a load and help prevent damage to an exposed edge when the joint is subjected to vehicles with hard-wheels such as forklifts. Table 3.1 provides recommended dowel sizes and spacing for round, square, and rectangular dowels. For dowels to be effective, they should be smooth, aligned, and supported so they will remain parallel in both the horizontal and the vertical planes during the placing and finishing operation. All dowels should be sawn and not sheared. Properly aligned, smooth dowels allow the joint to open as concrete shrinks. Dowel baskets (Fig. 3.9 to 3.11) should be used to maintain alignment of dowels in contraction joints, and alignment devices similar to the one shown in Fig. 3.6 should be used when detailing the doweled construction joints. Dowels should be placed no closer than 12 in. (300 mm) from the intersection of any joints.

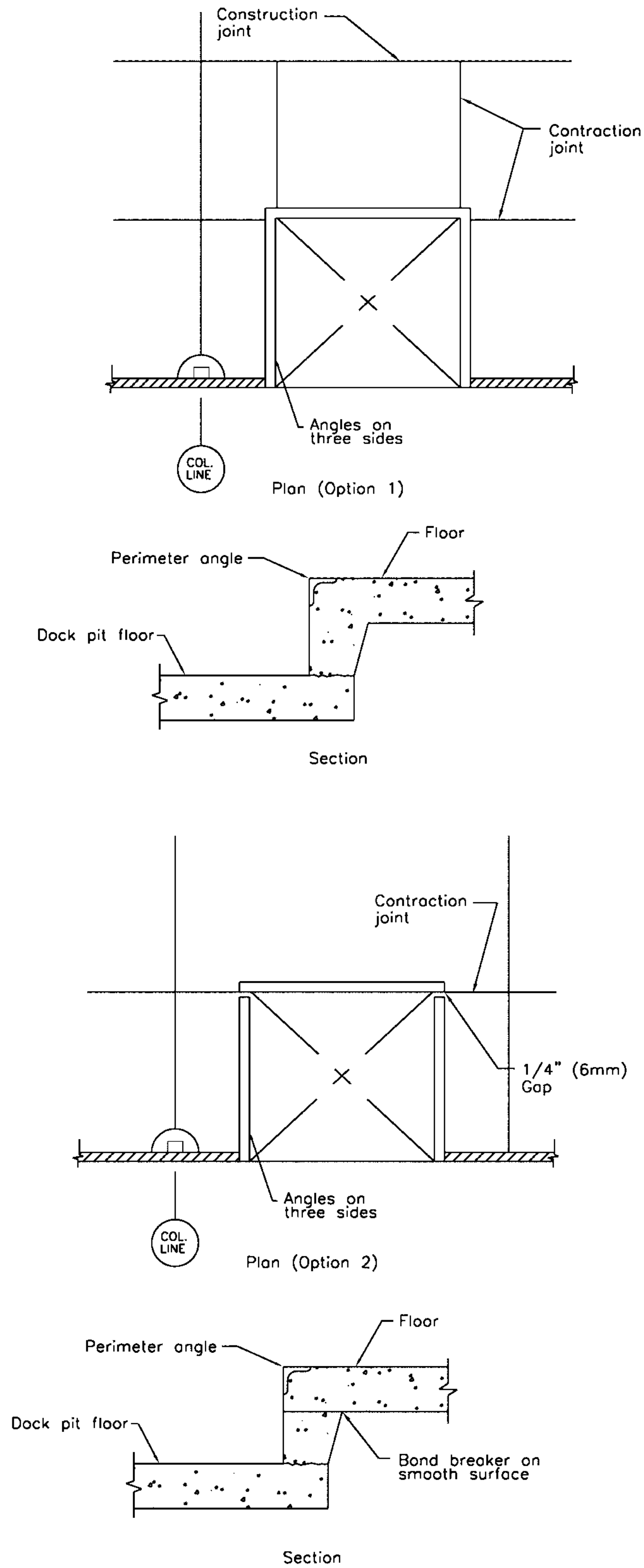


Fig. 3.8—Joint details at loading dock.

Diamond-shaped load plates (a square plate turned so that two corners line up with the joint, Fig. 3.12) can be used to replace dowels in construction joints (Walker and Holland 1998). The diamond shape allows the slab to move horizontally without restraint when the slab shrinkage opens the joint (Fig. 3.13). Table 3.2 provides the recommended size and

Table 3.1—Dowel size and spacing for round, square, and rectangular dowels (ACI Committee 325 1956)

Slab depth, in. (mm)	Dowel dimensions*, in. (mm)			Dowel spacing center-to-center, in. (mm)		
	Round	Square	Rectangular†	Round	Square	Rectangular
5 to 6 (125 to 150)	3/4 x 14 (19 x 350)	3/4 x 14 (19 x 350)	3/8 x 2 x 12 (10 x 50 x 300)	12 (300)	14 (350)	19 (475)
7 to 8 (175 to 200)	1 x 16 (25 x 400)	1 x 16 (25 x 400)	1/2 x 2-1/2 x 12 (12 x 60 x 300)	12 (300)	14 (350)	18 (450)
9 to 11 (225 to 275)	1-1/4 x 18 (30 x 450)	1-1/4 x 18 (30 x 450)	3/4 x 2-1/2 x 12 (19 x 60 x 300)	12 (300)	12 (300)	18 (450)

*Total dowel length includes allowance made for joint opening and minor errors in positioning dowels.
†Rectangular plates are typically used in contraction joints.
Notes: Table values based on a maximum joint opening of 0.20 in. (5 mm). Dowels must be carefully aligned and supported during concrete operations. Misaligned dowels cause cracking.

Table 3.2—Dowel size and spacing for diamond-shaped load plates

Slab depth, in. (mm)	Diamond load plate dimensions, in. (mm)	Diamond load plate spacing center-to-center, in. (mm)
5 to 6 (125 to 150)	1/4 x 4-1/2 x 4-1/2 (6 x 115 x 115)	18 (450)
7 to 8 (175 to 200)	3/8 x 4-1/2 x 4-1/2 (10 x 115 x 115)	18 (450)
9 to 11 (225 to 275)	3/4 x 4-1/2 x 4-1/2 (19 x 115 x 115)	20 (500)

Notes: Table values based on a maximum joint opening of 0.20 in. (5 mm). The construction tolerances required make it impractical to use diamond-shaped load plates in contraction joints.

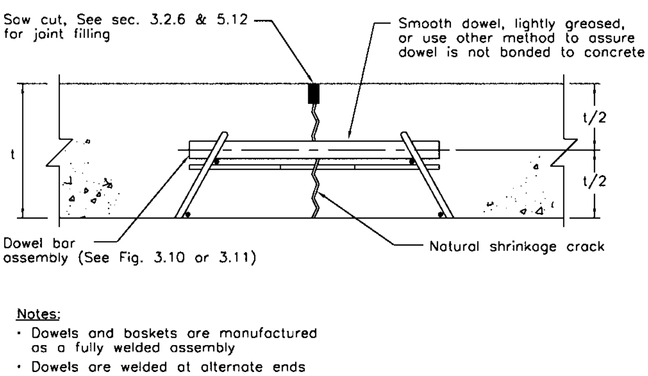


Fig. 3.9—Typical doweled contraction joint.

spacing of diamond-shaped load plates. This type of load-transfer device can be placed within 6 in. (150 mm) of an intersection (Fig. 3.13). Square and rectangular dowels cushioned on the vertical sides by a compressible material also permit movement parallel and perpendicular to the joint (Fig. 3.14). These types of load-transfer devices are useful in other slab types where the joint should have load-transfer capability while allowing some differential movement in the direction of the joint, such as might be necessary in post-tensioned and shrinkage-compensating concrete slabs or in slabs with two-directional doweling (Schrader 1987). In saw-cut contraction joints, aggregate interlock should not be relied upon for effective load transfer for wheeled traffic if the expected joint width exceeds 0.035 in. (0.9 mm) (Colley and Humphrey 1967).

Deformed reinforcing bars should not be used across contraction joints or construction joints because they restrain joints from opening as the slab shrinks during drying.

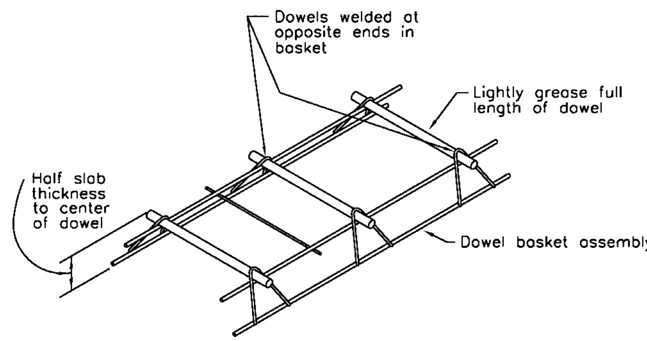


Fig. 3.10—Dowel basket assembly.

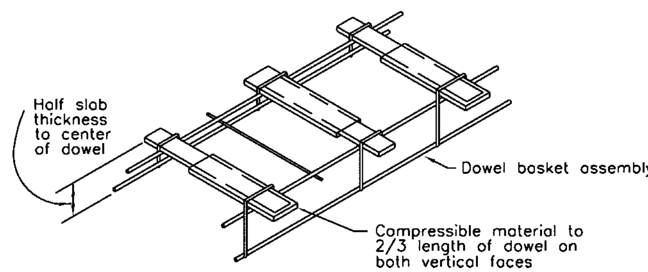


Fig. 3.11—Rectangular load plate basket assembly.

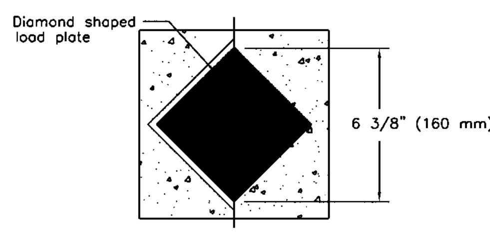


Fig. 3.12—Diamond-shaped load plate at construction joint.

Continuation of a part of the slab reinforcing through contraction joints can provide some load-transfer capability without using dowels but significantly increases the probability of out-of-joint random cracking.

Round, square, and rectangular dowels for slab-on-ground installation should meet ASTM A 36. The diameter or cross-sectional area, length, shape, and specific location of dowels as well as the method of support should be specified by the designer. Refer to Table 3.1 and Fig. 3.9 to 3.14.

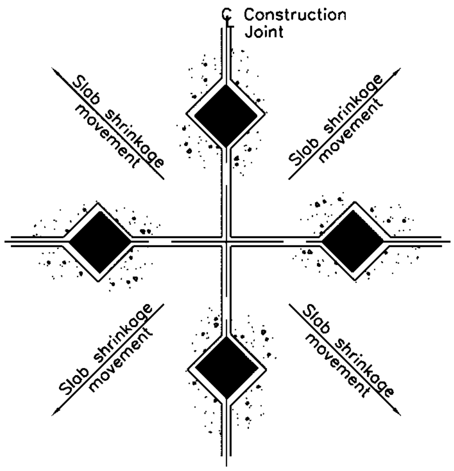


Fig. 3.13—Diamond-shaped load plates at slab corner.

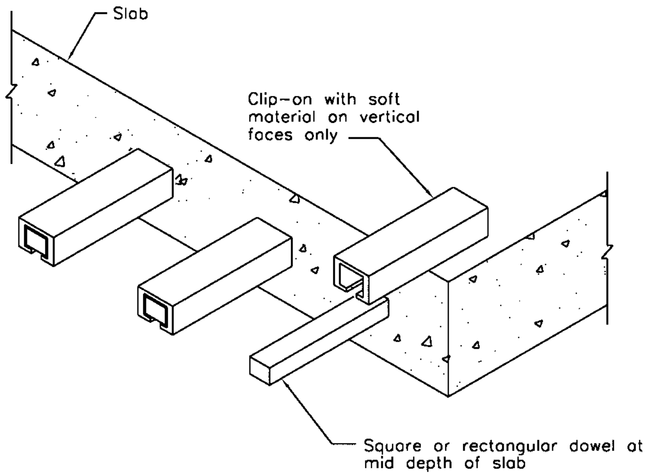


Fig. 3.14—Doweled joint detail for movement parallel and perpendicular to the joint.

Keyed joints are not recommended for load transfer in slabs-on-ground where heavy-wheeled traffic load is anticipated, because they do not provide effective load transfer. When the concrete shrinks, the keys and keyways do not retain contact and do not share the load between panels; this can eventually cause a breakdown of the concrete joint edges. For long post-tensioned floor strips and floors using shrinkage-compensating concrete with long joint spacing, care should be taken to accommodate significant slab movements. In most instances, post-tensioned slab joints are associated with a jacking gap. The filling of jacking gaps should be delayed as long as possible to accommodate shrinkage and creep (PTI 1990; PTI 2000). Where significant slab movement is expected, steel plating of the joint edges is recommended; for strengthening the edges (Fig. 3.15 and 3.16).

A doweled joint detail at a jacking gap in a post-tensioned slab (ASTM 1994; Spears and Panarese 1992) is shown in Fig. 3.16.

3.3—Suspended slabs

3.3.1 *Required design elements*—In addition to many of the items listed in Section 1.1.2, the following items specifically impact the construction of suspended slabs and should

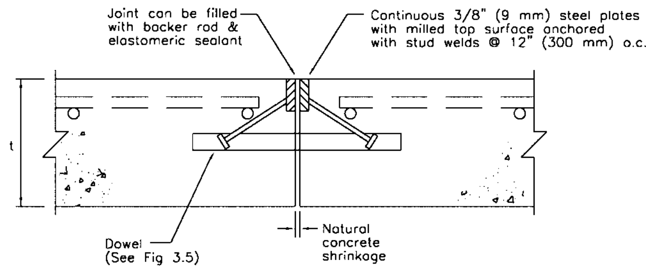


Fig. 3.15—Typical armored construction joint detail.

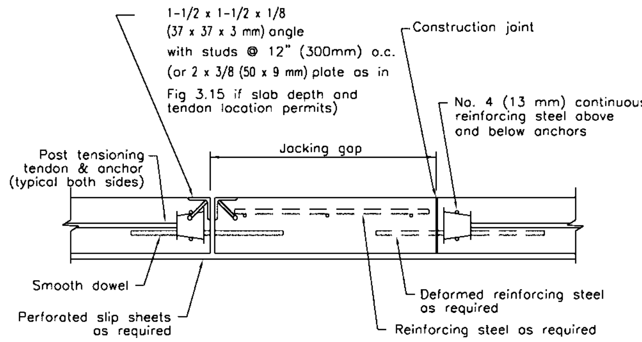


Fig. 3.16—Typical doweled joint detail for post-tensioned slab.

be included in the contract documents prepared by the designer:

- Frame geometry (member size and spacing);
- Reinforcement (type, size, location, and method of support);
- Shear connectors, if required;
- Construction joint location;
- Metal deck (type, depth, and gage), if required;
- Shoring, if required; and
- Tolerances (forms, structural steel, reinforcement, and concrete).

3.3.2 *Suspended slab types*—In general, suspended floor systems fall into four main categories:

1. Cast-in-place suspended floors;
2. Slabs with removable forms;
3. Slabs on metal decking; and
4. Topping slabs on precast concrete.

Design requirements for cast-in-place concrete suspended floor systems are covered by ACI 318 and ACI 421.1R. Refer to these documents to obtain design parameters for various cast-in-place systems. Slabs on metal decking and topping slabs on precast concrete are hybrid systems that involve design requirements established by ANSI, ASCE, The American Institute of Steel Construction, Precast/Prestressed Concrete Institute, and tolerances of ACI 117.

The levelness of suspended slabs depends on the accuracy of formwork and strikeoff but is further influenced (especially in the case of slabs on metal decking) by the behavior of the structural frame during and after completion of construction. Each type of structural frame behaves somewhat differently; it is important for the contractor to recognize these differences and plan accordingly.

The presence of camber in some floor members and the ACI 117 limitation on tolerances in slab thickness dictate that concrete be placed at a uniform thickness over the supporting steel. When placing slabs on metal decking, the contractor is cautioned that deflections of the structural steel members can vary from those anticipated by the designer. Achieving a level deflected surface can require increasing the slab thickness more than 3/8 in. (9.5 mm) in local areas. The committee recommends that concrete placement procedures and the basis for acceptance of the levelness of a completed concrete floor surface be established and agreed upon by key parties before beginning suspended floor construction (Tipping 1992).

3.3.3 *Slabs with removable forms*—Cast-in-place concrete construction can be either post-tensioned or conventionally reinforced. Both of these systems are supported during initial concrete placement, and they will deflect when supporting shores are removed.

Post-tensioned systems are normally used when larger spans are necessary or when the structural system is relatively shallow for the spans considered. Post-tensioned systems use high-strength steel tendons that are tensioned using a hydraulic jack designed for that purpose. The magnitude of floor slab deflection after supports are removed is less than that of comparable floors reinforced with conventional deformed reinforcing steel. At times, dead load deflection is entirely eliminated by the use of post-tensioning.

The magnitude of deflection in a conventionally mild steel reinforced floor system is dependent on a number of variables such as span, depth of structure, age at the time forms are stripped, concrete strength, and amount of reinforcement. In locations where the anticipated dead load deflection of a member is deemed excessive by the designer, an initial required camber, generally 1/2 in. (13 mm) or more, can be required. The amount of camber is determined by the designer based on an assessment of the loading conditions discussed. Ideally, the cambered floor system will deflect down to a level position after removal of the supporting shores.

3.3.4 *Slabs on carton forms*—Slabs on carton forms are a special application of slabs with removable forms (Tipping and North 1998). These slabs are necessary when slabs at ground level should remain independent of soil movement. Slabs on carton forms are most commonly used when soils at the building site are expansive clays subject to significant movement as a result of moisture variation. They provide a more economical construction solution than conventional framing systems, which require a crawl space to remove forms. The cardboard carton forms deteriorate in the months following construction, eventually leaving the desired void space below the slab and forcing the slab to span between supporting foundation elements.

Experience has shown that certain types of wet cardboard carton forms can fail locally under the weight of concrete and construction activities, with a resultant loss of part or all of the desired void space in the vicinity of the form failure. This failure can be instantaneous but can also occur 30 or 45 min after strikeoff. The latter type of failure, in addition to reducing desired void space, can result in a loss of local slab levelness. Forms that have been damaged by rain should be replaced or allowed to dry thoroughly, with their capacity verified, before placement of concrete.

3.3.5 *Slabs on metal deck*—Construction of slabs on metal deck involves the use of a concrete slab and a supporting platform consisting of structural steel and metal deck. The structural steel can be shored or unshored at the time of concrete placement, and the metal deck serves as a stay-in-place form for the concrete slab. This construction can be composite or noncomposite.

The supporting steel platform for slabs on metal deck is seldom level. Variation in elevations at which steel beams connect to columns and the presence of camber in some floor members combine to create variations in the initial elevation of steel members. Regardless of the initial levelness of the steel frame, unshored frames will deflect during concrete placement. These factors make the use of a laser or similar instrument impractical for the purpose of establishing a uniform elevation for strikeoff of the concrete surface of a slab on metal deck, unless the frame is preloaded to allow deflection to take place before strikeoff, and slab thickness is allowed to vary outside norms dictated by ACI 117. The presence of camber in some floor members and the ACI 117 limitation on variation in slab thickness generally dictates that concrete be placed to a uniform thickness over the supporting steel.

3.3.5.1 *Composite slabs on metal deck*—In composite construction, the composite section (concrete slab and steel beams) will work together to support any loads placed on the floor surface after the concrete has hardened. Composite behavior is normally developed through the use of shear connectors welded to the structural steel beam. These shear connectors physically connect the concrete slab to the beam and engage the concrete slab within a few feet of the steel beam; the resulting load-carrying element is configured much like a capital T. The steel beam forms the stem of the T, and the floor slab forms the cross-bar. Construction joints that are parallel to structural steel beams should be located far enough away to eliminate their impact on composite behavior. Questions about the location of construction joints should be referred to the designer on the project (Ryan 1997).

Unshored composite construction is the more common method used by designers because it is less expensive than shored construction. In unshored construction, the structural steel beams are sometimes cambered slightly during the fabrication process. This camber is intended to offset the anticipated deflection of that member under the weight of concrete. Ideally, after concrete has been placed and the system has deflected, the resulting floor surface will be level (Tipping 2002).

Shored composite concrete slabs on metal deck are similar to slabs with removable forms in that both are supported until the concrete has been placed and reaches the required strength. Structural steel floor framing members for shored composite slabs on metal deck are usually lighter and have less camber than those used for unshored construction with similar column spacings and floor loadings. One major concern with shored composite construction is the tendency for cracks wider than 1/8 in. (3 mm) to form in the concrete slab when the supporting shores are removed. These cracks do not normally impair the structural capacity of the floor but can become a severe aesthetic problem. The contractor is cautioned that this issue and any measures taken by the designer to avoid the formation of this type of crack should be addressed to the satisfaction of key parties before beginning suspended floor construction.

3.3.5.2 *Noncomposite slabs on metal deck*—In noncomposite construction, the slab and supporting structural steel work independently to support loads imposed after hardening of the concrete slab.

3.3.6 *Topping slabs on precast concrete*—A cast-in-place concrete topping on precast-prestressed concrete units involves the use of precast elements as a combination form and load-carrying element for the floor system. The cast-in-place portion of the system consists of a topping of some specified thickness placed on top of the precast units. The topping can be composite or noncomposite. In either case, added deflection of precast units under the weight of the topping slab is normally minor, so the finished surface will tend to follow the surface topography established by the supporting precast units. The camber in precast members, if they are prestressed, can change with time as a result of concrete creep. Depending on the length of time between casting of precast units and erection, this potential variation in camber of similar members can create significant challenges for the contractor. Care should be taken in the scheduling of such operations to minimize the potential impact of these variations. Precast members are less flexible and adaptable to changes or modifications that can be required on the jobsite than are the previously discussed systems.

3.3.7 *Reinforcement*—For cast-in-place concrete suspended slabs, reinforcing steel location varies as dictated by the contract documents. Post-tensioning reinforcement, when used, is enclosed in a plastic or metal sleeve and is tensioned by a hydraulic jack after the concrete reaches sufficient compressive strength. Elongation and subsequent anchoring of the ends of post-tensioning tendons results in the transfer of compressive force to the concrete (PTI 1990).

For slabs on metal deck, reinforcement is normally provided by deformed reinforcing steel, welded wire reinforcement, or a combination thereof.

3.3.8 *Construction joints*—The designer should provide criteria for location of construction joints in suspended slabs. The following is a general discussion of criteria that can influence these decisions.

3.3.8.1 *Slabs on removable forms*—Construction joints can introduce weak vertical planes in an otherwise monolithic concrete member, so they should be located where shear stresses are low. Under most gravity load conditions, shear stresses in flexural members are low in the middle of the span. ACI 318 requires that construction joints in floors be located within the middle third of spans of slabs, beams, and primary beams. Joints in girders should be offset a minimum distance of two times the width of any intersecting beams.

3.3.8.2 *Composite slabs on metal deck*—An important consideration when deciding on the location of construction joints in composite slabs on metal deck is that the joint location can influence deflection of the floor framing near the joint. A composite member (steel beam and hardened concrete slab working together) is stiffer and, therefore, deflects less than a noncomposite member (steel beam acting alone). Most composite slabs on metal deck are placed on an unshored structural steel floor frame. Often, structural steel members have initial camber to offset anticipated noncomposite deflection resulting from concrete placement. After hardening of the concrete, however, the composite member deflects much less than a comparable noncomposite beam or primary beam.

Following are general guidelines for deciding on the location of construction joints in composite slabs on metal deck:

1. Construction joints that parallel secondary structural steel beams should normally be placed near the midspan of the slab between beams;

2. Construction joints that parallel primary structural steel beams and cross secondary structural steel beams should be placed near the primary beam. The primary structural steel beam should not be included in the initial placement. It is important to place the construction joint far enough away from the primary beam to allow sufficient distance for development of the primary beam flange width. Placing the construction joint a distance of 4 ft (1.2 m) from the primary beam is usually sufficient for this purpose. This construction joint location allows nearly the full dead load from concrete placement to be applied to secondary beams that are included in the initial concrete placement. The primary beam should generally be included in the second placement at the construction joint. This will allow the primary beam to deflect completely before concrete at the primary beam hardens; and

3. Construction joints that cross primary structural steel beams should be placed near a support at one end of the primary beam. This will allow the beam to deflect completely before concrete at the beam hardens.

3.3.8.3 *Noncomposite slabs on metal deck*—The placement of construction joints in noncomposite slabs on metal deck should follow the same general guidelines discussed for slabs on removable forms in Section 3.3.8.1.

3.3.8.4 *Topping slabs on precast concrete*—Construction joints in topping slabs on precast concrete should be placed over joints in the supporting precast concrete.

3.3.9 *Cracks in slabs on metal deck*—Cracks often develop in slabs on metal deck. These cracks can result from drying shrinkage and thermal contraction or variations in flexibility of the supporting structural steel and metal deck. In a composite floor framing system, primary beams are the stiffest elements and generally deflect less than secondary beams. The most flexible part of the floor framing assembly is the metal deck, which is often designed for strength rather than for flexibility consideration.

Vibration as a result of power floating and power troweling operations can produce cracking over the structural steel beams during concrete finishing operations if the metal deck is flexible. As the concrete cures and shrinks, these cracks will open wide if not restrained by reinforcing steel, usually welded wire reinforcement, located near the top surface of the slab.

3.4—Miscellaneous details

3.4.1 *Heating ducts*—Heating ducts embedded in a concrete slab can be of metal, rigid plastic, or wax-impregnated cardboard. Ducts with waterproof joints are recommended. When metal ducts are used, calcium chloride should not be used in the concrete. Refer to Section 5.7.3 for a discussion on chlorides in concrete and Section 4.5.2 for installation of heating ducts.

3.4.2 *Edge insulation*—Edge insulation for slabs-on-ground is desirable in most heated buildings. The insulation should be in accordance with ASHRAE 90.1. It should not absorb moisture and should be resistant to fungus, rot, and insect damage; it should not be easily compressed.

Insulation should preferably be placed vertically on the inside of the foundation. It can also be placed in an L-shape configuration adjacent to the inside of the foundation and under the edge of the slab. If the L-shape configuration is used, the installation should extend horizontally under the slab a total distance of 24 in. (600 mm).

3.4.3 *Radiant heating: piped liquids*—Slabs can be heated by circulating heated liquids through embedded piping. Ferrous, copper, or plastic pipe is generally used with approximately 2 in. (50 mm) of concrete cover (not less than 1 in. [25 mm]) under the pipe and with 2 to 3 in. (50 to 75 mm) of concrete cover over the pipe. The slab is usually monolithic and the concrete is placed around the piping, which is fixed in place. Two-course slab construction has also been used, wherein the pipe is laid, connected, and pressure tested for tightness on a hardened concrete base course. Too often, however, the resulting cold joint is a source of distress during the service life.

Insulating concrete made with vermiculite or perlite aggregate or cellular foam concrete can be used as a subfloor. The piping should not rest directly on this or any other base material. Supports for piping during concreting should be inorganic and nonabsorbent; precast concrete bar supports (Section 3.2.4) are preferred to random lengths of pipe for use as supports and spacers. Wood, brick, or fragments of concrete or concrete masonry should not be used.

Sloping of the slab, where possible, can simplify sloping of the pipe. Reinforcement, such as welded wire reinforcement, should be used in the concrete over the piping. Where pipe passes through a contraction or construction joint, a provision should be made for possible movement across the joint. The piping should also be protected from possible corrosion induced by chemicals entering the joint. The piping should be pressure-tested before placing concrete, and air pressure (not water pressure) should be maintained in the pipe during concreting operations. After concreting, the slab should not be heated until curing is complete. The building owner should be warned to warm the slabs gradually using lukewarm liquid in the system to prevent cracking of the cold concrete.

3.4.4 *Radiant heating: electrical*—In some electrical radiant heating systems, insulated electrical cables are laid singly in place within the concrete or fastened together on transverse straps to form a mat. One system employs cable fastened to galvanized wire sheets or hardware cloth. The cables are embedded 1 to 3 in. (25 to 75 mm) below the concrete surface, depending on their size and operating temperature. In most systems the wires, cables, or mats are laid over a bottom course of unhardened concrete, and the top course is placed immediately over this assemblage with little lapse of time, thus avoiding the creation of a horizontal cold joint (ASHVE 1955).

Calcium chloride should not be used where copper wiring is embedded in the concrete; damage to insulation and subsequent contact between the exposed wiring and reinforcing steel will cause corrosion. If admixtures are used, their chloride contents should comply with the limits recommended by ACI 222R.

3.4.5 *Snow-melting*—Systems for melting snow and ice can be used in loading platforms or floor areas subjected to snow and ice. The concrete should be air-entrained for freezing-and-thawing resistance. Concrete surfaces should have a slope not less than 1/4 in./ft (20 mm/m) to prevent puddles from collecting. Piping systems should contain a suitable liquid heat-transfer medium that does not freeze at the lowest temperature anticipated. Calcium chloride should not be used (Section 5.7.3). Experience has shown that these snow-melting piping systems demand high energy consumption while displaying a high potential for failure and thermal cracking. The most successful applications appear to have been at parking garage entrances.

Some electrical systems are in use. These internally heated snow-melting systems have not been totally satisfactory.

3.4.6 *Pipe and conduit*—Water pipe and electrical conduit, if embedded in the floor, should have at least 1-1/2 in. (38 mm) of concrete cover on both the top and bottom.

3.4.7 *Slab embedments in harsh environments*—Care should be exercised in using heating, snow-melting, water, or electrical systems embedded in slabs exposed to harsh environments such as parking garages in northern climates and marine structures. If not properly embedded, systems can accelerate deterioration by increasing seepage of saltwater through the slab or by forming electrical corrosion circuits with reinforcing steel. If concrete deterioration occurs, the continuity and effective functioning of embedded systems are invariably disrupted.

CHAPTER 4—SITE PREPARATION AND PLACING ENVIRONMENT

4.1—Soil-support system preparation

The soil-support system should be well drained and provide adequate and uniform load-bearing support.

The ability of a slab to resist loads depends on the integrity of both the slab and full soil-support system. As a result, it is essential that the full soil-support system be tested or thoroughly evaluated before the slab is placed upon it (Ringo 1958).

The in-place density of the subgrade, subbase (if used), and base should be at least the minimum required by the

Fig. 4.1—Proof-rolling by loaded ready mix truck.

specifications, and the base should be free of frost before concrete placing begins and able to support construction traffic such as loaded truck mixers (Fig. 4.1).

The base should normally be dry at the time of concreting. If protection from the sun and wind cannot be provided as mentioned in Section 4.6 or if the concrete is placed in hot, dry conditions, the base should be lightly dampened with water in advance of concreting. There should be no free water standing on the base, nor should there be any muddy or soft spots when the concrete is placed (Section 4.1.5).

4.1.1 *Proof-rolling*—Proof-rolling is one of the most effective ways to determine if the full soil-support system is adequate to provide a uniformly stable and adequate bearing support during and after construction. If applicable, this process should be done after completion of the rough grading and, if required, can be repeated before the placement of the slab (Fig. 4.1).

Proof-rolling, observed and evaluated by the designer or the designer's representative, should be accomplished by a loaded tandem-axle dump truck, a loaded truck mixer, roller, or equivalent. In any case, multiple passes should be made using a pre-established grid pattern.

If rutting or pumping is evident at any time during the preparation of the subgrade, subbase, or base rolling, corrective action should be taken.

Rutting normally occurs when the surface of the base or subbase is wet and the underlying soils (subgrade) are firm. Pumping normally occurs when the surface of the base or subbase is dry and the underlying soils are wet. Any depression in the surface deeper than 1/2 in. (13 mm) should be repaired. Repair should include, but not be limited to, raking smooth or consolidating with suitable compaction equipment.

4.1.2 *Subgrade tolerance*—Industry practice is to plan and execute grading operations so that the final soil elevation is at the theoretical bottom of the slab-on-ground immediately before commencing concreting operations. Variations in grading equipment, subgrade material, and construction methods will result in inevitable local departures from this theoretical elevation. Studies have shown that these departures commonly result in slabs that vary in thickness as much as 1-1/2 in. (38 mm) from that shown on the contract documents (Gustaferro 1989; Gustaferro and Tipping 2000).

The designer should explicitly address the slab thickness issue in mandatory language in the project specifications on occasions where a result other than that which would commonly result from industry practice is desired. Further, the issue of minimum allowable slab-on-ground thickness should be addressed in a preconstruction meeting to ensure that all parties are aware of the designer's expectations. The committee recommends the following rough-grade and fine-grade tolerances as a necessary component of this process.

The necessary grading of the subgrade, often referred to as rough grading, should conform to a tolerance of +0 in./–1-1/2 in. (+0 mm/–38 mm). Compliance should be confirmed before removal of excavation equipment. A rod and level survey should be performed by a surveyor. Measurements should be taken at 20 ft (6 m) intervals in each of two perpendicular directions.

4.1.3 *Base tolerance*—Base tolerances, often referred to as fine grading, should conform to a tolerance of +0 in./–1 in. (+0 mm/–25 mm) for floor Classes 1 to 3 and +0 in./–3/4 in. (+0 mm/–19 mm) for floor Classes 4 to 9, when measured from bottom of slab elevation. Compliance with these fine-grade values should be based on the measurements of individual floor sections or placements. A rod and level survey should be performed; measurements should be taken at 20 ft (6 m) intervals in each direction.

4.1.4 *Base material*—Use of the proper materials is essential to achieve the tolerances suggested in Section 4.1.3 (Suprenant and Malisch 1999b). The base material should be a compactible, easy to trim, granular fill that will remain stable and support construction traffic. The tire of a loaded concrete truck mixer should not penetrate the surface more than 1/2 in. (13 mm) when driven across the base. The use of so-called cushion sand or clean sand with uniform particle size, such as concrete sand, meeting requirements of ASTM C 33, will not be adequate. This type of sand will be difficult, if not impossible, to compact and maintain until concrete placement is completed.

A clean, fine-graded material with at least 10 to 30% of particles passing a No. 100 (150 µm) sieve but not contaminated with clay, silt, or organic material is recommended. Manufactured sand from a rock-crushing operation works well; the irregular surfaces tend to interlock and stabilize the material when compacted. The material should have a uniform distribution of particle sizes ranging from No. 4 (4.75 mm) to the No. 200 (75 µm) sieve. Refer to ASTM C 33, Table 1, for limitation of deleterious material finer than No. 200 (75 µm) sieve. Unwashed size No. 10 (2 mm) per ASTM D 448 works well.

4.1.5 *Vapor barrier/vapor retarder*—If a vapor barrier or retarder is required to reduce the impact of moisture transmission from below the slab on moisture-sensitive floor finishes, adhesives, coatings, equipment, or environments, the decision whether to locate the material in direct contact with the slab or beneath a fill course should be made on a case-by-case basis. Each proposed installation should be independently evaluated as to the moisture-related sensitivity of subsequent floor finishes, project conditions, schedule, and the potential effects of slab curling and cracking.

When a fill course is used over the vapor barrier/retarder, it should be a minimum of 4 in. (100 mm) of trimmable, compactible, granular fill (not sand), a so-called crusher-run material. Usually graded from 1-1/2 to 2 in. (38 to 50 mm) down to rock dust is suitable. Following compaction, the surface can be choked off with a fine-grade material (Section 4.1.4) to reduce friction between the base material and the slab.

If it is not practical to install a crusher-run material, the vapor barrier/retarder should be covered with at least 3 in. (75 mm) of fine-graded material such as crusher fines or manufactured sand (Section 4.1.4). The granular fill and fine-graded material should have sufficient moisture content to be compactible but still be dry enough at the time of concrete placement to act as a blotter (Section 4.1).

If a fill course is used, it should be protected from taking on additional water from sources such as rain, curing, cutting, or cleaning. Wet fill courses have been directly linked to a significant lengthening of the time required for a slab to reach an acceptable level of dryness for floor covering applications. If a vapor barrier/retarder is to be placed over a rough granular fill, a thin layer of approximately 1/2 in. (13 mm) of fine-graded material should be rolled or compacted over the fill before installation of the vapor barrier/retarder to reduce the possibility of puncture (Section 4.1.4). Vapor barriers/retarders should be overlapped 6 in. (150 mm) at the joints and carefully fitted around service openings. See Section 3.2.3 for more information on vapor barriers/retarders for slabs-on-ground (Suprenant and Malisch 1998A).

4.2—Suspended slabs

Before concrete placement, bottom-of-slab elevation and the elevation of reinforcing steel and any embedments should be confirmed. Forms that are too high often result in reinforcements being above the desired elevation for the slab surface. Screed rails or guides should be set at elevations that will accommodate initial movement of the forms during concreting. Screed rails may also be set at elevations that will offset downward deflection of the structure following concrete placement (Section 3.3).

4.3—Bulkheads

Bulkheads can be wood or metal; they should be placed at the proper elevation with stakes and necessary support required to keep the bulkheads straight, true, and firm during the entire placing and finishing procedure. Keyways are not recommended. If specified, however, small wood or metal keys should be attached to the inside of the form.

When it is necessary to set bulkheads on insulation material, such as in cold storage or freezer rooms, extra attention should be given to keeping the forms secure during the placing and finishing process. The insulation material should not be punctured by stakes or pins. It may be necessary to place sand bags on top of form supports to ensure stability during concrete placement.

Circular or square forms can be used to isolate the columns. Square forms should be rotated 45 degrees (Fig. 3.3) or installed in a pinwheel configuration as indicated in Fig. 3.4. Walls, footings, and other elements of the structure should be isolated from the floors. Asphalt-impregnated sheet or other suitable preformed compressible joint material (ACI 504R) should be used. These joint materials should never be used as freestanding forms at construction joints or column block outs but should be installed after the original forms have been removed. After removal of forms around columns, preformed joint materials should be placed at the joint to the level of the floor surface and the intervening area concreted and finished. These preformed joint materials can be placed at the proper elevation to serve as screed guides during the concreting operations. The preformed joint material should be of the type specified and should conform to one of the following specifications, depending on the conditions of its use: ASTM D 994, D 1751, or D 1752.

4.4—Setting screed guides

The screed guides can be 2 in.-thick (50 mm) lumber, pieces of pipe, T-bars, or rails, the tops of which are set to the finished concrete grade without changing the design elevation of the reinforcing steel. Each type should have a tight-radius edge. If the wet-screed approach is used to establish concrete grade, the finished floor elevation for a slab-on-ground may be laid out by driving removable grade stakes into the subgrade at predetermined intervals that are appropriate for the width of placement strips being installed. The tops of these stakes should be set to the required concrete grade.

4.4.1 *Establishing grades for adequate drainage on the slab surface*—When positive drainage is desired, the forms and screed guides should be set to provide for a minimum slope of 1/4 in./ft (20 mm/m) to prevent ponding. Positive drainage should always be provided for exterior slabs and can be desirable for some interior slabs.

4.5—Installation of auxiliary materials

4.5.1 *Edge insulation*—Insulation (Section 3.4.2) should preferably be placed vertically on the inside of the foundation. It can also be placed in an inverted L-shape configuration adjacent to the foundation and under the edge of the slab.

4.5.2 *Heating ducts*—Metal, rigid plastic, or wax-impregnated cardboard ducts with watertight joints are recommended; they can be set on a sand-leveling bed and back-filled with sand to the underside of the slab. Precautions should be taken to ensure that the position of the ducts is not disturbed during concreting and that they are adequately protected from corrosion or deterioration.

If the ducts to be used are not waterproof, they should be completely encased in at least 2 in. (50 mm) of concrete to prevent the entrance of moisture.

4.6—Concrete placement conditions

When slabs are placed on ground, there should be no more than 30 °F (17 °C)—ideally 20 °F (11 °C)—difference between the temperature of the base and concrete at the time of placement.

Floor slab installations should be undertaken in a controlled environment where possible. Protection from the sun and wind is crucial to the placing and finishing process. The roof of the structure should be waterproof, and the walls should be completely up. The site should provide easy access for concrete trucks and other necessary materials and suppliers. The site should be have adequate light and ventilation. Temperatures inside the building should be maintained above 50 °F (10 °C) during placing, finishing, and curing the concrete. If heaters are required, they should be vented to the outside (Kauer and Freeman 1955). Salamanders or other open flame heaters that might cause carbonation of the concrete surface should not be used. When installation procedures are carried out each day under the same conditions, the resulting floors are significantly superior to those floors installed under varying or poor environmental conditions. Also, refer to Sections 9.5.1 and 9.5.2 for cold- and hot-weather considerations.

CHAPTER 5—MATERIALS

5.1—Introduction

Concrete produced in accordance with ASTM C 94 varies and produces concrete with different setting and finishing characteristics. These standards offer a wide window of acceptance (Bimel 1993). Therefore, the specific concrete mixture should be investigated before the preparation of mixture proportions for floors and slabs.

5.2—Concrete

Because minimizing shrinkage is of prime importance, special attention should be given to selecting the best possible concrete mixture proportions. The shrinkage characteristics of a concrete mixture can be determined by ASTM C 157. Should it be necessary to determine if a proposed concrete mixture has other than normal shrinkage (ACI 209R), the proposed concrete mixture should be compared to the specified or a reference concrete mixture using ASTM C 157. It is essential that the concrete used in these tests be made with the same materials that will be used in the actual construction.

In addition to meeting the specified compressive strength based on standard laboratory samples, a concrete mixture proportion for use in a floor slab should, if specified, also meet the flexural-strength requirements and the limits on *w/cm* for durability, if applicable (Section 6.2.3). The portland cement content and the content of other cementitious products, if used, should be sufficient to permit satisfactory finishability under the anticipated field conditions. The setting characteristics of the concrete should be relatively predictable. The concrete should not experience excessive retardation, differential set time, or surface crusting difficulties under the conditions of temperature and humidity expected on the project. Some admixture-cement combinations can cause these difficulties, particularly when multiple admixtures are used. Because there is not a generally recognized procedure for establishing these performance characteristics, the committee recommends placement of a sample floor slab as indicated in Section 6.2.4. Floor concrete requirements differ from those of other concrete used in the structure. Project requirements should be reviewed thoroughly before mixture proportioning. If possible, the concrete contractor should have the opportunity to review the proposed mixture proportions and to prepare a sample placement to verify the workability, finishability, and setting time for the proposed usage.

5.3—Portland cement

5.3.1—Concrete floors can incorporate a variety of portland cements that meet ASTM C 150, C 595, C 845, and C 1157.

Of the four cements used in floors and slabs described in ASTM C 150, Type I is the most common, and it is used when the special properties of another type are not required. Type II is also for general use, especially when moderate sulfate resistance or moderate heat of hydration is desired. Type III is used when high early strength is desired. Type V is used when high sulfate resistance is required. When the aggregate to be used on the project is possibly susceptible to alkali-aggregate reaction, it is recommended that the maximum equivalent alkali limits of ASTM C 150 (Table 2 Optional Chemical Requirements) be specified if supplementary cementitious materials demonstrated to control alkali-silica reactivity, or alkali silica reaction-inhibiting admixtures, are not available. Refer to the appendix of ASTM C 33 for further information.

If air-entrained concrete is required, air-entrainment should be obtained with an admixture, rather than by using an air-entraining cement, allowing for better control of air content.

5.3.2 *Blended hydraulic cements*—Blended hydraulic cements are produced by intimately and uniformly blending two or more types of fine materials, such as portland cement, ground-granulated blast-furnace slag, fly ash and other pozzolans, hydrated lime, and preblended cement combinations of these materials.

There are six recognized classes of blended cements that conform with ASTM C 595: Type IS portland blast-furnace slag cement; Type IP and P portland-pozzolan cements; Type I (PM) pozzolan-modified portland cement; Type S slag cement; and Type I (SM) slag-modified portland cement. Types P and S, however, are normally not available for use in general concrete construction. The manufacturers of these cements should be contacted for information regarding the specific product and the effect its use will have on setting time, strength, water demand, and shrinkage of concrete proposed for the project under anticipated field conditions. Conformance to the requirements of ASTM C 595 does not impose sufficient restrictions on the cement to be used. If the 28-day design strength is achieved but shrinkage is excessive and retardation is significant, the cement may not be suitable for the project.

ASTM C 1157 is a performance specification that establishes requirements for six types of cement mirroring the attributes of ASTM C 150 and ASTM C 595 cement types.

For information on pozzolans used as cement replacements or cementitious additions, refer to Section 5.7.5.

5.3.3 *Expansive cements*—Types K, M, and S are expansive cements meeting ASTM C 845 specifications that are used in shrinkage-compensating concrete floors. Refer to ACI 223 for specific details on shrinkage-compensating concrete floors. Shrinkage-compensating concrete can also be made by adding an expansive component as discussed in Section 5.7.4. When a component is used, it is essential that the component manufacturers work with the concrete producer and testing laboratory to determine the rate and level of expansion that can be expected under anticipated job conditions.

5.4—Aggregates

Aggregates should conform to ASTM C 33 or to ASTM C 330. These specifications are satisfactory for most Class 1, 2, 3, 4, 5, and 6 floors. Additional limitations on grading and quality can be required for the surface courses of heavy-duty Class 7 and 8 floors.

Although these ASTM standards set guidelines for source materials, they do not establish combined gradation requirements for the aggregate used in concrete floors. Compliance with the aggregate gradations discussed in Section 5.4.3 will produce a desirable matrix while reducing water demand of the concrete mixture and reducing the amount of cement paste required to coat the aggregate (Shilstone 1990). ASTM C 33 limits coal and lignite to no more than 0.5% in fine or coarse aggregate and limits low specific gravity chert to no more than 5.0% in coarse aggregate. Although the concrete used may comply with this standard, some popouts are always possible. In fact, concrete containing as little as 0.2% or less coal, lignite, or low-density deleterious material may not be acceptable, as this quantity of those products can affect both the overall durability and appearance of the finished floor.

5.4.1 *Fine aggregate grading*—Although ASTM C 33 and C 330 are acceptable specifications, Table 5.1 contains preferred grading specifications for the toppings for Class 7 floors. The amount of material passing through the No. 50 and 100 sieves (300 and 150 µm) should be limited as indicated for heavy-duty floor toppings for Class 7. When fine aggregates contain minimum percentages of material passing the No. 50 and 100 sieves (300 and 150 µm), however, the likelihood of excessive bleeding is increased and limitations on water content of the mixture become increasingly important. Natural sand is preferred to manufactured sand; the gradation indicated in Table 5.1 will minimize water demand.

5.4.2 *Coarse aggregate grading*—The maximum size of coarse aggregate should not exceed 3/4 the minimum clear spacing of the reinforcing bars in structural floors, or 1/3 the thickness of nonreinforced slabs (ACI 318-02, Section 3.3.2). In general, natural aggregate larger than 1-1/2 in. (38 mm) or lightweight aggregate larger than 1 in. (25 mm) is not used. Although the use of large aggregate is generally desired for lower water demand and shrinkage reduction, it is important to recognize the overall gradation of all the aggregate (Section 5.1). When aggregate sizes larger than 1 in. (25 mm) are used, the coarse aggregate can be batched as two sizes to prevent segregation. Drying shrinkage can be minimized by the use of the largest practical-size coarse aggregate. If flexural strength is of primary concern, however, the use of smaller-size coarse aggregate can help achieve better uniformity in strength.

Table 5.1—Preferred grading of fine aggregates for floors

Sieve designations		Percent passing		
Standard	Alternative	Normalweight aggregate	Lightweight aggregate	Heavy-duty toppings, Class 7 floors
9.5 mm	3/8 in.	100	100	100
4.75 mm	No. 4	85 to 100	85 to 100	95 to 100
2.36 mm	No. 8	80 to 90	—	65 to 80
1.18 mm	No. 16	50 to 75	40 to 80	45 to 65
600 µm	No. 30	30 to 50	30 to 65	25 to 45
300 µm	No. 50	10 to 20	10 to 35	5 to 15
150 µm	No. 100	2 to 5	5 to 20	0 to 5

5.4.3 *Combined aggregate grading*—Gradations requiring between 8 and 18% for large top size aggregates such as 1-1/2 in. (38 mm) or 8 and 22% for smaller maximum-size aggregates such as 1 or 3/4 in. (25 or 19 mm) retained on each sieve below the top size and above the No. 100 (150 µm) sieve have proven satisfactory in reducing water demand while providing good workability. The ideal range for No. 30 and 50 (600 and 300 µm) sieves is 8 to 15% retained on each. Often, a third aggregate is required to achieve this gradation (Shilstone 1990). Typically, 0 to 4% retained on the top size sieve and 1.5 to 5.0% on the No. 100 (150 µm) sieve will be a well-graded mixture. This particle-size distribution is appropriate for round or cubically shaped particles in the No. 4 to 16 (4.75 to 1.18 mm) sieve sizes. If the available aggregates for these sizes are slivered, sharp, or elongated, 4 to 8% retained on any single sieve is a reasonable compromise. Mixture proportions should be adjusted whenever individual aggregate grading varies during the course of the work. Refer to Sections 6.3.2 and 6.3.4 for additional information.

Limitations in locally available material may require some deviations from the aforementioned optimum recommendations. The following limitations should always be imposed:

1. Do not permit the percent retained on two adjacent sieve sizes to fall below 5%;

2. Do not allow the percent retained on three adjacent sieve sizes to fall below 8%; and

3. When the percent retained on each of two adjacent sieve sizes is less than 8%, the total percent retained on either of these sieves and the adjacent outside sieve should be at least 13% (for example, if both the No. 4 and No. 8 [4.75 and 2.36 mm] sieves have 6% retained on each, then: 1) the total retained on the 3/8 in. and No. 4 [9.5 and 4.75 mm] sieves should be at least 13%, and 2) the total retained on the No. 8 and No. 16 [2.36 and 1.18 mm] sieves should be at least 13%.)

5.4.4 *Aggregate quality*—Compliance with ASTM C 33 and C 330 generally ensures aggregate of adequate quality, except where either chemical attack or abrasion in Class 7 and 8 floors is severe. See ACI 201.2R for a more complete discussion of precautions under these conditions. Sections 5.4.6 and 5.4.8 discuss special abrasion-resistant and nonslip aggregates, respectively. The guidelines of ACI 201.2R and

ASTM C 33 and its appendix should be followed where there is concern about the possibility of alkali-aggregate reaction.

5.4.5 *Special-purpose aggregates*—Decorative and nondecorative mineral aggregate and metallic hardeners are used to improve the properties of the slab surface. These materials, applied as dry shakes on top of the concrete, are floated and troweled into the floor surface to improve the abrasion resistance, impact resistance, achieve nonslip surfaces, or to obtain a decorative finish. In this document, the term dry-shake is applied to premixed materials, which may be mineral aggregate, metallic, or colored. The term embedded is a more generic term used where the material can be furnished in either premixed or bulk form. Trap rock and emery are two examples of materials that can be furnished in bulk form. These bulk materials should be blended with locally available portland cement and meet the requirements of ASTM C 150 or C 1157 before being introduced to the concrete surface.

5.4.6 *Wear-resistant aggregates*—Hard, wear-resistant aggregates, such as quartz, emery, and traprock, as well as malleable metallic hardeners, are frequently used as surface treatments (ASTM 1994). They are applied as dry shakes and finished into the surface of the floor to improve its abrasion and wear resistance.

Nonmetallic surface hardeners should be used on floors subjected to heavy frequent forklift or hard-wheeled traffic (Table 2.1). Metallic hardeners in sufficient quantity should be considered for use when heavy steel wheel or intense point impact loading is anticipated. Chloride-bearing admixtures should not be used in conjunction with a metallic floor hardener.

Mineral aggregate and metallic surface hardeners are factory premixed with specially selected portland cement and plasticizers. Some mineral aggregates can be supplied in bulk and mixed with cement on site. These aggregates, in properly graded sizes, can also be used in topping mixtures.

5.4.7 *Surface treatment for electrically conductive floors*—Concrete floors can be made electrically conductive by using specially prepared metallic hardeners (dry shakes). Electrically conductive floors are also required to be spark-resistant under abrasion or impact. For protection against abrasion sparks, care should be taken in the choice of aggregates. Because construction techniques for these floors are rather specialized, specific recommendations of the product manufacturer and designer should be followed (Boone et al. 1958).

The electrical resistance of such floors can be determined by reference to the appropriate specification of the Naval Facilities Engineering Command (NFEC 1984). A typical test for spark resistance under abrasion or impact is given in the aforementioned specification and the National Fire Protection Association, NFPA 99, specification. A factory premixed metallic surface hardener containing a conductive binder is commonly used for these floors. This hardener is floated and troweled into the surface of freshly placed concrete (Section 8.6).

Special conductive curing compounds should be used to cure these floors. Conductive floors should not be used in areas expected to be continuously moist.

5.4.8 *Slip-resistant aggregates*—Slip-resistant aggregates should be hard and nonpolishing. Fine aggregates are usually emery or a manufactured abrasive. The slip resistance of some aggregates can be improved by replacing the fines with those of a more slip-resistant aggregate. To improve slip resistance, extremely soft aggregates like vermiculite can be troweled into the surface of freshly placed concrete and then removed later by scrubbing after the concrete has hardened.

5.4.9 *Decorative aggregates*—Decorative aggregates can be of many minerals and colors. They should be sound, clean, nonreactive, and of consistent quality. The most common are quartz, marble, granite, and some ceramics. Rocks, shells, brass turnings or other brass pieces, and ball bearings have also been used. Shapes resembling spheres and cubes are preferable to flat or highly irregularly shaped pieces, which can become dislodged easily. It is usually preferable to have aggregate of only one sieve size.

5.5—Water

Mixing water should be potable. Nonpotable water can be used if 7- and 28-day strengths of 2 in. (50 mm) mortar cubes made with it are equal to at least 90% of the strengths of cubes made from similar mixtures using distilled water and tested in accordance with ASTM C 109 (Section 3.4, ACI 318-02). ACI 301 discusses mixing water, as do Steinour (1960) and others (Kosmatka, Kerkhoff, and Panarese 2002a). Also refer to AASHTO T 26.

5.6—Curing materials

ACI 308R lists many coverings and membrane-forming liquids that are acceptable for curing concrete floors. Because curing is so vital to good flatwork, the characteristics of curing materials suitable for flatwork are set forth here in great detail. Also refer to Chapter 9 for the purpose, methods, and length of curing.

5.6.1 *Wet burlap*—Wet burlap, plastic film, waterproof paper, and combination polyethylene/ burlap sheets may all be generically referred to as reusable wet cure covers or blankets. All should meet requirements of AASHTO M 182. When water is used in the curing procedure, the difference in temperature between water and the concrete surface should not exceed 20 °F (11 °C).

If kept continually moist, burlap is an effective material for curing concrete surfaces. Old burlap from which the sizing has disappeared or has been removed is easier to wet than new burlap.

Care should be taken so the burlap used does not stain the concrete or come from sacks that once contained sugar; sugar retards the hardening of concrete and its presence could result in a soft surface. The requirements for burlap are described in AASHTO M 182. White, polyethylene-coated burlap is available; the polyethylene is helpful in keeping the burlap moist longer, but it makes rewetting more difficult. Refer to ASTM C 171.

5.6.2 *Plastic film, waterproof paper, or combination polyethylene/burlap sheets*—Plastic film, waterproof paper, or polyethylene/burlap sheets for curing should allow a moisture loss of no more than 1.8 oz./ft^2 (0.55 kg/m^2) in 72 h when tested according to ASTM C 156. Polyethylene plastic film with the same thickness and permanence used for vapor retarders below slabs-on-ground (Section 3.4) should be satisfactory. Waterproof paper should meet the requirements of ASTM C 171. These products should not be used on colored floors.

5.6.3 *Membrane-forming curing compounds*—Liquid membrane-forming curing compounds should meet the provisions of ASTM C 309, which describes the requirements for both clear and pigmented types. White or gray compounds are used for their good light reflection. Colored curing compounds are available for colored concrete. Dissipating or strippable resin-based materials can be used on slabs receiving applied finishes or subsequent liquid surface treatments. ASTM C 309 allows moisture loss of 1.8 oz./ft^2 (0.55 kg/m^2) in 72 h at a curing compound coverage of 200 ft^2/gal. (5.0 m^2/L) when applied in compliance with ASTM C 156. Special conductive curing compounds should be used to cure electrically conductive and spark-resistant floors. It is important to determine if a dissipating or nondissipating product should be used. The use of a nondissipating compound can be incompatible with the installation or application of future floor coverings.

For floors designed for high wear resistance, optimum top surface strength development, and minimal cracking, it is desirable to use curing compounds that offer high water retention. When a mineral aggregate or metallic surface hardener is used, the curing procedure and specific product used for curing should be approved by the manufacturer of the hardener. A high-solids-type curing compound can limit maximum moisture loss to 0.008 lb/ft^2 (0.04 kg/m^2) at a coverage of 300 ft^2/gal. (7.50 m^2/L)—less than 50% of that allowed by ASTM C 309 (ACI 308R).

More stringent criteria can be appropriate for some projects. Manufacturers' written instructions should be followed for both the number of coats and the coverage rate needed to meet the appropriate ASTM or project requirements. Periodic field testing to evaluate actual performance is recommended. One practical test for concrete surfaces to receive a moisture-sensitive covering is to apply a 18 x 18 in. (460 x 460 mm) transparent polyethylene sheet, sealed to the slab with tape at the edges. Visible liquid water should not be present when the sheet is removed after a minimum test period of 16 h. Three tests should be conducted for areas up to 500 ft^2 (46.5 m^2) and one for each additional 500 ft^2 (46.5 m^2). Refer to ASTM E 1907 and D 4263 for additional information.

When a mineral aggregate or metallic surface hardener is used, the curing method should be compatible with recommendations of the hardener manufacturer.

5.7—Admixtures

Admixtures should be used when they will effect a specific desired change in the properties of the freshly mixed or hardened concrete. They should be used in accordance with the instruction and principles given in ACI 212.1R and 212.2R and the guidelines for chloride limits given in Section 5.7.3. If more than one type of admixture is used in the same concrete, each should be batched separately. A second admixture can significantly affect the required dosage of both admixtures; therefore, preliminary tests are recommended to ensure compatibility. Sample slabs made under the anticipated job conditions of temperature and humidity can also be used to help evaluate admixture performance, and to allow necessary adjustments affecting workability, finishability, and setting time before the start of the slab installation. Some admixtures are not compatible with shrinkage-compensating concrete because they adversely affect expansion, bond to steel, and shrinkage (ACI 223).

5.7.1 *Air-entraining admixtures*—Concrete for use in areas that will be exposed to freezing temperatures while moist should contain entrained air (Section 6.2.7). Entrained air is not recommended for concrete to be given a smooth, dense, hard-troweled finish because blistering and delamination may occur (Suprenant and Malisch 1999b). For nontroweled finishes, smaller percentages of entrained air than those normally used for exposure to freezing-and-thawing cycles may reduce bleeding and segregation. Air-entraining admixtures, when used in the concrete as recommended in Chapter 6, should meet the requirements of ASTM C 260. Consistent control of air entrainment is necessary.

In most cases, concrete for trowel-finished interior concrete floors made with normalweight aggregates should not include an air-entraining admixture; the maximum total air content for this concrete should normally not exceed 3% at the point of placement. Air contents in excess of 3% make the surface difficult to finish and can lead to surface blistering and peeling during finishing. Troweled concrete with intentionally added air will typically not retain the proper bubble size required to provide scale resistance and freezing-and-thawing durability for most applications. Troweling can also reduce the ability of the concrete mortar at the surface to have adequate protection for resistance to freezing and thawing.

The committee recommends that the total air content of the concrete initially delivered to the jobsite be tested at the point of placement for air in accordance with ASTM C 173 or C 231. Air content can then later be checked as may be required by comparing density of concrete as defined in ASTM C 138.

5.7.2 *Chemical admixtures*—Chemical admixtures should meet the requirements of ASTM C 494 for whichever of the following types are to be used:

- Type A water-reducing;
- Type B retarding;
- Type C accelerating;
- Type D water-reducing and retarding;
- Type E water-reducing and accelerating;
- Type F high-range water-reducing; and
- Type G high-range water-reducing and retarding.

The high-range water reducers (Types F and G) should also meet the requirements of ASTM C 1017. Water-reducing and combination admixtures should provide the additional advantage of increased compressive and flexural strength at ages less than six months. The retarding admixtures can be useful in delaying initial set and possibly extending time available for final finishing in hot weather; however, excessive retardation can cause surface crusting or plastic-shrinkage cracking.

Accelerating admixtures increase the rate of strength gain at early ages and can be useful in cold weather.

High-range water-reducing admixtures meeting ASTM C 494, Types F or G, and midrange water-reducing admixtures meeting ASTM C 494, Type A, can be used to either reduce the water content required for a given slump or increase the slump of a given concrete while maintaining the same total water content. Water-reducing and high-range water-reducing admixtures used in industrial floor construction are most effective when the initial slump of the concrete, before introducing admixtures, is between 2 and 4 in. (50 and 100 mm). The admixture's impact on the workability and setting characteristics of the concrete for floor construction appear to be optimized when they are used in this manner.

The use of mid- or high-range water-reducing admixtures will not necessarily reduce the total water content of a concrete mixture as compared to that required for a Type A low-range water-reduced admixture. Even though these products have the capacity to reduce water content to a level below that which would correspond to pre-admixture slumps of 1 in. (25 mm) or less, the water content should not be reduced to less than that which would produce a minimum slump of 2 to 3 in. (50 to 75 mm). Water-reducing admixtures should not be relied on to reduce concrete shrinkage. Whiting and Dziedzic (1992) suggest that certain water-reducing admixtures can increase concrete shrinkage.

If the goal is to reduce concrete shrinkage by reducing the total water content in the concrete mixture, the designer should consider improving the characteristics of aggregate used to produce the concrete. Careful selection of characteristics, such as density, particle shape and texture, maximum size of the aggregate, and combined aggregate grading have a profound impact on reducing total water content, cementitious paste content, and long-term shrinkage (Section 6.3).

Considerations influencing a reduction in cement content should include the amount necessary to properly cut, trim, finish, and compact the floor slab surface. Reducing the total cement content may provide more than proportional reduction in shrinkage (Kosmatka and Panarese 2002b).

Although an initial slump of 2 to 4 in. (50 to 100 mm) is often recommended before the introduction of water-reducing admixtures, design water slump can be increased to 3 to 4 in. (75 to 100 mm) for lightweight concrete or when an embedded aggregate type hardener will be applied.

When using a high-range water-reducing admixture, the target slump at the point of placement can be increased to 6 to 8 in. (150 to 200 mm) without increasing the water content of the original concrete mixture. A mid-range water-reducing admixture can be used to increase the target slump at the point of placement to 4 to 6 in. (100 to 150 mm) without increasing the water content.

High-slump concrete may require less effort to place, consolidate, and finish compared with lower-slump concrete. If high slumps are used, excessive internal and external vibration can promote segregation of the concrete, excessive fines at the surface, or both, resulting in reduced abrasion resistance, especially for nonoptimized combined aggregate gradings. Caution should be exercised to avoid starting or continuing the finishing process before the concrete has achieved a sufficient degree of stiffness to support the type of finishing process and equipment used.

In special applications, such as parking garage surfaces, where low permeability is desirable, the reduction of water to produce *w/c* less than 0.42 in high-strength concrete can increase the chances of autogenous shrinkage when an external supply of water is not provided during curing. This shrinkage is caused by internal consumption of water during hydration (McGovern 2002).

The committee recommends that a representative test slab be cast at the jobsite so that the workability, finishability, and setting time of the proposed mixture can be evaluated by the project team (ACI 212.3R and ACI 212.4R).

5.7.3 *Chlorides*—Chlorides are significant contributors to corrosion of steel in concrete. The problem is particularly severe when dissimilar metals are embedded in concrete or when reinforced concrete is placed over galvanized decking. Corrosion products can cause expansion, cracking, and spalling.

Limits on chloride in fresh concrete mixtures are based on the recommendations of ACI 222R.

The following concrete should not include any intentionally added calcium chloride:

- Prestressed concrete;
- Floors over prestressed concrete or galvanized deck;
- Floors containing two kinds of embedded metals;
- Conventionally reinforced concrete in a moist environment and exposed to deicing salts or saltwater mist;
- Parking garage floors in areas where freezing and thawing should be considered;
- Structures near bodies of saltwater;
- Floors or slabs containing snow-melting electrical radiant heating systems; and
- Floors finished with metallic dry shakes.

Noncorrosive, nonchloride accelerators are available for use in cold weather. The admixture manufacturer should be able to provide long-term data (at least a year's duration) demonstrating noncorrosivity using an acceptable accelerated corrosion test method, such as one using electrical potential measurements. Data from an independent laboratory are preferable.

If accelerated set or high early strength is desired, either a noncorrosive nonchloride accelerator or high early-strength (Type III) cement can be used; alternatively, 100 to 150 lb/yd^3 (60 to 90 kg/m^3) of additional Type I or Type II cement can be used in the mixture. A significant decrease in setting time may not be realized with the increased cement content. The increased cement and water demand can increase shrinkage and curling.

Heated concrete may be required for cold-weather construction (ACI 306R). Chloride-based accelerators should only be used in nonreinforced concrete and when specifically permitted by project specifications.

When used, calcium chloride should be added as a water solution in amounts of not more than 1 to 2% by weight of cement. It will accelerate the rate of strength development and decrease setting time. Calcium chloride, in dosages as high as 1 to 2%, does not significantly lower the temperature at which the concrete will freeze. It accelerates the rate of strength development and thereby decreases the length of time during which protection against freezing should be provided. Setting time is decreased, thereby reducing finishing time.

Calcium chloride tends to darken the color of concrete and can cause variations in color of the hardened concrete. The difference in color is most noticeable when slabs with calcium chloride are adjacent to those without (Fig. 5.1). If concrete containing calcium chloride is not adequately cured, the surface can show light and dark spots. Calcium chloride should not be dispensed dry from bags. Dry-flake material frequently absorbs moisture and becomes lumpy. Pellet-type calcium chloride should be completely dissolved before addition to concrete or pop-outs will result from any undissolved pellets.

5.7.4 *Expansive cementitious admixtures*—Specifically formulated dry-powder admixtures can be blended with portland cement at the batch plant to produce shrinkage-compensating concrete. Concrete incorporating the same materials that will be used for the anticipated project should be tested for expansion by ASTM C 878 (refer to ACI 223 for full details). The compatibility of the expansive cementitious admixture and portland cement should be checked by the use of ASTM C 806.

The anticipated rate and quantity of expansion that can be obtained in the field should be established before beginning construction. This can be accomplished by conducting a series of tests using identical materials to those proposed for the project. These tests should be conducted by a testing laboratory that is familiar with ASTM C 878 procedures.

5.7.5 *Pozzolans*—A number of natural materials, such as metakaolin, diatomaceous earth, opaline cherts, clays, shales, volcanic tuffs, and pumicites, are used as pozzolans. ASTM C 618 pozzolans also include fly ash and silica fume and slag. Information on the use of these materials can be found in documents developed by ACI Committee 226. When these materials, excepting silica fume, are used in concrete, the time of set is frequently extended. The color of concrete can be different from that produced when portland cement is the only cementitious component.

ASTM C 618 fly ash, Class F or Class C, is frequently incorporated in concrete. Fly ash can affect the setting time, and it is often helpful in hot weather by delaying set time or as an aid in pumping concrete (ACI 226.3R). In floors and slabs, fly ash is often substituted for portland cement in quantities up to about 20% fly ash by mass of cementitious materials.

In cool weather, fly ash will usually delay the setting and finishing of the concrete unless measures are taken to compensate for the low temperatures, such as increasing the concrete temperature or using an accelerator.

Silica fume is used as a portland cement replacement or as a cementitious addition when using an accelerator to compensate for low temperatures. The amount of silica fume in a mixture typically varies between 5 and 10% by mass of the total cementitious material. Silica fume can increase both the impermeability and the strength of the concrete. Special attention should be given to avoiding plastic-shrinkage cracking during placing and finishing by using evaporation-retardant chemicals sprayed onto the plastic concrete surface or by using fog sprays in the air above the concrete. Early and thorough curing of the slab is also very important to minimize cracking.

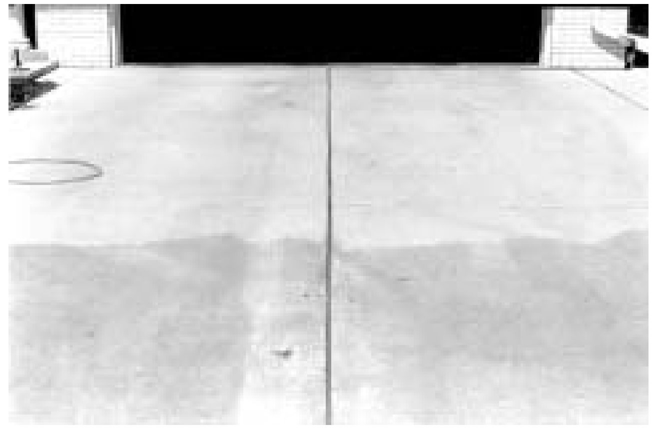


Fig. 5.1—Concrete slab discoloration due to the use of calcium chloride mixture. Concrete in upper part of the photo did not contain the admixture.

5.7.6 *Coloring admixtures*—Pigments for colored floors should be either natural or synthetic mineral oxides or colloidal carbon. Synthetic mineral oxides can offer more intensity in color, but they are normally more expensive. Pigments can be purchased alone or interground with a water-reducing admixture for mixing into the batched concrete to produce integrally colored concrete. Colored aggregate-type surface hardeners containing pigments can also be used. These pigmented mineral aggregates or metallic hardeners contain mineral oxide pigment, portland cement, a well-graded mineral aggregate, or metallic hardener and plasticizers. Pigments for integrally colored concrete should conform to ASTM C 979 and have uniform color. Carbon-black pigments, especially manufactured for this purpose, will appear lighter in color at an early age. The prepared mixtures should not contain pigments that are not mineral oxides. Job-proportioning or job-mixing of material for monolithic colored surfaces is not recommended. The use of these materials is described in Section 8.6. Coloring admixtures should be lime-proof and contain no calcium chloride. Curing compounds for these slabs should be the same as those used on the approved sample panels (Chapter 8).

5.8—Liquid surface treatments

Improperly constructed floor slabs can have relatively pervious and soft surfaces that wear or dust rapidly. Though the life of such surfaces can be short, it can be extended by using surface treatments containing certain chemicals, including sodium silicate and magnesium fluosilicate (Smith 1956; Vail 1952; Bhatty and Greening 1978). When these compounds penetrate the floor surface, they react chemically with calcium hydroxide (a product of cement hydration).

This broad classification covers a diverse group of products that are intended to penetrate the concrete and form a hard, glassy substance (calcium silicate) within the pores of the concrete. Effective use of the products generally results in reduced dusting and improved density of the concrete surface. Depth of penetration into concrete by these products varies with the porosity of the concrete surface and concrete moisture content at the time of application.

Products in this group are not specifically formulated for curing applications and do not meet the requirements of either ASTM C 309 or ASTM C 1315 for liquid membrane-forming compounds. While their use may offer some desirable benefits when applied after curing, they should not be applied on fresh concrete.

If these surface treatments are to be applied to new concrete floors, the floor should be moist cured for at least seven days and allowed to air dry in accordance with the product manufacturer's recommendations before application. Liquid membrane-forming curing compounds should generally be removed before application of surface treatments because they prevent penetration of the liquid. The lone exception to this requirement would be when compatible curing and sealing products from a single manufacturer are used.

Pozzalanic materials, including fly ash and silica fume, are siliceous or siliceous and aluminous materials that react with calcium hydroxide to form hydration products similar to those produced by portland cement and water, which, in turn, can contribute to the strength development and a reduced permeability of the concrete. This is the same calcium hydroxide needed to react with the liquid surface treatment that eventually hardens at the floor slab surface. Thus, less calcium hydroxide may be available to the floor treatment for concrete mixtures incorporating pozzolanic materials, slag cement, or both.

When a liquid surface treatment is applied to concrete mixtures incorporating pozzolanic materials or slag cement, the application should be delayed 28 days to ensure that the strength of the concrete has developed adequately before the application of the surface treatment.

Alternatively, the quantity of pozzolanic material should also be kept, as proposed by one manufacturer, to a maximum of 15% by mass of portland cement. If the percentage is not limited, calcium hydroxide may be depleted below the level necessary for the proper performance of the liquid surface treatment. Contact the manufacturer of the surface treatment for limits specific to the product to be used.

In view of the aforementioned, a number of specific items should be considered when liquid surface treatments are to be used. Specific considerations include, but are not limited to, the following:

- Anticipated application conditions;
- Timing of application for maximum benefit;
- Eventual appearance of the treated surface;
- Resistance of treated surface to wear, dusting, and tire marks;
- Coefficient of friction of treated surface; and
- Anticipated results if applied on a surface that has become carbonated.

Liquid surface treatments react with materials found in cement paste but not aggregate; they are not capable of providing abrasion resistance equal to that obtained by use of an embedded aggregate-type hardener.

5.9—Reinforcement

5.9.1 *Reinforcing steel, mats, or welded wire reinforcement*—Deformed bars, bar mats, or welded wire reinforcement are usually required in suspended structural floors as part of the structural design. They can also be called for in the specifications for slabs-on-ground as discussed in Section 3.2.4. Deformed bars should conform to the requirements of ASTM A 615, A 616, or A 617. Bar mats conforming to ASTM A 184 can also be used. Welded wire reinforcing should conform to ASTM A 185 or A 497. The use of widely spaced deformed reinforcing fabric conforming to ASTM A 497 will typically permit easier placement.

5.9.2 *Post-tensioning*—Post-tensioning can be used in slabs-on-ground and suspended slabs to address specific design requirements. Prestressing steel for use in floors and slabs should conform to the requirements of ASTM A 416. The post-tensioning tendons can be bonded or unbonded. Unbonded tendons should meet or exceed specifications published by the Post-Tensioning Institute (PTI 2000).

5.9.3 *Synthetic fibers*—Synthetic fibers for use in concrete floors increase the cohesiveness of concrete and should meet the requirements outlined in ASTM C 1116. The most widely used synthetic fibers are polypropylene and nylon, although other types are available. Polypropylene fibers are available in both fibrillated and monofilament form; nylon fibers are only available in monofilament form.

Synthetic fibers are added to the concrete mixer in quantities generally less than 0.2% by volume of the concrete. They are generally used in floors and slabs in quantities of from 0.75 to 1.5 lb/yd^3 (0.45 to 0.90 kg/m^3). Synthetic fibers have a tendency to reduce the formation of plastic-shrinkage and settlement cracks at the surface by increasing the tensile strain capacity of the plastic concrete. These fibers should not be used to replace temperature and shrinkage reinforcement because they have little impact on the behavior of concrete after it hardens.

5.9.4 *Steel fibers*—Steel fibers for use in floors and slabs should conform to the requirements of ASTM A 820. Steel fibers made from wire, slit sheet, milled steel, and melt extract are available and are normally deformed or hooked to improve bond to the hardened matrix. Steel fibers are added to the concrete mixer in quantities ranging from 0.0625 to 1% by volume of the concrete (8 to 132 lb/yd^3 [5 to 78 kg/m^3]), although quantities from 0.25 to 0.50% by volume of the concrete (34 to 68 lb/yd^3 [20 to 40 kg/m^3]) are more common.

Steel fibers are used in floors to minimize visible cracking, increase shear strength, increase the flexural fatigue endurance and impact resistance, and increase post-crack flexural toughness. The increases in mechanical properties achieved depend primarily on the type and amount of fiber used, and can result in reduced floor thickness and increased contraction joint spacing (Tatnall and Kuitenbrouwer 1992).

5.9.5 *Fiber characteristics*—Crack reduction, material properties, and mixture proportions are thoroughly discussed by Balaguru and Shah (1992). Additional information is available in ACI 544.1R, 544.2R, 544.3R, and 544.4R.

5.9.6 *Dowels and load-transfer devices*—Dowels required for load transfer can be round, square, or rectangular. Square and rectangular dowels cushioned on the vertical sides by a compressible material allow for some horizontal movement. Diamond-shaped load plates (a square plate turned so that two corners line up with the joint) can be used to replace dowels in construction joints. The diamond shape also allows the slab to move horizontally without restraint when slab shrinkage opens the joint. All dowels and load-transfer devices should meet requirements of ASTM A 36.

The diameter or cross-sectional area, length, shape, and the specific location of load transfer device and the method of support should be specified by the designer. Refer to Section 3.2.7 for more information on load-transfer mechanisms for slabs-on-ground.

5.10—Evaporation reducers

Evaporation-reducing chemicals can be sprayed on the plastic concrete one or more times during the finishing operation to minimize plastic-shrinkage cracking when the evaporation rate is high. These products should be used in strict accordance with the manufacturers' directions; they should never be used during the final troweling operations because they discolor the concrete surface.

5.11—Gloss-imparting waxes

Concrete waxes to impart gloss to concrete surfaces are available from various manufacturers. Some are curing compounds; for such use, they should meet or exceed the water-retention requirements of ASTM C 309.

5.12—Joint materials

Certain two-component semirigid epoxy resins and polyureas can be used to fill joints where the joint edges need support to withstand the action of small, hard-wheeled traffic. These are the only materials known to the committee that can provide sufficient shoulder support to the edges of the concrete and prevent joint breakdown. Two-component fillers are desirable because their curing is independent of jobsite conditions. Such joint materials should be 100% solids and have a minimum Shore A hardness of 80 when measured in accordance with ASTM D 2240. Refer to Section 9.10 for more details on joint filling and sealing.

Preformed elastomeric sealants are useful for some applications. They should not be used where subjected to the traffic of small, hard wheels. They can be quickly installed, they require no curing, and, if properly chosen, they can maintain a tight seal in joints that are subject to opening and closing. Refer to ACI 504R for more information on preformed elastomeric sealants.

Preformed asphalt impregnated or plain fiber materials or compressible foam are used in expansion and isolation joints, depending on the anticipated movement. These materials and their appropriate use are described in detail in ACI 504R.

5.13—Volatile organic compounds (VOC)

Many users and some states require materials to meet VOC limits. Liquid materials are of the greatest concern because they are often solvent-based. Certification of compliance with the applicable VOC limits should be required before the products are used.

Many curing compounds that comply with limits on VOC are water-based. They should not be permitted to freeze. In many cases, they cannot be reconstituted after freezing.

CHAPTER 6—CONCRETE PROPERTIES AND CONSISTENCY

6.1—Concrete properties

A concrete mixture for floor and slab construction should incorporate an optimized combination of locally available materials that will consistently produce concrete with the required workability and finishability properties in the plastic state during placement. After the concrete mixture hardens, it will be required to develop engineering properties that include surface abrasion, wear resistance, impact resistance, adequate flexural strength to accommodate anticipated loads, and shrinkage characteristics that minimize potential cracking from restrained shrinkage and curling stresses.

Concrete with good placing and finishing characteristics, that also meets the required engineering properties, can best be achieved by developing an understanding of the concrete mixture. Concrete mixtures are commonly defined by the proportions of individual materials that do not identify the qualities of the blended mixture delivered and placed on the site. To produce the best results, all parties involved in the design and construction of the slab should understand the characteristics of the combined materials in the mixture delivered to the project.

In most flatwork, the placeability of the concrete and finishability of the surface are at least as important as the abrasion resistance, durability, and strength. The former qualities will have a significant effect on the integrity of the top 1/16 or 1/8 in. (1.5 or 3 mm) of the concrete surface. Unfortunately, placeability and finishability are not easily measured. There is a tendency for specifiers to emphasize more easily determined properties, such as slump and compressive strength.

Other parameters being equal, a given concrete's shrinkage potential will decrease as its paste content is decreased and its paste quality is optimized. The quality of the concrete paste is reflected in the total water content necessary to produce a workable mixture while maintaining a reasonable *w/cm* that minimizes the amount of cementitious materials. The *w/cm* specified should not require arbitrary increases in the cementitious material or chemical admixture content, exceeding what is necessary to achieve the specified strength or required setting and finishing needs of the concrete materials. Acceptance of a mixture based on compliance with *w/cm* alone seldom produces desired results without first minimizing the total water content, which generally can be accomplished through adjustments in the combined aggregate size, uniformity of distribution, or material source. Therefore, the use of the minimum amount of water necessary to produce the required slump and workability is very important.

For steel-trowelled, slab-on-ground concrete, a minimum amount of water is required to produce a workable, finishable mixture with predictable, uniform setting characteristics. Currently available water-reducing admixtures perform best when they are mixed with concrete that has enough water to produce a slump of 2 to 3 in. (50 to 75 mm) if no admixture was added. If this "water slump" is not achievable without the admixture, setting time and finishability can vary when the concrete is subjected to normal variations of ambient temperature and time between batching and discharge (Harrison 2004).

The particular cementitious materials, aggregates, and admixtures used can significantly affect the strength, setting characteristics, workability, finishability, and shrinkage of the concrete at a given *w/cm* (Tremper and Spellman 1963; Kosmatka, Kerkhoff, and Panarese 2002b). Furthermore, the amount of water required to produce a given slump depends on the maximum size of coarse aggregate, the uniformity of the combined aggregate gradation, particle shape and surface texture of both fine and coarse aggregates, air content, admixtures used, and the temperature and humidity at time of placement. Using larger maximum-size aggregate and improving the overall aggregate gradation reduces the mixing-water requirement.

Air-entraining admixtures produce a system of small air bubbles that reduce the mixing water requirement. Concrete containing entrained air is proportioned to have the same amount of coarse aggregate as similar nonair-entrained concrete. Air-entrained concrete mixtures use less mixing water and less fine aggregate; however, in mixtures with higher cement content, this may not offset the strength reduction that can result from intentional entrainment of air. Air-entraining admixtures should not be used in floors that are to have a dense, smooth, hard-troweled surface.

The optimum quality and content of fine aggregate in concrete for floors should be related to the slump of the concrete and the abrasive exposure to which the floor will be subjected. Concrete should be sufficiently plastic and cohesive to avoid segregation and bleeding (Kosmatka, Kerkhoff, and Panarese 2002b). Less fine aggregate should be used in concrete with low slump—less than 1 in. (25 mm)—because this concrete does not normally bleed or segregate. Decreased fine aggregate contents can improve resistance to abrasion if the concrete exhibits little bleeding and segregation.

Previous field experience or laboratory trial batches should be used to establish the initial proportions of ingredients. Test placements can then be used to optimize the mixture proportions. The laboratory trial batches can be omitted if concrete mixtures have been used successfully under similar conditions in other jobs.

Current records of gradations of fine and coarse aggregates from concrete mixtures should be retained to produce a combined gradation analysis. This gradation analysis should evaluate the amount of aggregate retained on each of the following sieve sizes (percent of total mass): 1-1/2, 1, 3/4, 1/2, and 3/8 in.; 4, 8, 16, 30, 50, 100, and No. 200 (38.1, 25, 19, 12.5, 9.5, and 4.75 mm; 2.36 mm, 1.18 mm, and 600, 300, 150, and 75 μm, respectively).

Trial batch proportions should generally be in accordance with ACI 211.1 or 211.2. Adjustments of fine aggregate content, however, may be necessary to obtain the best workability (Martin 1983). The amount of the total combined aggregate passing the No. 8 (2.36 mm) sieve for a uniformly graded mixture should be between 32 and 42% of the total combined aggregate. This index is referred to as the workability factor and should be evaluated in relation to the coarseness factor of the larger aggregate particles as illustrated later in this chapter (Shilstone 1990). Adjustments in the fine aggregate content directly influence the workability factor.

6.2—Recommended concrete mixture

6.2.1 *Required compressive strength and slump*—Two approaches for selecting mixture proportions are discussed in Section 6.2.4. Regardless of the approach, the specified compressive strength f_c' shown in Table 6.1 should be used for the various classes of concrete floors.

The designer should be consulted as to the strength to be achieved by concrete before subjecting the slab to early construction loads. To obtain this strength quickly, it may be necessary to use more cementitious materials than the recommended amounts shown in Table 6.2, or to proportion the concrete for a 28-day strength higher than that shown in Table 6.1. The designer should take into account that increased concrete strengths achieved through higher cementitious material contents alone may adversely affect the shrinkage characteristics and stiffness (modulus of elasticity) of the concrete. Drying shrinkage potential and stiffness properties can greatly influence slab curling stresses and ultimate load capacity of the slab-on-ground (Walker and Holland 1999). Compressive strengths should be used to monitor batched material consistency.

The slump indicated for each floor class shown in Table 6.1 is the recommended maximum at the point of placement to prevent segregation and yet provide adequate workability of the concrete. A one-time jobsite slump adjustment should be permitted as outlined in the "Tempering and Control of Mixing Water" provisions of ACI 301 or the "Mixing and Delivery" provisions of ASTM C 94. Validation of total water content should be conducted periodically at the point of concrete placement, concurrent with other specified site testing.

6.2.2 *Required finishability*—Concrete for floors should have other desirable characteristics in addition to strength. There should be sufficient mortar content to allow the finisher to completely close the surface and to achieve the required surface tolerance, hardness, and durability (Martin 1983). The mortar fraction, the volume percentage of all materials in the mixture (cementitious materials, aggregate, water, and air) that pass the No. 8 (2.36 mm) sieve, should be balanced between the desired properties of both fresh and hardened concrete. During construction, sufficient mortar is desirable for pumping, placing, and finishing. Excess mortar, however, can increase shrinkage characteristics. Typically, a mortar fraction of 55 to 57% is sufficient for a 3/4 or 1 in. (19 or 25 mm) maximum-size aggregate slab-on-ground concrete placed directly from the mixer truck. Larger aggregates, improved uniform distribution of the combined aggregate particle sizes, or both will decrease the mortar content needed. Smaller 3/8 to 1/2 in. (9.5 to 12.5 mm) maximum-size aggregates can increase the mortar content by as much as 63%. Refer to Section 6.3.3 for other typical mortar contents.

6.2.3 *Required durability*—The procedures for producing durable concrete outlined in ACI 201.2R apply to floors and slabs. Concrete floors exposed to freezing and thawing while in a moist condition should have a *w/cm* not greater than the values given in the following paragraph. These *w/cm* requirements can be lower than those required for strength alone. Additionally, this type of concrete should have adequately entrained air.

Requirements based only on durability may yield concrete compressive strengths much higher than normally required for structural concerns. Concrete floors and slabs subjected to moderate and severe exposures to freezing and thawing, as defined in ACI 201.2R, should have a *w/cm* no greater than 0.50. Concrete subjected to deicing chemicals should have a *w/cm* no greater than 0.45. Reinforced concrete exposed to brackish water, seawater, deicing chemicals, or other aggressive materials should have a *w/cm* no greater than 0.40. The committee recognizes that there is no direct correlation between compressive strengths and *w/cm* and suggests that the two not be combined in a specification.

Entrained air is necessary in concrete subjected to freezing and thawing when moist or when subjected to deicing chemicals. Recommended air contents for hardened concrete for various exposure conditions, aggregate types, and maximum-size aggregates are given in ACI 201.2R. Properly air-entrained concrete should achieve a compressive strength of 4000 psi (28 MPa) before being subjected to freezing and thawing in a moist condition or to deicing chemicals. The use of deicing chemicals is not recommended in the first year of slab service in any event.

Air contents, within the limits recommended, will cause significant strength reductions in richer concrete, but the effect will be less in leaner concrete. Air contents in excess of the recommended quantities will reduce strength in richer mixtures, approximately 3 to 5% per 1% increase in air content, and will reduce abrasion resistance correspondingly. Air-entrained concrete should not be hard-troweled finished (Sections 6.2.7, 8.3.11, and 8.6).

6.2.4 *Concrete mixture*—In addition to meeting structural and drying-shrinkage requirements, concrete for floors should provide adequate workability and setting characteristics necessary to obtain the required finish and floor surface profile. Total water content can have a major impact on the bleeding characteristics of the concrete and the potential for shrinkage, so use of the lowest practical quantity of water in the concrete mixture is recommended. The amount of water needed to produce a workable mixture is generally determined by the characteristics of the combined aggregate materials used in the mixture and is not effectively controlled by specifying *w/cm*. If *w/cm* is specified, *w/cm* in the range of 0.47 to 0.55 are common for most interior floors of Classes 4 to 9. Floors that are required to be impermeable, resistant to freezing-and-thawing and deicing chemicals, or meet the requirements of ACI 211.2, 223, or 318 should conform to more stringent criteria.

The committee recommends that the concrete mixture be accepted on the basis of a satisfactory mixture design submittal and a successful test slab placement (if appropriate for the project). This submittal should include a combined aggregate distribution analysis derived from current, certified reports of gradations of the individual aggregates. The test placement should determine if the proposed concrete mixture is capable of producing a floor of acceptable finish and appearance and meet the project requirements.

If a history of finishing properties is not available for a concrete mixture, a test slab should be placed under job conditions to evaluate the workability, finishability, setting time, slump loss, and appearance of the concrete proposed for use. Materials, including all admixtures, equipment, and personnel proposed for the project, should be used. The test panel should be as large as possible and at least 20 x 20 ft (6 x 6 m), placed at the specified project thickness. A floor slab area in a noncritical section is often chosen as the test panel. The concrete contractor should review the proposed mixture proportions before the preconstruction meeting and placement of the test slab. If a pump will be used for the placement of concrete materials, the test slab should be placed with the same pump equipment.

6.2.5 *Consistency and placeability*—The maximum slump recommended for each class of floor is given in Table 6.1. These slumps should produce concrete of sufficient workability to be properly consolidated in the work without excessive bleeding or segregation during placing and finishing. Excessive bleeding and segregation can contribute to poor performance in concrete floors. If the finished floor is to be uniform in appearance and grade, successive batches placed in the floor should have very nearly the same slump and setting characteristics. See Sections 6.1, 6.2.1, and 7.3.2 regarding

Table 6.1—Recommended strength and maximum slump at point of placement for concrete floors

Floor class*	Specified compressive strength f_c' on 28-day tests, psi (MPa)	Maximum slump at placement†, in. (mm)
1, 2, and 3	3000 (21)	5 (125)
4, 5, and 6	3500 (24)	5 (125)
7 base	3500 (24)	5 (125)
7 bonded topping‡	5000 (35)	3 (75)
8 unbonded topping§	4000 (28)	3 (75)
9 superflat	4000 (28)	5 (125)

*Refer to Table 2.1 for floor class definitions.
†Maximum slump is assumed to be achieved using a Type A water-reducing admixture.
‡The strength specified will depend on the severity of usage.
§Maximum aggregate size not greater than 1/3 the thickness of unbonded topping.

Table 6.2—Recommended cementitious material contents for concrete floors

Nominal maximum-size aggregate,* in. (mm)	Cementitious material content, lb/yd³ (kg/m³)
1-1/2 (37.5)	470 to 560 (280 to 330)
1 (25)	520 to 610 (310 to 360)
3/4 (19)	540 to 630 (320 to 375)
1/2 (12.5)	590 to 680 (350 to 405)
3/8 (9.5)	610 to 700 (360 to 415)

*For normalweight aggregates.
Note: See ACI 318 for minimum portland cement requirements for structural applications.

jobsite slump adjustment. Workability of a concrete mixture is not directly proportional to the slump. Properly proportioned concrete with slumps less than that shown in Table 6.1 can respond very well to vibration and other consolidation procedures. Increased slump alone does not ensure satisfactory workability characteristics.

Recommended slump values in Table 6.1 are for concrete made with both normalweight and structural lightweight aggregate and assume the use of a normal water-reducing admixture, if required. Slumps in excess of those shown in the table, not to exceed 7 in. (175 mm), are acceptable when mid-range or high-range water-reducing admixtures are used. If structural lightweight-aggregate concrete is placed at slumps higher than that shown in Table 6.1, however, the coarse lightweight-aggregate particles can rise to the surface and the concrete can bleed excessively, particularly if the concrete does not contain an adequate amount of entrained air.

6.2.6 *Nominal maximum size of coarse aggregate*—The nominal maximum aggregate sizes in Table 6.2 are for normalweight aggregates. The largest practical-size aggregate should be used if economically available, and if it will satisfy the requirements that maximum size not exceed 3/4 of the minimum clear spacing of reinforcing bars or 1/3 of the depth of the section. Structural lightweight aggregates generally are not furnished in sizes larger than 3/4 or 1 in. (19 or 25 mm); however, some lightweight aggregates provide maximum strength with relatively fine gradings.

6.2.7 *Air content*—Moderate amounts of entrained air for purposes other than durability, as described in Section 6.2.3, can be used to improve workability, particularly with leaner and more harsh concrete mixtures or with poorly graded aggregates. Concrete made with structural lightweight aggregates should contain some entrained air. Minimum air content should be 4%, and specific recommendations for air content secured from the concrete supplier, the manufacturer of the lightweight aggregate, or both.

An air-entraining agent should not be specified or used for concrete to be given a smooth, dense, hard-troweled finish because blistering or delamination may occur. These troublesome finishing problems can develop any time the total air content is in excess of 3%. This is particularly true when embedded hardeners are applied.

Some variation in the air content of air-entrained concrete is common, and this can result in problems associated with finishing of concrete surface. Exposure conditions that dictate the need for air-entrainment should be discussed with the designer before the placement of concrete floors.

6.2.8 *Required yield and concrete mixture adjustment to correct yield*—A concrete mixture should be proportioned to yield a full 27 ft^3/yd^3 (1 m^3/m^3). The yield of the mixture proposed by a testing agency or concrete supplier is the total of the absolute volume of the mixture ingredients plus the volume of air. This proposed mixture should have been tested in accordance with the requirements of ASTM C 138 to determine its density (or unit weight) and yield, and the weights of the ingredients subsequently adjusted as necessary. The concrete mixture should be sampled and tested one or more times at the jobsite during placement of concrete floor for the purpose of confirming yield. These jobsite samples should be obtained from a mixer truck chute (the point of delivery), and the tests performed by a certified field technician as required by ASTM C 94. Concrete samples should be obtained after any necessary jobsite slump adjustment. The concrete supplier should adjust the concrete mixture, as necessary, to produce the proper yield. Adjustments in concrete mixture proportions should be made in accordance with the recommendations of ACI 211.1.

6.3—Concrete mixture analysis

6.3.1 *Evaluation of the concrete mixture*—Due to the many variables involved in the production of concrete, the ultimate evaluation of the concrete materials is when the concrete is mixed, placed, and finished under the anticipated conditions of the jobsite (Section 6.2.4). There are evaluation methods, however, that can be used to identify potential problem areas of defined proportioned materials before mixing and placing concrete.

For proper analysis, major emphasis is placed on the combined aggregates and mortar contents. The optimization of the combined aggregate materials not only improves the long-term strength and durability characteristics of the concrete, but it can also dramatically improve placing characteristics during construction (Shilstone 1990). The ideal mortar content is one that finds the balance between adequate mortar for placing and finishing of fresh concrete while minimizing the shrinkage and curling properties of the hardened material.

6.3.2 *Aggregate blending*—To maximize the uniform gradation distribution of the combined aggregates, blending of three or more individual aggregates may be necessary. Generally, this includes one coarse aggregate, one fine aggregate, and the addition of an intermediate-size aggregate, typically to compensate for deficiencies in particles' sizes retained on the 3/8 in. (9.5 mm) through No. 8 (2.36 mm) size sieves. There are times when the addition of a second fine aggregate source is necessary to supplement deficiencies in the finer aggregate particle sizes.

Many methods are used to blend both coarse and fine aggregate materials to produce an optimized proportioning from the largest to smallest particles. The importance of combined aggregate grading is not a new concept. It was recognized as early as 1918 by Abrams. Other recent publications include Shilstone (1990) and Weymouth (1933).

ASTM C 33—Since 1993, ASTM C 33 has provided a means to optimize combined aggregate grading by providing the following under Part 1, "Scope:" "...Those responsible for selecting the proportions for the concrete mixture shall have the responsibility for selecting the proportions of fine and coarse aggregate and the addition of blending aggregate sizes if required or approved." ASTM D 448 includes sizes 89 and 9 to provide the opportunity to blend these sizes with other classifications to obtain improved particle distribution. Sizes 89 and 9 are abundant in No. 4 (4.75 mm) and No. 8 (2.36 mm) size particles. These size and gradation designations were developed to supplement the intermediate-sized aggregate that is often missing in a standard single coarse plus single fine aggregate combination.

Blending aggregates to meet criteria for a combined grading is another proportioning method that can be used. The different procedures that have been used to determine proportions and potential concrete characteristics due to the gradations of the combined aggregates include:

1. Percentage of the combined aggregate retained on each of the standard sieves;
2. Coarseness factor chart; and
3. 0.45 power chart.

When one of the above or other similar methods is used, the specific combined grading to which aggregate is to be blended, along with tolerances for control, should be included with the mixture proportion submittal. The details of the above-mentioned procedures are described in the following.

1. Percent of the combined aggregate retained on each of the standard sieves—This procedure provides a tolerance of acceptable uniformity of distribution of the total combined aggregate particles found in the mixture. Recommended tolerance limits are defined in Section 5.4.3.

A deficiency in particles retained on the No. 8, 16, and 30 (2.36 mm, 1.18 mm, and 600 μm) sieves and an excess of particles retained on the No. 50 and 100 (300 and 150 μm) sieves occur in many areas of the U.S., leading to problems associated with cracking, curling, blistering, and spalling of concrete.

While the gradation specifications discussed in previous paragraphs set limits on the percent of aggregate retained on each sieve, this should only be a guide as it may not be easily attainable using available local resources. In 1933, Weymouth described the importance of clusters versus individual sieve sizes. If there is a deficiency on one sieve but excess on an adjacent sieve, the two sizes are a cluster and they balance one another. When there is a deficiency in particles on each of two adjacent sieve sizes but abundance on the sieves adjacent to each, the adjacent sizes tend to balance the two-point valley. If there are three adjacent deficient sizes, there is a problem that must be corrected.

2. Coarseness factor chart—Figure 6.1 illustrates an alternative method of analyzing the size and uniformity of the combined aggregate particle distribution, balanced with the fine aggregate content of the mixture. The x-axis, labeled as coarseness factor (CF), defines the relationship between the coarse and intermediate particles. It is the percent of the combined aggregate that is retained on the No. 8 (2.36 mm) sieve that is also retained on the 3/8 in. (9.5 mm) sieve.

The y-axis represents the percent of the combined aggregate that passes the No. 8 (2.36 mm) sieve. A correction based on cementitious material content should be made. This chart was developed for a cementitious material content of 564 lb/yd^3 (335 kg/m^3) of concrete. When a mixture contains 564 lb/yd^3 (335 kg/m^3) of cementitious materials, there is no correction factor. With respect to the workability factor, the impact of 94 lb (43 kg) of portland cement is approximately equal to a similar adjustment of 2.5% in the amount of fine aggregate. As cementitious materials are increased, the fine aggregate content should be reduced to maintain the same workability factor *W* and vice versa. An increase or decrease in either the cementitious material content or fine aggregate content without a compensating adjustment in the other of these two components will impact the workability of the mixture.

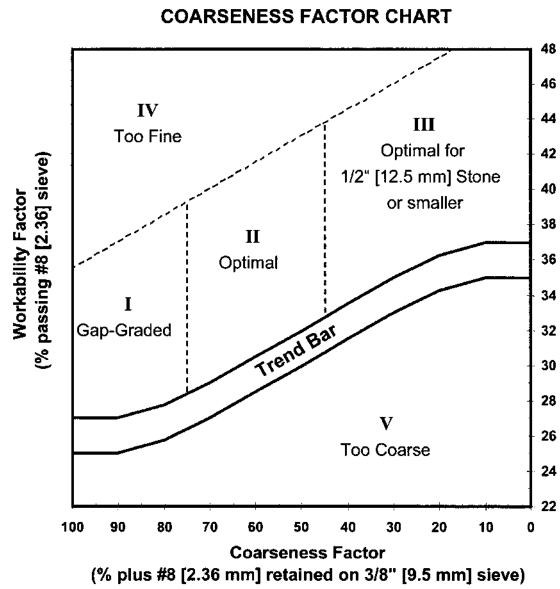


Fig. 6.1—Coarseness factor chart for evaluating the potential performance of a mixture.

The diagonal trend bar defines a region where combined rounded or cube-shaped crushed stone and well-graded natural sand are in near perfect balance to fill voids with aggregate. Variations in shape and texture of the coarse and fine aggregates that allow the combined mixture to fall within this region reflect maximum packing of aggregate within the concrete volume. Mixtures with aggregate combinations that fall in or near this region should be placed by bottom drop buckets or by paving machines.

Five zones are used to identify regions above the diagonal trend bar where variation in combined aggregate grading is indicative of certain general characteristics based upon the following field experience (Shilstone and Shilstone 2002).

Zone I—A mixture is seriously gap-graded and will have a high potential for segregation during placement or consolidation due to a deficiency in intermediate particles. These mixtures are readily identified in the field when placed by chute. They are not cohesive, so a clear separation between the coarse particles and the mortar can be seen as the concrete is deposited from the chute. Segregation is a major problem, especially for floor slabs and paving. Slab mixtures plotting in this zone and three points above the trend bar described in previous paragraphs segregated at a 1 in. (25 mm) slump. These mixtures lead to blistering, spalling, and scaling. As mixtures approach Zone IV, they can experience additional problems as described as follows.

Zone II—This is the optimum zone for mixtures with nominal maximum aggregate size from 1-1/2 to 3/4 in. (37.5 to 19 mm). Mixtures in this zone generally produce consistent, high-quality concrete. Field observations with multiple materials and construction types have produced outstanding results

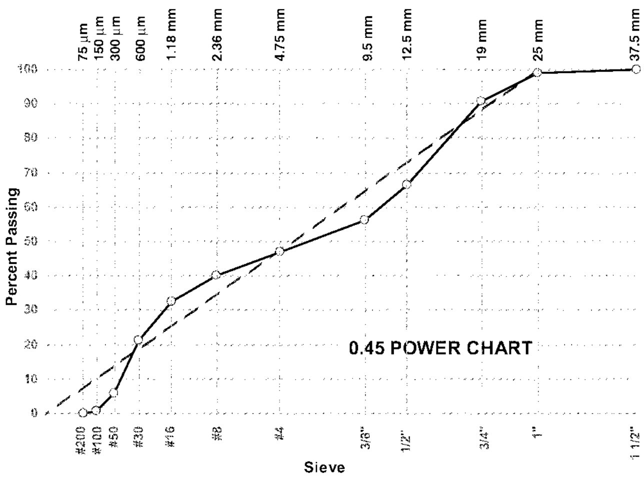


Fig. 6.2—The 0.45 power chart for determining the best combined gradation of aggregates.

when the coarseness factor is approximately 60 and the adjusted workability factor *W* is approximately 35. Mixtures that plot close to the trend bar require close control of the aggregate. Variations in grading can lead to problems caused by an excess of coarse particles. Mixtures that plot close to Zone IV should be placed with special care or they can experience problems found in that zone. Mixtures with slivered or flat intermediate aggregate require more fine sizes as their shape creates mobility problems.

Zone III—An extension of Zone II for maximum aggregate size equal to or smaller than 1/2 in. (12.5 mm).

Zone IV—Excessive fines lead to a high potential for segregation during consolidation and finishing. Such mixtures will produce variable strength, have high permeability, and exhibit shrinkage, which generally contributes to the development of cracking, curling, spalling, and scaling. They are undesirable.

Zone V—They are too coarse, that is, nonplastic; therefore, an increase in fines content is necessary.

3. 0.45 power chart—The 0.45 power chart (Fig. 6.2) is similar to a semi-log graph, except the x-axis is the sieve opening in microns to the 0.45 power. It has been widely used by the asphalt industry to determine the best combined grading to reduce voids and the amount of asphalt in a mixture. A straight line on this chart defines the densest grading for aggregate for asphalt. Because asphalt includes fine mineral filler while concrete includes cementitious materials, fewer fine particles passing the No. 8 (2.36 mm) sieve are necessary for concrete mixtures.

This chart, historically used to develop uniform gradations in the asphalt industry, can also be adapted for use with concrete materials. The mixture example at the end of this chapter shows acceptable and improved gradations. To create a 0.45 power curve, plot the mathematically combined percent passing for each sieve on a chart having percent passing on the y-axis and sieve sizes raised to the 0.45 power on the x-axis. Plot the maximum density line from the origin of the chart to the sieve one size larger than the first sieve to have 90% or less passing.

The deviations from the optimum line help identify the location of grading problems. Gradings that zigzag across the line are undesirable. A gap-graded aggregate combination will form an S-shaped curve deviating above and below the maximum density line.

6.3.3 *Mortar fraction*—Mortar fraction is an extension of the coarseness factor chart. The mortar fraction consists of all materials passing the No. 8 (2.36 mm) sieve (fine aggregate and paste) and is often at the center of conflicting interests. With reasonably sound and properly distributed aggregate, it is the mortar fraction of the concrete mixture that has a major affect on the designer's interest in strength, drying shrinkage, durability, and creep. The mortar fraction also provides the contractor with necessary workability, pumpability, placeability, and finishability. Neither should dominate. A mixture that is optimized for strength and shrinkage but can't be properly placed and consolidated will perform poorly regardless of the *w/cm* value.

The mortar factor needed for various construction types varies. A mat foundation with the concrete placed by chute requires less mortar than the same strength concrete cast in a thin slab to be trowel finished. Unless aggregate proportions are adjusted to compensate for differing needs, changes in slump to increase mortar content through the addition of water is the only option open to the contractor. Construction requirements that affect the amount and quality of mortar necessary to properly place and finish the concrete materials should be considered when optimizing a mixture. Mortar fractions are influenced by aggregate particle shape, texture, and distribution, and will vary with each mixture. Approximate mortar fractions for ten construction classifications are shown as follows (Shilstone 1990):

Mortar fractions for various construction methods

Construction classification	Placing and construction method	Approximate mortar fractions (% volume of concrete)
1	Steep sided bottom-dropped bucket, conveyor, or paving machine	48 to 50
2	Bottom-drop bucket or chute in open vertical construction	50 to 52
3	Chute, buggy, or conveyor in an 8 in. (200 mm) or deeper slab	51 to 53
4	1-1/2 in. (37.5 mm) maximum size aggregate mixture receiving high tolerance finish 5 in. (125 mm) or larger pump for use in vertical construction, thick flat slabs and larger walls, beams, and similar elements	52 to 54
5	3/4 to 1 in. (19 to 25 mm) maximum size aggregate mixture receiving high tolerance finish 5 in. (125 mm) pump for pan joist slabs, thin or small castings, and high reinforcing steel density	53 to 55
6	4 in. (100 mm) pump	55 to 57
7	Long cast-in-place piling shells	56 to 58
8	Pump smaller than 4 in. (100 mm)	58 to 60
9	Less than 4 in.-thick (100 mm) topping	60 to 62
10	Flowing fill	63 to 66

Table 6.3—Mixture design example

Mixture components	Density		Original mixture (gap graded)					Adjusted mixture (optimized)				
			Mass		Volume			Mass		Volume		
	lb/ft^3	kg/m^3	lb	kg	ft^3	m^3	% by volume	lb	kg	ft^3	m^3	% by volume
Portland cement	196.6	3150	480	217.7	2.44	0.07	9.0	440	199.6	2.24	0.06	8.3
Pozzolan	146.7	2350	84	38.1	0.57	0.02	2.1	77	34.9	0.52	0.01	1.9
1 in. (25 mm) aggregate	164.2	2630	1706	773.8	10.39	0.29	38.5	1223	554.7	7.45	0.21	27.6
3/8 in. (9.5 mm) aggregate	164.2	2630	0	0.0	0.00	0.00	0.0	658	298.5	4.01	0.11	14.8
Fine aggregate	162.3	2600	1380	626.0	8.50	0.24	31.5	1292	586.0	7.96	0.23	29.5
Water	62.4	1000	292	132.4	4.68	0.13	17.3	275	124.7	4.41	0.12	16.3
Air	0.0	0	0	0.0	0.42	0.01	1.6	0	0.0	0.42	0.01	1.6
Totals			**3942**	**1788.1**	**27.00**	**0.76**	**100.0**	**3965**	**1798.5**	**27.00**	**0.76**	**100.00**
Combined fineness modulus					5.16					5.09		
Paste + air fraction					30%					27%		
Mortar fraction					58%					55%		
Coarseness factor					84%					60%		
Workability factor					40%					36%		

Table 6.4—Aggregate gradation example

Sieve size	Individual percent retained			Combined percent retained	
	1 in. (25 mm)	3/8 in. (9.5 mm)	Fine	Original	Adjusted
1-1/2 in. (37.5 mm)	—	—	—	—	—
1 in. (25.0 mm)	2.0	—	—	1.1	0.8
3/4 in. (19.0 mm)	18.0	—	—	9.9	6.9
1/2 in. (12.5 mm)	52.0	—	—	28.6	19.9
3/8 in. (9.5 mm)	20.0	12.0	—	11.0	10.1
No. 4 (4.75 mm)	6.0	72.0	0.9	3.7	17.5
No. 8 (2.36 mm)	0.7	13.0	11.7	5.7	7.7
No. 16 (1.18 mm)	0.4	1.7	16.3	7.6	7.2
No. 30 (600 µm)	0.9	1.3	24.1	11.3	10.5
No. 50 (300 µm)	—	—	34.2	15.4	14.0
No. 100 (150 µm)	—	—	11.6	5.2	4.8
No. 200 (75 µm)	—	—	1.2	0.5	0.5
Combined fineness modulus				**5.16**	**5.09**

6.3.4 *Example slab mixture analysis*—Table 6.3 shows a concrete slab mixture design example that compares an original gap-graded mixture that is high in fine content with an adjusted mixture that uses an intermediate-size aggregate material to improve the uniformity of the combined aggregate particle size distribution. The total combined aggregates in the original mixture consist of blending a 1 in. (25 mm) maximum-sized stone source with a single sand source. The adjusted, or optimized, mixture adds a 3/8 in. (9.5 mm) intermediate aggregate to supplement the particle sizes that were previously lacking in the combined gradations of the original mixture (Table 6.4).

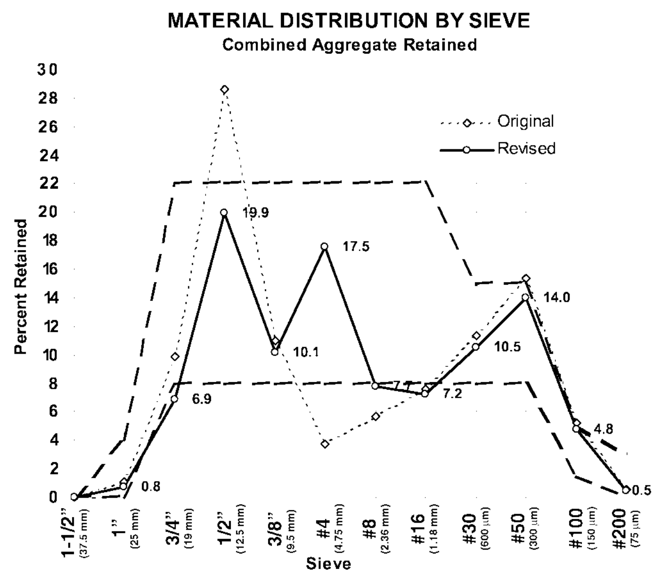


Fig. 6.3—Material sieve analysis showing change in aggregate distribution with blending of 3/8 in. (9.5 mm) aggregate (Section 6.3.4).

As shown in the following, improving the uniformity of aggregate particle size distribution (Fig. 6.3 and 6.4) will many times reduce the amount of paste necessary to coat the particles, also resulting in a reduction in the amount of water necessary to produce the same workability and finishability in the mixture. A reduction in paste also reduces the cost of producing the concrete mixture while maintaining equivalent strength and improved durability of the concrete. The potential for cracking and curling is reduced because shrinkage is reduced.

Affected changes in Coarseness Factor Chart—

1. The blending of the 3/8 in. (9.5 mm) aggregate changes the coarseness factor (Fig. 6.5) from 84 to 60%, moving the mixture optimization indicator (MOI) to the right. At this point, the total cementitious materials content is equal to 564 lb/yd^3 (335 kg/m^3). Therefore, both the MOI and the

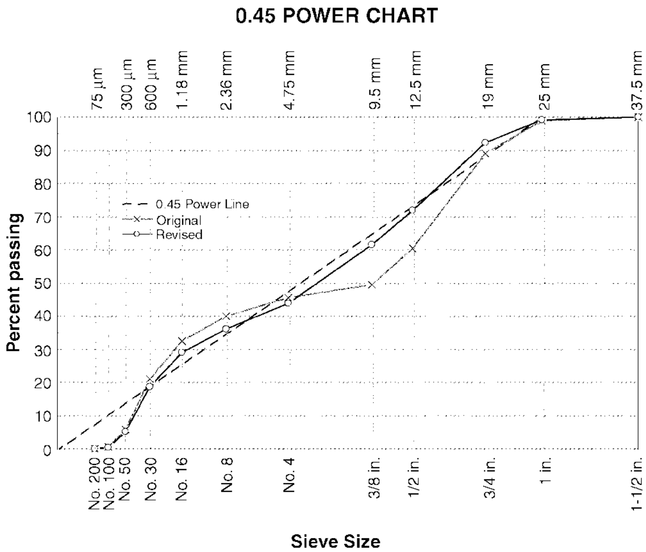


Fig. 6.4—The 0.45 power chart showing change in combined gradation of aggregates after blending of 3/8 in. (9.5 mm) aggregate (Section 6.3.4).

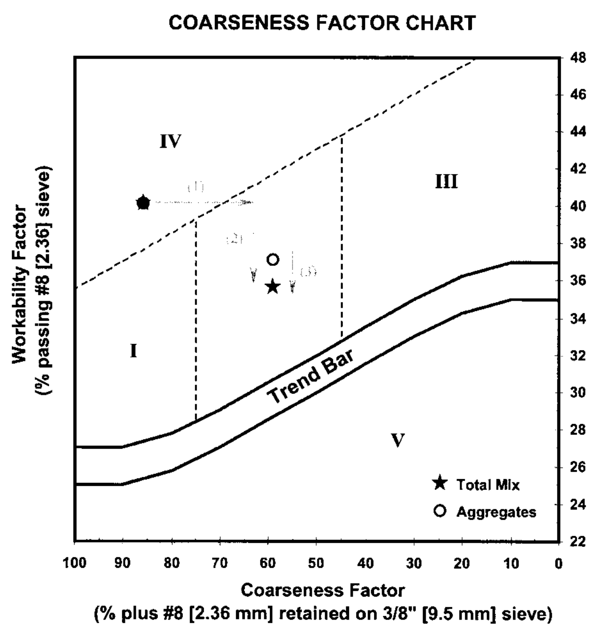


Fig. 6.5—Coarseness factor chart showing the impact of blending 3/8 in. (9.5 mm) aggregate (Section 6.3.4).

MOI-Adj (influenced by the adjusted workability factor W-Adj) are the same.

2. The fine aggregate content is reduced, changing the workability factor (WF) from 40 to 36% optimized for the new coarseness factor of 60%.

3. Due to the improved uniformity of the gradations, it is determined that less cementitious material is necessary to produce the same flexural strength without degrading the finishing characteristics of the mixture. This is due to a decrease in void space between the combined aggregates. The amount of fine paste materials necessary to fill these void spaces is reduced, thus reducing the amount of paste necessary for the mixture. The reduction in cementitious materials reduces the W-Adj value, thus moving MOI-Adj down the y-axis.

CHAPTER 7—BATCHING, MIXING, AND TRANSPORTING

Detailed provisions relating to batching, mixing, and transporting concrete are available in ASTM C 94, ASTM C 1116, and ASTM C 685.

7.1—Batching

Whether the concrete is centrally mixed on-site or in a ready-mixed concrete operation, the materials should be batched within the following ranges of the target batch weights:

Cement	±1%
Added water	±1%
Fine and coarse aggregate	±2% (if cumulative; 1% if individual)
Admixtures and pigments	±3%

Except for site mixing on small jobs, cement should be weighed on a scale separate from that used for weighing aggregates. If batching is by the bag, no fractional bags should be used.

Aggregate should be batched by weight (mass). Batching by volume should not be permitted, except with volumetric batching and continuous-mixing equipment (Section 7.2.2). Batch weights should be adjusted to compensate for absorbed and surface moisture. When the concrete mixture contains special aggregates, particular care should be exercised to prevent segregation or contamination.

Water can be batched by weight (mass) or volume. The measuring device used should have readily adjustable positive cutoff and should have provisions for calibration.

Accurate batching of admixtures and colored pigments is critical because they are used in relatively small quantities. Admixtures should be accurately batched at the concrete plant. Admixtures that are designed to be added to the concrete at the jobsite should be incorporated in accordance with the manufacturers' recommendations. When more than one admixture is batched, each should be batched separately and in such a way that the concentrated admixtures do not come into contact with each other. Care should be taken to avoid the freezing of admixtures in cold weather, as this can damage some of them. It is preferable to purchase pigments or colored admixtures prepackaged in batch-sized quantities. Powdered admixtures should be batched by weight, and paste or liquid admixtures by weight or volume. The volume of admixture batched should not be controlled by timing devices. Liquid admixtures are preferred but can require agitation to prevent the settling of solids.

7.2—Mixing

7.2.1 *Ready-mixed concrete*—Mixing should be in accordance with ASTM C 94 or ASTM C 1116 and should produce the required slump and air content without exceeding the specified *w/cm*. Close attention should be given to the moisture content of the aggregate and to the necessary adjustments to batched weights. Truck mixers should be in compliance with requirements of the project specification. To ensure consistent slump at the point of placement, a small quantity of adjustment water should be held out at the batch plant. The amount of withheld water should be indicated on the ticket; the truck should then leave the plant with a full water tank to allow the addition of any water on-site to be monitored and controlled.

7.2.2 *Site mixing*—Mixers that produce a volume of concrete requiring less than one bag of cement should not be used. For small quantities of concrete, packaged products meeting ASTM C 387 are more convenient and can be more accurately proportioned.

Mixing time should be sufficient to produce uniformly mixed concrete with the required slump and air content. Site mixers less than 1 yd^3 (0.75 m^3) in capacity should mix for no less than 3 min; ordinarily, 15 s should be added for each additional cubic yard (0.75 m^3) of capacity or fraction thereof, unless a turbine mixer is used. A longer mixing time is required for concrete with a slump of less than 3 in. (75 mm).

Equipment for volumetric batching and continuous mixing at the jobsite is available. Concrete produced in this manner should comply with ASTM C 685.

7.2.3 *Architectural concrete*—When special architectural concrete is produced using special aggregates, white cement, special cements, or pigments, mixer drums and equipment should be kept clean and any wash water should be disposed of before a new batch is introduced. Identical ingredients and quantities of materials should be used, using no less than 1/3 of the capacity of the mixing drum, a minimum of 3 yd in a 9 yd drum, and should always be in full yard increments. See ACI 303R for additional details.

7.2.4 *Shrinkage-compensating concrete*—When expansive cement or an expansive-component type admixture specifically designed for producing shrinkage-compensating concrete is required, refer to ACI 223 for details.

7.3—Transporting

7.3.1 *Discharge time*—Concrete mixed or delivered in a truck mixer should be completely discharged while the concrete still has sufficient workability to respond properly during the placing and finishing operations. The period after arrival at the jobsite during which the concrete can be properly worked will generally vary from less than 45 min to more than 90 min, depending on the weather, the concrete mixture proportions, and travel time from the batch plant to the jobsite. Prolonged mixing accelerates the rate of stiffening and can greatly complicate placing and timing of finishing operations.

7.3.2 *Jobsite slump control*—When concrete arrives at the point of placement with a slump below what will result in the specified slump at the point of placement and is unsuitable for placing at that slump, the slump may be adjusted to the required value by adding water up to the amount allowed in the accepted mixture proportions. The addition of water should be in accordance with ASTM C 94. The specified *w/cm* or slump should not be exceeded. Water should not be added to concrete delivered in a transit mix truck or similar equipment acceptable for mixing. Test samples for compressive strength, slump, air content, and temperature should be taken after any necessary adjustment. Refer to ACI 301 for further details.

7.3.3 *Delivery to point of discharge*—Concrete for floor and slab placement can be delivered to the forms directly from a truck mixer chute or by pump, belt conveyor, buggy, crane and bucket, or a combination of these methods. Delivery of concrete should be at a consistent rate, appropriate to the size of the placement, and should be deposited as close as possible to its final location. Concrete should not be moved horizontally by vibration, as this contributes to segregation. See ACI 304R for recommended procedures.

7.3.4 *Required yield and mixture adjustment to correct yield*—Refer to Section 6.2.

CHAPTER 8—PLACING, CONSOLIDATING, AND FINISHING

Most of this chapter applies to both normalweight and lightweight concrete. The proper procedures for finishing lightweight concrete floors differ somewhat from finishing normalweight concrete. Procedures specific to finishing lightweight concrete are discussed separately in Section 8.11.

Various finishing procedures should be executed sequentially and within the proper time period, neither too early nor too late in the concrete-hardening process. This time period is called the window of finishability. It refers to the time available for operations taking place after the concrete has been placed, consolidated, and struck off. Surface finish, surface treatment, and flatness/levelness requirements dictate the type and number of finishing operations. All should take place within the proper time period. If the floor slab is placed during a time period of rapid hardening, this window becomes so small that it can present considerable difficulties to the floor contractor. The preconstruction meeting should include discussion of the measures necessary to ensure a satisfactory window of finishability. The NRMCA/ASCC preconstruction checklist provides an outline of topics that might be considered for inclusion in the meeting agenda. ACI 311.4R also contains guidance that may be valuable.

8.1—Placing operations

8.1.1 *Caution*—All concrete handling operations should minimize segregation, because it is difficult to remix concrete after it has been placed.

8.1.1.1 *Placing sequence*—In many cases, the most efficient way to place concrete in large areas is in long alternating strips, as illustrated in Fig. 8.1. Strip placements allow superior access to the sections being placed. Intermediate contraction joints are installed at specified intervals transverse to the length of the strips. Wide strip placements can require installation of longitudinal contraction joints.

Large block placements with interior contraction joints are an acceptable alternative to strip placements if the contraction joints are installed at specified intervals in a timely manner. The use of shrinkage-compensating concrete (because of the decrease in jointing requirements) or laser screeds (because they provide accurate strikeoff without the use of edge forms) is compatible with large block placements.

A checkerboard sequence of placement with side dimensions of 50 ft (15 m) or less, as shown in Fig. 8.1, has been used in the past in an effort to permit earlier placements to shrink and to obtain minimum joint width. Experience has shown, however, that shrinkage of the earlier placements

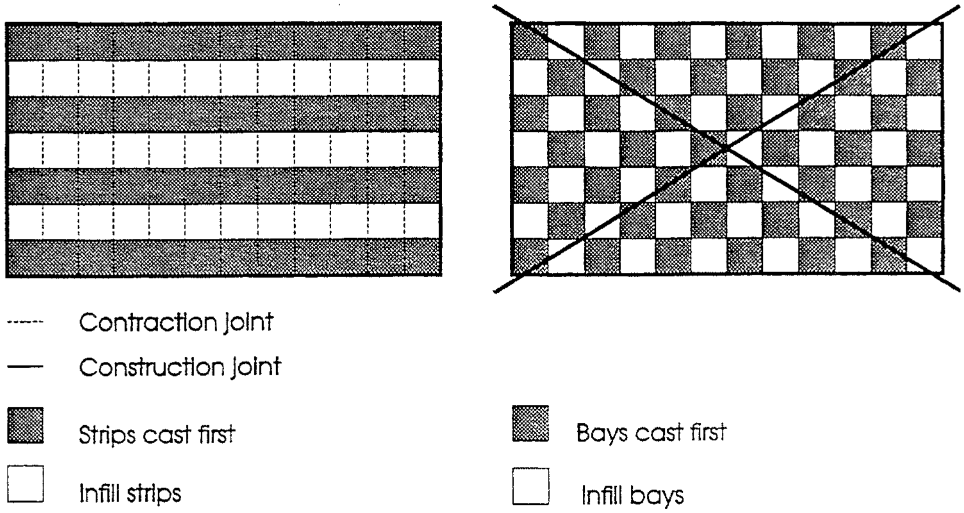


Fig. 8.1—Placing sequence: long-strip construction (left) is recommended; checkerboard construction (right) is not recommended.

occurs too slowly for this method to be effective. Access is more difficult and expensive, and joints may not be as smooth. The committee recommends that the checkerboard sequence of placement not be used.

8.1.1.2 *Placing sequence for shrinkage-compensating concrete*—Neither the strip method nor the checkerboard method described in Section 8.1.1.1 should be used with shrinkage-compensating concrete. Refer to ACI 223 for specific recommendations concerning placement configuration and sequence.

8.1.2 *Discharge rate of concrete*—The rate of discharge of concrete from a truck mixer can be controlled by varying the drum speed.

8.1.3 *Jobsite transfer*—Chutes should have rounded bottoms and be constructed of metal or be metal-lined. The chute slope should be constant and steep enough to permit concrete of the slump required to flow continuously down the chute without segregation. Long flat chutes should be avoided because they encourage the use of high-slump concrete. A baffle at the end of the chute helps to prevent segregation. The discharge end of the chute should be near the surface of previously deposited concrete. When concrete is being discharged directly onto the base, the chute should be moved at a rate sufficient to prevent accumulation of large piles of concrete. Allowing an excessively steep slope on chutes can result in high concrete velocity and segregation.

Regardless of the method of transportation and discharge, the concrete should be deposited as near as possible to its final position and toward previously placed concrete. Advance planning should include access to and around the site, suitable runways, and the use of other devices to avoid the use of concrete with a high *w/cm* or excessive delays.

8.1.4 *Placing on base*—Mixing and placing should be carefully coordinated with finishing operations. Concrete should not be placed on the base at a faster rate than it can be spread, bull floated or darbied, and restraightened because these latter operations should be performed before bleeding water has an opportunity to collect on the surface.

Proper sizing of finishing crews, with due regard for the effects of concrete temperature and atmospheric conditions on the rate of hardening of the concrete, will assist the contractor in obtaining good surfaces and avoiding cold joints. If construction joints become necessary, they should be produced using suitably placed bulkheads, with provisions made to provide load transfer between current and future work (Section 3.2.7).

8.2—Tools for spreading, consolidating, and finishing

The sequence of steps commonly used in finishing unformed concrete floor surfaces is illustrated in Fig. 8.2. Production of high-quality work requires that proper tools be available for the placing and finishing operations. Following is a list and description of typical tools that are commonly available. Refer to Section 8.3 for suggestions and cautions concerning uses of these tools. Definitions for many of these tools can be found in ACI 116R.

8.2.1 *Spreading*—Spreading is the act of extending or distributing concrete or embedding hardeners—often referred to as shake-on or dry-shake—or other special purpose aggregate over a desired area.

8.2.1.1 *Spreading concrete*—The goal of spreading operations for concrete is to avoid segregation.

8.2.1.1.1 *Hand spreading*—Short-handled, square-ended shovels, or come-alongs—hoe-like tools with blades about 4 in. (100 mm) high, 20 in. (500 mm) wide, and curved from top to bottom—should be used for the purpose of spreading concrete after it has been discharged.

8.2.1.2 *Spreading dry-shake hardeners, colored dry-shake hardeners, or other special-purpose material*—The goal of spreading operations for these materials is to provide an even distribution of product over the desired area. Generally, hand application should be used for distribution of these materials in areas where a mechanical spreader cannot be used.

8.2.1.2.1 *Mechanical spreaders*—Mechanical spreaders are the best method of uniformly applying dry-shake hardeners, colored dry-shake hardeners, or other special purpose materials to concrete during the finishing process. These devices generally consist of a bin or hopper to hold the material, a vibrator or motorized auger to assist in distribution of the material, and a supporting framework that allows the hopper to move smoothly over the concrete surface while distributing the material (Fig. 8.3).

8.2.2 *Tools for consolidating*—Consolidation is the process of removing entrapped air from freshly placed concrete, usually by vibration. Internal vibration and surface vibration are the most common methods of consolidating concrete in supported slabs and slabs-on-ground. Refer to ACI 309R for additional discussion of topics related to the consolidation of concrete.

8.2.2.1 *Internal vibration*—This method employs one or more vibrating elements that can be inserted into the fresh concrete at selected locations. Internal vibration is generally most applicable to supported cast-in-place construction.

8.2.2.2 *Surface vibration*—This process employs a portable horizontal platform on which a vibrating element is mounted. Surface vibration is commonly used in slab-on-ground, strip-type placements with edge forms. Refer to 8.2.3.2 for additional discussion.

8.2.3 *Tools for screeding*—Screeding is the act of striking off concrete lying above the desired plane or shape to a predetermined grade. Screeding can be accomplished by hand, using a straightedge consisting of a rigid, straight piece of wood or metal, or by using a mechanical screed.

8.2.3.1 *Hand screeding*—Hollow magnesium or solid wood straightedges are commonly used for hand-screeding of concrete. The length of these straightedges varies up to approximately 20 ft (6 m). Straightedge cross-sectional dimensions are generally 1 to 2 in. (25 to 50 mm) wide by 4 to 6 in. (100 to 150 mm) deep. Tools specifically made for screeding, such as hollow magnesium straightedges, should be used instead of randomly selected lumber.

8.2.3.2 *Mechanical screeding*—Various types of surface vibrators, including vibrating screeds, vibratory tampers, and vibratory roller screeds, are used mainly for screeding slab-on-ground construction. They consolidate concrete from the top down while performing the screeding function. Refer to ACI 309R for a detailed discussion of equipment and parameters for proper usage.

Vibrating screeds generally consist of either hand-drawn or power-drawn single-beam, double-beam, or truss assemblies. They are best suited for horizontal or nearly horizontal surfaces. Vibrating screeds should be of the low-frequency—3000 to 6000 vibrations per min (50 to 100 Hz)—high-amplitude type, to minimize wear on the machine and provide adequate depth of consolidation without creating an objectionable layer of fines at the surface. Frequency and amplitude should be coordinated with the concrete mixture designs being used.

Laser-controlled variations of this equipment can be used to produce finished slabs-on-ground with improved levelness over that which might otherwise be achieved. Laser-controlled screeds can ride on supporting forms or they can operate from a vehicle using a telescopic boom (Fig. 8.4).

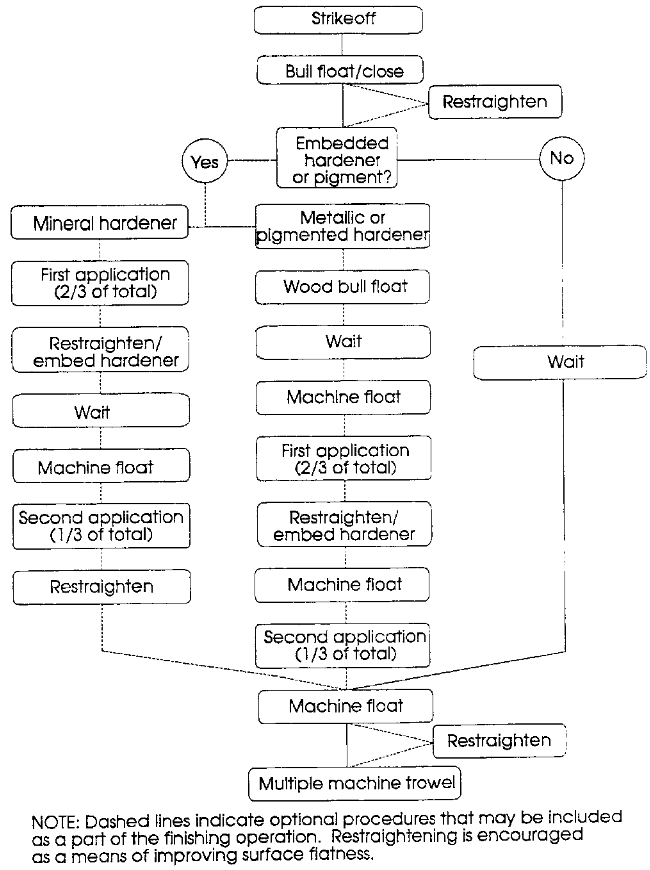


Fig. 8.2—Typical finishing procedures (subject to numerous conditions and variables).

Fig. 8.3—Mechanical spreader.

Plate-tamper screeds are vibratory screeds that are adjusted to a lower frequency and amplitude. Tamper screeds work best on very stiff concrete. These screeds are generally used to embed metallic or mineral aggregate hardeners. The contractor is cautioned that improper use of this screed could embed the hardener too deeply and negate the intended benefit.

Vibratory-roller screeds knock down, strike off, and provide mild vibration. They can rotate at varying rates up to several hundred revolutions per minute, as required by the

Fig. 8.4—Laser-controlled screed.

Fig. 8.5—Double-riding trowel with clip-on pans.

consistency of the concrete mixture. The direction of rotation of the rollers on the screed is opposite to the screed's direction of movement. These screeds are most suitable for concrete mixtures with higher slumps.

8.2.4 *Tools for floating*—Floating is the act of consolidating and compacting the unformed concrete surface in preparation for subsequent finishing operations. Initial floating of a concrete floor surface takes place after screeding and before bleed water comes to the surface and imparts a relatively even but still open texture to the fresh concrete surface. After evaporation of bleed water, additional floating operations prepare the surface for troweling.

8.2.4.1 *Bull floats (long-handled)*—Bull floats are used to consolidate and compact unformed surfaces of freshly placed concrete immediately after screeding operations, while imparting an open texture to the surface. They are usually composed of a large, flat, rectangular piece of wood or magnesium and a handle. The float part of the tool is usually 4 to 8 in. (100 to 200 mm) wide and 3.5 to 10 ft (1 to 3 m) long. The handle is usually 4 to 20 ft (1.2 to 6 m) long. The handle is attached to the float by means of an adjustable head that allows the angle between the two pieces to change during operation.

8.2.4.2 *Darby*—A darby is a hand-manipulated float, usually 3-1/2 in. (90 mm) wide and 3 to 8 ft (1 to 2.4 m) long. It is used in early-stage-floating operations near the edge of concrete placements.

8.2.4.3 *Hand floats*—Hand tools for basic floating operations are available in wood, magnesium, and composition materials. Hand float surfaces are generally about 3-1/2 in. (90 mm) wide and vary from 12 to 20 in. (300 to 500 mm) in length.

8.2.4.4 *Power floats*—Also known as rotary floats, power floats are engine-driven tools used to smooth and to compact the surface of concrete floors after evaporation of the bleed water. Two common types are heavy, revolving, single-disk-compactor types that often incorporate some vibration, and troweling machines equipped with float blades. Most troweling machines have four or more blades mounted to the base and a ring diameter that can vary from 36 to 46 in. (1 to 1.2 m); mass generally varies from about 150 to 250 lb (70 to 110 kg).

Two types of blades can be used for the floating operation. Float blades are designed to slip over trowel blades; they are generally 10 in. (250 mm) wide and 14 to 18 in. (350 to 450 mm) long. Both the leading edge and the trailing edge of float blades are turned up slightly. Combination blades are usually 8 in. (200 mm) wide and vary in length from 14 to 18 in. (350 to 450 mm). The leading edges of combination blades are turned up slightly. The use of float blades is recommended (Section 8.3.10).

Another attachment that is available to assist in power float operations is a pan with small brackets that slide over the trowel blades. These pans are normally used on double- or triple-platform ride-on machines and are very effective on concrete surfaces requiring an embedded hardener or coloring agent. The use of mechanical pan floating (Fig. 8.5) can also materially improve flatness of the finished floor.

8.2.5 *Tools for restraightening*—Straightedges are used to create and to maintain a flat surface during the finishing process. Straightedges vary in length from 8 to 12 ft (2.4 to 3.7 m) and are generally rectangular in cross section (though designs differ among manufacturers). When attached to a handle with an adjustable head (that is, a bull-float handle and head), these tools are frequently referred to as modified highway straightedges (Fig. 8.6).

8.2.6 *Tools for edging*—Edgers are finishing tools used on the edges of fresh concrete to provide a rounded edge. They are usually made of stainless steel and should be thin-lipped. Edgers for floors should have a lip radius of 1/8 in. (3 mm).

8.2.7 *Tools for troweling*—Trowels are used in the final stages of finishing operations to impart a relatively hard and dense surface to concrete floors and other unformed concrete surfaces.

8.2.7.1 *Hand trowels*—Hand trowels generally vary from 3 to 5 in. (75 to 125 mm) in width and from 10 to 20 in. (250 to 500 mm) in length. Larger sizes are used for the first troweling to spread the troweling force over a large area. After the surface has become harder, subsequent trowelings use smaller trowels to increase the pressure transmitted to the surface of the concrete.

8.2.7.2 *Fresno trowels*—A fresno is a long-handled trowel that is used in the same manner as a hand trowel. Fresnos are useful for troweling slabs that do not require a hard-troweled surface. These tools are generally 5 in. (125 mm) wide and vary in length from 24 to 48 in. (0.6 to 1.2 m).

8.2.7.3 *Power trowels*—Power trowels are gasoline engine-driven tools used to smooth and compact the surface of concrete floors after completion of the floating operation. Ring diameters on these machines generally vary from 36 to 46 in. (0.9 to 1.2 m); their mass generally varies from approximately 150 to 250 lb (70 to 110 kg). Trowel blades are usually 6 in. (150 mm) wide and vary in length from 14 to 18 in. (350 to 450 mm). Neither the leading nor the trailing edge of trowel blades is turned up. Power trowels can be walk-behind machines with one set of three or four or more blades or ride-on machines with two or three sets of four blades.

8.2.8 *Tools for jointing*—These tools are used for the purpose of creating contraction joints in slabs. Contraction joints can be created by using groovers, also called jointers, or by saw-cutting.

8.2.8.1 *Groovers*—Groovers can be handheld or walk-behind. Stainless steel is the most common material. Handheld groovers are generally from 2 to 4-3/4 in. (50 to 120 mm) wide and from 6 to 7-1/2 in. (150 to 190 mm) long. Groove depth varies from 3/16 to 1-1/2 in. (5 to 38 mm). Walk-behind groovers usually have a base with dimensions from 3-1/2 to 8 in. (90 to 200 mm) in width and from 6 to 10 in. (150 to 250 mm) in length. Groove depth for these tools varies from 1/2 to 1 in. (13 to 25 mm).

8.2.8.2 *Saw-cutting*—The following three types of tools can be used for saw-cutting joints: conventional wet-cut (water-injection) saws; conventional dry-cut saws; and early-entry dry-cut saws. Timing of the sawing operations will vary with manufacturer and equipment. The goal of saw-cutting is to create a weakened plane to influence the location of shrinkage crack formation as soon as the joint can be cut, preferably without creating spalling at the joint.

Both types of dry-cut tools can use either electrical or gasoline power. They provide the benefit of being generally lighter than wet-cut equipment. Early-entry dry-cut saws do not provide as deep a cut—generally 1-1/4 in. (32 mm) maximum—as can be achieved by conventional wet-cut and dry-cut saws.

Early-entry dry-cut saws use diamond-impregnated blades and a skid plate that helps prevent spalling. Timely changing of skid plates is necessary to effectively control spalling. It is best to change skid plates in accordance with manufacturers' recommendations.

Conventional wet-cut saws are gasoline powered and, with the proper blades, are capable of cutting joints with depths of up to 12 in. (300 mm) or more.

8.3—Spreading, consolidating, and finishing operations

This section describes the manner in which various placing and finishing operations can be completed successfully. The finishing sequence to be used after completion of the initial screeding operation depends on a number of variables related to project requirements or to the concrete finishing environment.

Fig. 8.6—"Modified highway" straightedge.

Project variables are generally controlled by requirements of the owner and are specified by the designer. Some examples are the choice of admixtures used in concrete, the requirement for an embedded hardener, and the final finish desired.

Variables subject to the environment include such items as setting time of the concrete, ambient temperature, timeliness of concrete delivery, consistency of concrete at the point of deposit, and site accessibility. Figure 8.2 is a flowchart that illustrates the normal sequence of steps in the finishing process.

8.3.1 *Spreading and consolidating*—Concrete, whether from a truck mixer chute, wheelbarrow, buggy, bucket, belt conveyor, pump, or a combination of these methods, should be delivered without segregation of the concrete components (Section 8.1). Spreading, the first operation in producing a plane surface (not necessarily a level surface because, in many cases, it can be sloped for surface drainage) should be performed with a come-along or a short-handled, square-ended shovel (Section 8.2.1.1).

Long-handled shovels, round-ended shovels, or garden-type rakes with widely spaced tines should not be used to spread concrete. Proper leverage, of prime importance for manipulating normalweight concrete, is lost with a long-handled shovel. Round-ended shovels do not permit proper leveling of the concrete. The tines of garden-type rakes can promote segregation and should not be used in any concrete.

Initial consolidation of concrete in floors, with the exception of heavily reinforced slabs, is usually accomplished in the first operations of spreading, vibrating, screeding, darbying or bull floating, and restraightening. The use of grate tampers or mesh rollers is usually neither desirable nor necessary, unless the concrete slump is less than 3 in. (75 mm). If grate tampers are used on lightweight-concrete floors, only one pass over the surface with a very light impact should be permitted. Spreading by vibration should be minimized. Refer to ACI 309R for detailed discussion.

8.3.1.1 *Structural floors*—Structural floors, both suspended and on ground, can be reinforced with relatively large deformed reinforcing bars or with post-tensioning tendons and typically contain other embedded items such as piping and conduit. Proper consolidation around reinforcing steel, post-tensioning anchorages, and embedded elements requires internal vibration, but care should be taken not to use the vibrator for spreading the concrete, especially in deeper sections where over-vibration can easily cause segregation. Restraint of concrete movement by embedded items such as piping and conduits can result in crack formation as the concrete shrinks.

The vibrator head should be completely immersed during vibration. Where slab thickness permits, it is proper to insert the vibrator vertically. On thin slabs, the use of short 5 in. (125 mm) vibrators permits vertical insertion. Where the slab is too thin to allow vertical insertion, the vibrator should be inserted at an angle or horizontally. The vibrator should not be permitted to contact the base because this might contaminate the concrete with foreign materials.

8.3.2 *Screeding*—Screeding is the act of striking off the surface of the concrete to a predetermined grade, usually set by the edge forms. This should be done immediately after placement. When hand strikeoff is used, a slump of 5 in. (125 mm) or higher should be used to facilitate strikeoff and consolidation of concrete without mechanical methods. Refer to Section 8.2.3 for tools used for screeding.

Of all the floor-placing and finishing operations, form setting and screeding have the greatest effect on achieving the specified grade. Accuracy of the screeding operation is directly impacted by the stability and the degree of levelness of the edge forms or screed guides selected by the contractor. Consequently, care should be taken to match the forming system and the screeding method to the levelness tolerance specified.

Edge forms for slab-on-ground and suspended-slab placements are normally constructed of wood or metal. Some edge forms are constructed of concrete. The spacing between edge forms, and the support provided for them, will influence the accuracy of the screeding operation. Where edge-form spacing exceeds the width of the screed strip, intermediate screed guides can improve the accuracy of the screeding operation. The width of these screed strips will generally vary between 10 and 16 ft (3 and 5 m) and will be influenced by column spacings. Generally, screed strips should be equal in width and should have edges that fall on column lines.

In general, slab-on-ground placements are either block placements or strip placements. Block placements generally have edge dimensions that exceed 50 ft (15 m). Strip placements are generally 50 ft (15 m) or less in width and vary in length up to several hundred feet. Suspended-slab placements are usually block placements. Where wood is used for edge forms, the use of dressed lumber is recommended. The base should be carefully fine-graded to ensure proper slab thickness.

Selection of the type of screed guide to be used for screeding operations is somewhat dependent on placement configuration. The maximum practical width of screed strips for hand screeding is approximately 20 ft (6 m). Where strict elevation tolerances apply, it is wise to limit the width of screed strips. The length of the hand screeding device should not be longer than 16 ft (5 m) and should overlap previously placed strips of wet concrete a minimum of 2 ft (600 mm). Screeding of strip placements for slabs-on-ground is generally completed using some type of a vibrating screed supported by edge forms. Screeding of block placements for slabs-on-ground is usually accomplished using wet-screed guides, dry-screed guides, a combination of these two, or some type of laser-guided screed. For slabs-on-ground, an elevation change no greater than 3/8 in. (9.5 mm) in 10 ft (3 m), approximately F_L35, can be achieved routinely through use of laser-guided screeds (refer to Section 8.15 for discussion of floor flatness and levelness). Screeding of block placements for suspended slabs is usually accomplished using either wet-screed guides, dry-screed guides, or a combination of the two.

Wet-screed guides, when used between points or grade stakes, are established immediately after placement and spreading; refer to Section 4.4 for setting of dry-screed guides. At the time of floor placement, before any excess moisture or bleed water is present on the surface, a narrow strip of concrete not less than 2 ft (600 mm) wide should be placed from one stake or other fixed marker to another, and straightedged to the top of the stakes or markers; then another parallel strip of concrete should be placed between the stakes or markers on the opposite side of the placement strip. These two strips of concrete, called wet-screed guides, establish grade for the concrete located between the guides. Immediately after wet-screed guides have been established, concrete should be placed in the area between, then spread and straightedged to conform to the surface of the wet-screed guides. The contractor should confirm that proper grade has been achieved following strikeoff. High spots and low spots should be identified and immediately corrected. Low spots left behind should be filled by placing additional concrete in them with a shovel, carefully avoiding segregation. Nonconforming areas should then be rescreeded. Difficulty in maintaining the correct grade of the floor while working to wet-screed guides is an indication that the concrete mixture does not have the proper consistency or that vibration is causing the guides to move.

Elevation stakes placed at regular intervals are one method of establishing grade for wet-screed guides in slab-on-ground construction. As screeding progresses, the stakes can be driven down flush with the base if expendable or pulled out one at a time to avoid walking back into the screeded concrete. This early removal of stakes is one of the big advantages in the use of wet-screeds; in addition, grade stakes are much easier and faster to set than dry-screeds. Screeding should be completed before any excess moisture or bleed water is present on the surface.

The benefits of using wet-screed guides include economical and rapid placement of the concrete. The successful use of wet-screed guides, however, requires careful workmanship by craftspeople who strike off the concrete because vibration can change the elevation of the wet-screed. Wet-screed guides are difficult to use when varying surface slopes are required and can produce inconsistent results when variations in slab thickness are required to compensate for deflection of a suspended slab. Special care is necessary to avoid poor consolidation or cold joints adjacent to wet-screed guides.

Wet-screed guides should not be used in suspended-slab construction, unless the finished floor surface is level and formwork is shored at the time of strikeoff. During construction activity, vibration of reinforcing steel and the supporting platform may result in an incorrect finished grade when wet-screed guides are used. It is imperative, therefore, that grade be confirmed after strikeoff and that errors be corrected at that time by restriking the area.

Wet-screed guides should be used only for surfaces where floor levelness is not critical. For slabs on grade where floor levelness requirements are important, dry-screed guides should be used instead of wet-screed guides. In general, surfaces produced using wet-screed guides will exhibit maximum elevation changes of at least 5/8 in. (16 mm) in 10 ft (3 m). This corresponds to an F_L20 floor.

Elevation variation of surfaces produced using dry-screed guides is dependent on placement-strip width and the accuracy the guides are installed with. Generally, the maximum elevation changes that can be anticipated will be reduced as the dry-screed guides are moved closer together.

For suspended-slab construction, the desirability of using dry-screed guides on both sides of each placement strip is diminished by the damage done when the contractor retrieves the guide system. For this reason, a combination of dry-screed guide and wet-screed guide techniques should be employed on suspended slabs.

The first placement strip should always start against a bulkhead or edge of the building. Strikeoff on the interior side of the strip should be controlled through the use of moveable dry-screed guides, which will provide positive control over the surface elevation along that line. The concrete edge along the moveable guide should be kept near vertical and straight. As concrete is placed and struck off, these guides are removed. When the next strip is placed, preferably in the same direction as the initial strip, the prior strip will normally have been in place for 30 min or more. The contractor can extend the straightedge 2 ft (600 mm) or more over the previous partially set placement to control grade of strikeoff on that side of the strip and use moveable dry-screed guides to control grade on the side of the strip not adjacent to previously placed concrete.

For suspended-slab construction, the procedure described in the previous paragraph has several advantages over unmodified wet-screed techniques or those techniques that use dry-screed guides on both sides of each placement strip.

1. Where previously placed concrete is used as a guide for strikeoff, it provides a relatively stable guide because it will have been in place for some time before it is used.

2. Retrieval of the dry-screed guide from areas surrounded by previously placed concrete is unnecessary because dry-rigid guides are not used in these locations.

Moveable dry-screed guides should be used to establish grade on any suspended slabs that are not level and shored at the time of strikeoff, and for any suspended slab where increases in local slab thickness might be used to compensate for anticipated or identified differential deflection of the structure. When an increase in local slab thickness is used to compensate for differential floor deflection, it is likely that the resulting slab will be more than 3/8 in. (9.5 mm) thicker than design thickness. The contractor should secure permission from the designer to exceed the plus tolerance for slab thickness before beginning construction. Refer to Section 3.3 for a discussion of suspended slab deflection and suggested construction techniques.

For construction of slabs-on-ground, the use of vibrating screeds—where edge forms or screed-guide rails can be used—will facilitate strike-off operations. By using a vibrating screed, crews can place concrete at a lower slump than might be practical if screeding were done by hand. Suspended slabs are seldom both level and supported at the time of construction. Vibrating screeds and roller screeds similar to those used for slab-on-ground strip placements are generally not appropriate for use in suspended-slab construction because of the probability that their use will result in slabs that are too thin in localized areas. It is essential that minimum slab thickness be maintained at all locations on suspended slabs because of compliance with contract documents and fire safety requirements.

Slumps up to 5 in. (125 mm) are often recommended for concrete consolidated by vibrating screeds. If slumps in excess of 4 in. (100 mm) are used, the amplitude of vibration should be decreased in accordance with the consistency of the concrete so that the concrete does not have an accumulation of excess mortar on the finished surface after vibration.

Vibrating screeds strikeoff and straightedge the concrete in addition to providing consolidation. To perform significant consolidation, the leading edge of the blade should be at an angle to the surface, and the proper surcharge (height of unconsolidated concrete required to produce a finished surface at the proper elevation) should be carried in front of the leading edge.

Vibrating screeds should be moved forward as rapidly as proper consolidation allows. If not used in this manner, too much mortar will be brought to the surface in normalweight concrete; conversely, too much coarse aggregate will be brought to the surface in lightweight concrete.

8.3.3 *Floating*—Floating is used to describe compaction and consolidation of the unformed concrete surface. Floating operations take place at two separate times during the concrete finishing process.

The first floating, generally called bull floating, is by hand and takes place immediately after screeding. Initial floating should be completed before any excess moisture or bleeding water is present on the surface. Any finishing operation performed while there is excess moisture or bleed water on the surface will cause dusting or scaling. This basic rule of concrete finishing cannot be over-emphasized. The first floating operation is performed using a wide bull float, darby, or modified highway straightedge. The second floating operation takes place after evaporation of most of the bleed water and is usually performed using a power trowel with float blades or a pan attached. The second floating operation is described in Section 8.3.10.

8.3.3.1 *Bull floating*—One of the bull float's purposes is to eliminate ridges and fill in voids left by screeding operations. Bull floating should embed the coarse aggregate only slightly. This process prepares the surface for subsequent edging, jointing, floating, and troweling.

When the specified finished floor flatness, using the F-number system, restricts the difference between successive 1 ft (300 mm) slopes to a maximum of 1/4 in. (6 mm), approximately F_F20 (Section 8.15), a traditional-width bull float of 4 to 5 ft (1.2 to 1.5 m) can be used to smooth and consolidate the concrete surface after screeding. The use of this width bull float, however, can adversely affect floor flatness and make it extremely difficult to achieve flatness F-numbers higher than 20. When the magnitude of difference between successive 1 ft (300 mm) slopes is limited to less than 1/4 in. (6 mm)—floor flatness greater than F_F20 (Section 8.15)—an 8 to 10 ft wide (2.4 to 3 m) bull float can be very useful in removing surface irregularities early in the finishing process. This is particularly true for suspended-slab construction, where local irregularities caused by form- or metal-deck deflection and concrete leakage can be significant.

Many contractors use an 8 to 10 ft wide (2.4 to 3 m) bull float or modified highway straightedge after initial strikeoff to restraighten any local irregularities that can be present. Use of a traditional 4 to 5 ft wide (1.2 to 1.5 m) bull float will provide little assistance to the finisher in correcting these irregularities. Using the wider bull float or modified highway straightedge allows the finisher to recognize and correct irregularities at a time when significant amounts of material can be moved with relatively little effort. This simple substitution of tools can routinely produce up to a 50% increase in floor flatness.

In block placements for slabs-on-ground, and for suspended-slab placements, a wide bull float or modified highway straightedge can also be used. Applied at an angle of approximately 45 degrees to the axis of the placement strip and extending across the joint between the current strip and the strip previously placed, these tools can remove many irregularities that would otherwise remain if they were used only in a direction perpendicular to the axis of the placement strip.

A magnesium bull float can be used for lightweight concrete and sticky mixtures or where a partially closed surface is desired until it is time to float. The magnesium face of the bull float slides along the fines at the surface and thus requires less effort and is much less likely to tear the surface.

When an embedded hardener or other special purpose aggregate is required and rapid stiffening is expected, the use of a bull float, preferably wooden, can be helpful in initially smoothing the surface after the aggregate is applied and before the modified highway straightedge is used in the initial cutting and filling operation. Inevitable variations in the uniformity of coverage when an embedded hardener or other special purpose aggregate is applied will create slight irregularities in the slab surface. Restraightening operations necessary to remove these irregularities will remove embedded material in some locations while adding to the thickness of embedded material in other locations. Experience has shown that some variations in the uniformity of embedded material coverage does not adversely impact the floor's function.

Wooden bull floats are preferable for use on normalweight concrete that receives an embedded hardener. The wood's coarse texture enables it to evenly spread the mortar mixture of cement and fine aggregate across the surface, leaving the surface of the concrete open and promoting uniform bleeding. If a magnesium bull float is used for normalweight concrete, the embedded hardener should first be forced into the concrete using a wooden float. This brings moisture to the surface and ensures proper bond of the hardener to the base slab. This is particularly important where dry shakes will be applied for color, increased wear resistance, or both.

8.3.3.2 *Darbying*—Darbying serves the same purpose as bull floating, and the same rules apply. Because bull floating and darbying have the same effect on the surface of fresh concrete, the two operations should never be performed on the same surface. Because of its long handle, the bull float is easy to use on a large scale, but the great length of the handle detracts from the attainable leverage, so high tolerances are more difficult to achieve. A darby is advantageous on narrow slabs and in restricted spaces. Long-handled darbies should be used for better leverage and control of level. Metal darbies are usually unsatisfactory for producing surfaces meeting high-tolerance requirements. The same principles regarding the use of wooden or magnesium bull floats (Section 8.3.3.1) apply to darbies because both darbies and bull floats are used for the same purpose following screeding.

8.3.3.3 *Hand floating*—Wooden hand floats encourage proper workmanship and timing. If used too early on any type of concrete, they stick, dig in, or can tear the surface. Used too late, they roll the coarser particles of fine aggregate out of the surface, at which time use of a magnesium float held in a flat position would be preferable. Wooden floats more easily fill in low spots with mortar; they should also be used in areas where embedded hardeners or other special purpose aggregates will be applied, floated, and finished by hand only. The use of wooden hand floats has declined largely due to the need for periodic replacement because of wear or breakage, and the greater effort and care in timing required in using them. Used at the proper time, their floating action is unequaled by other hand tools.

Magnesium hand floats require less effort. Like magnesium bull floats, they slide along largely on fines. They can be used on concrete from the time of placement to beyond the point of stiffening when a wooden float cannot be used. Magnesium floats are best used in the initial smoothing of the surface near screeds, walls, columns, or other projections, and during placing, screeding, and bull floating, when a wooden float would dig in or tear the surface. Magnesium floats can also be used on air-entrained concrete that is not to receive a troweled finish, or following wooden or power floating to produce a more uniform swirl finish not quite as roughly textured. Well-worn magnesium floats develop an edge almost as sharp as a steel trowel, so care should be exercised to use them flat to avoid closing the surface too early or causing blisters.

Composition hand floats using resin-impregnated canvas surfaces are smoother than wooden floats and only slightly rougher than magnesium floats. They are similar to magnesium hand floats and should be used in the same manner.

8.3.4 *Highway-type straightedging*—The use of a modified highway straightedge for restraightening of the surface varies with the type of slab being installed. Experienced finishers can use this tool early in the finishing process instead of an 8 to 10 ft wide (2.4 to 3 m) bull float. Care is needed, however, because the straightedge tends to dig into the concrete if it is used improperly. Initial restraightening with the modified highway straightedge should immediately follow screeding. Restraightening should be completed before any excess moisture or bleed water is present on the surface. When specified differences between successive 1 ft (300 mm) slopes are 3/16 in. (5 mm) or less—flatnesses higher than F_F20 (Section 8.15)—a modified highway straightedge is recommended to smooth and restraighten the surface after power floating or any floating operation that generates significant amounts of mortar. A weighted modified highway straightedge can also be used after power-trowel operations to scrape the surface, reducing local high spots. Filling of low spots is generally not appropriate after scraping with a weighted modified highway straightedge.

The flatness exhibited by any concrete floor will be determined almost exclusively by the effectiveness of corrective straightedging employed after each successive strikeoff, floating, and troweling step. Without restraightening, each step performed in a conventional concrete floor installation tends to make the surface less flat. Straightedges are capable of restraightening or reflattening the plastic concrete because they alone contain a reference line the resulting floor profile can be compared against. Restraightening operations are most effective when new passes with the modified highway straightedge overlap previous passes by approximately 50% of the straightedge width. In contrast, traditional 4 to 5 ft wide (1.2 to 1.5 m) bull floats, power floats, and power trowels are wave-inducing devices. To the extent that further restraightedgings can only reduce floor-wave amplitudes and enlarge floor-wave lengths, floor surface flatness can be further improved until Class 9 floor surface quality is obtained.

The modified highway straightedge is used in a cutting and filling operation to achieve surface flatness. When using this or any restraightening tool, it is desirable to overlap previous work with the tool by at least 50% of the tool width. The tool should be used in at least two directions, preferably in perpendicular directions to each other. For strip placements, this can be accomplished by using the straightedge at a 45 degree angle to the axis of the strip and toward the end of the strip, followed by use of the straightedge at a 45 degree angle toward the beginning of the strip. The cutting and filling operation taking place in these two directions from the edge of a placement strip will enable the straightedge passes to cross at right angles and to produce a flatter, smoother floor. Straightedging in a direction parallel to the strip-cast operation and to the construction joints is possible but less desirable because this would require the finisher to stand in the plastic concrete or on a bridge spanning the strip. This cut-and-fill process can also be performed after power-floating operations (Section 8.3.10) to further improve the floor's flatness.

For slabs-on-ground with an embedded metallic or mineral hardener, coloring agents, or other special-purpose material, the use of a modified highway straightedge plays an important part in reestablishing surface flatness after application of the material. These products are generally applied after initial screeding or strikeoff, and even the best of applications will create minor irregularities in the surface. After the hardener or special-purpose material has been worked into the surface of the concrete using a wooden bull float, a follow-up pass using the modified highway straightedge is desirable to restraighten the surface after the embedded metallic, mineral, and special-purpose material or its coating has absorbed sufficient moisture.

Some embedded metallic dry-shake hardeners and colored dry-shake hardeners are applied immediately after the initial power float pass (Section 8.3.10). When these materials are relatively fine, it is necessary to wait until this point in the finishing operation to begin their application. When applied too early in the finishing process, they tend to be forced below the surface by finishing operations. The use of a modified highway straightedge to embed these materials and to restraighten the surface after their application is a critical component of the finishing process.

Mechanical spreaders should be used for use in the application of metallic or mineral hardeners, colored dry-shake hardeners, or other special-purpose materials. Hand spreading often results in an inadequate and uneven application of the material, unless applied by highly skilled craftsmen.

8.3.5 *Waiting*—After initial floating and restraightening have been completed, a slight stiffening of concrete is necessary before proceeding with the finishing process. Depending on job conditions, it may be necessary to wait for this stiffening to occur. Waiting time can be reduced or eliminated by the use of dewatering techniques. No subsequent operation should be done until the concrete will sustain foot pressure with only approximately 1/4 in. (6 mm) indentation (Section 8.3.10).

8.3.6 *Dewatering techniques*—Completing the initial power float operation using a walk-behind machine and clip-on float blades can be very beneficial, particularly when steel fiber reinforcing is used. Mechanical pan floating should not begin until the surface has stiffened sufficiently so that footprints are barely perceived on the concrete surface.

For slabs-on-ground, the use of dewatering techniques as an alternative to waiting should be thoroughly discussed by key parties before implementation by the contractor. Either vacuum mats, or a blotter of cement on top of damp burlap, applied to the surface of freshly placed concrete, can be used to remove significant amounts of water. While this process quickly prepares the surface for final floating and troweling, it should only be undertaken by those with successful experience in the use of these techniques. The application of dry cement directly to the surface of freshly placed concrete should be avoided; this practice promotes dusting of the floor surface and can result in reduced abrasion resistance.

Vacuum mats, or a blotter of cement on top of damp burlap, are applied after the concrete has been placed, compacted, and floated. If vacuum mats are used, vacuum is applied for about 3 to 5 min per 1 in. (25 mm) thickness of slab (Wenander 1975; Wenander, Danielsson and Sendker 1975; Malinowski and Wenander 1975).

Vacuum dewatering has been used extensively in Europe. More detailed information is presented in several sources (Martin and Phelan 1995; ACI Committee 226 1987; USBR).

8.3.7 *Edging*—Edging is not required or recommended on most floors. Edgers should be used only when specifically required by the project documents. Where edging is required, use of walk-behind edgers is discouraged because their use can yield inconsistent results. If the floor is to be covered with tile, an edger should not be used. If edging is required by the project documents, a 1/8 in. (3 mm) or smaller radius edge should be used for construction joints subjected to regular vehicular traffic, although saw-cutting is the preferred method for this type of surface.

The edger is used to form a radius at the edge of the slab (Section 8.2.6). Edging, or stoning when the placement is finished flush with the edge forms, will also allow construction joints to be readily visible for accurate location of sawing, when used. The second placement at a construction joint will often bond to the first placement. Sawing this joint encourages development of a clean, straight crack at the construction joint. Edging is most commonly used on sidewalks, driveways, and steps; it produces a neater looking edge that is less vulnerable to chipping. Edging should not commence until most bleed water and excess moisture have left or been removed from the surface. Instead of being edged, construction joints of most floor work can be finished flush with the edge forms, and then lightly stoned to remove burrs after the bulkheads or edge forms are stripped and before the adjacent slab is placed.

8.3.8 *Hand-tooled joints*—Slabs-on-ground are jointed immediately following edging, or at the same time, unless the floor is to be covered with hard or soft tile. If the floor is to be covered with tile, jointing is unnecessary because random cracks are preferable to tooled joints under tile. For floors to be covered with quarry tile, ceramic tile, terrazzo pavers, or cast-in-place terrazzo, the joints in slabs-on-ground should be aligned with joints in the rigid coverings.

The cutting edge or bit of the jointing tool creates grooves in the slab, called contraction joints (Section 3.2.5.3). For contraction joints, the jointing tool should have a bit deep enough to cut grooves that are 1/4 the thickness of the slab. This forms a plane of weakness along which the slab will crack when it contracts. Jointers with worn-out or shallow bits should not be used except for forming decorative, nonfunctional groves in the concrete surface. The jointer should have a 1/8 in. (3 mm) radius for floors. Because of limitations on bit length, hand-tooled joints are not practical for slabs greater than 5 in. (125 mm) thick where the groove depth is 1/4 of the slab thickness.

It is good practice to use a straight 1 x 8 or 1 x 10 in. (25 x 200 or 25 x 250 mm) board as a guide when making the joint or groove in a concrete slab. If the board is not straight, it should be planed true. The same care should be taken in running joints as in edging because a hand-tooled joint can either add to or detract from the appearance of the finished slab.

8.3.9 *Preformed joints*—Preformed plastic and metal strips are also available as an alternative to the use of jointers or saw cuts for making contraction joints. If used, they are inserted in the fresh concrete at the time hand-tooled jointing would take place. Proper performance of these strips is extremely sensitive to installation. Plastic or metal inserts are not recommended in any floor surface subjected to wheeled traffic (Section 3.2.5.3).

8.3.10 *Power floating*—After edging and hand-jointing operations (if used), slab finishing operations should continue with use of either the hand float or the power float. Power floating is the normal method selected. The purposes of power floating are threefold:

1. To embed the large aggregate just beneath the surface of a mortar composed of cement and fine aggregate from the concrete;
2. To remove slight imperfections, humps, and voids; and
3. To compact the concrete and consolidate mortar at the surface in preparation for other finishing operations.

In the event that multiple floating passes are required, each floating operation should be made perpendicular to the direction of the immediately previous pass.

Nonvibratory, 24 to 36 in. diameter (600 to 900 mm) steel disk-type floats are usually employed to float low-slump or zero-slump concrete or toppings. They can also be used for additional consolidating or floating following normal floating operations when the surface has stiffened to a point where it can support the weight of the machine without disturbing the flatness of the concrete.

Troweling machines equipped with float blades or pans slipped over the trowel blades can be used for floating. Float blades are beneficial when steel fiber reinforcing, surface hardeners, or both are used. Troweling machines with combination blades could be used but are not recommended. Floating with a troweling machine equipped with normal trowel blades should not be permitted. Contract documents should also prohibit the use of any floating or troweling machine that has a water attachment for wetting the concrete surface during finishing of a floor. Application of water by brush or machine during finishing promotes dusting of the floor surface and should be done only to overcome adverse conditions. This should be discussed in the context of the placement environment at a pre-placement meeting.

Many variables—concrete temperature, air temperature, relative humidity, and wind—make it difficult to set a definite time to begin floating. The concrete is generally ready for hand floating when the water sheen has disappeared or has been removed, and the concrete will support a finisher on kneeboards without more than approximately a 1/8 in. (3 mm) indentation. The slab surface is ready for machine floating with the lightest machine available when the concrete will support a finisher on foot without more than approximately a 1/4 in. (6 mm) indentation, and the machine will neither dig in nor disrupt the levelness of the surface. Mechanical pan floating should not begin until the surface has stiffened sufficiently so that foot prints are barely perceived on the concrete surface.

Normally, concrete will be ready for power floating in the same order it was placed in. On a given placement, however, certain areas can become ready for power floating before others. The areas that should be floated first generally include surfaces adjacent to screed guides, edge forms, blockouts, walls, and columns. Areas exposed to sun tend to set more quickly than those protected by shade; surfaces exposed to wind also require attention before those protected from the wind. Generally, one or more finishers should be assigned to look after those areas that will set faster than the overall placement.

As a general rule, and under slow-setting conditions when flatness tolerances are not high, power floating should be started as late as possible; this is indicated by minimum machine indentation or when a footprint is barely perceptible. Under fast-setting conditions or when high-flatness tolerances are required, and with the understanding that abrasion resistance of the slab can be reduced, floating should be started as soon as possible; the maximum practical indentation is approximately 1/4 in. (6 mm). When higher-flatness quality is required, the floating operation should generate sufficient mortar to assist in restraightening operations with the modified highway straightedge. Flatness/levelness tolerances can require restraightening of the surface before and after the floating operation.

The marks left by the edger and jointer should be removed by floating, unless such marks are desired for decoration, in which case the edger or jointer should be rerun after the floating operation.

Generally, when the floating operation produces sufficient mortar, restraightening after the floating operation is very beneficial. After the initial power-float pass, and while the surface mortar is still fresh, the modified highway straightedge can be used to restraighten the slab surface by removing the troughs and ridges generated by the power float with float blades or combination blades attached. This is accomplished by cutting down the ridges and using that mortar to fill the troughs. These operations should be completed during the window of finishability.

The use of the power float tends to create troughs under the center of the machine in the direction of travel, with ridges of mortar occurring just outside the perimeter of the blades. Around projections such as columns and sleeves, the power float tends to push mortar up against the projection. If this mortar buildup is not removed by the hand finisher, it will remain when the concrete hardens and the surface will be at a higher elevation than desired. The use of float pan attachments on riding machines reduces the tendency to create troughs.

One method that allows proper grade to be maintained at projections is to place a bench mark a specified distance above design grade on the projection for subsequent use by the finisher. While completing hand work around the column or sleeve, the finisher can use a template to confirm that proper grade has been maintained. Excess material can then be removed as required.

8.3.11 *Troweling*—The purpose of troweling is to produce a dense, smooth, hard surface. Troweling is done immediately following floating; no troweling should ever be done on a surface that has not been floated by power or by hand. Use of a bull float or darby without following by hand or machine floating is not sufficient.

If troweling is done by hand, it is customary for the concrete finisher to float and then steel trowel an area before moving kneeboards. If necessary, tooled joints and edges should be rerun before and after troweling to maintain uniformity and true lines.

Hand trowels that are short, narrow, or of inferior construction should not be used for first troweling. Mechanical troweling machines can be used. The mechanical trowel can be fitted with either combination blades or with those intended specifically for the troweling operation.

For the first troweling, whether by power or by hand, the trowel blade should be kept as flat against the surface as possible; in the case of power troweling, use a slow speed. If the trowel blade is tilted or pitched at too great an angle, an objectionable washboard or chatter surface will result. A trowel that has been properly broken in can be worked quite flat without the edges digging into the concrete. Each subsequent troweling should be made perpendicular to the previous pass. Smoothness of the surface can be improved by restraightening operations with the modified highway straightedge and by timely additional trowelings. There should be a time lapse between successive trowelings to permit concrete to become harder. As the surface stiffens, each successive troweling should be made with smaller trowel blades or with blades tipped at a progressively higher angle to enable the concrete finisher to apply sufficient pressure for proper finishing. Additional troweling increases the compaction of fines at the surface and decreases the *w/cm* of concrete near the slab surface where the trowel blades agitate surface paste and hasten the evaporation rate of water within the paste; this process results in increased surface density and improved wear resistance. Extensive steel-troweling of surfaces receiving a colored dry-shake hardener can have a negative impact on the uniformity of color. Refer to Section 8.6.2 for a detailed discussion.

The formation of blisters in the surface of the concrete during troweling can be the result of entrained air or excessive fines in the concrete mixture, of early troweling, or of an excessive angle of the trowel blades. Air-entrained concrete should never be used in any normalweight concrete floor slab that is to receive a hard-troweled finish (Section 6.2.7). By hindering the passage of bleed water to the surface, such purposeful air entrainment can compel the finisher to start the troweling process too quickly, leading to the entrapment of a liquid water layer immediately beneath the prematurely closed surface. Unfortunately, the concrete will appear to behave normally in the initial troweling stages, so there is no way for the finisher to know that the slab is being damaged.

If the air content is acceptable, then blister formation is an immediate indication that the angle of the trowel blade is too great for the surface in that area at that particular time for the concrete and job conditions involved.

Extensive steel-troweling leaves the concrete surface with a very high sheen. Such surfaces become quite slippery when wet and should be slightly roughened to produce a nonslip surface if they are to be exposed to the weather. A smooth-textured swirl finish can be produced by using a steel trowel in a swirling motion (also known as a sweat finish) or by brooming the freshly troweled surface.

A fine-broomed surface is created by drawing a soft-bristled broom over a freshly troweled surface. When coarser textures are desired, a stiffer bristled broom can be used after the floating operation. A coarse-textured swirl finish can be created after completion of the power float pass and subsequent restraightening using a modified highway straightedge. A coarse swirl pattern is normally created using a hand-held wood or magnesium float (Section 8.13.4).

During periods of hot, dry, and windy weather, troweling should be kept to the minimum necessary to obtain the desired finish. When ambient conditions create high water loss due to slab evaporation, fog spraying above the concrete or use of an evaporation retardant is necessary. After finishing, any delay in protecting the slab with curing compounds or other water-retaining materials can result in an increase in plastic-shrinkage cracking, crazing, low surface strength, dusting, and early deterioration.

8.3.12 *Saw-cut joints*—On large flat concrete surfaces, rather than hand-tooling joints, it can be more convenient to cut joints with an electric or gasoline-driven power saw fitted with an abrasive or diamond blade, and using one of the following three types of saws: conventional wet-cut, conventional dry-cut, or early-entry dry-cut.

The early-entry dry-cut process is normally used when early sawing is desired. Early-entry dry-cut joints are formed using diamond-impregnated blades. The saw cuts resulting from this process are not as deep as those produced using the conventional wet-cut process—typically no more than 1-1/4 in. (32 mm). The timing of the early-entry process, however, allows joints to be in place before development of significant tensile stresses in the concrete; this increases the probability of cracks forming at the joint when sufficient stresses are developed in the concrete. Care should be taken to make sure the early-entry saw does not ride up over hard or large coarse aggregate. The highest coarse aggregate should be notched by the saw to ensure the proper function of the contraction joint. State-of-the-art early-entry saws have an indicator that shows the operator if the saw cut becomes too shallow.

Typically, joints produced using conventional processes are made within 4 to 12 h after the slab has been finished in an area—4 h in hot weather to 12 h in cold weather. For early-entry dry-cut saws, the waiting period will typically vary from 1 h in hot weather to 4 h in cold weather after completing the finishing of the slab in that joint location. Longer waiting periods can be necessary for all three types of sawing for floors with steel-fiber reinforcement or embedded-mineral-aggregate hardeners with long-slivered particles such as traprock.

The depth of saw-cut using a conventional saw should be at least 1/4 of the slab depth or a minimum of 1 in. (25 mm), whichever is greater. The depth of a saw-cut using an early-entry dry-cut saw should be 1 in. (25 mm) minimum for slab depths up to 9 in. (225 mm). This recommendation assumes that the early-entry dry-cut saw is used within the time constraints noted previously. For steel fiber-reinforced slabs, the saw cut using the conventional saw should be 1/3 of the slab depth. Typically, when timely cutting is done with an early-entry saw, the depth can be the same as for concrete without steel fibers.

Regardless of the process chosen, saw-cutting should be performed before concrete starts to cool, as soon as the concrete surface is firm enough not to be torn or damaged by the blade, and before random drying-shrinkage cracks can form in the concrete slab. Shrinkage stresses start building up in the concrete as it sets and cools. If sawing is unduly delayed, the concrete can crack randomly before it is sawed. Additionally, delay can generate cracks that run off from the saw blade toward the edge of the slab at an obtuse or skewed angle to the saw cut.

Under hot, dry, or windy conditions, especially when placing exterior slabs, initial cracking can occur before final troweling. These random cracks can also appear hours or days after saw-cutting. The tendency for these cracks to form can be reduced by fogging the air over the concrete, using a monomolecular film, and starting the placement at night to minimize the impact of temperature, wind, and exposure to direct sunlight.

When these conditions occur, it may be prudent to stop floor placement until a time when conditions are more favorable. Project delay may be more desirable than random out-of-joint cracking.

8.4—Finishing Class 1, 2, and 3 floors

Class 1, 2, and 3 floors (Table 2.1) include tile covered, offices, churches, schools, hospitals, and garages. The placing and finishing operations described under Section 8.3 should be followed. Multiple restraightening operations and two hand or machine trowelings are recommended, particularly if a floor is to be covered with thin-set flooring or resilient tile; this will give closer surface tolerances and a better surface for application of the floor covering.

The use of silica fume concrete for parking garage construction lends itself to a one-pass finishing approach. After initial strikeoff and bull floating have been completed, the concrete placement strips can be textured using a broom. Normally, a light broom with widely spaced, stiff bristles will be satisfactory for this purpose.

Because silica fume concrete exhibits virtually no bleeding, it is necessary to keep the surface moist during concrete finishing operations to prevent plastic-shrinkage cracking. This normally requires use of an evaporation retarder or a pressure fogger with a reach capable of covering the entire surface. Fogging should be performed continuously between finishing operations until the surface has been textured. The goal of the fogging operation should be to keep the concrete surface moist but not wet. Curing operations should commence as quickly as possible after texturing has been completed (ACI Committee 226 1987).

If decorative or nonslip finishes are desired, refer to the procedures described in Section 8.13.

8.5—Finishing Class 4 and 5 floors

Class 4 and 5 floors (Table 2.1) may be light-duty industrial or commercial. The placing and finishing operations described in Section 8.3 should be followed. Three machine trowelings can be specified for increased wear resistance.

8.6—Finishing Class 6 floors and monolithic-surface treatments for wear resistance

Industrial floors using embedded mineral or metallic hardeners are usually intended for moderate or heavy traffic and, in some cases, to resist impact. These hardeners should be properly embedded near the top surface of the slab to provide the required surface hardness, toughness, and impact resistance.

The total air content of normalweight concrete should exceed 3% only if the concrete is subject to freezing-and-thawing cycles under service conditions and the concrete floor slab is not to receive a hard-troweled finish. As with any commercial or industrial floor subjected to wheeled traffic, special care should be exercised to obtain flat and level surfaces and joints. Metallic hardeners should not be placed over concrete with intentionally added chloride. The proposed mixture proportions should be used in the installation of any test panel or test placement. If adjustments to the concrete mixture are required, they can be made at that time.

8.6.1 *Embedded mineral-aggregate hardener*—The application and finishing of embedded mineral-aggregate hardeners should follow the basic procedures outlined below. Concrete installations are subject to numerous conditions and variables. Experience is necessary to determine proper timing for the required procedures. These procedures should be discussed and agreed upon at the preconstruction meeting:

1. Place, consolidate, and strike off concrete to the proper grade.

2. Compact and consolidate the concrete surface using a bull float.

3. Restraighten the surface using a modified highway straightedge. Occasionally, compacting, consolidating, and restraightening are accomplished in one step by using a wide bull float or a modified highway straightedge with the straightedge rotated so its wide dimension is in contact with the surface.

4. Evenly distribute approximately 2/3 of the specified amount of mineral-aggregate hardener immediately following strike-off, and before the appearance of bleed water on the slab surface. The first application generally consists of a larger, coarser material than will be used in the final application. Distribution of the hardener by mechanical spreader is the preferred method. The concrete mixture should have proportions such that excessive bleed water does not appear on the surface after application of the hardener.

5. As soon as the hardener darkens slightly from absorbed moisture, a modified highway straightedge should be used to embed the hardener and remove any irregularities in the surface.

6. Wait until the concrete sets up sufficiently to support the weight of a power trowel with float blades or a pan attached. Combination blades should not be used. The float breaks the surface and agitates concrete paste at the surface of the slab. The first power-float passes should be across the placement strip in the short direction. This will ensure that irregularities resulting from the power floating can be easily identified and corrected in subsequent operations.

7. Apply the remaining one-third of the specified mineral aggregate, preferably at right angles to the first application. This material generally consists of finer-size aggregate and may be broadcast evenly over the surface of the slab by hand.

8. Restraighten the surface using a modified highway straightedge. Remove irregularities and move excess material to low spots.

9. Embed the mineral-aggregate fines using a power trowel with float blades or a pan attached.

10. Restraighten the surface following the power-floating operation using a weighted modified highway straightedge if its use is seen to be effective or necessary to achieve required surface tolerances. One method of increasing the weight of a modified highway straightedge is to wedge a No. 11 bar (35 mm) inside the rectangular section of the straightedge.

11. Continue finishing with multiple power trowelings as required to produce a smooth, dense, wear-resistant surface (Section 8.3.11). Provide a burnished (hard) troweled surface where required by specification.

12. Cure immediately after finishing by following the curing material manufacturer's recommendations. Curing methods should be in accordance with those used and approved in construction of any test panel.

8.6.2 *Metallic dry-shake hardener and colored dry-shake hardeners*—Metallic dry-shake hardeners and colored dry-shake hardeners can be finer in texture than uncolored mineral-aggregate dry-shake hardeners. This difference, along with the fact that the metallic dry-shake hardener has a higher specific gravity, dictates that the material normally be embedded in the concrete later in the setting process than is common for uncolored mineral-aggregate dry-shake hardeners. Some metallic and colored dry-shake hardeners are designed by their manufacturers to allow application of all the hardener at one time. When such procedures are used, however, caution should be exercised to ensure that manufacturer's recommendations are followed, and that the material is thoroughly wetted-out because a one-time application significantly increases the possibility of surface delamination or related finishing problems. Typical installation techniques for metallic dry-shake hardeners and colored dry-shake hardeners are similar to those described in Section 8.6.1, but the following sequence is recommended (refer to Section 8.13.1):

1. Place, consolidate, and strike off concrete to the proper grade.

2. Compact and consolidate the concrete surface using a bull float.

3. Restraighten the surface using a modified highway straightedge. A wide bull float or a modified highway straightedge can be used to accomplish both steps in one operation.

4. Open the surface to promote movement of bleed water to the top of the slab by using a wooden bull float. Steps 3 and 4 can be accomplished in one operation if the wide bull float or modified highway straightedge is made of wood.

5. Wait until the concrete sets up sufficiently to support the weight of a power trowel.

6. Break the surface using a power trowel with float blades or a pan attached.

7. Evenly distribute approximately 2/3 of the specified amount of metallic dry-shake hardener or colored dry-shake hardener. Application of the material by mechanical spreader is the preferred method.

8. Restraighten the surface after application of the metallic dry-shake hardener or colored dry-shake hardener to remove irregularities. Some contractors find that embedding the materials and restraightening can be accomplished in one step using a modified highway straightedge.

9. Complete initial embedment and prepare the surface for additional material by using a power trowel with float blades or a pan attached.

10. Apply the remaining 1/3 of the specified amount of metallic dry-shake hardener or colored dry-shake hardener, preferably at right angles to the first application.

11. Embed metallic dry-shake hardener or colored dry-shake hardener using a power trowel with float blades or a pan attached. Thorough embedment and integration of the metallic dry-shake hardener or colored dry-shake hardener with the concrete by floating is very important. Failure to accomplish this goal can result in blistering or delamination of the slab.

12. Restraighten the surface following the power-floating operation using a weighted modified highway straightedge, if effective.

13. Continue finishing with multiple power trowelings as required to produce a smooth, dense, wear-resistant surface (Section 8.3.11). Proper and uniform troweling is essential. Colored surfaces should not be burnished (hard-troweled); the result would be uneven color and a darkening of the surface.

14. Cure immediately after finishing by following the curing material manufacturer's recommendations. Curing methods should be in accordance with those used and approved in construction of any test panel. Colored floors should not be cured with plastic sheeting, curing paper, damp sand, or wet burlap. These materials promote uneven color, staining, or efflorescence.

8.7—Finishing Class 7 floors

The topping course of heavy-duty industrial floors should have a minimum thickness of 3/4 in. (19 mm). The concrete topping used should have a maximum slump of 3 in. (75 mm), unless a water-reducing admixture or high-range water-reducing admixture is used to increase the slump, or unless dewatering techniques are used. Because of the relatively small amount of concrete in the topping course and the low slump required, concrete for the topping could be job-mixed.

Embedded metallic dry-shake hardeners, mineral-aggregate dry shakes, and colored dry-shakes can be applied to produce the desired combination of increased wear resistance or color as described in Sections 8.6.1 and 8.6.2, respectively.

The base course should be screeded and bull floated; close maintenance of the elevation tolerance for the base course surface is important. Class 7 floors (Table 2.1) can be constructed in two ways: (1) the topping installation can be bonded monolithically to the base slab before the base slab has completely set, or (2) the topping can be deferred for several days.

For suspended slabs, the deferred bonded approach should be used. This will allow the structure to deflect under its own weight before application of the topping. The additional weight of the topping will have little impact on subsequent deflection of the slab.

8.7.1 *Bonded monolithic two-course floors*—In most cases, wet curing is recommended for the bonded topping. Special precautions should be taken to prevent premature drying of the edges because curling of the topping and delamination from the base slab can result.

For these floors, the topping course is placed before the base course has completely set. Any excess moisture or laitance should be removed from the surface of the base course, and the surface floated before the top course is placed. When the topping is being placed, the concrete in the base slab should be sufficiently hard that footprints are barely perceptible. The use of a disk-type power float can be necessary to bring sufficient paste to the surface to allow restraightening to take place. The power-floating operation should be followed by a minimum of two power trowelings. This method of topping application is generally not appropriate for a suspended slab.

8.7.2 *Deferred bonded two-course floors*—Bonding of two-course floors is a highly critical operation requiring the most meticulous attention to the procedure described. Even with such care, such bonding has not always been successful. As a result, contractors using this type of construction for heavy-duty industrial applications should be experienced and familiar with the challenges presented.

Locations of joints in the base course should be marked so that joints in the topping course can be placed directly over them.

After the base course has partially set, the surface should be brushed with a coarse-wire broom. This removes laitance and scores the surface to improve bond of the topping course.

Concrete base courses should be wet-cured a minimum of 3 days (Sections 9.2.1 and 9.2.2). Shrinkage-compensating concrete base courses should be wet-cured a minimum of 7 to 10 days, and preferably until the topping is applied. Refer to ACI 223 for additional information.

If the topping is to be applied immediately after the minimum 3-day curing time has elapsed, the curing cover or water should be removed from the slab and any collected dirt and debris washed or hosed off. After most free water has evaporated or has been removed from the surface, a bonding grout should be scrubbed in. The bonding grout should be composed, by volume, of one part cement, 1.5 parts fine sand passing the No. 8 sieve (2.36 mm), and sufficient water to achieve the consistency of thick paint. The grout should be applied to the floor in segments, keeping only a short distance ahead of the concrete topping placing operations that follow it.

While the bonding grout is still tacky, the topping course should be spread and screeded. The use of a disk-type power float is suggested, followed by a minimum of two power trowelings.

If 3 to 7 days are to elapse between placing the base and the topping course, the surface of the base course should be protected from dirt, grease, plaster, paint, or other substances that would interfere with the bond. Immediately before placing the topping, the base course should be thoroughly cleaned by scrubbing with a brush and clean water. Most excess water should be removed and a thin scrub-coat of grout applied. While this grout is still tacky, the topping course should be spread and screeded.

If the floor is to be subjected to construction activities after curing and before application of the topping, more thorough cleaning may be necessary. One method of cleaning the base slab is to scrub the surface with water containing detergent. If oil or grease has been spilled on the floor, a mixture of sodium metasilicate and resin soap is useful. If this method is used, the floor should then be rinsed thoroughly with water. Shot-blasting, sandblasting, or mechanical scarification by scabbling can also be employed instead of cleaning with detergent to achieve a bondable surface.

In some circumstances, it can be convenient or desirable to bond the topping with an epoxy adhesive appropriate for the particular application. Methods are described in ACI 503R, and a standard specification is given in ACI 503.2.

Joints in the topping above the joints in the base slab should be saw-cut to a depth equal to twice the thickness of the topping and should match the location of joints in the base slab, where applicable.

8.8—Finishing Class 8 floors (two-course unbonded)

The unbonded topping for two-course unbonded floors should be a minimum of 4 in. (100 mm) thick. An unbonded topping thickness of 3 in. (75 mm) has been used with some success for Class 3 floors, but thickness for strength and control of curling is less important for a Class 3 slab because of its duty, loading, and because it may also be covered. A Class 8 floor (Table 2.1) is intended for industrial applications where strength and control of curling is more important. The base course, whether old or new, should be covered with plastic sheeting, felt, a sand cushion, or other approved bond-breaker, and spread as wrinkle-free as possible.

The topping slab should contain sufficient steel reinforcement to limit the width of shrinkage cracks in the topping and the displacement of the topping concrete on either side of any cracks that might form. Steel fiber and high-volume synthetic fibers in proper quantities may be used effectively to minimize crack opening widths. Although reinforcing steel is normally discontinued at joints, engineering considerations can make it desirable to carry reinforcement through construction joints in specified locations in a topping. Reinforcement that is continuous through contraction and construction joints will cause restraint against movement that will inevitably result in cracks in the concrete.

Concrete for the top course should comply with the requirements of Table 6.1.

Power floats and power trowels are recommended and usually required. The practice of completing troweling by hand is counterproductive because hand troweling is less effective than power troweling in consolidating the surface.

Embedded mineral-aggregate hardeners for increased wear resistance can be applied as described in Section 8.6.1.

Embedded metallic dry-shake hardeners and colored dry-shake hardeners can be applied as described in Section 8.6.2.

8.9—Finishing Class 9 floors

Class 9 floors (Table 2.1) may be superflat or require critical surface tolerance. Floor surfaces of this quality can be subdivided by function into two separate groups. Refer to Section 8.9.1 for special considerations dealing with construction of Class 9 floor surfaces.

The more common group of these floor surfaces should support vehicular traffic along paths that are defined before construction and that do not change during the life of the floor surface (that is, defined traffic). A typical example of a defined-traffic floor would be a distribution center that uses very narrow aisles and high-bay racking systems. In this type of facility, tolerances across aisles and the joints that parallel them are less critical than those along the axis of the aisle. This type of floor surface is often referred to as superflat.

Floor surfaces in the second group are less common but should support traffic in all directions (that is, random traffic). A typical example of a random-traffic floor would be a gymnasium, ice rink, television studio, or movie studio. The random nature of traffic in these facilities requires that tolerances across placement strips and their joints should match those achieved parallel to the axis of the strip.

Finishing procedures required to produce Class 9 floors represent the most rigorous and demanding floor installation technology now being performed. If discipline and preplanning are a part of the overall process, however, installation of Class 9 floors is neither complex nor especially difficult. Proper timing and execution of various procedures will usually ensure that the floor produced is of a predictable quality.

Class 9 defined-traffic floor construction requires that:

1. Slabs be constructed in long strips less than 20 ft (6 m) in width;

2. Concrete slump be adjusted on-site to within ±1/2 in. (±13 mm) of the target slump;

3. Slump at point of deposit be sufficient to permit use of the modified highway straightedge to close the floor surface without difficulty after the initial strikeoff;

4. Window of finishability be sufficient for the concrete contractor to perform the necessary finishing operations; and

5. Concrete supplier use enough trucks to ensure an uninterrupted concrete supply.

In addition, because environmental factors can significantly alter the setting rate of concrete, an effort is usually made to construct Class 9 floors out of the weather.

On Class 9 defined-traffic floors, construction joints between placement strips are located out of the traffic pattern where racks abut each other. These surfaces are evaluated by taking measurements only in locations matching the wheel-paths of the vehicles that will eventually use the floor. The part of the floor surface falling under racks is not tested.

While the same construction techniques can be used to produce Class 9 random-traffic floors—television studios or similar surfaces—the entire floor surface should be evaluated because the entire surface will be subjected to traffic. The contractor is cautioned that grinding of the entire length of the joints will be necessary to produce Class 9 quality across the width of concrete placement strips.

On most projects with Class 9 defined-traffic floors, surfaces are measured for flatness and levelness immediately following the final troweling of each placement; placements are frequently scheduled for consecutive days. Where Class 9 random-traffic quality is required across multiple placement strips, initial testing should take place as each strip is placed, but final testing should be deferred until the installation is complete.

Nonetheless, it is imperative that surface-profile testing and defect identification be accomplished on each new slab as soon as possible. To maintain satisfactory results, the contractor requires continuous feedback to gage the effectiveness of construction techniques against ever-changing job conditions (Section 8.9.1). Refer to Figure 8.7 for additional information.

Achieving Class 9 quality levels on suspended slabs is impractical in a one-course placement. Deflection of the surface between supports occurs after removal of supporting shores. If the surface were to meet Class 9 requirements in a shored condition, it is likely that the deflected surface after shores are removed would be less level than is required to meet Class 9 requirements. Two-course placements using methods similar to those discussed for Class 7 and 8 floors provide the best opportunity for achieving Class 9 quality levels on suspended floors.

8.9.1 *Special considerations for construction of Class 9 floor surfaces*—Certain specialized operations—narrow-aisle warehouses, gymnasiums, ice rinks, television studios, and air-pallet systems—require extraordinarily flat and level floors for proper equipment performance. Such superflat floors generally exhibit F_F numbers and F_L numbers above 50 in the direction of travel for the particular application. Refer to Section 8.15 for additional discussion.

The floor-finish tolerance employed in the contract specification should meet the equipment supplier's published requirements, unless there is reason to doubt the validity of such requirements. In any case, written approval of the contract floor tolerance should be obtained from the appropriate equipment supplier before finalizing the bid package. In this way, equipment warranties will not be jeopardized, and the special superflat nature of the project will be identified to key parties from the outset.

Superflat floors have very specific design requirements. Chief among these is the limit imposed on placement width. In general, superflat floors cannot be produced if the placement strip width exceeds 20 ft (6 m). Because hand-finishing procedures and curling effects are known to make floors in the vicinity of construction joints less flat than in the middle of the slab, joints should be located out of the main traffic areas, or provisions should be made for their correction. Contraction joints oriented transverse to the longitudinal axis of a Class 9 placement strip can curl and reduce surface flatness along aisles. Limited placement width, consequent increased forming requirements, and reduced daily floor production are primary factors that increase the cost of Class 9 floors.

The prebid meeting is an essential component of any superflat project. Because floor flatness/levelness is one of the primary construction requirements, a thorough prebid review of the design, specification, and method of compliance testing is required. This will enable the prospective contractor to price the project realistically (thereby avoiding costly misunderstandings and change orders), and will greatly increase the chances of obtaining the desired results at the lowest possible cost.

To further reduce the risk of problems, the installation of test slabs has become a standard part of superflat floor construction. If the contractor is inexperienced with superflat construction or with the concrete to be used, at least two test slabs should be installed and approved before the contractor is permitted to proceed with the balance of the superflat floor construction.

Superflat floor tolerances should be inspected within 24 h after slab installation. This eliminates the possibility of large areas being placed before any tolerance problem is discovered. In narrow-aisle warehouses, tolerances are measured using a continuous recording floor profilograph or other device. In these facilities, floor tolerances are based on the lift-truck wheel dimensions, and compliance measurements and corrections are required only in the future wheel tracks.

In television studios and other similar random-traffic installations, the use of F_F and F_L to specify the floor-surface tolerances is appropriate. Measurements for compliance should be made in accordance with ASTM E 1155 (Section 8.15), except that measurements should extend to the joints.

8.10—Toppings for precast floors

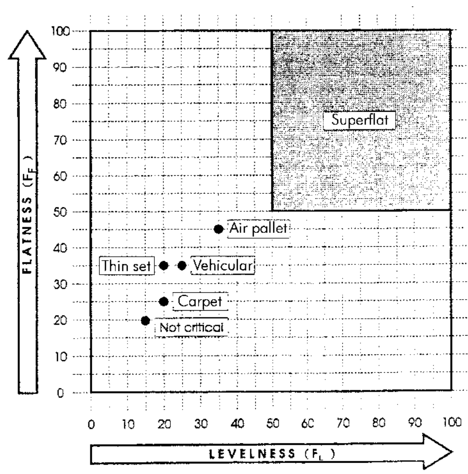
Many types of precast floors require toppings. These include double tees, hollow-core slabs, and other kinds of precast floor elements. When these floors are to be covered with bonded toppings, the procedures in Section 8.7.2 or 8.8 should be followed, as appropriate. High-strength concrete is often used for precast floor elements; roughening of the surface of such members can be difficult if delayed too long.

8.11—Finishing lightweight concrete

This section concerns finishing lightweight concrete floors. Finishing lightweight insulating-type concrete, having fresh density of 60 lb/ft^3 (960 kg/m^3) or less, that is sometimes used below slabs, generally involves little more than screeding.

Lightweight concrete for floors usually contains expanded shale, clay, slate, or slag coarse aggregate—expanded shale is most common. The fine aggregate can consist of manufactured lightweight sand, natural sand, or a combination of the two, but natural sand is most common. The finishing procedures differ somewhat from those used for a normalweight concrete. In lightweight concrete, the density of the coarse aggregate is generally less than that of the sand and cement. Working the concrete has a tendency to bring coarse aggregate rather than

FLATNESS/LEVELNESS TYPICAL USE GUIDE



SLABS ON GROUND

Composite Overall Flatness (F_F)	Composite Overall Levelness (F_L)	Typical Use	Typical Class
20	15	Noncritical: mechanical rooms, non-public areas, surfaces to have raised computer flooring, surfaces to have thick-set tile, and parking structure slabs	1 or 2
25	20	Carpeted areas of commercial office buildings or lightly-trafficked office/industrial buildings	2
35	25	Thin-set flooring or warehouse floor with moderate or heavy traffic	2, 3, 4, 5, 6, 7, or 8
45	35	Warehouse with air-pallet use, ice or roller rinks, gymnasium floors[4]	9
>50	>50	Movie or television studios	3 or 9

SUSPENDED SLABS

Composite Overall Flatness (F_F)	Composite Overall Levelness (F_L)	Typical Use	Typical Class
20	15[2] or N/A	Noncritical: mechanical rooms, non-public areas, surfaces to have raised computer flooring, surfaces to have thick-set tile, and parking structure slabs	1 or 2
25	20[1] or N/A	Carpeted areas of commercial office buildings or lightly-trafficked office/industrial buildings	2
35	20[2] or N/A	Surfaces to receive thin-set flooring	2, 3, or 4
45	35[3]	Ice or roller rinks, gymnasium floors[4]	3
>50	>50[1,3]	Movie or television studios	3 or 9

NOTES

1. Multi-directional quality of this level requires grinding of joints.
2. Levelness F-number only applies to level slabs shored at time of testing.
3. This levelness quality on a suspended slab requires a two-course placement.
4. All elevation samples should fall inside a 1/2 in. deep envelope.

Fig. 8.7—Typical use guide for flatness and levelness.

mortar to the surface. This should be taken into account in the finishing operations (ESCSI 1958).

Observing the following rules will control this tendency so that lightweight concrete can be finished as easily as normal-weight concrete, provided the mixture has been properly proportioned:

1. The mixture should not be oversanded in an effort to bring more mortar to the surface for finishing. This usually will aggravate rather than eliminate finishing difficulties.

2. The mixture should not be undersanded in an attempt to meet the unit weight requirements. Neither mixing to the recommended slump nor entrainment of air will effectively control segregation in such a mixture.

3. The lightweight concrete mixture should be proportioned to provide proper workability, pumpability, finishing characteristics, and required setting time, and to minimize segregation or the tendency for coarse aggregate particles to rise above the heavier mortar.

4. Some lightweight aggregates can require further control of segregation, bleeding, or both. For this purpose, use no less than 4% entrained air in accordance with ACI 211.2. Note: unlike its effect on normalweight concrete, the use of an air-entraining admixture in lightweight concrete that is to be hard-troweled does not lead to blistering.

5. Presaturate lightweight aggregates for use in concrete that will be pumped, in accordance with the manufacturer's recommendations.

6. Overworking or overvibrating lightweight concrete should be avoided. A well-proportioned mixture can generally be placed, screeded, and bull floated with approximately half the effort considered good practice for normalweight concrete. Excess darbying or bull floating are often principal causes of finishing problems because they only serve to drive down the heavier mortar that is required for finishing and to bring an excess of the coarse aggregate to the surface.

7. A magnesium darby or bull float should be used in preference to wood. Metal will slide over coarse aggregate and embed it rather than tear or dislodge it.

8. The surface should be floated and flat troweled while the concrete is still plastic, taking care to ensure bleeding is complete. Premature sealing of the surface can trap bleed water and result in blisters and delamination. If floating is being done by hand, use a magnesium float. If evaporation is not taking place soon enough (while concrete is still plastic), other measures should be taken. Water and excess moisture should be removed from the surface with as little disturbance as possible. A simple but reliable method is to drag a loop of heavy rubber garden hose over the surface.

8.12—Nonslip floors

Nonslip surfaces are produced by using the following finishing procedures: swirl or broom finish (Section 8.13.4), or nonslip special-purpose aggregate (Section 8.13.2). The nonslip special-purpose aggregate is recommended for heavy foot traffic.

Brungraber (1976, 1977) describes methods of measuring and evaluating the relative skid resistance of floors.

8.13—Decorative and nonslip treatments

8.13.1 *Colored dry-shake hardener surface treatment*—The installation of a colored surface treatment is particularly sensitive to the finishing and curing techniques employed by the contractor. Sample panels should be constructed before beginning actual placement on the project to confirm that the proposed procedures are adequate and that the uniformity of color is acceptable. Any sample panel should be larger than 200 ft^2 (18 m^2) and should be prepared using the concrete mixture and finishing and curing techniques planned for the project (Kosmatka 1991).

Coloring agents are normally included with an embedded hardener when a hardener is applied and color is desired. Finishing procedures should follow the steps described in Section 8.6.2.

8.13.2 *Nonslip monolithic surface treatment*—Before being applied to the surface, the slip-resistant material (Section 5.4.7) should be mixed with dry portland cement, if not already so formulated. Volumetric proportions usually range from 1:1 to one part slip-resistant material:two parts portland cement, but the manufacturer's directions should be followed. The treatment procedure is the same as that outlined for the colored treatment (Section 8.6.2). A swirl finish produced using natural or colored embedded mineral or metallic hardeners provides increased wear resistance and also produces a long-lasting, nonslip finish (Section 8.13.1).

8.13.3 *Exposed aggregate surface treatment*—Exposed aggregate surfaces are commonly used to create decorative effects. Both the selection of the aggregates and the techniques employed for exposing them are important to the effect obtained; test panels should be made before the job is started. Colorful, uniform-sized gravel or crushed aggregate is recommended.

Aggregates should not be reactive with cement (ACI 201.2R). Aggregates can be tested by using ASTM C 227 or by petrographic examination (ASTM C 295). If information or a service record is lacking, the aggregates and the cement aggregate combinations should be evaluated using the guideline in the appendix to ASTM C 33.

Flat particles, sliver-shaped particles, and particles smaller than 1/4 in. (6 mm) do not bond well. As a result, they can easily become dislodged during the operation of exposing the aggregate. The use of aggregate ordinarily used in concrete is not satisfactory, unless the aggregate is sufficiently uniform in size, bright in color, and can be closely packed, and uniformly distributed.

Immediately after the slab has been screeded and darbied or bull floated, the selected aggregate should be broadcast and evenly distributed so that the entire surface is completely covered with one layer of the select aggregate. The aggregate should be free of dust to promote good bond with the base slab. Initial embedding of the aggregate is usually done by patting with a darby or the broad side of a short piece of 2 x 4 in. (50 x 100 mm) lumber. After the aggregate has been thoroughly embedded and as soon as the concrete will support the weight of a finisher on kneeboards, the surface should be floated using a magnesium hand float, darby, or bull float, until the aggregate is entirely embedded and slightly covered with mortar. This operation should leave no holes in the surface.

Shortly after floating, a reliable surface set retarder can be sprayed over the surface in accordance with the manufacturer's recommendations. Retarders may not be necessary on small jobs, but they are generally used on large jobs to ensure better control of the exposing operations. Use of a surface set retarder ordinarily permits several hours to elapse before brushing and hosing the surface with water to expose the aggregate. The proper timing for exposing the aggregate is critical, whether or not a retarder has been used, and this timing is very dependent upon the temperature and other weather conditions. Recommendations of the retarder manufacturer should be followed closely.

Operations to expose the aggregate should begin as soon as the surface can be brushed and washed without overexposing or dislodging the aggregate. If it becomes necessary for finishers to move about on the newly exposed surface, kneeboards should be used, gently brought into contact with the surface, and neither slid nor twisted on it. If possible, however, finishers should stay off the surface entirely because of the risk of breaking the aggregate bond.

If a smooth surface is desired, as might be the case in an interior area, no retarder should be used. The aggregate is not exposed until the surface has hardened. Exposure is accomplished after hardening entirely by grinding. If grinding is followed by polishing, a terrazzo-like surface can be produced.

Alternative methods of placement are available. A top course, 1 in. (25 mm) or more thick, that contains the select aggregate can be applied, or the monolithic method can be used. The monolithic method does not use aggregate seeding; the select aggregate to be exposed is mixed throughout the concrete during batching.

Tooled joints are not practical in exposed-aggregate concrete, because the aggregate completely covers the surface. Decorative or working joints are best produced by wet-cut sawing (Section 8.3.12). Another method of providing joints is to install permanent strips of wood (redwood, cypress, or cedar) before placing concrete (Fig. 3.7).

Exposed-aggregate slabs should be cured thoroughly. The method of curing should not stain the surface. Straw, earth, and any type of sheet membrane, such as polyethylene or building paper, can cause discoloration (Section 9.2.1).

8.13.4 *Geometric designs, patterns, and textures*—Concrete surfaces are frequently scored or tooled with a jointer to produce various decorative patterns. For random geometric designs, the concrete should be scored after it has been screeded, bull floated, or darbied, and excess moisture has left the surface. Scoring can be done using a jointer, groover, or piece of pipe bent to resemble an S-shaped jointer tool. The tool is made of 1/2 or 3/4 in. (13 or 19 mm) pipe, approximately 18 in. (450 mm) long. Cobblestone, brick, tile, and many other patterns can be impressed deeply into partially set concrete slabs with special imprinting tools (Kosmatka 1991).

A swirl-float finish or swirl design can be produced using a magnesium or wooden hand float or a steel finishing trowel. After the concrete surface has received the first power-float pass and subsequent restraightening using a modified highway straightedge, a float should be worked flat on the surface in a semicircular or fan-like motion using pressure. A finer-textured swirl design can be obtained with the same motion by using a steel finishing trowel held flat. An alternative method is to draw a soft-bristled broom across the slab in a wavy motion.

After the concrete has set sufficiently that these surface textures or patterns will not be marred, the slab should be moist-cured. Plastic membranes or waterproof curing paper should not be used on colored concrete (Sections 9.2.1 and 9.2.2).

8.14—Grinding as a repair procedure

Grinding can be used to repair certain surface defects. Grinding has been used successfully to repair the following kinds of problems:

1. Unacceptable flatness and levelness;
2. Curled joints;
3. Surface irregularities that might show through thin floor coverings, such as resilient tile;
4. Poor resistance to wear, when this is due to a weak floor surface with sound concrete underneath; and
5. Rain damage. Corrective grinding upon completion should return the surface to the specified texture. Treatment of the newly ground area with a liquid chemical surface treatment (Section 5.8) is also recommended.

8.14.1 *Cautions*—Grinding does not always produce the desired effect, and it sometimes makes the floor look worse. If improperly executed, grinding can adversely affect the floor's resistance to wear, particularly in industrial applications where the surface is subject to heavy traffic and abuse. For these reasons, it is usually wise to make a small trial section before starting full-scale repairs. Only wet grinding should be used, primarily to minimize dust, and also because diamond-disk grinders are more effective when used with water.

8.14.2 *Types of grinders*—Many types of grinders are available. The two types most often used on floor slabs are diamond-disk grinders and stone grinders.

8.14.2.1 *Diamond-disk grinder*—This grinder uses one or more diamond-impregnated steel disks. Each disk is mounted horizontally and is driven by a vertical shaft. The most common type of diamond-disk grinder has a single 10 in. (250 mm) grinding disk powered by a gasoline engine or electric motor of 5 to 10 hp (3.7 to 7.5 kW). Bigger, more powerful machines are available for floors that need extensive grinding. Diamond-disk grinders are much faster than stone grinders and are usually the better choice to correct the aforementioned problems 1 and 2.

8.14.2.2 *Stone grinder*—This grinder uses multiple abrasive blocks, called stones, mounted on one or more steel disks. The abrasive material is usually silicon carbide. The most widely used type of stone grinder has two disks with three stones on each disk. One-disk and four-disk machines are also available. Stone grinders can be effective on aforementioned problems 3 to 5, particularly where the floor surface is soft or where the amount of material to be removed is small.

8.15—Floor flatness and levelness

8.15.1 *Floor flatness/levelness tolerances*—Tolerances for various floor uses should conform to the requirements set forth in ACI 117. A discussion of floor flatness/levelness is given in the commentary to ACI 117.

ACI 117 specifies that overall conformance to design grade shall be within 3/4 in. (19 mm) of design elevation. For suspended cast-in-place concrete slabs, this tolerance is to be achieved before removal of any supporting shores. For suspended slabs on metal deck, this tolerance for overall conformance to design grade does not apply because tolerances for erected steel frames are not consistent with those for formwork in cast-in-place concrete frames.

8.15.1.1 F-*number system*—Both flatness and levelness requirements should be described by Face Floor Profile Numbers (Face 1987). Two separate F-numbers are required to define the required flatness and levelness of the constructed floor surface. Refer to the commentary in ACI 117 for additional discussion of this method.

The flatness F-number (F_F) controls local surface bumpiness by limiting the magnitude of successive 1 ft (300 mm) slope changes when measured along sample measurement lines in accordance with ASTM E 1155.

The levelness F-number (F_L) controls local conformance to design grade by limiting differences in departures from design grade over distances of 10 ft (3 m), when measured along sample measurement lines in accordance with ASTM E 1155.

The *F*-number pair is always written in the order F_F/F_L. In theory, the range of flatness and levelness F-numbers extends from zero to infinity. In practice, F_F and F_L values generally fall between 12 and 45. The scale is linear, so the relative flatness/levelness of two different floors will be in proportion to the ratio of their F-numbers. For example, an F_F30/F_L24 floor is twice as flat and twice as level as an F_F15/F_L12 floor.

On random-traffic floors—those with varied and unpredictable traffic patterns—two tiers of specified F_F/F_L values should be indicated: one for the composite values to be achieved (specified overall value), and one for the minimum quality level that will be accepted without repair (minimum local value).

Compliance with the specified overall value is based on the composite of all measured values. For any given floor, the composite F_F/F_L values are derived in accordance with ASTM E 1155.

Minimum local values represent the minimum acceptable flatness and levelness to be exhibited by any individual floor section. Minimum local values are generally set at 67% of the specified overall values and are not normally set lower than 50% of the specified overall F_F/F_L requirements. Minimum local values should never be less than F_F13/F_L10, because these values represent the minimum local results achievable by any concrete floor construction method.

Remedial measures can be required:

- If the composite value of the entire floor installation (when completed) measures less than either of the specified overall F-numbers; or
- If any individual section measures less than either of the specified minimum local F_F/F_L numbers. Sectional boundaries are usually set at the column and half-column lines on suspended slabs, or at the construction and contraction joints for slabs-on-ground. They should be no closer together than 1/2 bay.

Remedial measures for slabs-on-ground might include grinding, planing, surface repair, retopping, or removal and replacement. For suspended slabs, remedial measures are generally limited to grinding or use of an underlayment or topping material. Contract documents should clearly identify the acceptable corrective method(s) to be used.

The selection of proper F_F/F_L tolerances for a project is best made by measurement of a similar satisfactory floor. This measurement is then used as the basis for the F_F/F_L tolerance specification for the new project. If this method is used, the slab-on-ground floor surfaces change after construction as a result of shrinkage and curling, and the surfaces of suspended slabs change as a result of deflection. Because of these post-construction changes, it is likely that measurements of an existing project will yield results of a lower quality than can be achieved by the contractor because all of the post-construction changes create slightly diminished F_F/F_L measurement results. When measurement of a similar satisfactory floor is not possible or practical, the flatness/levelness quality levels provided in Fig. 8.7 have been found to be reasonable for the stated applications.

8.15.1.2 *The 10 ft (3 m) straightedge method*—The older method of using a 10 ft (3 m) straightedge can also be used to measure floor flatness, but it is much less satisfactory than the F-number system. There is no nationally accepted method for taking measurements or for establishing compliance of a test surface using this tolerance approach. This lack of an accepted standard test procedure often leads to conflict and litigation. The straightedge-tolerance method also has a number of other serious deficiencies. Refer to the Commentary on ACI 117 for additional discussion.

When straightedge tolerances are specified, 100% compliance with 10 ft (3 m) straightedge tolerances is unrealistic. Compliance with four of five consecutive measurements is more realistic, with a provision that obvious faults be corrected.

8.15.1.3 *Other measurement methods*—Measurement methods are not limited to the F-number (ASTM E 1155) or the 10 ft (3 m) straightedge systems. Alternative tolerancing systems that adequately control critical floor surface characteristics can be used.

8.15.2 *Precautions*—Floor tolerance specification and measurement procedures are currently undergoing technological change. Much remains to be learned about which tolerances can be reasonably expected from a given construction method. On those projects where floor flatness/levelness constitutes a potential issue, the following precautions are suggested:

- The exact meaning of the flatness/levelness requirement, and the exact method and time of measurement to determine compliance, should be established before beginning construction;
- The contractor should confirm an ability to satisfy the floor tolerance requirement by profiling previous installations;
- Where feasible, test slabs should be installed to verify

the effectiveness of proposed installation procedures under actual job conditions. If necessary, methods and procedures should then be modified for the actual job installation based on these results. The acceptance of the test slab by the owner as to tolerances and surface finish should clarify requirements for the project slab; and

- The exact remedy to be applied to every possible floor tolerance deficiency should be confirmed with the designer.

8.15.3 *Factors influencing floor flatness and levelness*—The flatness and levelness exhibited by a newly installed concrete slab-on-ground will depend upon the effectiveness of the specific placement and finishing procedures employed during its construction. In general, the forming, placement, and initial strikeoff phases of the installation will establish the floor's relative levelness, while subsequent finishing operations (floating, restraightening, and troweling) will determine the floor's relative flatness. Any factor that complicates placing or finishing operations will have an adverse effect upon the flatness/levelness produced.

The flatness and levelness F-numbers normally obtained using a given floor construction procedure are summarized in Table 8.1 and 8.2.

These are the floor-finish tolerances expected to be achieved by competent, knowledgeable finishers under standard job conditions. Difficult job environments could result in significantly lower values. Both specifiers and contractors should approach each new concrete floor project using the guidelines set forth in Section 8.15.2.

8.15.3.1 *Flatness*—On those projects where flatness is an important consideration, precautions should be taken to provide an adequate construction environment. Of particular concern for both slabs-on-ground and suspended slabs are:

- Workability, finishability, and setting times of concrete to be used;
- The window of finishability, which should be sufficient for the contractor to perform the required finishing operations;
- Sun, wind, rain, temperature, and other exposure conditions and their effects on personnel and concrete;
- Amount and angle of light;
- Timeliness of concrete delivery;
- Consistency of delivered slump;
- Consistency of final setting time; and
- Site accessibility.

8.15.3.2 *Levelness*—For slabs-on-ground, accuracy of formwork and initial strikeoff establish the overall levelness of the surface. Form spacing, therefore, is an important consideration when developing a construction program intended to produce a certain quality. The use of block-placement techniques with wet-screed strikeoff provides the least accurate control of grade. Block placements with moveable rigid-screed guides provides an improvement in the levelness quality that can be achieved. Further improvement in levelness generally requires the use of either strip placements and vibrating screeds or self-propelled laser-guided strike-off equipment. Strip widths up to 50 ft (15 m) have provided levelness quality comparable to that which can be achieved using moveable dry-screeds in a block placement. Reducing the width of strips improves the ability of the contractor to produce level surfaces because there is less tendency for the vibrating screed to oscillate or deflect, and the controlling edge form elevations are closer together. The highest quality of levelness can be achieved using strip widths between 10 and 20 ft (3 and 6 m). This width allows the contractor to follow the vibrating screed with hand straightedging operations to remove any imperfections in the surface left by the vibrating screed.

Levelness of suspended slabs is dependent on accuracy of formwork and strikeoff, but is further influenced by behavior of the structural frame during and after completion of construction. Each type of structural frame behaves somewhat differently; the contractor should recognize those differences and plan accordingly. Refer to Chapter 3 for a more detailed discussion of behavior of different types of structural systems.

The F_L tolerance should only be applied to slabs-on-ground that are level and suspended slabs that are both level and shored at the time data are taken. The F_L levelness tolerance should not apply to slabs placed on unsupported form surfaces. It should not be applied to cambered or inclined slab surfaces. Concrete slabs placed over unshored structural steel and metal deck surfaces can exhibit significant deflection in the hardened state. The resulting slab surfaces have occasionally required extensive repair to achieve a product satisfactory for applied finishes or partitions.

8.15.4 *Timeliness of tolerance measurement*—To establish the flooring contractor's compliance with specified floor tolerances, the contract documents should stipulate that floor tolerance compliance tests be performed and defective areas identified. This should be completed by the owner's agent as soon as possible, preferably within 24 h after placement, and be reported to key parties as soon as possible, but not later than 72 h after installation. For suspended cast-in-place slabs, tests for acceptance should be conducted before forms and shoring have been removed. In this way, the effects of deflection and shrinkage on the tolerance data can be minimized.

As a practical matter, measurements for suspended-slab construction should usually be made within a few hours of slab placement. In vertical construction, the only available surface for staging materials is often the slab that has just been placed and finished. Failure to take advantage of this very short window of availability following completion of finishing operations will hamper, if not preclude, the tolerance data collection.

Early measurement also relates directly to the contractor's performance. If methods and procedures require modification, changes can be made after the initial placement, minimizing the amount of unsatisfactory floor surface and repair required. At times, later measurements will be needed to see whether other influences have impacted flatness or levelness. For example, slabs-on-ground are subject to edge curling in the weeks following construction; cast-in-place suspended slabs deflect from their supported position when shores are removed. These possible later changes are affected by various design choices and the implementation of these choices by the contractor. For slabs-on-ground, such

Table 8.1—Slab on ground flatness/levelness construction guide

Notes:
1. These descriptions illustrate typical tolerance levels and construction procedures for floor surfaces in which direction and location of traffic may vary (random-traffic pattern). Most surfaces must accommodate random-traffic patterns.
2. The use of F-numbers to specify tolerances allows the specifier and contractor independent control of surface waviness and levelness. The Flatness F-number (F_F) controls waviness; the Levelness F-number (F_L) controls local levelness. Levelness quality is mainly dependent on accuracy of formwork and initial strikeoff.
3. The tolerance examples illustrate average to high floor tolerances; specified quality levels should be dictated by facility use.
4. Descriptions of placing and finishing methods are intended to assist the contractor in evaluation and "fine-tuning" of relative costs associated with producing the various levels of quality in flatness and levelness.
5. Finishing sequences described in this table require a slight modification when a metallic hardener, mineral-aggregate hardener, pigmented hardener, or pigment is to be applied. Refer to Section 8.6 for detailed discussion of suggested techniques. Proposed techniques for application of hardener and finishing concrete should be confirmed with a successful panel installation.

FLATNESS

Typical specification requirements	Typical finishing requirements
Specified overall value—20 Minimum local value—15	1. Smooth surface using 4 to 5 ft wide bull float. 2. Wait until bleed water sheen has disappeared. 3. Float surface with one or more passes using a power float (float-shoe blades or pans). 4. Make multiple passes with a power trowel (trowel blades).
Specified overall value—25 Minimum local value—17	1. Smooth and restraighten surface using 8 to 10 ft wide bull float. 2. Wait until bleed water sheen has disappeared. 3. Float surface with one or more passes using a power float (float-shoe blades or pans). 4. Restraighten surface following paste-generating float passes using 10 ft wide highway straightedge. 5. Make multiple passes with a power trowel (trowel blades).
Specified overall value—35 Minimum local value—24	1. Smooth and restraighten surface using 8 to 10 ft wide bull float. Apply in two directions at 45 degree angle to strip. 2. Wait until bleed water sheen has disappeared. 3. Float surface with one or more passes using a power float (float-shoe blades or pans). 4. Restraighten surface following paste-generating float passes using 10 ft wide highway straightedge. Use in two directions at 45 degree angle to strip. Use supplementary material to fill low spots. 5. Multiple passes with a power trowel (trowel blades).
Specified overall value—50 Minimum local value—35	1. Smooth and restraighten surface using 8 to 10 ft wide bull float or highway straightedge. Apply in two directions at 45 degree angle to strip. 2. Wait until bleed water sheen has disappeared. 3. Float surface with one or more passes using a power float (float-shoe blades or pans). First float pass should be across width of strip. 4. Restraighten surface following paste-generating float passes using 10 ft wide highway straightedge. Use in two directions at 45 degree angle to strip. Use supplementary material to fill low spots. 5. Multiple passes with a power trowel (trowel blades). 6. Restraighten surface after trowel passes using multiple passes with weighted highway straightedge to scrape the high points. No filling of the low spots is done at this stage.

LEVELNESS

Typical specification requirements	Typical forming and strikeoff requirements
Specified overall value—15 Minimum local value—10	1. Set perimeter forms (optical or laser instruments). 2. Use block placements of varying dimensions. Use wet screed strikeoff techniques to establish initial grade.
Specified overall value—20 Minimum local value—15	1. Set perimeter forms (optical or laser instruments). 2. Use block placements of varying dimensions. Use wet screed strikeoff techniques to establish initial grade. 3. Check grade after strikeoff. Repeat strikeoff as necessary.
Specified overall value—25 Minimum local value—17	1. Set edge forms using optical or laser instruments. Optical instruments provide more accurate elevation control. 2. Use strip placements with maximum widths of 50 ft. Use edge forms to establish initial grade. 3. Use vibratory screed for initial strikeoff.
Specified overall value—30 Minimum local value—20	1. Set edge forms using optical or laser instruments. Optical instruments provide more accurate elevation control. 2. Use strip placements with maximum widths of 30 ft. Use edge forms to establish initial grade. 3. Use vibratory screed for initial strikeoff. 4. Check grade after strikeoff. Repeat strikeoff as necessary. 5. Use a laser screed instead of rigid strikeoff guides and vibratory screed to produce this same quality.
Specified overall value—50 Minimum local value—35	1. Set edge forms using optical instrument to ±1/16 in. in accuracy. Use straightedge to identify form high spots; place top surface to fit inside 1/16 in. envelope. 2. Use strip placements with maximum widths of 20 ft. Use edge forms to establish initial grade. 3. Use vibratory screed for initial strikeoff. 4. Check grade after strikeoff. Repeat strikeoff as necessary. 5. Follow vibratory screed pass with two or three hand straightedge passes along the axis of the strip.

Table 8.2—Suspended slab flatness/levelness construction guide

FLATNESS

Typical specification requirements	Typical finishing requirements
Level and shored until after testing: Specified overall value—20 Minimum local value—15 Unshored: Specified overall value—20 Minimum local value—15	1. Smooth surface using 4 to 5 ft wide bull float. 2. Wait until bleed water sheen has disappeared. 3. Float surface with one or more passes using a power float (float-shoe blades or pans). 4. Make multiple passes with a power trowel (trowel blades).
Level and shored until after testing: Specified overall value—25 Minimum local value—17 Unshored: Specified overall value—25 Minimum local value—17	1. Smooth and restraighten surface using 8 to 10 ft wide bull float. 2. Wait until bleed water sheen has disappeared. 3. Float surface with one or more passes using a power float (float-shoe blades or pans). 4. Restraighten surface following paste-generating float passes using 10 ft wide highway straightedge. 5. Make multiple passes with a power trowel (trowel blades).
Level and shored until after testing: Specified overall value—30 Minimum local value—24 Unshored: Specified overall value—30 Minimum local value—24	1. Smooth and restraighten surface using 8 to 10 ft wide bull float. Apply in two directions at 45 degree angle to strip. 2. Wait until bleed water sheen has disappeared. 3. Float surface with one or more passes using a power float (float-shoe blades or pans). 4. Restraighten surface following paste-generating float passes using 10 ft wide highway straightedge. Use in two directions at 45 degree angle to strip. Use supplementary material to fill low spots. 5. Make multiple passes with a power trowel (trowel blades are preferable).
Level and shored until after testing: Specified overall value—50 Minimum local value—35 Unshored: Specified overall value—50 Minimum local value—35	1. Smooth and restraighten surface using 8 to 10 ft wide bull float or highway straightedge. Apply in two directions at 45 degree angle to strip. 2. Wait until bleed water sheen has disappeared. 3. Float surface with one or more (float-shoe blades or pans). First float pass should be across width of strip. 4. Restraighten surface following paste-generating float passes using 10 ft wide highway straightedge. Use in two directions at 45 degree angle to strip. Use supplementary material to fill low spots. 5. Make multiple passes with a power trowel (trowel blades are preferable). 6. Restraighten surface after trowel passes using multiple passes with weighted highway straightedge to scrape the high spots. No filling of low spots is done at this stage.

LEVELNESS

Typical specification requirements	Typical forming and strikeoff requirements
Level and shored until after testing: Specified overall value—15 Minimum local value—10 Unshored: Specified overall value—N/A Minimum local value—N/A	1. Set perimeter forms (optical or laser instruments). 2. Use block placements of varying dimensions. Use wet screed strikeoff techniques to establish initial grade.
Level and shored until after testing: Specified overall value—20 Minimum local value—15 Unshored: Specified overall value—N/A Minimum local value—N/A	1. Set perimeter forms (optical or laser instruments). 2. Use block placements of varying dimensions. Use wet screed strikeoff techniques to establish initial grade. 3. Check grade after strikeoff. Repeat strikeoff as necessary.
Level and shored until after testing: Specified overall value—N/A Minimum local value—N/A Unshored: Specified overall value—50 Minimum local value—30	1. Use a two-course placement to achieve this levelness quality. Topping slab must be placed using slab on grade techniques after shoring has been removed. 2. Set edge forms using optical instrument to ±1/16 in. accuracy. Use straightedge to identify form high spots; place top surface to fit inside 1/16 in. in envelope. 3. Use strip placements with maximum widths of 20 ft. Use edge forms to establish initial grade. 4. Use vibratory screed for initial strikeoff. 5. Check grade after strikeoff. Repeat strikeoff as necessary. 6. Follow vibratory screed pass with two or three hand straightedge passes along the axis of the strip.

Metric Equivalents

1/16 in.	=	1.5 mm
4 ft	=	1.2 m
5 ft	=	1.5 m
8 ft	=	2.4 m
10 ft	=	3 m
20 ft	=	6.1 m
30 ft	=	9.1 m
50 ft	=	15.2 m

design choices include slab thickness, joint spacing, use of reinforcing steel, and vapor retarders. Inadequate curing can also accelerate curling of slabs-on-ground. For cast-in-place suspended slabs, deflection can be influenced by a number of variables, including depth of the structure, quantity of reinforcing steel, form-stripping procedures, and concrete strength when shoring is removed.

Because curling of slabs-on-ground will adversely affect flatness/levelness in service, methods to limit curling (Section 11.10) should be identified in the contract documents. Concrete with the lowest practical water content and low-shrinkage characteristics should be required. In addition, base conditions should not be such that the concrete underside remains wet while the top dries out. Joint spacings, load-transfer device, and reinforcement should be designated to minimize curling. Proper curing measures are essential and should be started as soon as possible after final finishing. These requirements should be clearly defined in the contract documents and adhered to during the concreting operations.

8.16—Treatment when bleeding is a problem

Prolonged bleeding can occur with poorly proportioned mixtures, poorly graded aggregates, excessive slump, or under conditions of low temperature, high humidity, or no air circulation. Bleed water may not evaporate, and the surface may not be sufficiently dry for floating and troweling.

One method to remedy the problem is to use fans or blower heaters of adequate size and in sufficient numbers to evaporate the excess moisture while the concrete is still plastic. Avoid using nonvented heaters, particularly those impinging on the surface of new concrete. They will cause carbonation of the surface, which can create a soft, dusty, chalky surface (Section 11.3).

If the concrete is firm enough for floating but the surface is still wet, the following methods can be used to obtain a drier surface:

1. Drag a rubber hose slowly over the entire surface; the concrete should be stiff enough so that only water is removed. In limited small areas that are difficult to reach with a hose, a single pass of a trowel tipped on edge can be used to remove water; however, slowly dragging a hose is much less likely to damage the surface, and this method should be used for the problem whenever possible.

2. Where required after removal of bleed water, apply additional concrete to fill low spots. This can be accomplished by discharging a small amount of concrete in a container during placing operations. The material in the container should have setting characteristics similar to those of the in-place concrete.

In general, the bleeding tendencies of concrete can be reduced significantly by the following actions. Every reasonable effort should be made to take such measures when bleeding is a problem:

1. Correct any aggregate gradation deficiency problem where materials of the required size gradations are economically available. The use of gap-graded aggregates results in increased bleeding. Ideally, combined gradation of all aggregates should yield a percent retained on each sieve below the largest and above the No. 100 (150 μm) of somewhere between 8 and 18%. The most common deficiency is in the 3/8 in., No. 4, 8, or 16 (9.5, 4.75, 2.36, or 1.18 mm) sieve sizes.

2. Use more cement if paste content is low, or lower the water content of the mixture.

3. Use pozzolan to replace part of cement or as an addition to the cement. (Note: Pozzolan should be finer than cement, and if the pozzolan is fly ash, it should conform to the requirements of ASTM C 618.)

4. Use the maximum allowable amount of entrained air. However, the use of air-entrained concrete containing in excess of 3% air for hard-troweled surfaces can promote development of blisters, delamination, and surface peeling.

5. Increase the amount of fine aggregate passing the No. 50, 100, and 200 (300, 150, and 75 μm) sieves to near the maximum allowable amount. More water (and possibly more cement) may be needed due to more paste being required; more shrinkage could result.

6. Use the lowest practicable water content.

7. Avoid admixtures that augment bleeding.

8. Use an accelerating admixture (see Section 5.7.3 for potentially deleterious effects).

9. Use concrete approaching the highest as-placed temperature permitted by the contract documents. (Note: Except for bleeding, there are benefits to be derived from placing concrete at the lowest permissible temperature.)

10. Use dewatering techniques (Section 8.3.6).

8.17—Delays in cold-weather finishing

Because concrete sets more slowly in cold weather and can be damaged by freezing, measures should be taken to keep the concrete temperature above 50 °F (10 °C). Appropriate curing procedures (Section 9.5.1) should be provided to prevent moisture loss and to keep every portion of the slab, including the edges, above freezing temperature. Any of the concrete's tendency toward bleeding will be considerably aggravated by the slower setting, and more work will be required to take care of it properly (Section 8.16). Many extra hours of finishers' time will be required, unless acceptable means can be found to shorten the setting time. Often, some extra expense to speed up the operation is justified by whichever of the following methods are most appropriate and least costly for a particular situation. Before adopting any method, tests should be made with job materials at job temperature conditions to confirm that acceptable results will be obtained.

Where it can be used without violating the precautions of Sections 5.7.3 and 8.6, a 1 to 2% addition of calcium chloride by weight of cement will accelerate setting significantly. When used, it should be added as a water solution.

Where the use of calcium chloride is prohibited:

1. A change to high early-strength cement (Type III), or use of a larger amount of Type I or II cement than usually required, can provide sufficient acceleration. Increases in cement content above approximately 600 to 625 lb/yd^3 (355 to 370 kg/m^3) can cause additional drying shrinkage and cracking in the hardened concrete.

2. Noncorrosive, nonchloride accelerating admixtures are available. The dosage rate can be varied to provide the optimum acceleration.

3. An increase in concrete temperate to 70 °F (21 °C) will noticeably reduce the setting time, although a low as-placed concrete temperature has many benefits (ACI 306R).

4. Early access for floating can be achieved by the application of dewatering techniques after first strikeoff and bull floating (Section 8.3.6).

The *w/cm* should be reduced and the minimum slump selected that can be easily handled and placed. Overworking the concrete should be avoided during the strikeoff and bull-floating operations.

CHAPTER 9—CURING, PROTECTION, AND JOINT FILLING

9.1—Purpose of curing

After proper placement and finishing of suitable quality concrete, curing is the single most important factor in achieving a high quality slab. The primary purpose of curing is to slow the loss of moisture from the slab and reduce early carbonation of the surface. A longer period of moisture retention permits more complete hydration of the cement, resulting in greater strength. Refer to ACI 308R for details on recommended curing time and minimum recommended temperatures.

9.2—Methods of curing

Moisture retention can be enhanced by several methods including moisture addition, moisture-retaining covers, and liquid membrane-forming curing compound. The characteristics of curing materials are set forth in detail in Section 5.6.

9.2.1 *Water curing*—Water curing by ponding, sprinkling, or fogging is practical only for slab areas without joints or where the water is positively confined by dams to prevent flooding the base course or saturating the subbase/subgrade. This is necessary to limit potential slab curling due to moisture gradients and to preserve compaction of the soil-support system. Water used for curing should be within 20 °F (7 °C) of the concrete temperature to avoid thermal shock. Continuous wetting should be maintained to avoid isolated dry spots. Water curing or wet covering should be used for shrinkage-compensating concrete slabs (ACI 223). Wet covering is generally the more practical and satisfactory method of water curing.

9.2.2 *Wet covering*—When properly applied and maintained, burlap and other wet coverings provide a continuous supply of moisture uniformly distributed on the slab surface. Burlap has been the most commonly used wet covering; wet burlap tends to reduce the temperature of the hydrating concrete slabs. Moist hay, straw, earth, or sand have been used, but their use is usually too labor-intensive for large projects and can discolor the surface. If sand or earth is used, it should be applied at least 1 in. (25 mm) deep and kept continuously wet during the curing period. Wet coverings should be laid over the concrete as soon as finishing operations are complete and surface marring can be avoided. Exposed concrete edges should be carefully covered. The coverings should be kept wet so that a film of moisture remains continuously in contact with the concrete throughout the curing period. Burlaps are available that resist rot and fire or that reflect light—reducing heat absorption from sunlight—or a combination thereof. Coverings with burlap on one side and polyethylene on the other are also available; the polyethylene is helpful in keeping the burlap moist longer, but it makes rewetting more difficult. Other polyethylene-backed fabrics are also available. These fabrics do not stain concrete like some burlaps and are often lighter and more durable than the burlap-backed product.

9.2.3 *Moisture retaining coverings*—Although not usually as effective as water curing and wet coverings, moisture-retaining coverings are widely used due to their convenience.

9.2.3.1 *Polyethylene (plastic) film* **—** Polyethylene film and other plastic sheet materials are available in clear, white, or black and are easily handled; the white is especially good for covering fresh concrete subject to sunlight. These films avoid leaving a residue that can prevent the bond of new concrete to hardened concrete or the bond of resilient floor coverings to concrete. Plastic films are particularly effective for curing the base slab of two-course floors. They can, however, leave blotchy spots on the slab and should not be used for colored concrete or where appearance of the slab surface is important. The sheets should be spread as soon as possible after finishing operations without marring the surface finish. Edges of sheets should be lapped a sufficient distance to prevent moisture loss and sealed with tape, mastic or glue, or held in place with wood planks or sand. Construction traffic should be restricted because the film can be extremely slippery.

9.2.3.2 *Waterproof paper*—Waterproof paper has the same advantages and disadvantages as plastic film, except that discoloration is less likely. It should be light in color; the edges should be lapped and sealed and left in place for the duration of the curing period. Tears caused by construction traffic should be repaired to maintain proper moisture retention.

9.2.4 *Liquid membrane-forming curing compounds*—Application of liquid membrane-forming curing compounds is the most widely used method for curing concrete. Advantages are relatively low in-place cost, early access to the floor, elimination of need to monitor the curing process, and the opportunity for longer uninterrupted cure. The membrane should be protected from damage due to construction traffic. Disadvantages include the potential for insufficient and uneven coverage, conflict with regulations on the release of volatile organic compounds, interference with bond of surfacing materials, and variability of quality and solids content. Liquid membrane-forming curing compounds should be applied as soon as finishing operations are complete while the surface is still damp but without free water. Machine spraying is preferable, but manual spraying is acceptable if accomplished with sufficient care to ensure uniform and complete coverage. Manual application should be accomplished by either spraying or rolling and by back-rolling with a wide short-nap paint roller. This can ensure full coverage without ponding of the curing compound in low spots. White-pigmented or fugitive-dye compounds help ensure even coverage and can be considered to reflect light and heat for floors exposed to sunlight. Generally, the curing compound should meet or exceed the minimum moisture retention requirements of ASTM C 309 (Section 5.6.3) or ASTM C 1315 (Section 5.6.3).

Curing compounds leave a film that can interfere with the adhesion of other materials to the treated surface; they should not be used on the base slab of a bonded two-course floor. Their use should also be avoided on surfaces that will later be covered with resilient floor coverings, protective coatings, sealers, or other special treatments. Where applicable, a letter of compatibility should be obtained from the manufacturer before the use of a curing compound on a floor receiving a subsequent finish. Curing compounds can also aggravate tire marking problems from forklift traffic; special nonmarking tires can be effective in minimizing these problems.

9.3—Curing at joints

Edges of joints should be cured to ensure maximum concrete strength to increase the durability of joint edges subject to solid wheeled traffic and to further reduce the potential for curling. Joints are cured adequately when wet coverings or moisture-retaining coverings are used. If a liquid membrane-forming curing compound is used, it should be applied to the inner joint walls. The curing compound may later require removal by sawing if a joint filler is installed. Alternatively, joints can be temporarily filled with wet sand or compressed backer rod during the curing period. If sand is used, it should be rewetted periodically.

9.4—Curing special concrete

Colored concrete and metallic-hardened floors require special curing techniques. Refer to Section 8.6 and recommendations of the material's manufacturer.

9.5—Length of curing

Regardless of the method used, the curing process should begin as soon as finishing operations are completed. If concrete begins to dry excessively before completion of finishing operations, the surface should be protected by fogging or use of a monomolecular film. The duration of curing will vary with the method, ambient temperature, humidity, and type of cement. With any type of cement, in temperatures above 40 °F (5 °C) 7 days of uninterrupted curing is normally recommended for water curing or moisture-retaining-cover curing. This time period can be reduced to 3 days when high early-strength concrete is used and temperatures are 73 °F (23 °C) or higher.

9.5.1 *Cold-weather considerations*—Slabs should not be placed on a frozen base. Cold-weather protective measures should maintain a concrete temperature above 50 °F (10 °C), and appropriate curing procedures should be provided to minimize moisture loss. Insulating blankets placed over the top of a curing membrane will retain heat, provided there is no danger of serious loss of heat from below the slab—for example, an upper floor of an open, unheated building. Particular care should be given to the corners and edges of the slab, which are more vulnerable to rapid heat loss. The amount of insulation required can be calculated from tables furnished in ACI 306R. When there is a danger of freezing—particularly when mean daily temperatures are lower than 40 °F (4 °C)—insulation is frequently not sufficient to protect thin slabs of concrete used for floors, and auxiliary heat is required. The area should be enclosed with tarpaulins or plastic sheeting and heated with live steam or vented heaters. The use of salamander-type heaters or other equipment that exhaust carbon dioxide gases into the area above the concrete floor should be avoided because of the danger of carbonation of the fresh concrete; carbonation will result in a soft, dusty surface (Kauer and Freeman 1955).

Where freezing is anticipated during or within a few days following the curing period, consideration should be given to protection of the concrete. Concrete saturated with water is vulnerable to freezing damage; the use of thermal blankets or other protective measures may be necessary. The curing method and procedure should cure the concrete satisfactorily and allow appropriate drying of the concrete before freezing. Refer to Section 4.6 for other concrete placement conditions, and refer to ACI 306R for more information on cold-weather concreting procedures.

9.5.2 *Hot-weather considerations*—In hot weather, curing procedures should begin as soon as an area of slab is finished to prevent surface drying. Continuous moist-curing methods—water curing and wet coverings—are the most effective because they provide adequate moisture and tend to prevent excessive heat build-up. Moisture-retaining coverings limit evaporation; conditions creating temperature gradients in the slab should be avoided. Curing compounds used for exterior work should be white-pigmented. Refer to Section 4.6 for other concrete placement conditions, and refer to ACI 305R for more information on hot-weather concreting procedures.

9.6—Preventing plastic-shrinkage cracking

Plastic-shrinkage cracking in newly floated or troweled slabs results when the rate of drying at the surface is more rapid than the upward movement of bleed water. Plastic-shrinkage cracking occurs in the presence of such factors as moderate to high winds, low relative humidity, and high concrete and air temperatures. The use of latex-modified concrete, high-range water reducers, and silica fume tends to increase plastic-shrinkage cracking potential because these materials usually reduce the bleed rate of concrete.

Vapor retarders/barriers immediately under the concrete may aggravate plastic and drying-shrinkage cracking and slab curling because the bottom of the slab loses little or no moisture, while the top dries and shrinks at a faster rate (Anderson and Roper 1977, Nicholson 1981, Turenne 1978).

If the rate of water evaporation from the concrete exceeds 0.2 lb/ft^2/h (1.0 kg/m^2/h), precautions should be taken to reduce evaporation (ACI 305R). Measures helpful in preventing or reducing plastic-shrinkage cracking are given in Section 11.2.2.1; additional information is presented in ACI 305R.

9.7—Curing after grinding

If grinding is required, it should be initiated as soon as the floor is hard enough to avoid tearing out aggregate particles. Curing should be maintained both before and after early grinding.

9.8—Protection of slab during construction

Protection should be provided against:

a. Heavy construction traffic;
b. Hard-wheeled traffic;
c. Impact and abrasion;
d. Imposed loads (cranes, concrete trucks);
e. Stains (grease, oil, chemicals, paints, plaster, clay soil);
f. Rubber tire marks;
g. Deicers; and
h. Freezing.

9.9—Temperature drawdown in cold storage and freezer rooms

The temperature reduction in freezer and cold storage rooms should be gradual to control cracking caused by differential thermal contraction and to allow drying to remove excess moisture from the slab after curing. A typical drawdown schedule might be as follows:

Temperature	Time
Ambient to 35 °F (2 °C)	10 °F (5.5 °C) Per 24 h
Hold at 35 °F (2 °C)	2 to 5 days
35 °F (2 °C) to final	10 °F (5.5 °C) per 24 h

9.10—Joint filling and sealing

Materials for joint fillers and sealants are discussed in Section 5.12 Contraction joints are normally sawn using the narrowest blade practical. Formed construction joints should be similarly sawn but to a depth of only 1 in. (25 mm). Saw-cuts at the construction joints should not be introduced until a crack is perceptible at the cold joint between adjacent placements. Compressible backer rods should not be used in joints that will be exposed to heavy traffic. Isolation joints can be formed with preformed fiberboard, polyethylene foam, or similar materials before concrete placement begins. This is described in Section 3.2.5.1 and detailed in ACI 504R. Isolation joints are sometimes sealed with an elastomeric sealant to prevent accumulation of moisture, dirt, or debris. Asphalt-impregnated or similar materials should not be used in isolation joints that will be sealed.

9.10.1 *Time of filling and sealing*—Concrete slabs-on-ground continue to shrink for years; most shrinkage takes place within the first 4 years. The most significant shrinkage takes place within the first year, especially the first 60 to 90 days. It is advisable to defer joint filling and sealing as long as possible to minimize the effects of shrinkage-related joint opening on the filler or sealant. This is especially important where semirigid fillers are used in traffic-bearing joints; such fillers have minimal extensibility. If the joint should be filled before most of the shrinkage has occurred, separation should be expected between the joint edge and the joint filler or within the joint filler itself. These slight openings can subsequently be filled with a low-viscosity filler recommended by the same manufacturer as the original filler. If construction traffic dictates that joints be filled early, provisions should be made to require that the contractor return at a preestablished date to complete the necessary work using the same manufacturer's products. Earlier filling will result in greater separation and will lead to the need for more substantial correction; this separation does not indicate a failure of the filler. For cold storage and freezer room floors, the joint filler should be installed only after the room has been held at its final operating temperature for a minimum of 48 h. For rooms with operating temperatures below 0 °F (–18 °C), the operating temperature should be maintained for at least 14 days before starting joint filling.

9.10.2 *Installation*—Elastomeric sealants should be installed over a backer rod or other bondbreaker as described in ACI 504R. The use of elastomeric sealants is not recommended in joints exposed to solid-wheel traffic. Semirigid epoxy and polyurea fillers should be installed full-depth in saw-cut joints. Joints should be suitably cleaned to provide optimum contact between the filler or sealant and bare concrete. Vacuuming is recommended rather than blowing the joint out with compressed air. Dirt, debris, saw-cuttings, curing compounds, and sealers should be removed. Cured semirigid fillers should be finished flush with the floor surface to protect the joint edges and to re-create an interruption-free floor surface. Specific installation instructions should be requested of the filler/sealant manufacturer if the floor is to receive a nonbreathing covering such as vinyl, epoxy, or a similar finish.

CHAPTER 10—QUALITY CONTROL CHECKLIST

10.1—Introduction

Details on a quality control program should be included in the contract documents. To ensure that the program will be fully complied with for the duration of the project, procedures should be presented to the involved parties in the prebid meeting and reviewed in detail at the preconstruction meeting. ACI 311.4R is a good source to use in the development of the program. Because the eventual success of any project is the result of a team effort, there should be a complete understanding and agreement regarding the provisions of the program before any concrete construction is started.

Many items involved with quality control will be covered in the preconstruction meeting, but some questions or concerns will invariably come up on site that are not covered in the bid documents or at the meeting. Therefore, it is essential to have a person on site who has the experience and background necessary to use the best possible judgment. Personnel with ACI certification can contribute greatly toward resolving these concerns and ensuring quality construction in the field. The NRMCA/ASCC Preconstruction Checklist is a good source of items that should be addressed before construction.

10.2—Partial list of important items to be observed

Additional background information regarding important items, such as concrete reinforcement, surface hardeners, and joint sealants, can be applicable during the actual construction phase.

10.2.1 *Slump control and testing*—The addition of trim water to the concrete at the jobsite (Section 7.3.2) can be required to ensure consistent placeability, workability, and finishability; no more water should be added than is necessary to meet the overall project requirements. The committee recommends that an agreed-on amount of trim water—part of the design mixture water—be withheld at the plant to permit this on-site adjustment. Two practices that help ensure adequate control of slump at the jobsite are: 1) be sure truck mixers come to the site with full water tanks, and 2) designate one specific person to authorize adding water at the site. An ACI Certified Concrete Field Technician should be present during the entire placement to perform the required slump and other tests.

Testing, including provisions for handling and storing cylinders or cores, should be completed in accordance with ASTM procedures by a testing agency meeting accreditation requirements of ASTM E 329. This is particularly significant when air-entrained concrete is used; the actual air content is subject to change and requires repeated testing. When entrained air is prohibited or less than 3% total air is desired, the air content should be checked on the first truck and occasionally thereafter. ACI 311.5R contains guidance on plant inspection and field testing.

10.2.2 *Avoid delays*—Anything that would result in slump loss should be avoided—delays in delivery of concrete, delays in placing or finishing operations, and interruptions by other trades. Although the mixture proportions may have been approved, some minor adjustments could be required due to locally available materials or jobsite conditions.

10.2.3 *Forms, reinforcement, dowels, and joints*—Forms, reinforcement, and dowels should be secured and remain straight and true during the entire placing and finishing operation. Unless otherwise stated in the contract documents, reinforcement should be discontinued at joints. If the contract documents indicate that reinforcement is to continue through joints, the possibility that some out-of-joint random cracking could occur should be discussed during the preconstruction meeting with the designer and owner. The alignment of reinforcement along joints should permit a straight saw-cut to be effective and allow joints to open. Smooth dowels should be used in joints where load transfer is required. Dowels in contraction joints should be positively supported and aligned. Any conditions that create restraint to the normal shrinkage process should be noted—for example, the condition of the base on which the concrete is placed. Although the practice of cutting every other bar or wire has been used with some success, there is always the possibility of some cracks forming in the intermediate panels due to partial restraint at the joint (Section 3.2.4).

10.2.4 *Finishing*—The finishing process should be discussed with the finishing supervisor because no specification can be sufficiently accurate as to the actual timing of most finishing operations. Slab edges should be given special attention, beginning with the initial floating step and continuing through the entire finishing process. ACI Certified Finishers should be used whenever possible.

If an aggregate- or metallic-surface hardener is used, the hardener should be completely moistened so no dry material will be floated into the surface before machine floating.

10.2.5 *Curing, saw-cutting, joint filling, and tolerances*—The proposed method of curing, the necessary timing for sawing joints, the protection of joint edges until the joints are filled, the timing of joint filling, and the protection required of the completed floor should be reviewed in detail. There should be a complete understanding regarding the order in which the curing, sawing, and floor tolerance testing are to be performed.

10.2.6 *On-site meeting*—After initial placement, additional on-site meetings may be necessary to review actual results and discuss any required adjustments in the overall plan. Also, backup procedures for equipment breakdowns should be discussed with the concrete superintendent—for example, pumps, troweling machines, spreaders, and saws.

CHAPTER 11—CAUSES OF FLOOR AND SLAB SURFACE IMPERFECTIONS

11.1—Introduction

Concrete is a forgiving material; however, concrete quality can be adversely affected by conditions over which the designer or the contractor has little control. This chapter lists the conditions and circumstances that can cause imperfections in concrete floor and slab surfaces. Concrete is capable of providing a highly durable, serviceable, and attractive surface. When it does not do so, there are always reasons. By keeping the causes of certain imperfections in mind, it is possible to reduce the likelihood of unsatisfactory results; these causes will be described briefly in this chapter. When the corrective action to eliminate a particular cause is not obvious, the most promising suitable procedure described in preceding chapters will be referenced.

In reviewing the causes of floor and slab surface imperfections, the reader should keep in mind the inherent characteristics of portland cement concrete, such as drying-shrinkage cracking. Some curling and cracking can be expected on every project. Also, it will be evident that the most common imperfections stem from failure to follow the basic rules of concrete finishing given in Section 8.3.3, such as “Any finishing operation performed while there is excess moisture or bleed water on the surface will cause dusting or scaling” (and also cause crazing and reduced resistance to wear), and as is stated in Section 8.3.5, “No subsequent operation (after bull floating and restraightening) should be done until the concrete will sustain foot pressure with only about 1/4 in. (6 mm) indentation,” that is, no premature finishing.

Another common cause of floor and slab surface imperfections is the lack of prompt curing. The keyword is prompt, and the degree to which this can be accomplished, especially in dry or windy weather, will improve the quality of floor and slab surfaces tremendously. Moist curing is best, provided the slab is kept continuously moist (Section 9.2).

Rarely will there be a single cause for a given imperfection; usually some combination will be responsible. The influence of any cause will vary with the degree of its departure from best practice, with the properties of the materials used, and with the ambient temperature and other weather conditions present during the work. Satisfactory results are more likely to be obtained if the causes mentioned for the various kinds of imperfections are carefully avoided.

11.2—Cracking

Cracking of concrete (Fig. 11.1) is a frequent complaint. Cracking is caused by restraint (internal or external) of volume change, commonly brought about by a combination of factors such as drying shrinkage, thermal contraction, curling, settlement of the soil-support system, and applied loads. Cracking can be significantly reduced when the causes are understood and preventive steps are taken. For example, joints that are properly designed, detailed, and installed at the proper spacing and time during construction will cause cracks to occur in the joints where they remain inconspicuous, instead of random locations.

Contractors are not necessarily responsible for all cracks. Many floor or slab design features and concrete mixture proportions are responsible for, or contribute to, cracking of concrete construction. If a contractor believes there are problems with slab design, mixture proportions, or other problems, they should be pointed out before installation; the prebid and preconstruction meetings should be used for this purpose. Designers should pay careful attention to the causes of cracking, and contractors need to understand floor and slab design and concrete mixture proportioning to avoid problems. Designers also should understand slab construction to avoid "building in" problems for the contractor. For more information on control, causes, evaluation, and repair of cracks in concrete structures, refer to ACI 224R and 224.1R.

11.2.1 *Restraint*—Because cracking is caused by restraint of volume changes, normal volume changes would be of little consequence if concrete were free of any restraint. Concrete in service, however, is usually restrained by foundations, subgrade, reinforcement, or connecting members, significant stresses can develop—particularly tensile stresses.

The amount of drying shrinkage will be reduced somewhat by taking practical measures to place the concrete with the lowest possible water content. Water reduction through use of admixtures—water-reducing admixtures meeting ASTM C 494, Types A and D, and air-entraining admixtures—has little effect on drying shrinkage (Ytterberg 1987; Martin and Phelan 1995; Whiting and Dziedzic 1992). Refer to Section 5.4.2 for additional information concerning use of these admixtures. Thus, drying shrinkage of concrete containing water reducers can still cause unsightly cracking, unless the following good practices are employed:

1. Contraction joints not spaced too far apart (Section 3.2.5.3);
2. Contraction joints deep enough;
3. Contraction joints sawn early enough;
4. Slabs not strongly restrained at their perimeters by bond of floor or slab concrete to foundation walls or other construction, or by tying-in reinforcement to foundations, docks, and tilt-up walls (Section 3.2.5);
5. Isolation joints provided around columns (Fig. 3.3 and 3.4);

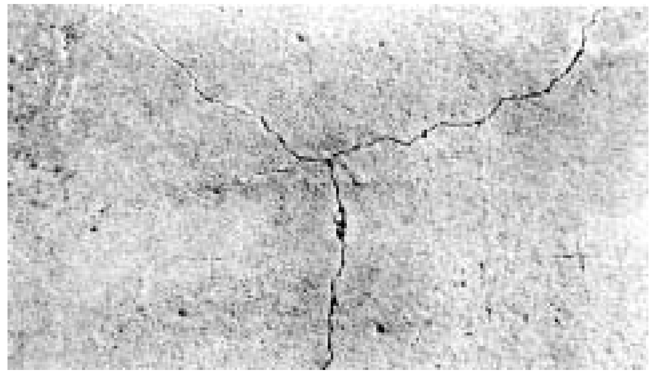


Fig. 11.1—Drying-shrinkage cracks such as these are a frequent cause of complaint (PCA A5271).

6. Joint or extra reinforcing steel placed diagonally to reentrant corners;
7. Concrete mixtures of necessary strength with the proper amount of cement and water, Also, mixtures that do not include any ingredient, such as aggregates or admixtures, with high-shrinkage characteristics;
8. Proper curing;
9. Slabs not restrained by a rutted or uneven base and changes in slab thickness;
10. Discontinued reinforcement at joints, thus encouraging joints to open; and
11. Slabs cast upon a base which has a low coefficient of friction, such as a fine-graded crushed stone. This will provide a smooth surface on which the slab can slide (Section 4.1).

11.2.2 *Early cracking*—Some cracking can occur before the concrete has hardened. This can complicate the finishing operations considerably. Some examples are:

1. Plastic-shrinkage cracking (Sections 9.6 and 11.2.2.1);
2. Cracking from settlement of concrete around reinforcing bars or other embedments (Sections 5.8 and 6.2.5);
3. Cracking along edges where forms are not rigid;
4. Early thermal cracking; and
5. Damage from form removal.

11.2.2.1 *Plastic-shrinkage cracking*—Plastic-shrinkage cracks (Fig. 11.2) are relatively short, shallow, random (but sometimes parallel) cracks that can occur before final finishing on days when wind, low humidity, and high concrete and ambient temperatures occur. Surface moisture evaporates faster than it can be replaced by rising bleed water, causing the surface to shrink more than the interior concrete. As the interior concrete restrains shrinkage of the surface concrete, stresses that exceed the concrete's tensile strength develop, resulting in surface cracks. These cracks range approximately from 4 in. to 3 ft (100 mm to 1 m) or more in length. They can be roughly parallel to one another and spaced about from a 4 in. to 2 ft (100 to 600 mm) apart, but usually occur in a random, irregular pattern. Crack formation begins at the surface and continues downward for some distance, rapidly becoming narrower with depth. Though usually only 1 to 3 in. (25 to 75 mm) deep, they can go completely through the slab. Plastic-shrinkage cracks in the still-unhardened concrete can sometimes be closed by

Fig. 11.2—Plastic-shrinkage cracks are caused by rapid loss of mixing water from the surface while the concrete is still plastic (PCA 1311).

Fig. 11.3—Crazing is a network of very fine superficial surface cracks (PCA 4099).

tamping and beating the surface with a hand float. While this should be done, the more effective protective measures listed below should also be undertaken immediately to remove the causes of plastic-shrinkage cracking in the remaining work:

1. Dampen the base when no vapor retarder is used;
2. Erect windbreaks;
3. Erect sunshades;
4. Cool aggregates and mixing water before mixing; and
5. Prevent rapid drying by one of the following:
   a. Protect concrete with moisture-retaining coverings (Section 9.2.3) during any delay between placing and finishing.
   b. Cover with damp burlap or with white polyethylene sheeting (Section 9.2.2) immediately after screeding and bull-floating. Keep burlap moist until the concrete is ready for finishing. Uncover only a small area at one time, just ahead of the finishers. Begin curing as soon as possible.
   c. Use monomolecular films to reduce evaporation between the various placing and finishing operations.
   d. Use a fog spray located upwind of the freshly placed concrete. The spray device should use metered heads and discharge spray into the air above the concrete.
6. Postpone each step of finishing (and its inherent reworking of the surface) as long as possible without endangering results; and
7. Avoid the use of a vapor retarder where not needed.

11.2.2.2 *Crazing*—Crazing, a pattern of fine cracks that do not penetrate much below the surface, is caused by minor surface shrinkage (Fig. 11.3). Crazing cracks are very fine and barely visible, except when the concrete is drying after the surface has been wet. They are similar to mud cracking in shape and in generation. The cracks encompass small concrete areas less than approximately 2 in. (50 mm) in dimension, forming a chicken-wire-like pattern. The term map cracking is often used to refer to cracks that are similar to crazing cracks only more visible and involving larger areas of concrete. Although crazing cracks can be unsightly and can collect dirt, crazing is not structurally serious and does not necessarily indicate the start of future deterioration in interior slabs.

When concrete is just beginning to gain strength, climatic conditions, particularly the relative humidity during the drying period in a wetting-and-drying cycle, are an important cause of crazing. Low humidity, high air and concrete temperatures, hot sun, or drying wind, either separately or in any combination, can cause rapid surface drying that encourages crazing. The conditions that contribute to dusting, as described in Section 11.4, also will increase the tendency to craze.

To prevent crazing, curing procedures should begin immediately, within minutes after final finishing, particularly after hard troweling. This is especially important when weather conditions are adverse. When the temperature is high and the sun is shining with high winds and low humidity, some method of moist curing should be used to stop rapid drying. The concrete should be protected against rapid changes in temperature and moisture wherever feasible. Other conditions to be avoided that can cause craze cracking are:

1. Curing with water that is more than 20 °F (11 °C) cooler than the concrete;
2. Alternate wetting and drying of the concrete surface at early ages;
3. Overuse of jitterbugs, vibrating screeds, and bull floats (Section 8.3.2);
4. Overworking and overtroweling, especially when the surface is too wet (Sections 8.3.10 and 8.3.11);
5. Premature floating and troweling (Section 8.3.3);
6. Dusting dry cement onto a surface to hasten drying before finishing;
7. Too much clay and dirt in aggregates; and
8. Sprinkling water onto the surface of a slab during finishing.

11.2.3 *Other causes*—Cracking over the long term can result from causes other than shrinkage. Prominent causes are:

1. Uneven support by a poorly prepared subgrade, subbase, or base; poor drainage; or uneven support due to curling of slab edges (Section 11.11);
2. Expansive clay in the subgrade;
3. Sulfates in subgrade soil or groundwater;

4. Placing concrete over preformed joint filler (when placing adjacent concrete);

5. Improper jointing and sealing (Sections 3.2.5, 5.11, 9.10, and ACI 504R);

6. Structural overloading, especially following the floor construction phase of a building project;

7. Impact loads;

8. Disruption from expansive alkali-silica reaction;

9. Disruption from corrosion of reinforcing steel;

10. Disruption from freezing and thawing along edges and at corners;

11. Earth movements from contiguous construction, for example, blasting or pile driving;

12. Thermal contraction, such as a sharp drop in ambient temperature shortly after casting a floor or slab;

13. Early or excessive construction traffic; and

14. Improper design (for example, selection of an inadequate safety factor), resulting in a slab of inadequate thickness for service conditions.

11.3—Low wear resistance

Low wear resistance is due primarily to low-strength concrete, particularly at the surface. Such low strengths result from:

1. Too much mixing water;

2. Use of concrete with too high a *w*/*cm*;

3. Excessive slump, which promotes bleeding and carries softer, lighter-weight material (laitance) to the surface. (After considering the unavoidable causes for slump loss, use the lowest practical water content and slump (Table 6.1));

4. Overworking overly wet concrete. (This does not mean that it is acceptable to use overly wet concrete under any conditions. It should be rejected and removed from the site. Whatever is placed must be worked, but if concrete is overly wet, the ready-mix plant should be called to make sure no more wet batches are delivered. In addition to producing a surface with low wear resistance, overworking of overly wet concrete also will cause segregation; fluid mortar will flow into low areas, settle, and leave low spots.);

5. Premature floating and troweling, which works bleed water into the surface (see Section 8.16 if bleeding is a problem);

6. Excessive use of water by finishers (Section 8.3.3);

7. Excessive entrained air in the surface mortar, although occurrence of this is not common;

8. Deficient curing (Chapter 9);

9. Surface carbonation from unvented heaters used for cold-weather protection (ACI 306R);

10. Impairment of surface strength potential by early-age freezing (ACI 306R);

11. Opening slab to abrasive traffic before sufficient strength has developed; and

12. Poor finishing techniques and improper timing during and between finishing operations (Section 8.3).

11.4—Dusting

Dusting (Fig. 11.4) is another aspect of weak concrete at the surface of a floor or slab. Dusting (the development of a fine, powdery material that easily rubs off the surface of hardened concrete) can occur either indoors or outdoors but is more likely to be a problem when it occurs indoors. Dusting is the result of a thin, weak surface layer, called laitance, which is composed of water, cement, and fine particles.

Fig. 11.4—Dusting is evident when a fine, powdery material can be easily rubbed off the surface of a slab (PCA 1297).

Fresh concrete is a fairly cohesive mass, with the aggregates, cement, and water uniformly distributed throughout. A certain amount of time must elapse before the cement and water react sufficiently to stiffen and develop hardened concrete. During this period, the cement and aggregate particles are partly suspended in the water. Because the cement and aggregates are heavier than water, they tend to sink. As they move downward, the displaced water and fines move upward and appear at the surface, resulting in more water and fines near and at the surface than in the lower portion of the concrete. This laitance—the weakest, most permeable, and least wear-resistant material—is at the top surface, exactly where the strongest, most impermeable, and most wear-resistant concrete is needed. Floating and troweling concrete with bleed water on the surface mixes the excess water back into the surface, further reducing the strength and wear resistance at the surface and giving rise to dusting (Section 8.3.3). Dusting can also be caused by:

1. Overly wet mixtures with poor finishing characteristics;

2. Insufficient cement (Table 6.2);

3. Excessive clay, dirt, and organic materials in the aggregate;

4. Use of dry cement as a blotter to speed up finishing;

5. Water applied to the surface to facilitate finishing;

6. Carbonation of the surface during winter concreting, caused by unvented heaters (ACI 306R);

7. Inadequate curing, allowing rapid drying of the surface, especially in hot, dry, and windy weather; and

8. Freezing of the surface (ACI 306R).

11.5—Scaling

Scaling is the loss of surface mortar and mortar surrounding the coarse-aggregate particles (Fig. 11.5). The aggregate is usually clearly exposed and often stands out from the concrete. Scaling is primarily a physical action caused by hydraulic pressure from water freezing within the concrete; it is not usually caused by chemical corrosive

Fig. 11.5—Scaling is the loss of surface mortar, usually exposing the coarse aggregate (PCA A5273).

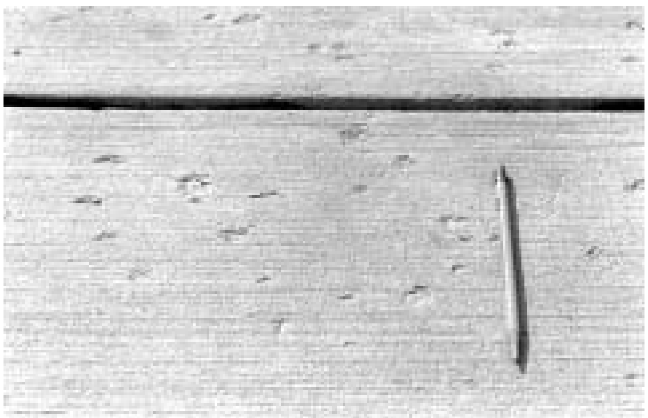


Fig. 11.6—Mortar flaking over coarse aggregate particles is another form of scaling that resembles a surface with popouts (PCA 52225).

action. When pressure exceeds the tensile strength of concrete, scaling can result if entrained air voids are not present in the surface concrete to act as internal pressure-relief valves. The presence of a deicing solution in water-soaked concrete during freezing causes an additional buildup of internal pressure. Properly designed and placed air-entrained concrete, however, will withstand deicers for many years.

Deicers, such as sodium chloride, urea, and weak solutions of calcium chloride, do not chemically attack concrete; however, deicers containing ammonium sulfate or ammonium nitrate will rapidly disintegrate concrete and should not be used. Several deicers, particularly those containing chloride ions, can accelerate corrosion of embedded steel.

Prominent among the causes of scaling are:

1. Permeable and poor quality concrete due to:
   a. High *w/cm* (over 0.50);
   b. Excessive slump for prevailing job conditions (Table 6.1);
   c. Overworking of wet concrete (Section 8.3.10);
   d. Premature finishing operations (Section 8.3.3);
   e. Inadequate curing (Chapter 9); and
   f. Low compressive strength at the surface (Section 6.2.3);
2. In concrete to be exposed to freezing and thawing in service, little or no entrained air due to:
   a. Failure to use an air-entraining agent;
   b. Air worked out by overworking overly wet concrete in premature finishing operations (Sections 8.3.10 and 8.3.3);
   c. Air content too low due to: mixing too long, concrete temperature too high for a given dosage of air-entraining agent, or improper dispensing of air-entraining agent;
3. Air content too low to resist the effect of chemicals used for snow and ice removal (Section 6.2.3);
4. Inadequate thermal protection, allowing freezing of the surface at an early age;
5. Exposure of new concrete to freezing and thawing before it has been adequately cured, achieving a compressive strength of 4000 psi (28 MPa), and allowed to air dry. Application of deicing chemicals at this early age greatly increases the likelihood of scaling;
6. Blistering (Section 11.7), which increases vulnerability to scaling; and
7. Inadequate slope to properly drain water away from the slab; saturated concrete is more susceptible to damage from freezing and thawing than drier concrete.

11.5.1 *Mortar flaking*—Mortar flaking over coarse-aggregate particles (Fig. 11.6) is another form of scaling. Aggregate particles with flat surfaces are more susceptible to this type of imperfection than round particles. Mortar flaking occasionally precedes more widespread surface scaling, but its presence is not necessarily an indication of an onslaught of more extensive scaling.

Mortar flaking over coarse-aggregate particles is caused essentially by the same actions that cause regular scaling and often results from placing concrete on hot, windy days. Excessive and early drying out of the surface mortar can alone aggravate scaling; however, the moisture loss is accentuated over aggregate particles near the surface as bleed water beneath the aggregates cannot readily migrate to the surface to replenish the evaporated water. This combination of bleed-water blockage, high rate of evaporation, and lack of moisture necessary for cement hydration results in a dry-mortar layer of low strength, poor durability, high shrinkage, and poor aggregate bond. Upon freezing in a saturated condition, this thin, weakened mortar layer breaks away from the aggregate. Poor finishing practices can also aggravate mortar flaking.

11.6—Popouts

Popouts are roughly cone-shaped pits left in the surface of flatwork after a small piece of concrete has broken away by internal pressure (Fig. 11.7). This pressure is generated by the expansion of a piece of chert, soft fine-grained limestone, shale, hard-burned lime, hard-burned dolomite, pyrite, or coal. The first two are natural constituents of some aggregates; the others sometimes find their way into aggregates as impurities. In some materials, the expansion is caused by freezing or absorption of moisture; in others, it is caused by a chemical change. For example, popouts can occur from the chemical reaction between alkalies in concrete and reactive siliceous aggregates. Popouts range in size from about 1/4 to 2 in. (6 to 50 mm) or more in diameter.

Because popouts usually do not significantly diminish the integrity of concrete flatwork, they are sometimes tolerated. Nevertheless, they are usually unsightly and interfere with the performance of any slab required to be smooth. On floors with hard-wheeled traffic, popouts can degenerate into larger imperfections. Early repair should minimize further problems in high-traffic areas.

The occurrence of impurities in the concrete can be beyond the control of the floor constructor, because it usually occurs inadvertently in the production and handling of ready-mixed concrete or its constituents. The presence of naturally occurring chert or soft fine-grained limestone, however, can be a continuing problem in some locales. Measures that can be taken to alleviate the problem are:

1. Switching to a nonoffending source of aggregate for floors and slabs, if possible;

2. Using two-course construction with selected or imported aggregate without popout potential for the topping course;

3. Using aggregates from which the offending particles have been removed by heavy-media separation, if available and economically feasible;

4. Using wet-curing methods such as continuous fogging or covering with wet burlap immediately after final finishing. Wet-cure for a minimum of 7 days, as wet curing can greatly reduce or eliminate popouts caused by alkali-aggregate reactivity (Landgren and Hadley 2002). Avoid plastic film, curing paper, and especially curing compounds, as they allow an accumulation of alkalies at the surface. Impervious floor coverings or membranes, such as wax, epoxy, or other coatings, should be avoided as they can aggravate popout development; and

5. Using the lowest practical slump possible to prevent potential popout-causing particles from floating to the surface.

In some areas and situations, these measures may not be practical. Specific local practices have been developed that have been helpful in minimizing popouts. For example, in some regions ready-mix producers can supply popout-free concrete.

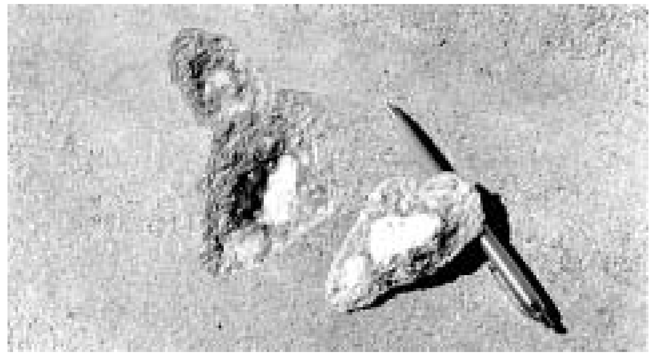


Fig. 11.7—A popout is a small fragment of concrete broken away from the surface of a slab due to internal pressure, leaving a shallow, typically conical, depression (PCA 0113).

Fig. 11.8—Blisters (courtesy of NRMCA).

11.7—Blisters and delamination

The appearance of blisters (Fig. 11.8) on the surface of a concrete slab during finishing operations is annoying and an imperfection that can leave portions of the top surface vulnerable to delamination once the concrete hardens. Blisters are “bumps” that can range in size from 1/4 to 4 in. (6 to 100 mm) in diameter and approximately 1/8 in. (3 mm) deep. They appear when bubbles of entrapped air or water rise through the plastic concrete and are trapped under an already sealed, airtight surface. This early closing of the surface frequently happens when the top of a slab stiffens, dries, or sets faster than the underlying concrete. Several factors are attributed to blistering.

An excessive amount of entrapped or entrained air held within the concrete by excessive fines—material passing the No. 30, 50, and 100 sieves (600, 300, and 150 μm)—resulting in a sticky mixture that can become more easily sealed during the raised troweling and closing operations. Sticky mixtures have a tendency to crust under drying winds, while the remainder of the concrete stays plastic. Usually, what is needed to relieve this condition is to reduce the amount of sand in the mixture by 100 to 200 lb/yd^3 (60 to 120 kg/m^3) and to replace the removed sand with a like amount of the smallest-size coarse aggregate available (PCA 2001). The resulting slightly harsher mixture should release most of the entrapped air using normal vibration. On days when surface crusting occurs, slightly modified finishing techniques may be needed, such as the use of wooden floats to keep the surface open and flat troweling to avoid enfolding air into the surface under the blade action.

Insufficient vibration during compaction may not adequately release entrapped air or overuse of vibration may leave the surface with excessive fines, inviting crusting and early finishing.

Power finishing operations should continue before the initial set of the slab is over its full depth. Any tool used to compact or finish the surface will tend to force the entrapped air toward the surface. Blisters may not appear after the first finishing pass, but may appear, as the work progresses to the second or third troweling. At this stage in finishing, the trowel blade is tilted to increase surface density; air and water just under the surface are forced ahead of the blade until enough is concentrated (usually near a piece of large aggregate) to form a blister. Blisters, which can be full of air, water, or both, when punctured, can also appear at any time during finishing operations and without apparent cause. Floating the concrete a second time helps to reduce blistering. Delayed troweling will depress the blisters even though it may not reestablish complete bond.

Project specifications that require combination blades, float pans, or trowel blades should be used on concrete with intentionally entrained air (Refer to Sections 5.7.1 and 6.2.7).

To avoid blisters, the following should be considered:

1. Avoid the use of concrete with excessively high slump, water content, air content, or fines;

2. Use appropriate cement contents (Table 6.2);

3. Warm the base before placing concrete during cool weather. During hot, dry, windy weather, reduce evaporation over the slab by using an evaporation retardant (monomolecular film), a fog spray, or a slab cover (polyethylene film or wet burlap);

4. Avoid placing a slab directly on polyethylene film or any other vapor retarder. Use a minimum 4 in. thick (100 mm) layer of trimmable, compactible granular fill (not sand) to separate the vapor retarder from the concrete (Section 4.1.5);

5. Avoid overworking the concrete, especially with vibrating screeds, jitterbugs, or bull floats. Overworking causes coarse aggregate to settle, and bleed water and excess fines to rise to the surface. Properly vibrate concrete to release entrapped air;

6. Do not attempt to seal (finish) the surface too soon. Hand floating should be started when a worker standing on a slab makes a 1/4 in. (6 mm) footprint. For machine floating, the footprint should be only about 1/8 in. (3 mm) deep. If moisture is deficient, a magnesium float should be used;

7. Use a wooden bull float on non-air-entrained concrete to avoid early sealing. Magnesium or aluminum tools should be used on air-entrained concrete. Slabs that incorporate a surface hardener are more prone to blister if not properly finished (Sections 8.6.1 and 8.6.2); and

8. Use proper finishing techniques and proper timing during and between finishing operations (Section 8.3). The formation of blisters is an immediate indication that the angle of the trowel is too great for the surface in that area at that particular time with the concrete and job conditions involved. The position of the trowel should be flattened, and the blistered area retroweled immediately to eliminate and rebond the blisters. If frequent blistering occurs despite reasonable care in the timing and technique employed in the finished troweling, attention should be directed to the job and climatic conditions and to the concrete mixture as discussed as follows.

Most skilled finishers know when a concrete surface is ready for the raised and final troweling and closing of the surface, and how to accomplish this operation; however, circumstances are often beyond their control. For instance, if there are too few finishers for the climatic conditions, finishers may have to close some portions of a floor too early to get it troweled before it has set too much. Similarly, if supervisors insist that a floor be finished by a certain time, whether it is ready or not, blisters, trowel marks, and poor surfaces can result.

11.8—Spalling

Unlike scaling and blistering, spalling is a deeper surface imperfection, often extending to the top layers of reinforcing steel or to the horizontal joint between the base and topping in two-course construction. Spalls can be 6 in. (150 mm) or more in diameter and 1 in. (25 mm) or more in depth; although, smaller spalls also occur (Fig. 11.9 and 11.10). Spalls are caused by pressure or expansion within the concrete, bond failure in two-course construction, impact loads, fire, or weathering. Joint spalls are often caused by improperly constructed joints. Spalls can occur over corroding reinforcing steel because the corrosion products (rust) occupy more volume than the original steel, and the resultant pressure spalls the concrete.

In addition to its poor appearance, spalling can seriously impair the strength or serviceability of a floor or slab. Indoor spalling is more likely to result from improper joint design or installation or bond failure in two-course floor construction, but obviously this can happen outdoors as well. Causes for the various kinds of spalling include:

1. Insufficient depth of cover over reinforcement;

2. Inferior concrete in the cover over reinforcing steel. Such concrete can fail to protect the steel from disruptive corrosion because of its high permeability due to:

   a. Overworking overly wet concrete during finishing (Sections 8.3.10 and 8.3.3);
   b. Serious loss of entrained air during such wet-finishing operations;
   c. Problems with excessive bleeding during finishing, especially in cold weather (Sections 8.16 and 8.17);
   d. Inadequate or delayed curing;
   e. Severe cracking that permits water and salts to attack the steel;
   f. Loss of bond between concrete and reinforcing steel bars, caused by placement of concrete on top of excessively hot steel during hot-weather concreting;

3. Joint edge spalls caused by small hard-wheeled vehicles traveling across improperly installed or filled joints (Sections 3.6, 5.11, and 9.10), and spalls on the upper flange of the female side of keyed-construction joints;

4. Poor bonding of topping to base course in two-course floors (Sections 8.7.1 and 8.7.2) due to:

   a. Inferior quality of surface concrete in the base course;
   b. Unremoved contamination in, or poor preparation of, the surface of the base course;
   c. Differences in shrinkage between topping and base courses;
   d. Drying of the bonding grout before the topping concrete is placed;
   e. Excessive pressure developed at joints, where preformed joint material was topped by continuous concrete; and
   f. Restraint of movement of deck slabs on supporting walls and piers due to inadequate provision for such movement.

11.9—Discoloration

Surface discoloration of concrete flatwork can appear as gross color changes in large areas of concrete, as spotted or mottled light or dark blotches on the surface, or as early light patches of efflorescence. Laboratory studies to determine the effects of various concrete materials and concreting procedures show that no single factor is responsible for discoloration (Landgren and Hadley 2002). Factors found to influence discoloration are calcium chloride admixtures, concrete alkalies, hard-troweled surfaces, inadequate or inappropriate curing, variations in *w/cm* at the surface, and changes in the concrete mixture. Like many other surface imperfections, discoloration is generally a cosmetic nuisance rather than a structural or serviceability problem.

Dark areas do not necessarily denote inferior serviceability, unless there is evidence that dry cement has been troweled into the surface to absorb excess bleed water (Section 8.16). The following are causes of dark areas:

1. The use of calcium chloride in concrete can discolor the surface (Fig. 5.1). Calcium chloride accelerates the overall hydration process but has a retarding effect on the hydration of the ferrite compounds in portland cement. The ferrite phases normally become lighter with hydration; however, in the presence of calcium chloride, the retarded, unhydrated ferrite phases remain dark in color;

2. Low spots where water stands longer before evaporating can cause dark areas;

3. Curing with waterproof paper and plastic sheets can cause a lighter color where the sheet is in contact with the surface and a darker color where the sheet is not in contact with the surface. This type of discoloration is aggravated when concrete contains calcium chloride;

4. Changes in the *w/cm* of concrete mixtures can significantly affect color. Such a change can result from localized changes in construction practices, from a batch-to-batch variation in the concrete's water or cementitious material content, or from steel troweling. A high *w/cm* will usually produce a light-colored concrete, a low ratio a darker color. Repeated hard-steel troweling in areas of advanced setting reduces the *w/cm* at the surface, darkening its color;

5. Changes in source or type of cement. Individual brands and types of cement can differ in color; therefore, changing brand or type of cement in the middle of a job can noticeably change the color of concrete;

6. Another cause is the uneven application of dry-shake materials, such as mineral-aggregate or metallic hardeners; and

7. Changes in the amount, source, and chemistry of a mineral admixture also affect discoloration. The extent of the discoloration will depend upon the color and the amount of admixture used. Some mineral admixtures resemble portland cement and have no effects on concrete color. Silica fume can give concrete a dark gray tint. Dark gray fly ashes can also give concrete a darker color, whereas tan- or beige-colored fly ashes, if used in large quantities, can produce a tan color in concrete.

Light-colored areas can simply be the result of contrast to adjacent dark areas; these would not normally impair serviceability. If light-colored areas are caused by local overworking of excessively wet concrete, however, the surface will be weaker and serviceability may be impaired. This can be caused by high concrete water content or finishing while there is excess moisture or bleed water on the surface.

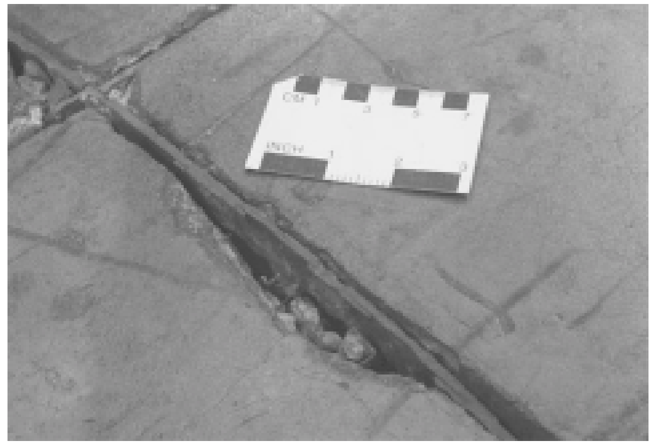


Fig. 11.9—Spalled joint (courtesy of Eldon Tipping).

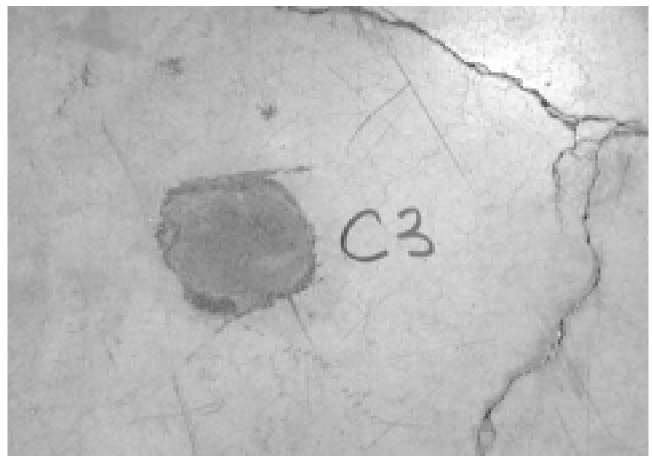


Fig. 11.10—Spalled crack (courtesy of Eldon Tipping).

Light-colored areas also can be caused by efflorescence (a crystalline deposit—usually white in color—that occasionally develops on the surface of concrete slabs after construction is completed). Moisture present in hardened concrete dissolves soluble salts. These salts in solution migrate to the surface by evaporation or hydraulic pressure where the water evaporates and leaves a deposit of salt at the surface. If the water, the evaporation, or the salts are not present, efflorescence will not occur.

11.10—Low spots and poor drainage

Puddles or bird baths on an outdoor concrete slab after a rain, or on a floor after hosing, characterize poor slab or floor surface drainage or serviceability (Fig. 11.11). Among the primary causes:

1. Inadequate slope. Positive drainage requires a slope of 1/4 in./ft (20 mm/m) for an exterior slab; for an interior floor slab, 1/16 in./ft (5 mm/m) minimum is adequate for drainage, but 1/8 in./ft (10 mm/m) is preferred;

2. Inaccuracy in setting grades for forms and screeds;

Fig. 11.11—Low spots in a slab after rain shower (courtesy of Eldon Tipping).

Fig. 11.12—Curling at joint in a 2 in. (50 mm) unbonded topping (courtesy of Eldon Tipping).

3. Damage to grade settings of forms and screeds during construction;

4. Strikeoff operation in which low spots are filled in with extra-wet concrete. The wetter concrete settles more than the surrounding areas during the interval between strikeoff and floating operations;

5. Fresh concrete that is too wet or variably wet. A little working of such concrete results in areas with excessive mortar at the surface, which settles more than the surrounding areas;

6. Failure to frequently check grades, levels, and slopes with long straightedges (Sections 8.2.5 and 8.3.4), and to properly build up low spots in areas detected;

7. By tooling joint grooves without removing the small amount of mortar displaced, the ridge of mortar formed in this way can act as a dam;

8. Failure to check the finished grade following strikeoff when wet-screeds are used (Section 8.3.2);

9. Poor lighting during placing and finishing; and

10. Deflection of suspended slabs between supports after removal of supporting shores.

11.11—Curling

Curling is the distortion (rising up) of a slab's corners and edges due to differences in moisture content or temperature between the top and bottom of a slab (Fig. 11.12). The top dries out or cools and contracts more than the wetter or warmer bottom. If the curled section of a slab is loaded beyond the flexural strength of the concrete, cracks will develop parallel to the joints at which curling occurs.

Slabs also can be dished in the center because the centers were finished lower than the screeds. This is readily apparent from straightedging after finishing. There are a number of ways to reduce slab curling:

1. Equalize moisture content and temperature between the top and bottom of a slab;

2. Use a concrete mixture with low-shrinkage characteristics, that is, a stony concrete mixture with large maximum-size coarse aggregate at the highest quantity consistent with the required workability. Such mixtures minimize water content;

3. Use a permeable (porous) dry—or almost dry—base;

4. Use shrinkage-compensating concrete;

5. Place a generous amount of reinforcement in the top third of the slab. One percent reinforcement could be justified in the direction perpendicular to the slab edge or construction joint, and for approximately 10 ft (3 m) in from the slab edge or construction joint; and

6. Use post-tensioning.

Some of the measures that can reduce moisture differentials between the top and the bottom of a slab are:

1. Cure the slab well, particularly during early ages. Use of a continuous moist cure or a high-solids curing compound (Sections 5.9.3 and 9.2.4)—especially during the first few days—can greatly reduce the rate of water lost from the concrete and help reduce moisture differentials;

2. After proper curing, further reduce moisture loss from the top of slabs by using coatings, sealers, and waxes. These also reduce carbonation, which adds to surface shrinkage; and

3. If a vapor retarder is necessary, use a minimum 4 in. thick (100 mm) layer of trimmable, compactible granular fill (not sand) between the vapor retarder and concrete slab (Section 4.1.5). Material conforming to ASTM D 448, No. 10, with plenty of rock fines, has been used successfully. If the fill is dry, or almost dry, this will permit some moisture loss from the slab bottom. The fill should be designed so that it does not retain water.

Measures to reduce the shrinkage potential of a concrete mixture include:

1. Reduce total water content of concrete by:
   a. Maintaining the proper slump (Table 6.1);
   b. Reducing the as-mixed temperature of the concrete;
   c. Avoiding delays in placement that require large quantities of retempering water;
   d. Selecting hard aggregates that are well graded for good workability at minimum water contents, and contain a minimum of fines; aggregates should be generally rounded or cubical in shape, with a minimum of flat or elongated particles;
   e. Increasing the maximum size of coarse aggregate and using coarser sand;
   f. Reducing the sand content to the lowest level consistent with adequate workability and mixing water requirements; and

g. Using a high-range water-reducing admixture with good shrinkage-reduction history and tests;

2. Avoid aggregates known to have high-shrinkage potential, such as sandstone, slate, hornblende, and some types of basalt. Hard, rigid aggregates that are difficult to compress provide more restraint to shrinkage of cement paste in concrete than softer aggregates. Quartz, granite, feldspar, limestone, dolomite, and some basalt aggregates generally produce concrete with low drying shrinkage (ACI 224R);

3. Minimize aggregate gap-grading;

4. Avoid admixtures or concrete constituents that increase drying shrinkage. Use of a water-reducing admixture, or other admixture conforming to ASTM C 494 and intended for reducing the water demand of concrete, will not necessarily decrease the drying shrinkage of concrete. Unless concrete contains very low levels of calcium chloride or triethanolamine, drying shrinkage generally will be increased. Chlorides can get into concrete from admixtures, water, aggregates, or cement; and

5. Dewatering techniques (Section 8.3.6) of fresh concrete slab surfaces can significantly reduce water content, and thus help reduce slab curling. Because vacuum mats do not extend fully to the edges of the forms and screeds, however, it is possible for the joints at the forms and screeds to end up slightly higher than the overall slab surface after vacuum dewatering is completed. Where wheeled traffic, especially automated guided vehicles, will be involved, this should be taken into consideration during screeding, leveling, and bull floating to the forms and screeds.

Placing concrete at lower temperatures can reduce thermal contraction from cooling. Curling magnitude can diminish with age as moisture and temperature equalize throughout the slab thickness. In addition, creep probably reduces curling over a period of months.

Concrete strength should be only as high as necessary for the floor or slab to fulfill its function (Table 2.1 and 6.1). Excessively high strengths reduce creep, and this can accentuate curling. High–strength, quality concrete slabs, however, have less cracking due to higher early flexural and tensile strengths.

11.12—Analysis of surface imperfections

The cause of most surface imperfections can be determined by petrographic (microscopic) analysis on samples of the concrete. A petrographic analysis of concrete is performed in accordance with ASTM C 856.

Samples for the analysis are usually 4 in. diameter (100 mm) drilled cores or saw-cut sections. Broken sections can be used, but cores or saw-cut sections are preferred because they are less apt to be disturbed. Samples should represent concrete from both the problem and the nonproblem areas. The petrographer should be provided with a description and photographs of the problem, in addition to information on the concrete mixture proportions, construction practices used, and environmental conditions. A field review by a petrographer, designer, or concrete technologist is also helpful in analyzing the imperfection.

The petrographic report often includes the probable cause of the problem, extent of distress, the general quality of the concrete, and expected durability and performance of the concrete. Corrective action, if necessary, would be based to a great extent on the petrographic report.

CHAPTER 12—REFERENCES

12.1—Referenced standards and reports

The standards and reports listed below were the latest editions at the time this document was prepared. Because these documents are revised frequently, the reader is advised to contact the proper sponsoring group if it is desired to refer to the latest version.

American Association of State Highway and Transportation Officials (AASHTO)

M 182 Standard Specification for Burlap Cloth Made from Jute or Kenaf

T 26 Standard Method of Test for Quality of Water to be Used in Concrete

American Concrete Institute (ACI)

116R Cement and Concrete Terminology

117 Standard Specifications for Tolerances for Concrete Construction and Materials

201.2R Guide to Durable Concrete

209R Prediction of Creep, Shrinkage, and Temperature Effects in Concrete Structures

211.1 Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete

211.2 Standard Practice for Selecting Proportions for Structural Lightweight Concrete

212.1R/212.2R Admixtures for Concrete and Guide for Use of Admixtures in Concrete

212.3R Chemical Admixtures for Concrete

212.4R Guide for the Use of High-Range Water-Reducing Admixtures (Superplasticizers) in Concrete

222R Corrosion of Metals in Concrete

223 Standard Practice for the Use of Shrinkage-Compensating Concrete

224R Control of Cracking in Concrete Structures

224.1R Causes, Evaluation, and Repair of Cracks in Concrete Structures

224.3R Joints in Concrete Construction

226.1R Ground Granulated Blast-Furnace Slag as a Cementitious Constituent in Concrete

226.3R Use of Fly Ash in Concrete

301 Specifications for Structural Concrete

303R Guide to Cast-in-Place Architectural Concrete Practice

304R Guide for Measuring, Mixing, Transporting, and Placing Concrete

305R Hot Weather Concreting

306R Cold Weather Concreting

306.1 Standard Specification for Cold Weather Concreting

308R Guide for Curing Concrete

309R Guide for Consolidation of Concrete
311.4R Guide for Concrete Inspection
311.5R Guide for Concrete Plant Inspection and Field Testing of Ready-Mixed Concrete
318/318R Building Code Requirements for Structural Concrete and Commentary
360R Design of Slabs on Grade
421.1R Shear Reinforcement for Slabs
435 Control of Deflection in Concrete Structures
503R Use of Epoxy Compounds with Concrete
503.2 Standard Specifications for Bonding Plastic Concrete to Hardened Concrete with a Multi-Component Epoxy Adhesive
504R Guide to Sealing Joints in Concrete Structures
515.1R A Guide to Use of Waterproofing, Damp-proofing, Protective and Decorative Barrier Systems for Concrete
544.1R State-of-the-Art Report on Fiber Reinforced Concrete
544.2R Measurement of Properties of Fiber Reinforced Concrete
544.3R Guide for Specifying, Proportioning, Mixing, Placing, and Finishing Steel Fiber Reinforced Concrete
544.4R Design Considerations for Steel Fiber Reinforced Concrete

American Society of Civil Engineers (ASCE)

ANSI/ASCE 3 Standard for the Structural Design of Composite Slabs
ANSI/ASCE 9 Standard Practice for Construction and Inspection of Composite Slabs

American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE)

90.1 Energy Conservation in New Building Design (Sections 1 through 9)

ASTM International

A 36 Specification for Structural Steel
A 184 Specification for Fabricated Deformed Steel Bar Mats for Concrete Reinforcement
A 185 Specification for Steel Welded Wire Fabric, Plain, for Concrete Reinforcement
A 416 Specification for Steel Strand, Uncoated Seven-Wire for Prestressed Concrete
A 497 Specification for Steel Welded Wire Fabric, Deformed, for Concrete Reinforcement
A 615 Specification for Deformed and Plain Billet-Steel Bars for Concrete Reinforcement
A 616 Specification for Rail-Steel Deformed and Plain Bars for Concrete Reinforcement
A 617 Specification for Axle-Steel Deformed and Plain Bars for Concrete Reinforcement
A 820 Specification for Steel Fibers for Use in Fiber Reinforced Concrete
C 33 Specification for Concrete Aggregates
C 94 Specification for Ready-Mixed Concrete
C 109 Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or 50-mm Cube Specimens)
C 138 Standard Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete
C 143 Standard Test Method for Slump of Hydraulic Cement Concrete
C 150 Specification for Portland Cement
C 156 Test Method for Water Retention by Concrete Curing Materials
C 157 Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete
C 171 Specification for Sheet Materials for Curing Concrete
C 173 Standard Test Method for Air Content of Freshly Mixed Concrete by the Volumetric Method
C 227 Test Method for Potential Alkali Reactivity of Cement-Aggregate Combinations (Mortar-Bar Method)
C 231 Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method
C 260 Specification for Air-Entraining Admixtures for Concrete
C 295 Practice for Petrographic Examination of Aggregates for Concrete
C 309 Specification for Liquid Membrane-Forming Compounds for Curing Concrete
C 330 Specification for Lightweight Aggregates for Structural Concrete
C 387 Specification for Packaged, Dry, Combined Materials for Mortar and Concrete
C 494 Specification for Chemical Admixtures for Concrete
C 595 Specification for Blended Hydraulic Cements
C 618 Specification for Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Portland Cement Concrete
C 685 Specification for Concrete Made by Volumetric Batching and Continuous Mixing
C 806 Test Method for Restrained Expansion of Expansive Cement Mortar
C 845 Specification for Expansive Hydraulic Cement
C 856 Standard Practice for Petrographic Examination of Hardened Concrete
C 878 Test Method for Restrained Expansion of Shrinkage-Compensating Concrete
C 979 Specification for Pigments for Integrally Colored Concrete
C 1017 Specification for Chemical Admixtures for Use in Producing Flowing Concrete
C 1116 Specification for Fiber-Reinforced Concrete and Shotcrete
C 1151 Test Method for Evaluating the Effectiveness of Materials for Curing Concrete

C 1157 Performance Specification for Blended Hydraulic Cement

C 1315 Standard Specification for Liquid Membrane-Forming Compounds Having Special Properties for Curing and Sealing Concrete

D 448 Classification for Sizes of Aggregate for Road and Bridge Construction

D 994 Specification for Preformed Expansion Joint Filler for Concrete (Bituminous Type)

D 1751 Specification for Preformed Expansion Joint Filler for Concrete Paving and Structural Construction (Nonextruding and Resilient Bituminous Types)

D 1752 Specification for Preformed Sponge Rubber and Cork Expansion Joint Fillers for Concrete Paving and Structural Construction

D 2240 Test Method for Rubber Property—Durometer Hardness

D 4263 Test Method for Indicating Moisture in Concrete by the Plastic Sheet Method

E 96 Test Method for Water Vapor Transmission of Materials

E 329 Standard Specification for Agencies Engaged in the Testing and/or Inspection of Materials Used in Construction

E 1077 Standard Practice for Laboratories Testing Concrete and Concrete Aggregates for Use in Construction and Criteria for Laboratory Evaluation

E 1155 Test Method for Determining Floor Flatness and Levelness Using the F-Number System

E 1643 Standard Practice for Installation of Water Vapor Retarders Used in Contact with Earth or Granular Fill Under Concrete Slabs

E 1745 Standard Specification for Water Vapor Retarders Used in Contact with Soil or Granular Fill under Concrete Slabs

E 1907 Standard Practices for Determining Moisture-Related Acceptability of Concrete Floors to Receive Moisture-Sensitive Finishes

The aforementioned publications may be obtained from the following organizations:

American Association of State Highway and Transportation Officials
333 West Capitol Street, NW, Suite 225
Washington, DC 20001

American Concrete Institute
P.O. Box 9094
Farmington Hills, MI 48333-9094

American Society of Civil Engineers
345 East 47th Street
New York, NY 10017-2398

American Society of Heating, Refrigerating, and Air-Conditioning Engineers
1791 Tullie Circle, NE
Atlanta, GA 30329

American Society of Concrete Contractors
2025 S. Brentwood Blvd.
St. Louis, MO 63144

ASTM International
100 Barr Harbor Drive
West Conshohocken, PA 19428-2959

National Ready Mixed Concrete Association
900 Spring Street
Silver Spring, MD 20910

National Fire Protection Association
1 Batterymarch Park
P.O. Box 1901
Quincy, MA 02269-9101

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