IN-LB	Inch-Pound Units
SI	International System of Units

An ACI Standard

Concrete Slabs that Receive Moisture-Sensitive Flooring Materials—Guide

Reported by ACI Committee 302

ACI PRC-302.2-22

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Concrete Slabs that Receive Moisture-Sensitive Flooring Materials—Guide

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This guide contains materials, design, and construction recommendations for concrete slabs-on-ground and suspended slabs that are to receive moisture-sensitive flooring materials. These flooring materials include sheet rubber, epoxy coatings, vinyl composition tile, sheet vinyl, carpet, athletic flooring, laminates, and hardwood.

Keywords: admixtures; cracking; curing; curling; drying; mixture proportioning; moisture movement; moisture test; relative humidity; slabs-on-ground; specifications; vapor retarder.

CONTENTS

ACI PRC-302.2-22 supersedes ACI 302.2R-06 and was adopted and published in February 2023.

CHAPTER 1—INTRODUCTION AND SCOPE

1.1—Introduction

Moisture-related problems with floor covering materials are a serious and costly construction issue. Such problems include blistering, delamination, adhesive degradation, adhesive bleed, and mold growth. Claims for the correction of these problems may call for full or partial replacement of the flooring system. Claims may also be made for construction delays, lost revenue, or health issues related to indoor air quality. It is currently up to architects, engineers, flooring installers, flooring and adhesive manufacturers, concrete contractors, and concrete producers to solve these problems.

1.2—Scope

Chapters 1 through 8 provide an understanding of concrete moisture behavior and drying and show how recommended construction practices can contribute to successful performance of floor covering materials. This background provides a basis for the recommendations in Chapter 9 to improve the performance of floor covering materials in contact with concrete moisture and alkalinity.

Because this guide is specific to floor moisture problems and solutions, refer to ACI 302.1R and ACI 360R for general information. These two documents contain guidance on floor design and construction that is needed to achieve successful floor covering performance.

The objective of this document is to provide information and guidance to help reduce the potential for moisture-related flooring problems to occur with both slabs-on-ground and suspended slabs. It provides basic information on the

Fig. 1.3a—Debonded sheet flooring due to moisture in the concrete slab (photo courtesy of P. Craig and H. Protze III).

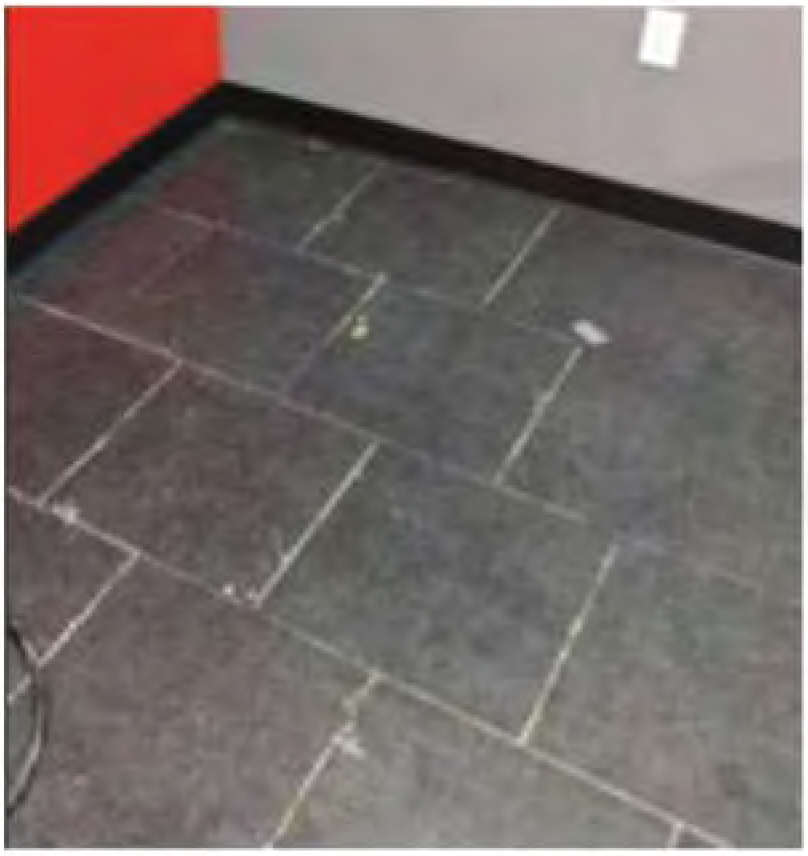

Fig. 1.3b—Adhesive bleed (image courtesy of Adam Bakeman).

concrete drying process, moisture behavior in concrete, testing for moisture, the use of below-slab vapor retarders, and corrective options.

1.3—Flooring moisture issues

Figures 1.3a to 1.3e show typical problems that can occur in concrete slabs covered with flooring materials. These problems include debonding, adhesive bleed, blistering, mold growth, and adhesive degradation.

1.4—Concrete slabs that receive flooring materials

This document focuses on the behavior of moisture in concrete slabs and the effect of the concrete moisture condition on the performance of applied flooring materials. Reaching a desired moisture state, however, should not be the only acceptance criterion for a concrete slab that will be coated or covered. Floor flatness, surface texture and finish, cracking, curling, structural capacity, jointing requirements, and the potential for the slab to stay acceptably dry should also be considered. The goal is installation of a flooring system—subgrade, subbase, vapor retarder, concrete slab (and possibly reinforcement), coating or flooring adhesive, and floor covering—that satisfies performance requirements.

ACI 360R and 302.1R provide recommendations for designing and building concrete slab-on-ground substrates that are suitable for receiving flooring materials. This docu-

Fig. 1.3c—Blisters due to moisture in concrete (photo courtesy of P. Craig).

Fig. 1.3d—Mold growth in carpet due to moisture in concrete (photo courtesy of Floor Seal Technology, Inc.).

Fig. 1.3e—Adhesive degradation leading to debonded solid vinyl tile installed over asbestos tile (photo courtesy of P. Craig).

ment supplements information contained in ACI 360R and 302.1R and also applies to suspended slabs. When designing and building suspended slabs, this guide should be used in conjunction with ACI 318 and 302.1R.

1.5—Changes in construction methods and materials that affect floor systems

Changes in construction methods and materials over the years have affected the success rate of flooring installations. For example, many projects are now constructed on a fast-track schedule that may not provide sufficient time for concrete to dry naturally to an acceptable moisture level. Recommendations concerning the type and location of below-slab vapor retarders have changed and floor covering adhesive formulations have been changed to limit the use of volatile organic compounds (VOCs).

1.6—Floor flatness changes with time

Concrete shrinks when it loses moisture and expands when it gains moisture. When the top of a slab loses more moisture than the bottom, the differential shrinkage causes edges and corners of the slab to deflect upward. This is called curling or warping. Because of this, concrete slabs that are built flat do not always stay flat.

ACI 302.1R states that it is normal to expect some amount of curling on every project. Control of curling will be a design challenge if floor specifications are written to meet both CSI Division 3 and Division 9 flatness criteria (Construction Specifications Institute 2000; Craig 2004; Holland and Walker 1998; Suprenant 2002a,b). As shown in Suprenant (2003d), curling or warping can cause floor flatness and levelness, as measured by F-numbers, to decrease by 20 to 50% in a year. The use of a low-shrinkage mixture can minimize these changes.

Time-dependent changes in floor profiles occur on every project, but the magnitude of the profile change can vary. ACI 117 states, "Since neither deflection nor curling will significantly change a floor's F_F value, there is no time limit on the measurement of this characteristic." Flatness measurements on given floors at different ages, however, indicate that this statement is not true (Suprenant 2003d), and ACI 117-06 requires flatness measurements within 72 hours after finishing. Therefore, the design team should consider how changes in floor profiles with time might affect:

(a) The cost to reestablish floor tolerance requirements that had originally been achieved at the time of placement

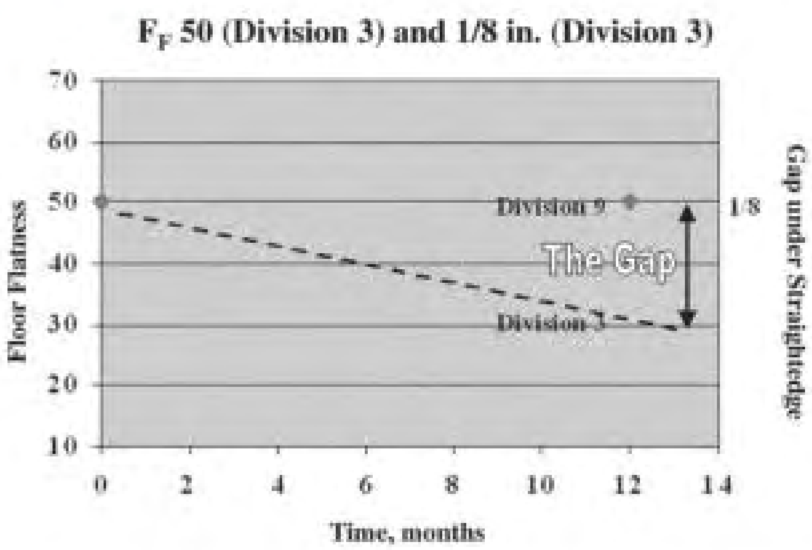

Fig. 1.6a—When flatness of an unreinforced floor is measured initially, F-numbers may indicate a very flat floor. When flooring installers start their work, however, flatness may have changed, as indicated by the gap between Division 3 and Division 9 flatness (Suprenant 2003d).

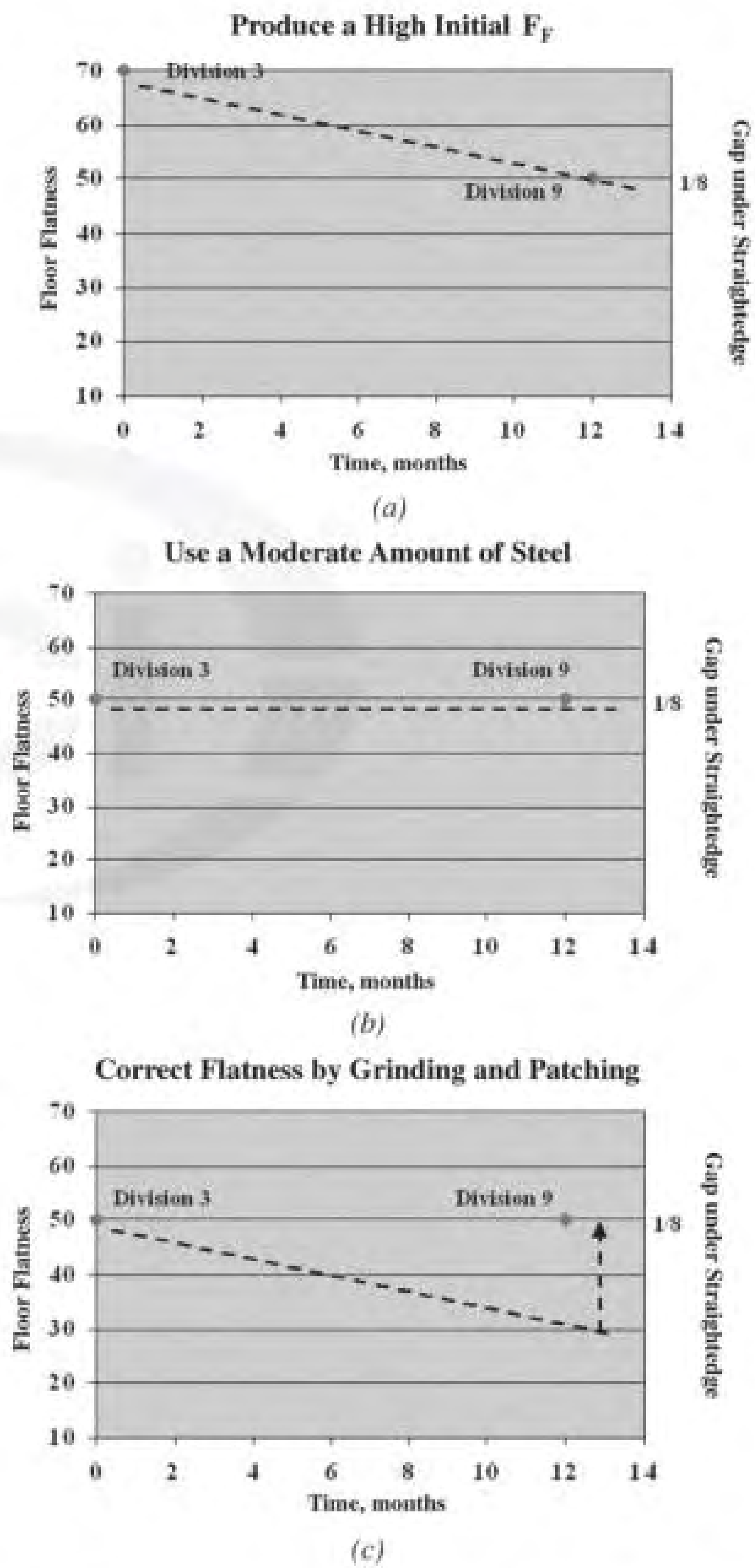

Fig. 1.6b—Approaches to providing a floor that meets the needs of the floor covering installer: (a) produce a higher initial F_F; (b) use reinforcing steel to reduce curling; and (c) correct flatness problems by grinding and patching (Suprenant 2003d).

(b) The long-term floor performance after the floor covering has been installed

Figure 1.6a shows schematically how flatness of an unreinforced floor can vary over time. The F_F 50 required by a Division 3 specification—and produced by the contractor—decreases after 12 months. Because of curling, unreinforced jointed floors exhibit a similar flatness loss with time. This creates the gap between Division 3 and 9 requirements. Design professionals can use one of several approaches to provide a floor that meets the flatness needs of the floor covering installer.

Figures 1.6b(a) through (c) show three possible approaches:

(a) **Produce a higher initial F_F**—The engineer estimates the decrease in floor flatness with time, then specifies an initial F_F that later drops to the value needed by the floor covering installer. Making the estimate is difficult because the amount of curling varies with the concrete properties and service environment. In addition, a floor with a high initial F_F experiences a greater percentage flatness loss for a given curling deflection. A low-shrinkage mixture is one means of helping to reduce curl.

(b) **Use reinforcing steel**—The engineer selects a ratio of reinforcement area to gross concrete area—typically approximately 0.5% for Grade 60 steel—that minimizes curling. Refer to ACI 360R for more information.

(c) **Correct flatness problems**—Some measure of slab curl is to be expected on all projects. An allowance should be provided in the bid to cover the cost of stabilizing and reprofiling curled slab sections and curled and noncurled random cracks. Sections 6.2.9 and 10.9 discuss various repair options.

1.7—Other considerations

Wide, random cracks in slabs create problems when flooring materials are placed over them. Most floor covering manufacturers require some form of crack treatment for wide cracks. To minimize crack width and crack repair, steel reinforcement should be considered for use in the slab (Fig. 1.7a), as recommended by Holland and Walker (1998). Other methods for reducing the potential for excessive cracking include low-shrinkage concrete mixtures, macrosynthetic or steel fibers, or other types of reinforcement such as post-tensioning. Narrow joint spacing has also been used to help reduce the development of random cracks in slabs with minimal or no reinforcing. However, joints beneath resilient flooring that are not brought to a stable, nonmoving condition can telegraph, or cause deformity in floor covering installations. Concrete slabs to be covered can be designed to control the width of cracks that occur such that contraction joints can be eliminated.

Contraction, construction, and column isolation joints often visibly telegraph through thin flooring materials. Because of this problem, Holland and Walker (1998) recommend using continuous reinforcing bars to minimize crack widths, and eliminate sawcut contraction joints and the traditional diamond-shaped isolation joints at columns when floors will receive a covering. Instead of using diamond-shaped isolation joints, columns in a floor system should be wrapped for the full floor depth with 1/2 in. (12.7 mm) thick compressible isolation joint material (Fig. 1.7b). Refer to ACI 360R for more information.

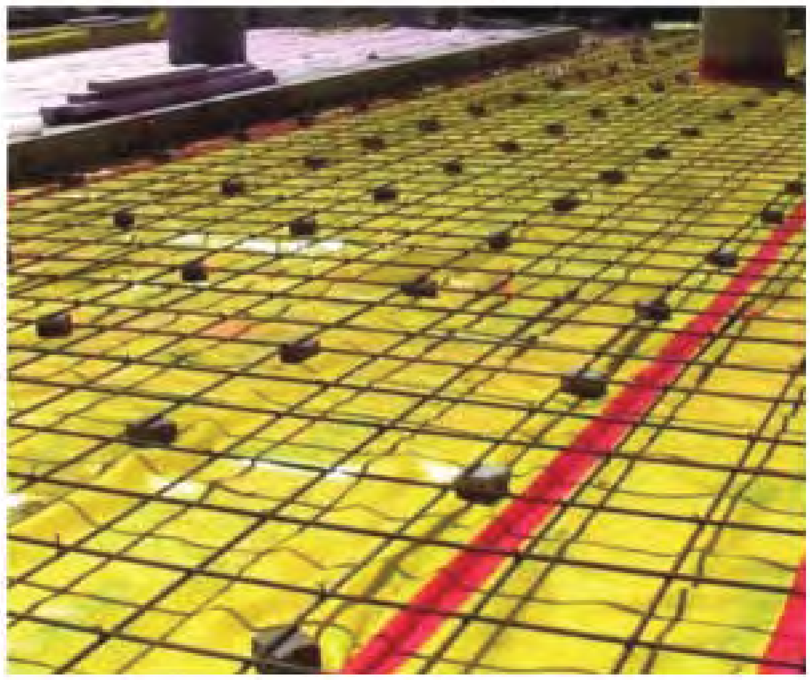

Fig. 1.7a—Proper sized and supported reinforcing bars help control slab curling and the width of cracking in slabs placed directly on a vapor retarder.

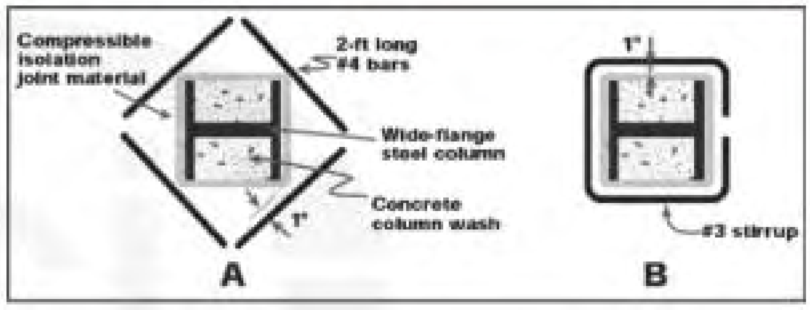

Fig. 1.7b—Eliminate the normal isolation-joint boxouts at wide-flange steel columns by wrapping the column with compressible materials and using 2 ft (0.6 m) lengths of No. 4 (No. 13) bars (A) to control cracking at the reentrant corners. To speed up steel placement at the columns, have the reinforcing bar supplier fabricate continuous No. 3 stirrups that workers can easily bend open to fit around the column (B). In either case, the steel should be positioned with a top-and-side clear cover of 1 in. (25 mm) (Holland and Walker 1998). (Note: 1 ft = 0.3 m; 1 in. = 25.4 mm.)

Carpeting and some types of unbonded floor coverings can typically tolerate larger crack widths in the concrete floor without noticeable telegraphing of the crack through the flooring material. When these coverings are used, crack-control measures at columns may not be needed. The column-slab interfaces should simply be wrapped to isolate them from the slab. Refer to ACI 360R for more detailed information on the design of slabs-on-ground.

CHAPTER 2—DEFINITIONS

2.2—Definitions

Please refer to the latest version of ACI Concrete Terminology for a comprehensive list of definitions.

CHAPTER 3—CONCRETE MOISTURE BASICS

3.1—Introduction

Hardened concrete slabs contain water in either a liquid or vapor form. The amount and distribution of this water is of primary concern with regard to the installation and performance of floors and flooring materials. The amount of water in fresh concrete is determined by the concrete mixture proportions, the concrete batch weights, and any water added after batching. Initially, the distribution of water in a fresh concrete slab may be slightly affected by bleeding, placing, finishing practices, evaporation during finishing, and curing methods. It is, however, the effect of moisture redistribution in the slab after it is covered, the introduction of additional moisture from below the slab, or both, that can lead to the development of a high pH environment at the surface of the slab that has the greatest adverse effect on the performance of flooring materials. Understanding how water moves through hardened concrete is important in determining:

(a) Consequences of the moisture movement
(b) Effectiveness of moisture testing methods
(c) Validity of flooring manufacturers' warranty recommendations

3.2—Moisture movement

After curing and before drying begins, the moisture distribution in a hardened concrete slab is reasonably uniform throughout the member thickness (Hanson 1968). As concrete dries, the amount and distribution of moisture changes (Hedenblad 1997).

3.2.1 *Drying of concrete slab-on-ground*—Figure 3.2.1, adapted from Hedenblad (1997), shows schematically the change in internal relative humidity (RH) of a concrete slab-on-ground as it dries from the top surface only. The vertical line at 100% RH (Curve A) shows the initial distribution when drying begins. As the slab dries, the concrete loses more moisture from the top than from the middle or bottom. This results in a moisture differential within the slab, with the internal RH lower at the top. The profile of the drying curve (Curve B) varies with the temperature and RH at the concrete surface, the length of the drying period, and the concrete properties.

Depending on the permeability of the flooring material, slab drying ceases or slows when a floor covering is installed. With the flooring in place, moisture within the concrete redistributes throughout the slab before reaching an equilibrium level at which the RH is nearly uniform throughout the concrete. With moisture prevented from entering the slab from below, after a period of drying, the reequalization level of moisture in the slab will be lower than when the slab was originally placed. Figure 3.2.1 shows the new RH profile as a vertical line (uniform moisture) at 90% RH (Curve C). The

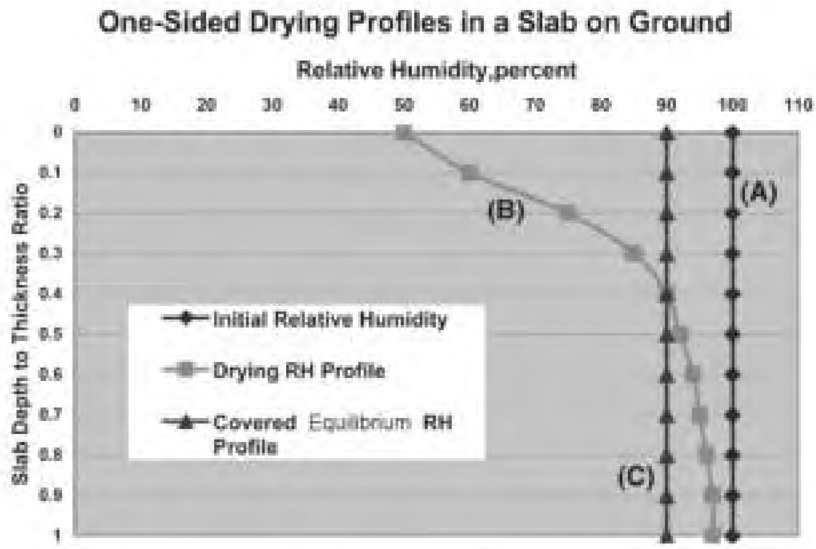

Fig. 3.2.1—One-sided drying profiles in a slab-on-ground showing initial, drying, and covered equilibrium RH profiles (adapted from Hedenblad [1997]).

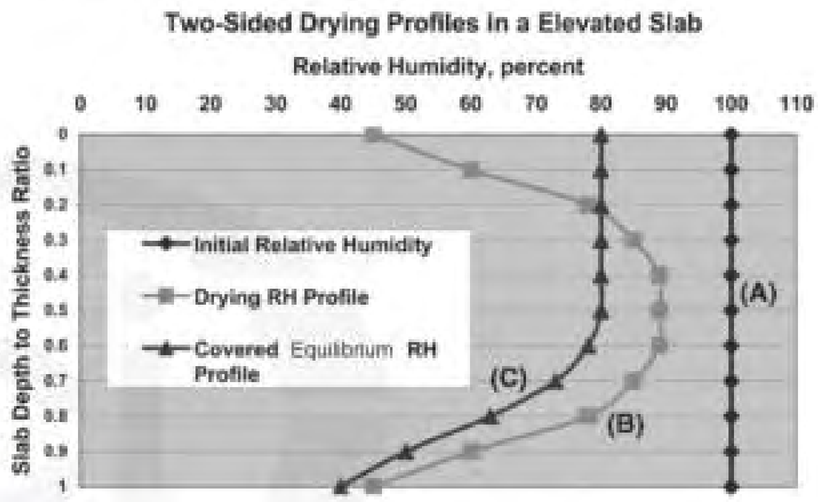

Fig. 3.2.2—Two-sided drying profiles in suspended slab showing initial, drying, and covered equilibrium RH profiles (adapted from Hedenblad [1997]).

absolute RH value at equilibrium varies depending on the initial moisture content, drying conditions, and length of the drying period (Hedenblad 1997).

3.2.2 *Drying of suspended concrete slab*—Figure 3.2.2 (adapted from Hedenblad 1997) shows schematically the change in internal RH of a concrete slab drying from both the top and bottom. Similar to the concrete slab-on-ground, the vertical line at 100% RH (Curve A) shows the initial distribution when drying begins. As it dries, the concrete loses moisture from both the top and bottom of the slab. This results in a moisture differential within the slab, but now with the maximum RH at middepth of the slab (Curve B). The profile of the drying curve again varies with the temperature and RH at the concrete surfaces, the length of the drying period, and the concrete properties.

Drying at the top of a suspended slab ceases or slows when a floor covering is installed, depending on the permeability of the floor covering, but the bottom concrete surface can still dry (this discussion does not apply to concrete placed on leave-in-place forms such as metal decking). The internal moisture now redistributes throughout the concrete, creating a higher RH at the top surface, but a lower RH at the bottom that is still drying. Figure 3.2.2 shows the equi-

librium internal RH profile after the floor covering has been placed (Curve C). Continued drying from the bottom of the slab may occur. The amount of drying depends on the interior ambient RH and the slab thickness. Subsequent possible drying, however, should not be considered when determining the appropriate moisture condition at which the floor covering should be placed.

3.2.3 *Drying of concrete slab-on-ground with water or water vapor below*—Initially, a concrete slab placed directly on a granular subbase or subgrade behaves like a concrete slab placed on a vapor retarder, with an initially vertical RH profile and a drying curve similar to that shown in Fig. 3.2.1. After the floor covering is placed, however, moisture inflow from the bottom changes the equilibrium profile. The amount of moisture entering from the bottom is unpredictable but, depending on the available moisture supply and the concrete properties, RH at equilibrium could be close to 100%. A concrete slab-on-ground without a vapor retarder directly beneath it may have a final RH profile that does not benefit from any initial slab drying.

3.3—Concrete drying profiles

Many investigators have measured the moisture condition of concrete in the field and laboratory. Some investigators plotted drying profiles showing variations in RH or moisture content through the cross section of the specimens in which measurements were made. Their results verify the theory discussed in 3.2.

3.3.1 Hanson (1968)—Figure 3.3.1 shows drying curves for both normalweight and lightweight concrete (Hanson 1968). Relative humidity was measured at cover depths of 1/4, 3/4, 1-3/4, and 3 in. (6.4, 19, 44, and 76 mm) in 6 x 12 in. (150 x 300 mm) concrete cylinders that were moist-cured for 7 days. Figure 3.3.1 shows that:

(a) Drying profiles differ for normalweight and lightweight concrete.

(b) Lightweight concrete took longer to dry than normalweight concrete.

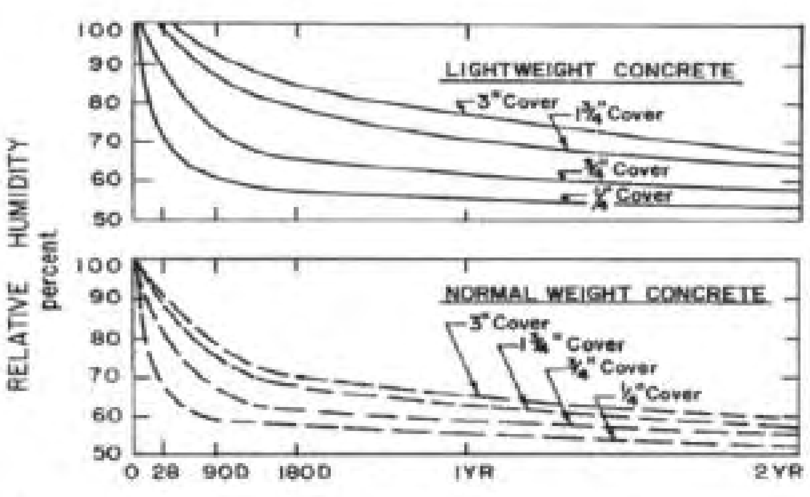

Fig. 3.3.1—Typical RH distribution for lightweight and normalweight concrete in 6 x 12 in. (150 x 300 mm) concrete cylinders moist cured for 7 days, then dried (Hanson 1968). Cover refers to depth at which the relative humidity was measured. (Note: 1 in. = 25.4 mm.)

(c) Normalweight concrete took less than 90 days and lightweight concrete took more than 180 days to reach 85% RH at the center of a 6 in. (150 mm) diameter specimen.

3.3.2 Abrams and Orals (1965)—The effect of moisture content on the fire resistance of concrete is well known. ASTM E119 requires the concrete test specimen to be at a maximum RH of 75%. Fire investigators should measure the concrete's internal RH before fire testing the specimen. Figure 3.3.2 shows moisture profile curves from the surface to the center of a 6 in. (150 mm) thick slab (Abrams and Orals 1965). The test specimens were subjected to external RH of 10, 35, 50, and 75%. Specimens were dried to levels that produced RH of 90 and 75% at the slab center. Figure 3.3.2 shows that:

(a) The concrete moisture profiles are curvilinear.

(b) Differences in RH of up to 65% (10 versus 75% RH) at the drying surface resulted in small (approximately 3%) RH differences at a depth of 3 in. (76 mm) from the drying surface.

(c) Even when the surface was exposed to a very dry environment (10% RH), concrete at a depth of 3 in. (76 mm) reached only 75% RH.

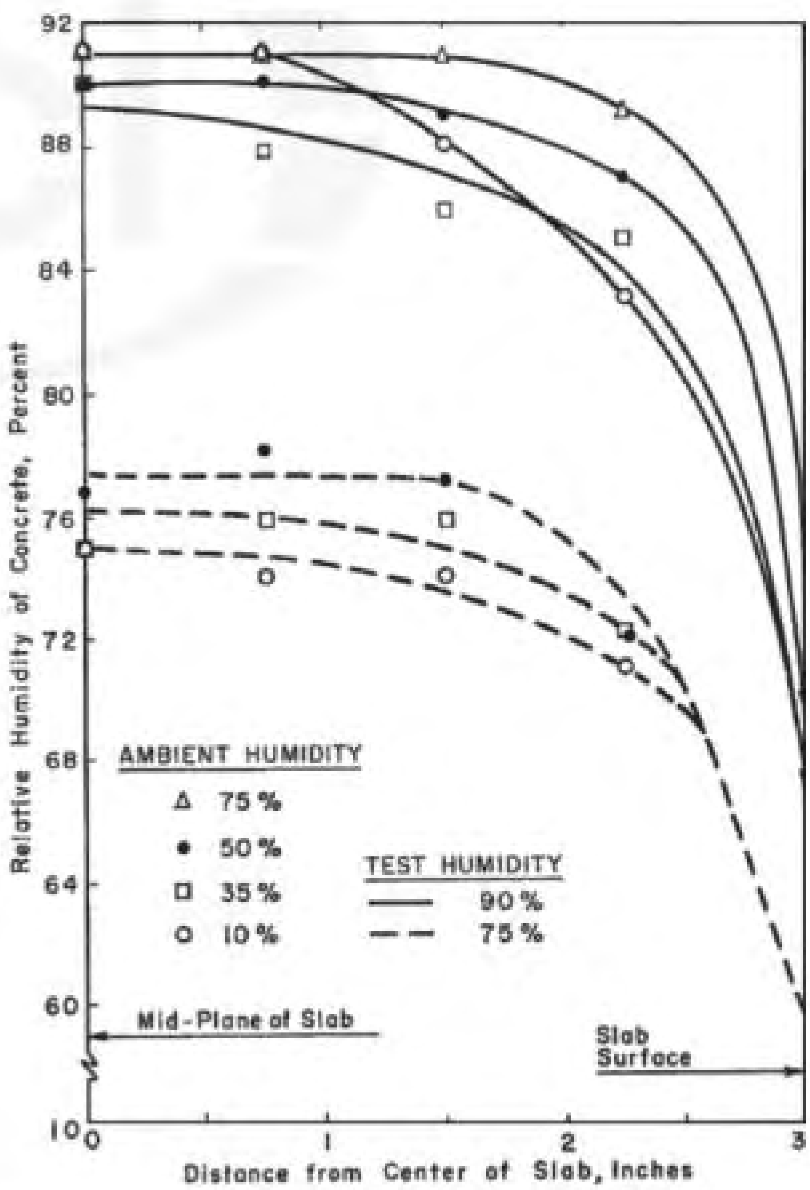

Fig. 3.3.2—Moisture profiles for slabs dried at differing ambient RH (Abrams and Orals 1965). (Note: 1 in. = 25.4 mm.)

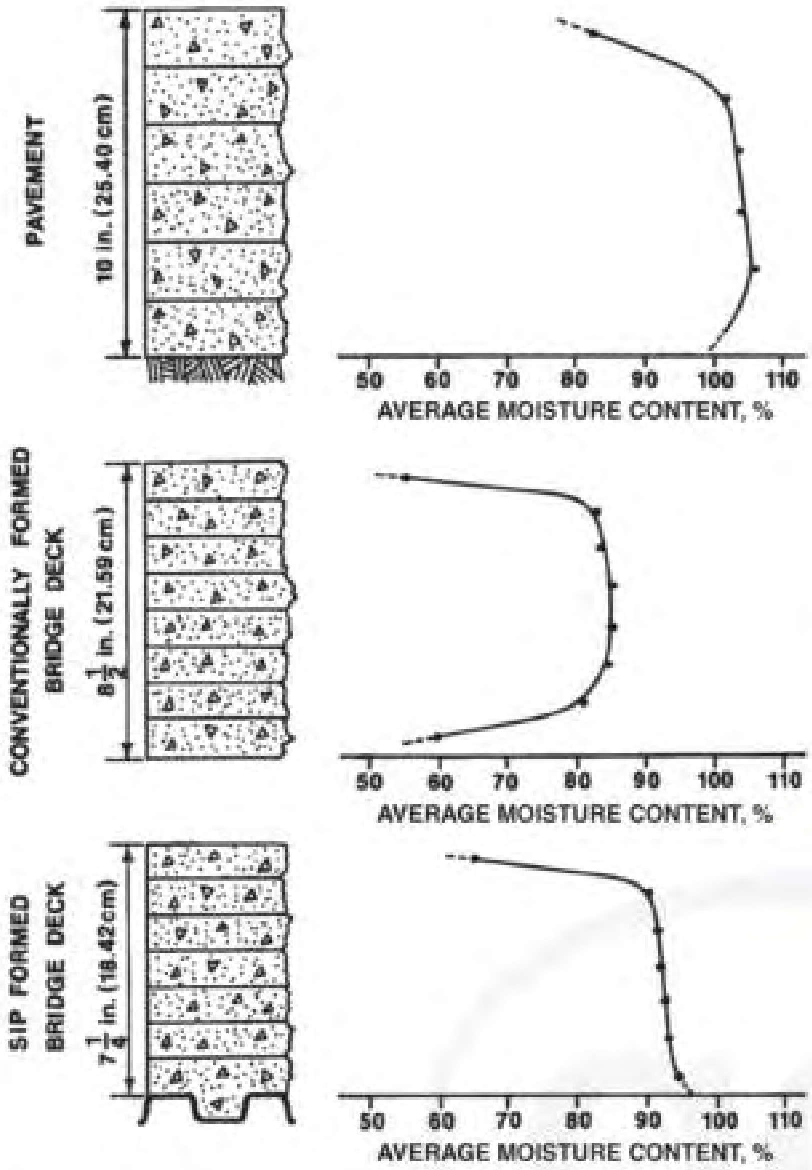

Fig. 3.3.3—Moisture profiles for concrete slab-on-ground drying from top only, suspended bridge deck drying from both top and bottom surfaces, and suspended deck placed on stay-in-place metal form drying from top only (Carrier et al. 1975).

3.3.3 *Carrier et al. (1975)*—Field moisture-content testing was conducted on a pavement, a bridge deck, and on concrete placed on a stay-in-place form (Carrier et al. 1975). During this investigation, concrete cores were removed from the test specimen, sliced into discs, weighed, and then replaced in the structure with gaskets around each disc so that no drying occurred in the annular space between the cores and the core hole. The discs were removed and weighed at regular intervals.

Figure 3.3.3 shows the results of these studies. The concrete drying profile for the pavement shows significant drying from the top only, whereas the bridge deck shows drying from both the top and bottom. The drying profile for the bridge deck on stay-in-place metal forms shows that the deck can dry from the top only, similar to an interior building slab placed on a metal deck.

3.3.4 *Initial moisture profile*—Hanson's (1968) internal RH measurements on normalweight and lightweight concrete 6 x 12 in. (150 x 300 mm) cylinders also verify the assumption that the moisture distribution in concrete after curing is initially reasonably uniform throughout the member thickness. Table 3.3.4 shows RH test results for two lightweight and two normalweight concrete cylinders moist-cured for 7 and 28 days before drying. As expected, the measured internal RH immediately after curing was 100%. The test data for 3, 7, 14, and 28 days all show a drying profile in which the RH decreases with time.

Table 3.3.4—Internal RH distribution, % (Hanson 1968)

Lightweight concrete (6 x 12 in. [150 x 300 mm] Cylinder 1), moist-cured 7 days					
Depth, in. (mm)	**0 days**	**3 days**	**7 days**	**14 days**	**28 days**
0.25 (6.4)	100	94	89	81	73
0.75 (19)	100	100	98	94	89
1.75 (44)	100	100	100	100	98
3.00 (76)	100	100	100	100	99
Lightweight concrete (6 x 12 in. [150 x 300 mm] Cylinder 2), moist-cured 28 days					
Depth, in. (mm)	**0 days**	**3 days**	**7 days**	**14 days**	**28 days**
0.25 (6.4)	100	92	86	79	71
0.75 (19)	100	100	99	96	91
1.75 (44)	100	100	100	100	99
3.00 (76)	100	100	100	100	99
Normalweight concrete (6 x 12 in. [150 x 300 mm] Cylinder 1), moist-cured 7 days					
Depth, in. (mm)	**0 days**	**3 days**	**7 days**	**14 days**	**28 days**
0.25 (6.4)	100	89	84	77	68
0.75 (19)	100	97	93	88	81
1.75 (44)	100	100	98	94	89
3.00 (76)	100	100	99	96	92
Normalweight concrete (6 x 12 in. [150 x 300 mm] Cylinder 2), moist-cured 28 days					
Depth, in. (mm)	**0 days**	**3 days**	**7 days**	**14 days**	**28 days**
0.25 (6.4)	100	85	82	76	69
0.75 (19)	100	98	94	87	80
1.75 (44)	100	100	97	94	90
3.00 (76)	100	100	99	96	92

3.4—Effects of moisture movement

The time required for changes in moisture distribution within concrete slabs affects slab curling and joint bulging. Moisture testing is also affected by moisture movement.

3.4.1 *Slab curling*—Concrete shrinks when it loses moisture and expands when it gains moisture. When the top of a slab loses more moisture than the bottom, the differential shrinkage causes edges and corners of the slab to deflect upward. This is called curling or warping. When a floor covering is installed, however, the moisture profile changes, with moisture moving from the bottom to the top of the slab. This reduces, and may eliminate, the initial curling deflection because the concrete at the top expands as the moisture content increases, and the concrete at the bottom of the slab shrinks as the moisture content decreases (Tarr et al. 2006).

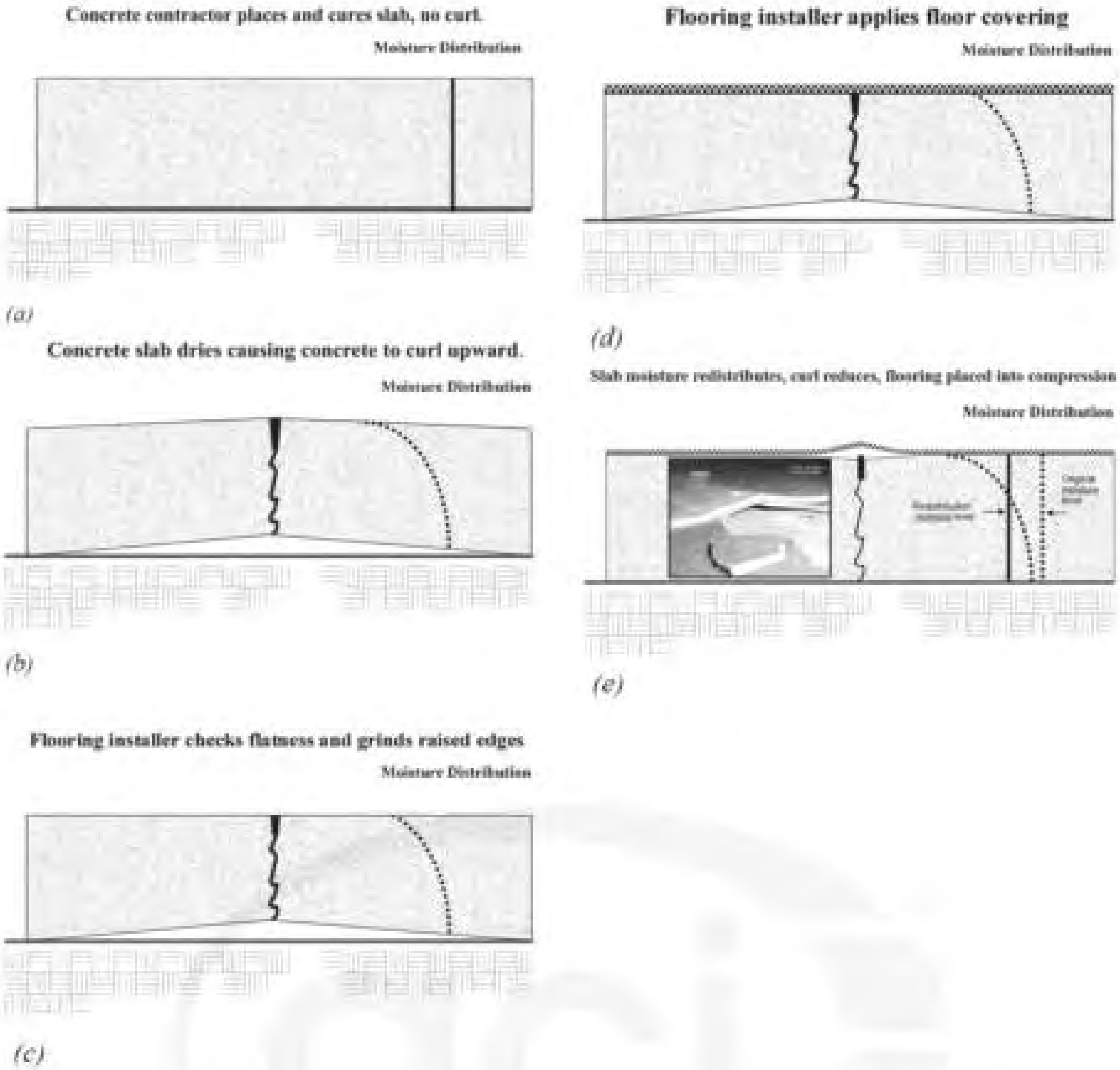

Fig. 3.4.1—Sequence showing how moisture redistribution after floor covering placement can place flooring and underlayment materials into compression over curled joints.

One possible consequence of changes in curling deflection is illustrated by the construction sequence described as follows (Fig. 3.4.1):

(a) Concrete slab is placed and cured

(b) Concrete slab dries, causing the slab edges to curl upward

(c) The floor covering installer checks concrete flatness and grinds the curled edges of some concrete panels to provide a level surface.

(d) Installer applies floor covering

(e) After some time, slab moisture redistributes to equilibrium, reducing slab curling deflection. A reduction in edge curl can cause a joint filler material, leveling compound, or the flooring material itself, to be placed in compression and create a visible ridge in the flooring (refer to 3.4.2). When this occurs, additional remedial work is typically required.

Unfortunately, the amount of reduction in curling deflection after the floor is covered, and the time it takes to achieve that reduction, are difficult or impossible to predict. One option is to inject rigid foam or polyurea into the cavity beneath curled edges to prevent relaxation of the slab edges when moisture redistributes within the slab after it is covered. After the under-slab cavity is injected, grinding can produce a flat joint that should remain flat after the flooring materials are placed.

3.4.2 *Joint bulging*—To minimize random cracking, contraction joints in floors should be cut before drying has occurred—usually either immediately after final finishing (with early-entry saws) or within approximately 6 to 12 hours after final finishing (with conventional saws). Because slab drying is nonuniform with respect to slab depth, the sawcut notch develops a more V-shaped geometry, with the top opening wider than the bottom. Specifications typically require that joints be filled as late as possible to allow for the greatest amount of drying shrinkage. The joints are then filled flush with the top concrete surface.

As shown in Fig. 3.4.2 and described as follows, subsequent changes in moisture content can create flooring problems:

(a) Concrete contractor places and cures slab

(b) Concrete contractor sawcuts joint before slab dries

(c) Sawcut opens and a V-shape geometry is formed from the top down as the slab dries

(d) Sawcut is filled just before the floor covering is installed. Moisture redistributes upward in the slab causing the top portion of the slab to expand, which places the filler material into compression, which can force many types of joint filler materials upward.

Slab curling can make this situation worse. If the slab curls after the joint is cut and then relaxes after the floor covering

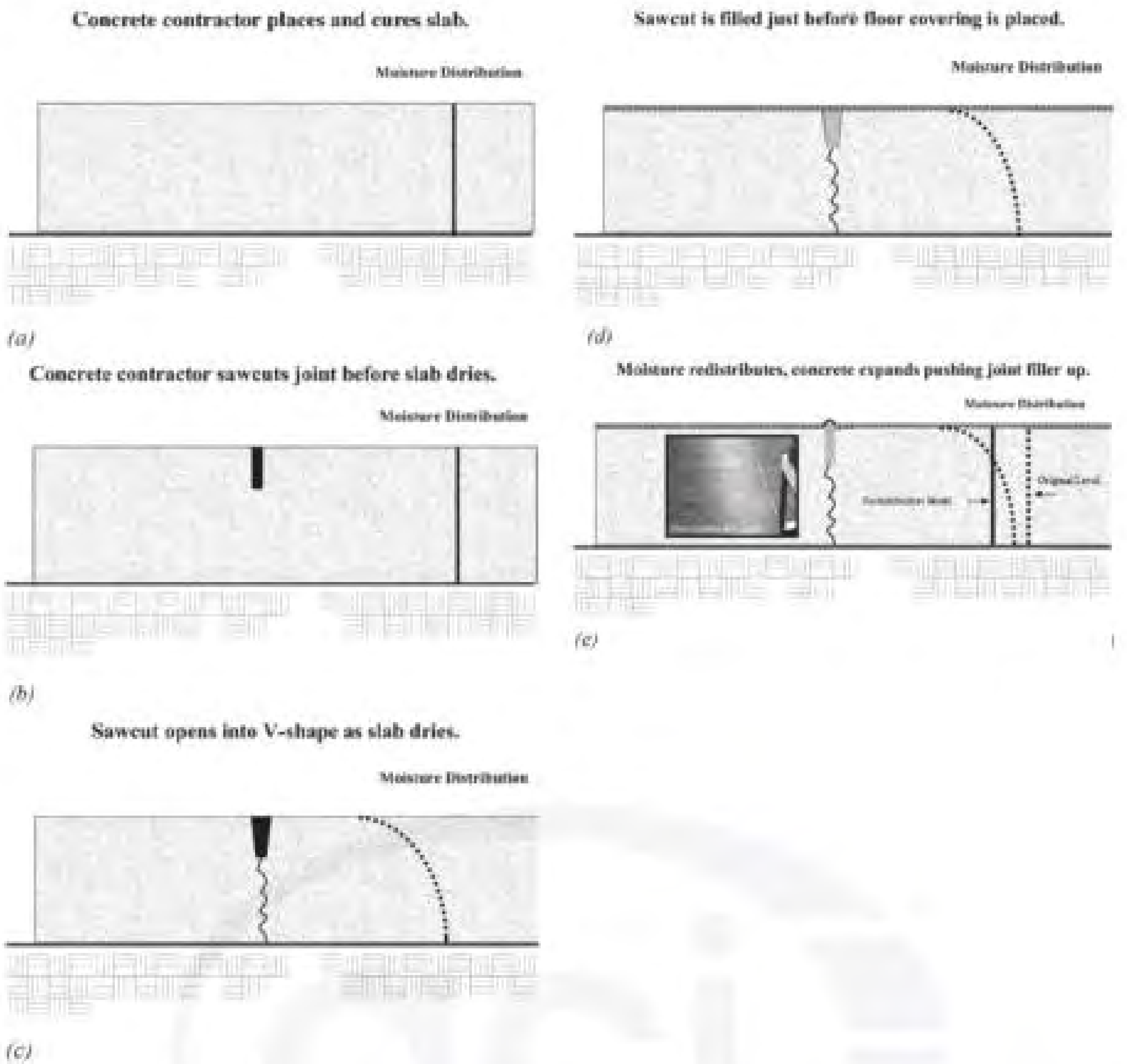

Fig. 3.4.2—Joint bulge sequence illustrating how moisture redistribution after floor covering is placed can create a joint filler bulge under installed floor covering.

is placed, that movement can also cause the joint filler, leveling compound, or flooring material to bulge upward.

Floor covering installers often attempt to repair this problem by removing the row (or strip) of covering directly above the joint bulge and then use a razor scraper or grinder to trim the joint filler that has bulged. If this solution is implemented before the slab moisture is in equilibrium, additional moisture movement may cause the joint to bulge further and require a second repair. In many cases it is necessary to fill the void beneath the curled edges of the slab to prevent settlement of the slab after the flooring is installed.

3.4.3 *Moisture movement effects on testing*—Moisture test results can be misleading. Results from moisture testing should be interpreted, understanding that:

(a) During drying, moisture in the top portion of the concrete will be lower than the moisture content measured at the midpoint, or at greater depths for slabs placed on vapor retarders.

(b) RH measurements taken at the surface of an uncovered concrete slab will be lower than measurements taken with an RH probe embedded at the required depth in the slab.

(c) Surface moisture measurements taken before a floor covering is placed will indicate a drier moisture condition than after the floor covering is placed and the moisture redistributes.

(d) RH measurements for slabs drying from one side only are typically taken at a depth of 40% of the slab thickness. For example, RH measurements in a 5 in. (130 mm) thick slab would be taken at a depth 2 in. (51 mm) below the slab surface. The RH level measured at 40% of the slab thickness is approximately where the drying profile curve and a line representing the redistribution RH level in the slab after it is covered intersect (Fig. 3.2.1). Thus, for slabs that are adequately protected from moisture below, the RH measured at 40% of the slab thickness will be approximately equal to the equilibrium RH in the slab once it is covered (Hedenblad 1997; ASTM F2170).

(e) RH measurements for slabs drying from both the top and bottom are typically taken at 20% of the slab depth from the top surface because that is where the drying profile curve and the equilibrium curve intersect (Fig. 3.2.2). Thus, the RH measured during drying at that location will be approximately equal to the equilibrium RH measurement for the slab after it is covered (Hedenblad 1997; ASTM F2170).

After the floor covering is installed, moisture in the surface region of the slab will increase but the time required to reach the equilibrium state is not known. To simulate placement of a floor covering, several investigators have covered areas of the dried concrete floor or laboratory specimens with plastic sheeting or rubber-backed carpet tile and left it in place for

a week or more. They then removed the covering, measured the moisture vapor emission rate (MVER), and compared it with the MVER before the covering had been applied (Suprenant and Malisch 1998a).

Measurements in accordance with ASTM F1869 on these floors or laboratory specimens indicated that the MVER increased significantly (a 1 to 2 lb/1000 ft^2/24 h [0.5 to 1.0 kg/100 m^2/24 h] increase for floors initially in the 3 to 5 lb/1000 ft^2/24 h [1.5 to 2.4 kg/100 m^2/24 h] MVER range). These tests showed that the surface moisture condition had changed after the floor covering was placed but did not indicate the time at which it reached equilibrium.

Many tests for determining the surface moisture condition of the concrete are conducted by covering the slab for 24 to 72 hours. Often, the moisture condition has not stabilized in this short time. Unless the coverings for the surface tests are left in place until an equilibrium moisture condition is reached, these tests give only an indication of the effects of surface moisture condition at the time the test was conducted.

3.5—Equilibrium moisture content

The equilibrium moisture content (EMC) concept used for wood products can also be applied to concrete. The moisture content (mass percent) of wood depends on the RH and temperature of the air surrounding it. If wood remains in air long enough at a constant RH and temperature, the moisture content will also become constant at a value known as the EMC. Thus, every combination of RH and temperature has an associated EMC value that increases with increasing RH and decreasing temperature (Simpson 1998).

Data (Simpson 1998) show how the EMC of wood in outdoor locations varies throughout the United States and worldwide. As is the case for wood, the equilibrium moisture content for a concrete slab drying while exposed to a high RH environment will not be the same as that for a slab in a low RH environment. Figure 3.5 (Straube 2000) shows that if the average RH to which the concrete is exposed is above 80%, the moisture content will never fall below 2% (by mass). Similarly, if the average RH is below 40%, the moisture content can reach 1% or lower.

Test methods for measuring concrete moisture content as a percentage of concrete by mass are sometimes specified, as are moisture-content criteria for determining when floor coverings can be placed. Some manufacturers require moisture contents as low as 2 or 2.5% before a floor covering can be applied. Such single moisture-content criteria may not be appropriate because whether or not the concrete reaches the specified moisture content depends on the drying environment:

(a) Exterior conditions (open building)

(b) Interior conditions (building is enclosed and the heating, ventilation, or air conditioning system is operating)

3.6—Drying and wetting of concrete

3.6.1 *Adsorption and desorption effects*—When concrete dries, the moisture loss is referred to as desorption, and when it is wetted, the moisture gain is referred to as adsorption. Figure 3.6.1a (Powers and Brownyard 1947) illustrates a typical drying and wetting (desorption and adsorption) curve. In addition to showing that the drying and wetting curves do not follow the same path, Powers and Brownyard (1947) showed that there are different drying and wetting

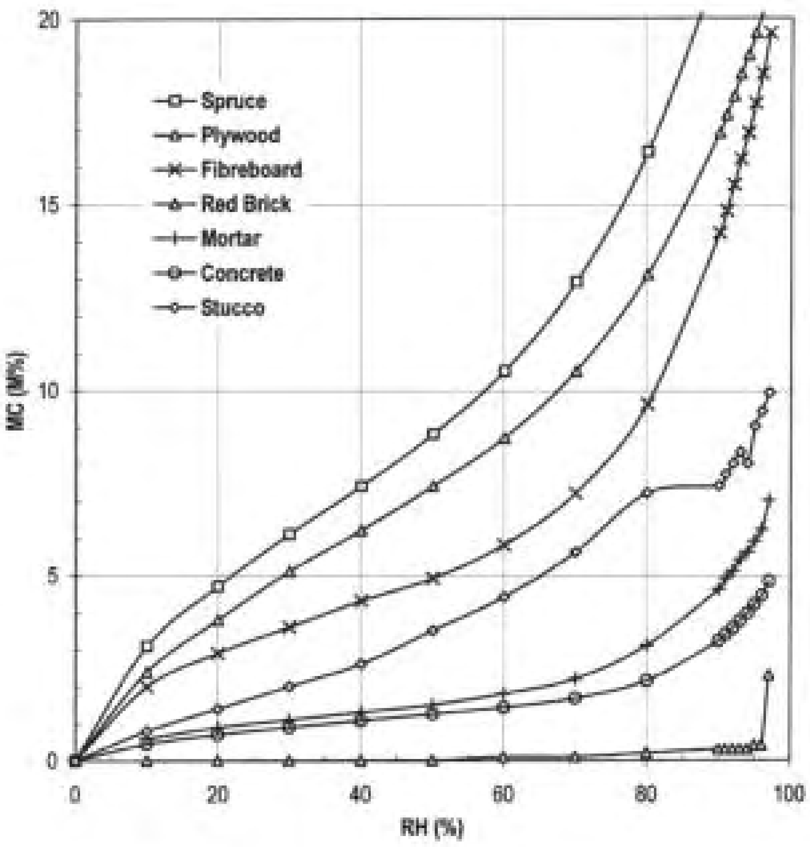

Fig. 3.5—Sorption isotherms for several common building materials (Straube 2000).

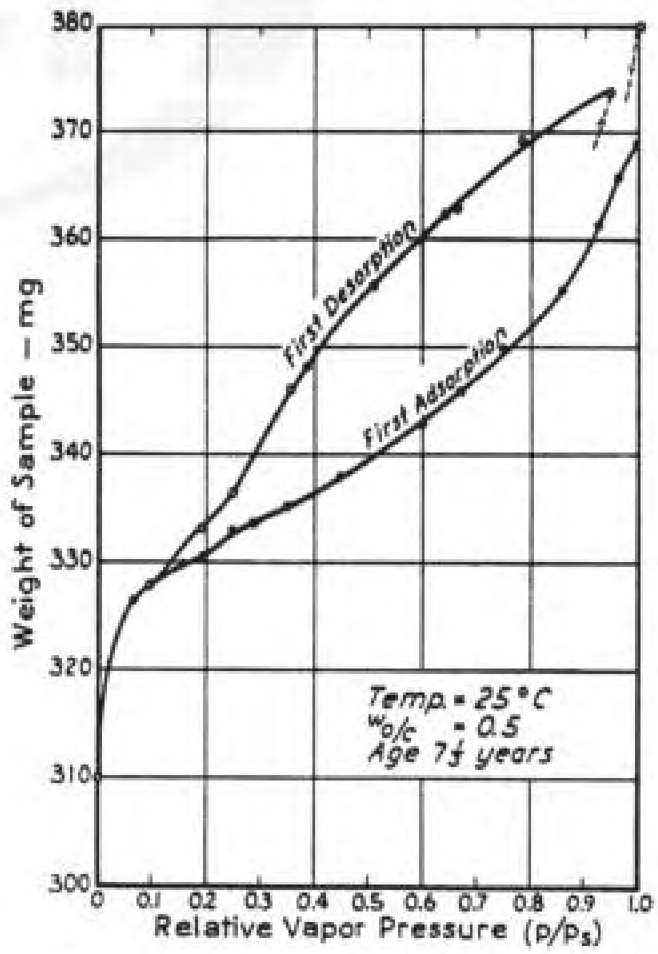

Fig. 3.6.1a—Typical drying (desorption) and wetting (adsorption) curves showing that behavior is different and that concrete contains a different moisture content at the same RH depending on whether it is drying or wetting (Powers and Brownyard 1947). (Note: °C = 5/9 × [°F – 32].)

curves for concretes with differing water-cement ratios (*w/c*), cement content and composition, curing conditions, and age when dried or wetted.

A significant characteristic of the drying and wetting cycle is that moisture lost during the first drying (desorption) is not completely replaced through wetting (adsorption) except at very low RH (less than 20%). Therefore, moisture content on rewetting will be lower than that measured on drying if both are measured at the same RH. Experiments (Powers and Brownyard 1947) show that at 75% RH, the moisture contents of samples can differ by 25% or more depending on whether the moisture content was measured during drying or wetting.

Hedenblad (1997) and Kanare (2005) both showed that the moisture contents of concretes with different *w/c* may be identical even though the measured internal RH vary. Conversely, at a fixed internal RH, the moisture content of different concretes can vary (Fig. 3.6.1b).

Lightweight concrete drying and wetting curves exhibit the same behavior as normalweight concrete (Landgren 1964). Similar to normalweight concrete, lightweight concrete will lose more water during drying than will be absorbed during rewetting. There are, however, two significant differences in the drying and wetting curves for lightweight concrete: 1) the water retained within the cement paste at normal ambient RH is small when compared with the water absorbed by the aggregate; and 2) for some lightweight aggregates, the shape of the desorption and adsorption curves changes due to permanent weight changes that occur during drying and wetting.

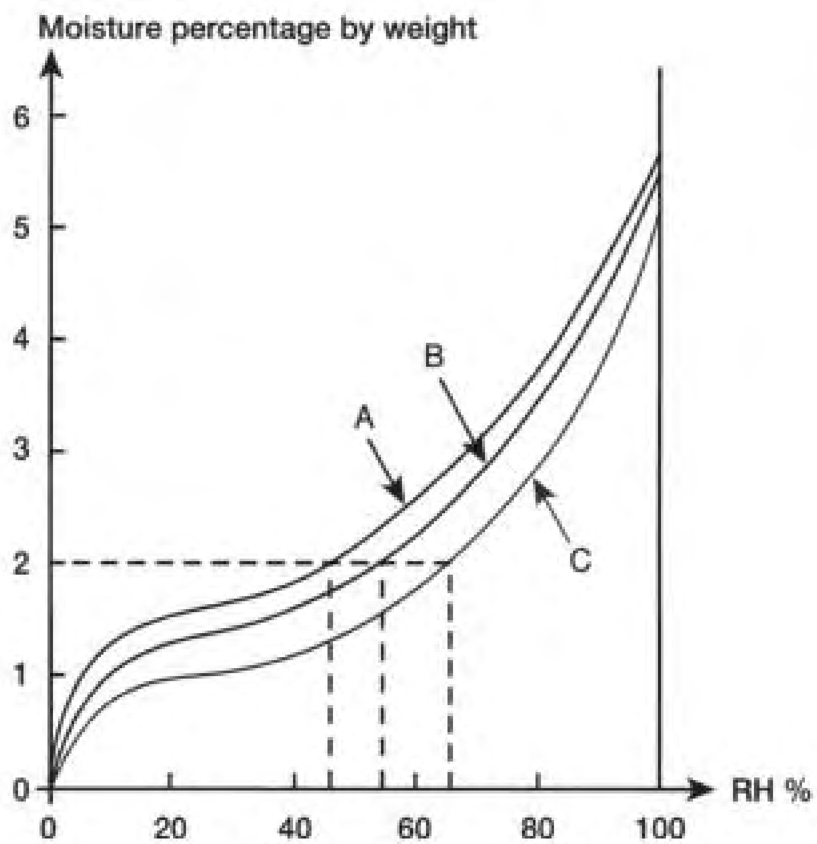

Fig. 3.6.1b—Idealized wetting (adsorption) curves illustrating that at the same moisture content the concretes will have different measured internal relative humidity. Consider A, B, and C to be concretes with w/cm *of 0.4, 0.5, and 0.7, respectively (Kanare 2005).*

Powers and Brownyard (1947) and Hedenblad (1997) also illustrated the effect of alkali content on drying and wetting curves. For concretes with similar mixture proportions and the same moisture content, measured RH is lower in concrete with a higher alkali content. Thus, the concrete with the higher alkali content will dry to a given RH in a shorter time than will concrete with a lower alkali content.

Because concretes with the same moisture content but different degrees of alkalinity can produce different values of RH, specifying one acceptable RH value for all concretes does not ensure that all concretes will have reached the same moisture content. The critical RH varies depending on the type of concrete and its alkalinity (Hedenblad 1997). This variation may not be important when the acceptable internal RH is approximately 80% because, at this RH, differences in moisture content at different points on the adsorption or desorption curves may be slight. It is also likely that for field concrete that goes through wetting and drying cycles, the actual moisture content at 80% RH will fall somewhere between the different values on the adsorption and desorption curves. If a single, but conservative, critical RH is selected, it is likely that the desired moisture content will

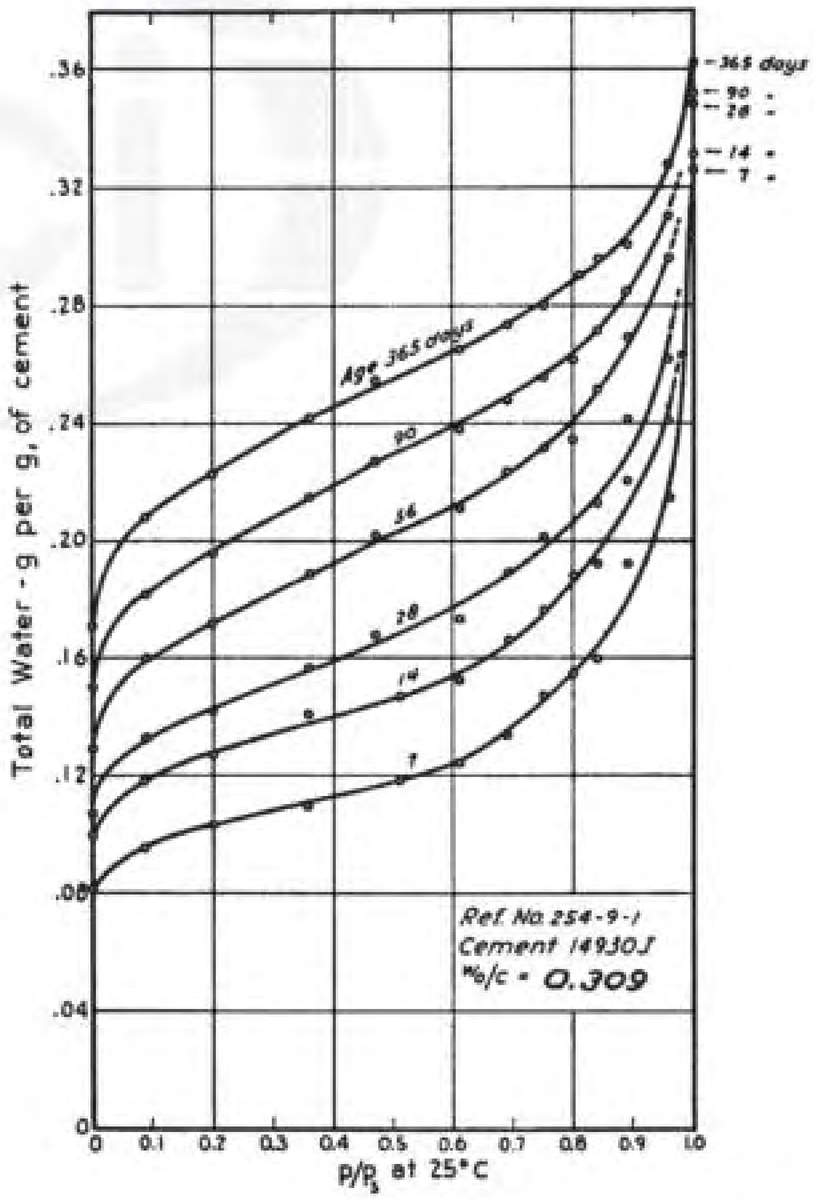

Fig. 3.6.1c—Measured soprtion curves for samples at different ages. Note that the 365-day-old sample has approximately 50% more moisture than the 28-day-old sample at a RH range from 80 to 90% (Powers and Brownyard 1947).

be attained regardless of whether the concrete is drying or absorbing moisture when the measurement is taken.

One important factor in the behavior of concrete during drying and wetting is often overlooked. Hedenblad (1997) states, "The drying times given cannot be used in drying out concrete after water damage. The reason for this is that old and mature concrete has different drying properties from those of younger concrete."

Figure 3.6.1c (Powers and Brownyard 1947) illustrates measured wetting (adsorption) curves for samples of different ages. The 365-day-old sample has approximately 50% more water in it at the important RH range of 80 to 90% than the 28-day-old sample. Hedenblad (1993) and Suprenant and Malisch (1999b) show that the drying time required for mature concrete to reach a given moisture state can be twice as long as for young concrete. If concrete on a project is exposed to high outdoor RH for a year before the project is enclosed and the heating, ventilating, and air-conditioning (HVAC) system is turned on, that concrete will not dry as quickly as it would have if drying had started within the first month after the concrete was placed.

Knowing that older concrete dries more slowly might provide a better understanding of why concrete in the field does not always dry as quickly as expected. It might also justify added expense for protecting the concrete from moisture before it ages.

3.6.2 *Effect of sorption hysteresis on testing*—Most test criteria are established in the laboratory on the drying curve. For instance, some manufacturers of moisture meters calibrate their device on concrete cubes. As the concrete cube dries, the meter is used to obtain a surface reading, and then the cube is weighed. Thus, the moisture meter is calibrated on the drying curve, relating the meter reading to the moisture content of the cube. Calibrating the meter surface reading after wetting the cube provides a different calibration curve.

3.6.3 *Rewetting of concrete*—Concrete placed in the field is often subject to surface wetting due to curing by adding water, sawcutting or grinding with water, rain, or cleaning

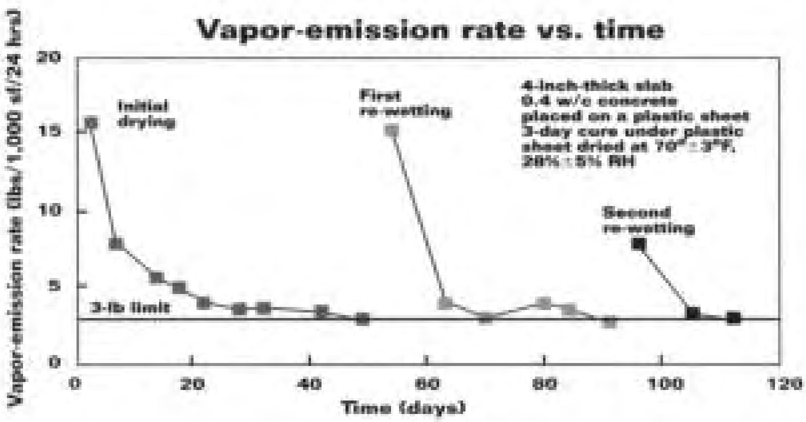

Fig. 3.6.3—Even with a low w/cm *and a 3-day cure under plastic sheeting, these slabs took approximately 7 weeks to dry to a 3 lb/1000 ft²/24 h (1.5 kg/100 m²/24 h) emission rate. After rewetting, the slabs took several weeks to again reach the 3 lb/1000 ft²/24 h (1.5 kg/100 m²/24 h) emission rate (Suprenant and Malisch 1998c). (Note: 1 in. = 25.4 mm; °F = [(°F – 32)/1.8] °C.)*

with water. The effect of repeated wetting on the time required to reach a given moisture vapor emission rate is shown in Fig. 3.6.3 (Suprenant and Malisch 1998c). The investigators simulated two separate rains, then measured the moisture vapor emissions from the concrete surface using calcium chloride tests. As expected, concrete absorbs moisture when wetted and then takes time (sometimes several weeks) to dry to the MVER it had reached before the wetting. The drying time needed to reach a given MVER is thus extended each time the concrete is wetted.

3.7—Moisture loss during drying

Concretes used in floor construction commonly have a water/cementitious materials ratio (*w/cm*) of approximately 0.50 (ACI 302.1R). Approximately 24 lb (11 kg) of water is needed to hydrate 100 lb (45 kg) of portland cement. This nonevaporable water is chemically combined in the hydration reactions. Approximately 18 lb (8.2 kg) of water for every 100 lb (45 kg) of portland cement is held in gel pores—the very small pores of cement hydration products (calcium-silicate hydrates)—and adsorbed on their surfaces. Larger capillary pores contain remnants of mixing water not consumed by hydration or adsorbed on hydration products. The capillary water evaporates first, followed by water in the gel pores.

If all the cement hydrated in a cubic yard (cubic meter) of concrete containing 600 lb (356 kg) of cement and 300 lb (178 kg) of mixing water, approximately 48 lb (28 kg) of water, or approximately 16% of the mixing water, would be present in the capillary pores (Mindess and Young 1981). Based on Brewer (1965), Suprenant and Malisch (1998c) calculated the amount of water lost by concrete with a *w/cm* of 0.50 in reaching the commonly specified moisture-emission rate of 3 lb/1000 ft²/24 h (1.5 kg/100 m²/24 h). The water loss was calculated as approximately 19% of the mixing water, slightly higher than the 16% that would be held in the capillary pores assuming complete hydration.

For a 4 in. (100 mm) thick slab, the concrete needs to lose approximately 0.6 lb/ft² (2.9 kg/m²) of water to be sufficiently dry before placing a floor covering (Suprenant and Malisch 1998c). Others (Harriman 1995; Kercheval 1999) have indicated that two to three times more water than shown by Brewer's (1965) experiments should be lost from the slab. Their analyses involve incorrect assumptions regarding how much water chemically combines with cement and how much is adsorbed in the gel pores.

CHAPTER 4—CONCRETE MOISTURE TESTING

4.1—Introduction

To provide warranties, the manufacturers of most types of flooring materials require moisture testing. Project specifications should describe required tests or refer to floor covering installation instructions. The following issues, however, should be addressed:

(a) Standard test method, if applicable
(b) Acceptable test methods
(c) Frequency and location of testing

(d) Environment (before and during the test)
(e) Surface preparation, if applicable
(f) Responsible testing party
(g) Acceptance criteria
(h) Interpretation of results

4.2—Standard guides and test methods

The current ASTM standard guides and test methods for moisture testing of concrete slabs are:

(a) ASTM D4263—Standard Test Method for Indicating Moisture in Concrete by the Plastic Sheet Method

(b) ASTM F1869—Standard Test Method for Measuring Moisture Vapor Emission Rate of Concrete Subfloor Using Anhydrous Calcium Chloride

(c) ASTM F2170—Standard Test Method for Determining Relative Humidity in Concrete Floor Slabs Using in situ Probes

(d) ASTM F2659—Standard Guide for Preliminary Evaluation of Comparative Moisture Condition of Concrete, Gypsum Cement and Other Floor Slabs and Screeds Using a Non-Destructive Electronic Moisture Meter

Moisture tests required by project specifications or manufacturer's recommendations are typically those found in the aforementioned ASTM standards. Occasionally, test methods used in Europe are included as well.

4.3—Qualitative and quantitative tests

4.3.1 *Introduction*—Testing methods used to evaluate the moisture condition of concrete slabs include both qualitative and quantitative procedures. Qualitative tests provide a general indication of moisture conditions, but do not give a quantitative measure of the amount of moisture. Quantitative tests provide a measured numerical value for the moisture condition, but not necessarily the moisture content by mass. Qualitative and quantitative procedures listed in ASTM F710 are as follows:

Qualitative tests	Quantitative tests
Plastic sheet test (ASTM D4263)	Electrical resistance test (No ASTM standard test method)
Mat bond test (ASTM F3311)	Electrical impedance test (ASTM F2659)
	Calcium chloride test (ASTM F1869)
	Concrete relative humidity test (ASTM F2170)

While not currently listed in ASTM F710, a quantitative calcium carbide test method used in Europe is occasionally specified in the United States.

4.3.2 *Plastic sheet test*—ASTM D4263 and ASTM F710 describe this test procedure as follows. Using 2 in. (51 mm) wide duct tape, an 18 in. (460 mm) square transparent polyethylene sheet, at least 4 mils (0.10 mm) thick, is taped tightly to the concrete surface; all edges should be sealed. The plastic sheet should remain in place for a minimum of 16 hours, after which the plastic is removed; the underside of the sheet and the concrete surface should then be visually inspected for the presence of moisture. Fingers should be wiped across the underside of the sheet or along the concrete surface to feel any moisture. Moisture on the concrete surface causes the surface to feel cooler, and often results in a darker surface color (Fig. 4.3.2a).

Another option is to use a moisture meter to check moisture at the surface of the slab before and after covering the slab surface with a plastic sheet for an extended period.

The plastic sheet test has been used for more than 50 years. However, the test has two limitations:

(a) Leaving the sheet in place for 16 hours does not provide enough time for the test to reflect the result of moisture movement from the bottom to the top of the slab. Thus, it indicates only what is happening at the surface at that point in time.

(b) Moisture under the plastic sheet may be more related to moisture condensation due to the slab surface being at the dew-point temperature rather than being related to moisture flow.

Fig. 4.3.2a—When moisture is present after the plastic sheet test has been conducted, the surface feels cooler and is often a darker color (Kanare 2005).

Fig. 4.3.2b—Even though plastic sheet tests can show no evidence of moisture, calcium chloride tests conducted on adjacent concrete can indicate moisture vapor emission rates as high as 13 lb/1000 ft²/24 h (6.3 kg/100 m²/24 h) (Suprenant 2003b; Kanare 2005).

Fig. 4.3.3—Mat test performed on sample (photo courtesy of S. Tarr).

Figure 4.3.2b shows two plastic sheet tests being conducted beside a calcium chloride test for comparison testing. Plastic sheet tests can show no evidence of moisture, while calcium chloride tests conducted adjacent to the sheets measure emissions as high as 13 lb/1000 ft^2/24 h (6.3 kg/100 m^2/24 h) (Suprenant 2003b). Although the practice may still be recognized by some manufacturers, the plastic sheet test does not give a reliable indication of the floor moisture condition (Kanare 2005; Suprenant 2003b).

4.3.3 *Mat bond evaluation tests*—In addition to a quantitative moisture test, some manufacturers also recommend a mat test (Fig. 4.3.3), as described in ASTM F3311. Using the specified adhesive and floor covering, a 2 ft (610 mm) square sample is applied to the concrete floor using the manufacturer's recommended surface preparation and installation procedure. The perimeter of each flooring sample is sealed using 2 in. (51 mm) wide duct tape. After the specified curing time has elapsed, both visual and physical testing are performed. If the adhesive is still wet, or very soft, that may indicate that the substrate is either too wet, non-absorptive, or a contaminant is present. If the floor covering is firmly bonded and removal of the covering with a putty knife or scraper reveals good adhesion, the substrate condition and preparation procedure may be considered acceptable.

While this test is not the definitive moisture test, it is a good method for evaluating concrete surface preparation and the worker's installation procedure. Because of this, it is advantageous to specify a mat test along with a more definitive moisture test. Just as with the plastic sheet test (ASTM D4263), the mat test can falsely indicate that the floor is ready for covering but will not falsely indicate that the floor is not ready for covering. If the mat is not well adhered, the floor moisture condition or surface preparation is problematic.

4.3.4 *Moisture meters*—Electrical resistance and impedance meters (Fig. 4.3.4) are used to measure moisture in concrete. Electrical resistance relates the moisture content to the measured electrical conductivity of concrete between the sensing pins or probes. Electrical impedance (ASTM F2659) relates the moisture content to the measured electrical AC impedance. Electrical impedance meters measure moisture in concrete to a depth of approximately 1 in. (25 mm).

Fig. 4.3.4—Electrical resistance and impedance moisture meters (photo courtesy of S. Tarr).

Electrical impedance meters can be useful for making a quick survey (similar to using a rebound hammer on concrete as described in ASTM C805/C805M) to determine where to place quantitative moisture tests. They can also be used to determine whether moisture problems are occurring around the perimeter of the floor or at the location of buried pipes that may be leaking. While pin-type meters aren't typically used, some underlayment manufacturers require their use to determine the moisture condition of their products.

Moisture meters are calibrated by the manufacturer and should be checked by the user. Check the manufacturer's calibration procedures that accompany the meter. Although the moisture meters read only to a depth of approximately 1 in. (25 mm), calibration curves may be developed by taking readings on, and simultaneously weighing, samples that are thicker than 1 in. (25 mm). The moisture content determined by weighing the sample is an average throughout the full sample thickness, so it may vary significantly with a sample thickness. Thus, a 1 in. (25 mm) thick sample could produce a meter calibration curve that differed significantly from a curve for a 6 in. (150 mm) thick sample.

4.3.5 *Calcium chloride tests*—The test kit for the quantitative calcium chloride test (ASTM F1869) consists of:

(a) A plastic dish containing 16 g (0.56 oz) ± 1 g (0.035 oz) of anhydrous calcium chloride and covered with a lid that can be sealed around the circumference with pressure-sensitive tape that does not absorb moisture, or a mechanical seal provided by a screw top or snap lid

(b) A flanged transparent plastic cover that has a preformed sealant strip attached to the flanges (Fig. 4.3.5a and 4.3.5b)

To conduct the test, the surface is first prepared by lightly grinding to remove all foreign substances (Fig. 4.3.5c) and to produce a surface profile equal to ICRI concrete surface profiles CSP 1 to CSP 2 (Fig. 4.3.5d). The dish, calcium chloride, lid, and tape are weighed to the nearest 0.1 g (0.004 oz). The starting weight, time, date, test location, and name of the person performing the test are recorded. The dish is then opened and placed on the prepared concrete surface. The plastic cover is placed over the dish and fastened to the concrete surface using the preformed sealant tape attached to the flanges. After 60 to 72 hours, a cut is made around the

Fig. 4.3.5a—Typical calcium chloride test kit for measuring moisture vapor emission rates (photo courtesy of C. McCall).

Fig. 4.3.5b—Moisture vapor emission tests used to determine precision and bias statement (Suprenant and Malisch 2000a).

plastic cover, and the dish is removed. The lid is replaced, attached with the pressure-sensitive tape, and the sealed dish is weighed again. The MVER is calculated based on the increased weight of the calcium chloride, test time, and surface area inside the plastic cover.

If the plastic cover is not tightly sealed to the concrete, the final result will not be valid. To check for an adequate seal, the top of the cover can be pushed down. If the seal is tight, no air will be heard escaping from under the dome and the cover will pop back up. If the seal is broken, air can be heard escaping and the cover will not return to its original position. Some testers use 2 in. (51 mm) wide duct tape to seal around the flanges to ensure an adequate seal.

Because calcium chloride MVER results are affected by ambient temperature and relative humidity (RH), record both these measurements at least at the start and completion of testing to enhance the interpretation of the test results. Data logging of ambient conditions throughout the test period is helpful in detecting changes that may have taken place between the starting and ending time.

4.3.6 *Concrete RH test*—To perform tests in accordance with ASTM F2170, an RH sensing probe (Fig. 4.3.6a) is inserted into a lined hole drilled into the concrete. Holes are drilled to the required depth using a rotary hammer drill with a carbide-tipped drill bit. For slabs drying from one side only, the hole depth should be 40% of the slab thickness. For slabs drying from both sides (suspended concrete slabs not on metal decks), the hole depth should be 20% of the slab thickness. A depth gauge is useful for determining the correct depth.

Fig. 4.3.5c—Surface preparation using grinder before installing a moisture vapor emission test (photo courtesy of P. Craig).

The holes are drilled dry, brushed, vacuumed, and a small-diameter nozzle used to vacuum the bottom of the drilled hole. A ribbed hole liner, intended to isolate the measurement to the bottom of the drilled hole, is inserted and a cap or stopper placed at the top of the liner. Currently, an RH measurement is made after allowing 24 hours for the air in the hole to achieve equilibrium with the concrete at the target depth. To make a measurement, the liner cap is removed and the RH probe inserted. The probe is connected to the meter and the sensor element of the probe allowed sufficient time to reach RH equilibrium with the captured air at the bottom of the hole (Fig. 4.3.6a and 4.3.6b). The time required to reach equilibrium depends on the type of instrument, condition of the concrete, and temperature stability. In most cases, after inserting the probe, a minimum of 1 hour is necessary to reach a measurement where no more than 1% drift in 5 minutes has occurred. The sensor measures RH to the nearest 1% and measures the temperature in the hole.

While not currently described in ASTM F2170, many testing technicians have historically installed probes for the entire test period to eliminate the waiting period.

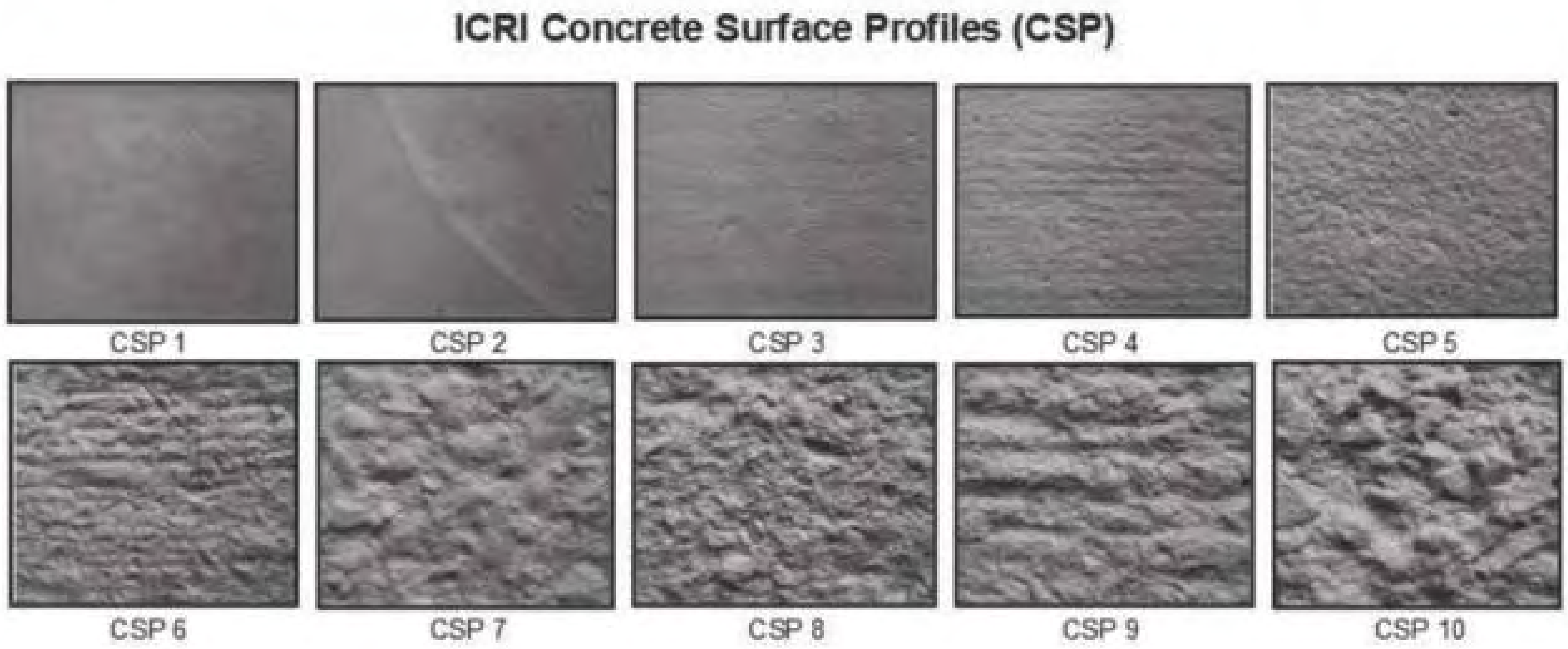

Fig. 4.3.5d—ICRI concrete surface profiles.

Fig. 4.3.6a—RH measurement in a floor slab (photo courtesy of P. Craig).

4.4—Test parameters

4.4.1 *Test frequency*—ASTM D4263, F1869, F2170, and F2659 all state the required number of tests. The required number of tests is as follows:

(a) ASTM D4263 (plastic sheet test) requires one test area per 500 ft² (46 m²) of surface area, or portion thereof, unless otherwise specified.

(b) ASTM F1869 (calcium chloride test) says to use the following guidelines to determine the number of test locations to be used simultaneously: three test locations for areas up to 1000 ft² (93 m²), and one additional test for each 1000 ft² (93 m²) or fraction thereof.

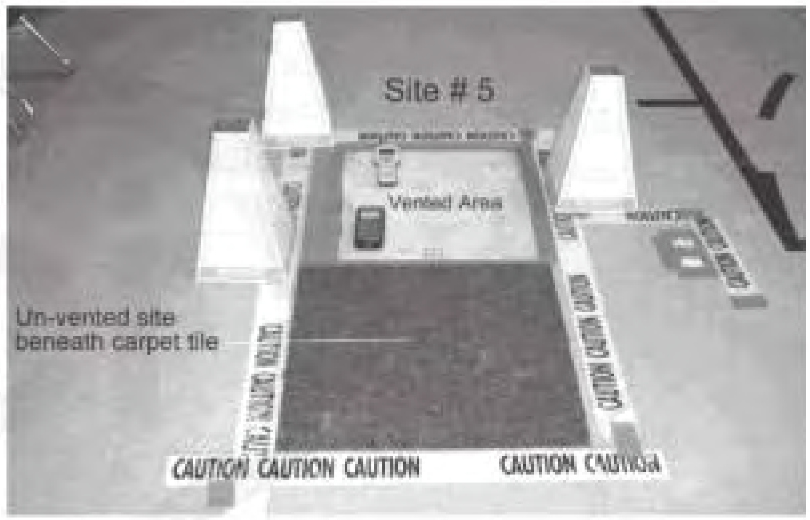

Fig. 4.3.6b—RH measurements being taken in a vented area (no floor covering), and an unvented area (covered by carpet tile) using equipment described in ASTM F2170 (photo courtesy of P. Craig).

(c) ASTM F2170 (concrete relative humidity test) says to perform three tests for the first 1000 ft² (93 m²), and at least one additional test for each additional 1000 ft² (93 m²).

(d) ASTM F2659 (electronic meter test) says to perform eight tests for the first 1000 ft² (93 m²), and five tests for each additional 1000 ft² (93 m²). The test method also says that numerous measurements are to be taken in close proximity to one another such as three to five readings within an area of 1 ft² (929 cm²) at each location.

Meeting the ASTM test frequency requirements for a 100,000 ft² (9290 m²) floor using ASTM F1869 or F2170 would require installing 102 tests. The rationale for this is that a 10 yd³ (7.6 m³) truckload of concrete covers approximately 800 ft² (74 m²) of a 4 in. (100 mm) thick floor. Thus, testing every truckload requires a moisture test every 1000 ft² (93 m²).

The testing performed on many projects does not comply with the ASTM test frequency requirements typically called for either directly, or by reference, in the project specifica-

tions. A practical approach that is being used on many projects is to first perform a lesser frequency of tests to track the drying progress of the slabs. If these pilot tests reach an acceptable level, the full frequency of tests should then be performed to conform to the ASTM requirement.

Conducting numerous tests does not guarantee an acceptable concrete moisture condition for floor coverings. A thorough understanding of what each of the tests actually measures, along with knowledgeable interpretation of the test results, is more helpful than conducting a large number of tests. A statistical sampling approach for evaluating the in-place moisture level would be preferable to specifying a test frequency based on having a test that attempts to represent every truckload of concrete.

4.4.2 *Test location*—Choosing the proper test locations is important. ASTM F1869 provides the following advice: "When conducting moisture emission tests, the test units should not be concentrated in an area but shall be located in various parts of the floor area. Tests shall be placed using the testing agent's judgment to represent areas of potential concern including the perimeter and center of the floor area".

Moisture meters can be used to quickly locate areas where potentially high moisture is present and further testing is warranted. The meters can be used to quickly survey many test locations and check different concrete placements such as along joints, near exterior walls, near water and drain lines under the slab, and other areas of potentially high moisture.

4.4.3 *Test environment*—The test environment is very important and especially so for tests that evaluate the concrete surface moisture condition. For surface moisture tests, such as the calcium chloride test, if the environment does not reflect normal operating conditions when the building is in service, the results will not accurately reflect the in-service moisture condition of the slab. If the normal operating conditions are not known, maintaining a temperature of 65 to 85°F (18 to 29°C) and an RH of 40 to 60% is needed for at least 48 hours before starting the test and throughout the test duration (ASTM F1869).

ASTM F1869, F2170, and F2659, all indicate what is considered an appropriate test environment. To allow for the meaningful interpretation of test results, the environmental conditions at least at the beginning and end of any type of moisture test should be reported.

Testing personnel and floor covering installers are often asked to test a concrete slab in an environment that is not appropriate for the test. As those performing moisture tests seldom have control over the environment, they should rely on the general contractor or construction manager to understand the need to provide a suitable environment for testing. The specifier should notify the general contractor of the need for an appropriate environment during moisture testing, and thus allow that activity to be included in the bid (Construction Specifications Institute 2000).

4.4.4 *Surface preparation*—The plastic sheet test, mat test, and calcium chloride test results can be affected by the surface preparation. Coatings, curing compounds, finishes, or other substances (such as oil or wax from spills or sweeping compound) can affect the rate of moisture dissipation and the adhesion of the finishes. ASTM F1869 requires that for each test a 20 x 20 in. (508 x 508 mm) area of concrete surface be lightly ground to remove any substance on the concrete surface that could impede the free emission of moisture from the concrete. When curing compounds or residual adhesive from a previous flooring installation is present, wait a minimum of 24 hours after surface preparation before installing the test kits. If the surface has not been previously covered for at least 30 days, it is acceptable to install the test kits immediately following surface preparation. Checking to see if water drops bead on the surface is the most frequently used field test to check for coatings and to determine whether the surface preparation is adequate. Water beads on surfaces that have coatings but is absorbed on porous open concrete surfaces such as those produced by grinding or shotblasting.

4.4.5 *Responsible testing party*—The floor covering installer has traditionally been responsible for taking moisture tests and determining when the concrete slab is ready to receive a floor covering. The installer may not always forward these results to the general contractor or construction manager, who may not always forward the test results to the design team. This is a crucial checkpoint in the decision-making process, and all parties should be aware of the test results. When the floor has not reached the desired moisture condition, the construction schedule is impacted by further waiting. Failing to wait may result in a flooring failure. Because all parties are likely to be involved in a dispute if there is a moisture-related flooring failure, it is best to notify all parties of the moisture test results.

It has been recommended that a qualified independent testing agency perform the moisture tests rather than the floor covering installer (World Flooring Covering Association 2001) because:

(a) An independent party provides an unbiased test result.

(b) An independent, certified moisture testing technician is typically more experienced in following ASTM test standards.

(c) Test reports from an independent testing company are more likely to be distributed to all parties, so all parties can consider the ramifications of the results.

The testing company should not be made responsible for the decision to place or not place the flooring based on the moisture test. Typically, testing companies are prohibited by the project specifications and their contract from making any interpretations or decisions regarding the meaning of a test result, and do not have the authority to accept or reject work.

When the project specifications require an independent testing agency to perform moisture tests, the flooring installer may also want to perform some tests as a quality-control check. If a moisture-related floor covering failure occurs, the ramifications for the flooring installers are such that it is prudent for them to have their own test results. Some general contractors are learning to perform moisture tests themselves, in part because they are on the site throughout the entire construction process and can control the building environment during the testing.

Table 4.4.6a—Typical limits for moisture vapor emission test (Resilient Floor Covering Institute 2022)

Moisture vapor emission rate	Floor covering materials
5 lb/1000 ft²/24 h (2.4 kg/100 m²/24 h) 80% RH	Vinyl composition tile Felt-backed resilient sheet flooring Porous-backed carpet Linoleum
3 lb/1000 ft²/24 h (1.5 kg/100 m²/24 h) 75% RH	Solid vinyl sheet flooring Vinyl-backed carpet Nonporous-backed carpet Cork Direct glue-down flooring
8 lb/1000 ft²/24 h (3.6 kg/100 m²/24 h) 85% RH	Modular floating rigid core floors (plank and tile)

Note: For moisture levels above these limits, check with the manufacturer for specific recommendations.

Table 4.4.6b—Maximum value of relative humidity in concrete (Finnish SisäRYL 2013)

Maximum relative humidity, %	Floor covering material
90	Plastic tiles Plastic carpet with no felt or cellular plastic base Linoleum
85	Plastic carpet with felt or cellular plastic base Rubberized carpet Cork tile with plastic film barrier Textile carpet with rubber, PVC, or rubber-latex coated Textile carpet made of natural fibers
80	Mosaic parquet on concrete
60	Parquet board with no plastic film between wood and concrete

It is now possible for project specifications to also include the requirement that moisture testing be performed by an independent, ICRI, Grade 1, Certified Moisture Testing Technician.

4.4.6 *Acceptance criteria*—Tables 4.4.6a through 4.4.6c show typical acceptance criteria based on different test methods. A number of floor covering manufacturers were surveyed in an attempt to determine the origins of the acceptance criteria for moisture vapor emission rate (MVER) (Craig 2003). The selection of an emission rate of 3 to 5 lb/1000 ft²/24 h (1.5 to 2.4 kg/100 m²/24 h) appears to have been based on historical observations and field experience. No laboratory data from a floor covering or adhesive manufacturer was presented at the time to establish the basis for the 3 or 5 lb/1000 ft²/24 h (1.5 or 2.4 kg/100 m²/24 h) limits.

Laboratory testing (Suprenant and Malisch 1999a) has shown that the adhesive strength decreases with an increase in the concrete's MVER. When these tests were conducted, however, there were no criteria for acceptable bond strength, and scatter in the test results did not indicate a clear dividing line between acceptable and nonacceptable adhesive bond strength.

Table 4.4.6c—Recommended moisture contents for subfloors for use with wood flooring (Sika 2003)

Moisture content	Subfloor material
Maximum 2.5%	Concrete floor without in-floor heating
Maximum 1.5%	Concrete floor with in-floor heating
Maximum 0.5%	Gypsum floor without in-floor heating
Maximum 0.3%	Gypsum floor with in-floor heating

Field experience and research studies (ASTM Committee F06 study) have found that reaching a concrete internal RH of 75% within the schedule of many construction projects may not be possible. Many floor covering systems do not require that the concrete in-place RH level be as low as 75%. Careful review and consideration of the product manufacturer's moisture level requirements, the project schedule, and the additional costs that may be required if these requirements are not achieved (that is, moisture mitigation treatments) should be part of the project review and specification process.

The Concrete Society (2004) reported on testing that attempted to correlate moisture in the concrete with floor covering performance and concluded that: "The evidence presented suggests that there is no relationship between the relative humidity of a concrete base or screed and adhesion of resilient floor coverings."

While moisture criteria are often used, the relationship between these criteria and floor covering performance is not well understood.

4.4.7 *Using multiple test methods*—Most project specifications require that the flooring manufacturer's recommendations for moisture testing be followed. In many cases, flooring manufacturers require that only one specific type of moisture test be performed, or the requirement is stated as an option between testing the MVER (ASTM F1869) and concrete internal RH (ASTM F2170). More than one moisture test method may be needed to accurately determine the moisture-related suitability of a concrete subfloor, along with a thorough understanding of the slab design system. Using multiple test methods, however, can result in potential conflicts when acceptable results are recorded with one test method but not with the other. For instance, the concrete internal RH tests may record an acceptable level when the MVER tests do not, or vice versa. When multiple tests are specified, the governing criteria for acceptance should be clearly defined. To ensure a reliable flooring installation, interpretation of test results requires a thorough understanding of the test methods, their limitations, and the slab design system.

4.4.8 *Modified surface testing*—Instead of measuring surface moisture in a state that does not reflect the actual condition that the flooring materials will be exposed to, some moisture testing specialists precover the prepared test areas with a low-permeance material such as poly- or rubber-backed carpet tile for a minimum period of 2 weeks prior to testing. Precovering the test sites simulates the effect of the floor covering being installed and allows a more accu-

rate estimation of the moisture condition to which the floor covering will be exposed when it is installed. When precovering is performed, it is important to achieve and maintain uniform contact of the plastic sheet or carpet tile with the concrete surface.

4.4.9 *Testing with no vapor retarder directly under concrete*—For any moisture test, the acceptable moisture condition is based on the assumption that no water (moisture) enters the slab from the bottom. Even if moisture testing results in values that are considered acceptable, these levels will increase over time if moisture is not prevented from entering the slab from below. For instance, tests have shown that, for slabs drying only from the top, RH measured at a depth equal to 40% of the slab thickness is approximately the same as the equilibrium RH attained after the floor covering is installed (Hedenblad 1997). This isn't the case if water is entering the slab from the bottom, so a vapor retarder is needed directly beneath the slab. Without an effective vapor retarder directly beneath the slab, the results of any moisture test cannot be considered a true indicator of the moisture condition that will develop once the floor is covered.

Acceptance limits for all moisture tests are established based on the assumption that an effective vapor retarder is present directly below the slab. With adequate moisture, protection directly below the slab moisture in the slab will redistribute uniformly in the slab after the flooring is installed, but the supply of water will not be replenished from an external source.

For slabs not placed on a vapor retarder, the reliability of any moisture test taken at the surface or with probes in the concrete should be questioned. Moisture tests performed on a concrete slab-on-ground that is not in direct contact with an effective vapor retarder do not represent what the moisture level will become in the slab once the floor covering or coating is installed. In Publication 596 of the National Academy of Sciences, statements from the Building Research Advisory Board support that the relative humidity below a slab-on-ground should be expected to be 100% regardless of the depth of the water table or the amount of precipitation. Without an effective vapor retarder directly below the slab, moisture in the ground below is free to enter the slab, which, over time, will increase the measured levels of moisture in the slab which can lead to flooring and coating problems.

ACI 302.1R recommends that a concrete slab to receive a moisture-sensitive floor covering be placed directly on a vapor retarder. Previous versions of this document recommended placing a granular layer between the vapor retarder and the concrete. However, if a granular layer is placed between the vapor retarder and the slab, the fill material may take on additional water from rainfall, wet-cutting, wet-curing, or compaction. In addition, a layer of fill material sandwiched between the vapor retarder and the concrete can serve as a conduit for moisture entering the fill layer from openings, punctures, tears, or penetrations. Moisture present or increasing within the fill layer, from any source, can increase the moisture level in the slab, which can ultimately lead to a flooring problem. A moisture test should not be used to predict future concrete drying behavior, to provide evidence that moisture criteria are satisfied, or to establish expected floor covering performance if the concrete slab has not been placed directly on a vapor retarder.

4.5—Underlayment testing

Specifiers should verify that the underlayment/leveling products they specify are compatible with the concrete moisture content, floor covering adhesive, and flooring before accepting a product for use under a floor covering. Obtaining the adhesive and floor covering manufacturer's written permission before using an underlayment or patching product can help to ensure that the warranty will still be in effect.

Some underlayment manufacturers recommend moisture tests for use with their products while others do not. When moisture testing is recommended, most manufacturers do not recommend using the calcium chloride MVER test or internal RH test to validate the dryness of their product. Some recommend using a plastic sheet test, an electrical resistance moisture meter, or the calcium carbide test method.

4.6—Comments on moisture vapor emission rate tests

The MVER test is still being required by some floor covering and adhesive manufacturers. Some specific issues investigated with respect to this test are:

(a) **Test duration effects**—ASTM F1869 requires a test duration between 60 to 72 hours; however, some tests are cut short. When the concrete is drying, tests conducted for a shorter period will typically yield higher emission rates than those conducted for longer test periods (Suprenant 2003e). One investigator conducted calcium chloride tests at 24, 48, and 72 hours. If the concrete was drying, tests at the later ages produced lower emission rates. If the emission rates did not decrease, the investigator checked for problems such as moisture being present beneath a slab that wasn't placed on a vapor retarder (*Concrete Repair Digest* 1997).

(b) **Effect of tests conducted over holes drilled in the concrete surface**—At one time, a calcium chloride test kit manufacturer recommended drilling three holes in the concrete and placing the test kit over the holes to evaluate the moisture condition at a greater depth. To determine the effects of this testing method, tests were conducted on a concrete surface with no holes, and with three 1/2 in. (13 mm) diameter holes drilled to 1/2, 1, and 1-1/2 in. (13, 25, and 38 mm) depths. The tests were repeated 10 times, and no effect of the drilled holes was found (Suprenant 2003e).

(c) **Effect of moisture inside the plastic cover**—Some investigators have suggested that the initial RH inside the plastic cover affects the test result. In one study (Suprenant 2003e), the MVER was measured under two different ambient RH conditions by placing a plastic cover over a calcium chloride dish on glass plate. Because the plate was impermeable, the MVER measured by the test would be an indicator of the initial RH effect. The measured average MVERs inside the test kits were 0.84 and 0.25 lb/1000 ft^2/24 h (0.41 and 0.12 kg/100 m^2/24 h) for an RH of 74 and 33%, respectively. This indicated that a correction factor might

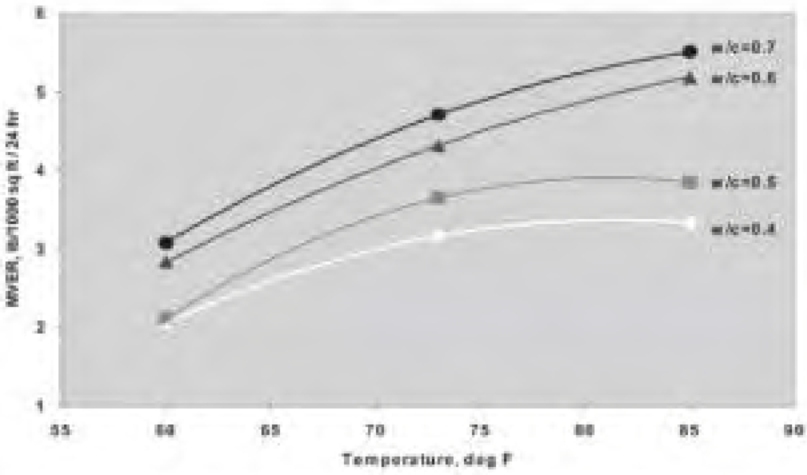

Fig. 4.6—Effect of temperature on calcium chloride emission tests for different concretes (Kanare 2005). (Note: °F = [(°F – 32)/1.8] °C; 1 lb/1000 ft²/24 h = 0.488 kg/100 m²/24 h.)

be required to account for moisture initially present in the air inside the plastic cover. RH measurements made with a surface-mounted hygrometer inside the plastic cover showed that the calcium chloride absorbed all the moisture under the plastic cover within a few hours. Further RH measurements were made inside a plastic cover that was sealed to concrete with an initial MVER of 4.5 lb/1000 ft^2/24 h (2.2 kg/100 m^2/24 h). The initial RH inside the plastic cover was approximately 44%. The RH rose to approximately 50% and remained at that level until the test was completed at 72 hours. For MVERs in the range of interest, usually 3 to 5 lb/1000 ft^2/24 h (1.5 to 2.4 kg/100 m^2/24 h), it appears that the moisture condition under the plastic cover at the start of the test is approximately the same as it is at the end of the test. Thus, no correction is needed (Suprenant 2003e).

(d) **Effect of test environment**—Figure 4.6 shows the results of MVER tests on concrete with different *w/c* and at different temperatures (Kanare 2005). Note that the emission rate varies by approximately 1 lb (0.5 kg) or more in the 65 to 85°F (18 to 29°C) temperature range that is permitted by ASTM F1869. The effect is greatest for concretes with *w/c* larger than 0.5.

(e) **Test as a measure of concrete quality**—The MVER test does not measure a fundamental concrete property and should not be used to evaluate the concrete (ASCC 2005; Suprenant 2003e). Measurement of the MVER by ASTM F1869 is an indication of moisture present and emitting from the surface region of the slab only. While the information this test method provides can be valuable, a MVER value alone is considered by many as insufficient information upon which to base a flooring installation decision.

CHAPTER 5—CONCRETE pH TESTING

5.1—Introduction

Historically, most flooring and adhesive manufacturers required pre-installation pH testing of the concrete slab surface due to the potentially damaging effect that a highly alkaline solution such as concrete porewater can have on the adhesive. The requirement and procedure for pre-installation pH testing was also formerly included in ASTM F710. In 2021, the requirement for pre-installation pH testing was removed from ASTM F710 due to the potentially misleading results that can be obtained by introducing an external source of liquid water that may or may not ever be present in sufficient quantity within the concrete to create and maintain a high-pH solution.

Testing the pH level of wet adhesive or fluid below a failed flooring installation is, however, a valuable tool in a forensic investigation.

Manufacturers who wish to continue the pre-installation practice of pH testing are to provide instruction as to how the test is to be performed, and what is considered an acceptable pH level.

The pH is a measure of hydrogen ion concentration and indicates the acidity or alkalinity of a solution. Neutral solutions, such as distilled water, have a pH of 7. Values above 7 indicate solutions of increasing alkalinity, and values below 7 indicate solutions of increasing acidity. Because pH is a log scale based on 10, a solution with a pH of 3 has a hydrogen ion concentration 10 times that of a solution with a pH of 4, and 100 times that of a solution with a pH of 5. A pH measurement, however, is not a measurement of the total alkalinity within the concrete.

When portland cement hydrates, the calcium silicates react to form calcium silicate hydrates and calcium hydroxide [$Ca(OH)_2$]. The $Ca(OH)_2$ provides a substantial buffer for the pore solution, maintaining the pH level at approximately 12.6, which is that of the saturated $Ca(OH)_2$ solution. The pH can initially be higher than this value (typically up to 13.5) because of the presence of potassium and sodium hydroxides (KOH and NaOH), which are considerably more soluble than $Ca(OH)_2$. These alkalis are present in limited quantities, however, and any carbonation or pozzolanic reaction rapidly reduces the pH to approximately 12.6.

5.2—Carbonation

As portland cement hydrates, calcium hydroxide and other alkaline hydroxides are formed. The pH of wet concrete is extremely alkaline, typically around pH of 12 to 13. The surface of concrete will naturally react with atmospheric carbon dioxide to produce calcium carbonate in the hydraulic cement paste, which reduces the pH of the surface. Results in the range of pH 8 to 10 are typical for a floor with at least a thin layer of carbonation (approximately 0.04 in. [1.0 mm]).

In concrete terminology, carbonation is the reaction of carbon dioxide (CO_2) in the atmosphere with moisture and alkaline components of the cement paste. Calcium compounds in the concrete produce calcium carbonate as a result of carbonation. Because the reaction proceeds in solution, the first indication of carbonation is a decrease in pH of the pore solution to 8.5. Carbonation generally proceeds in concrete as a front; beyond which the concrete is not affected and the pH is not reduced (Fig. 5.2).

In one study, mean carbonation depths ranged from 1/8 to 3/8 in. (3.2 to 9.5 mm) for concrete specimens with *w/c* between 0.55 and 0.64, cured in water for 7 days, and then stored in the laboratory at 50% relative humidity (RH) for a year. Mean carbonation depths for concretes with *w/c* from 0.40 to 0.45, cured and stored as previously described, were

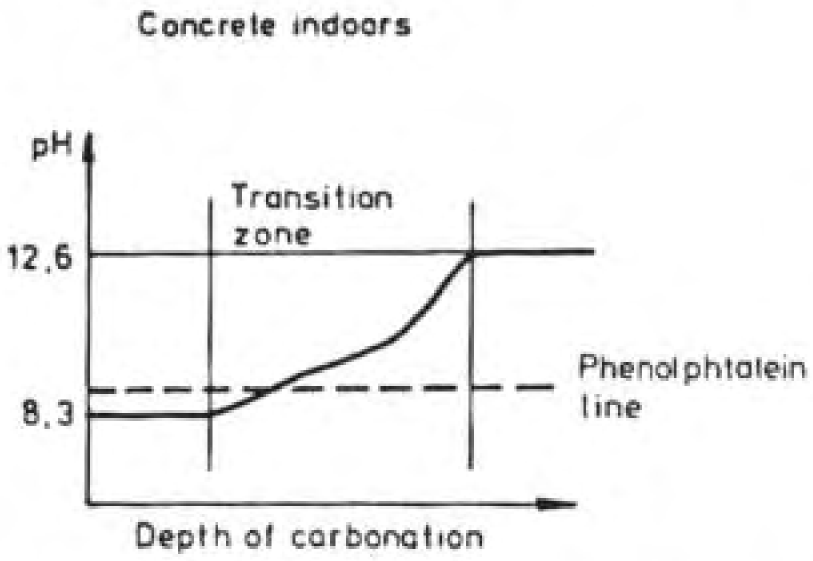

Fig. 5.2—Typical carbonation front showing carbonated concrete at pH of 8.3 and transition zone to uncarbonated concrete at pH of 12.6 (Tuutti 1982).

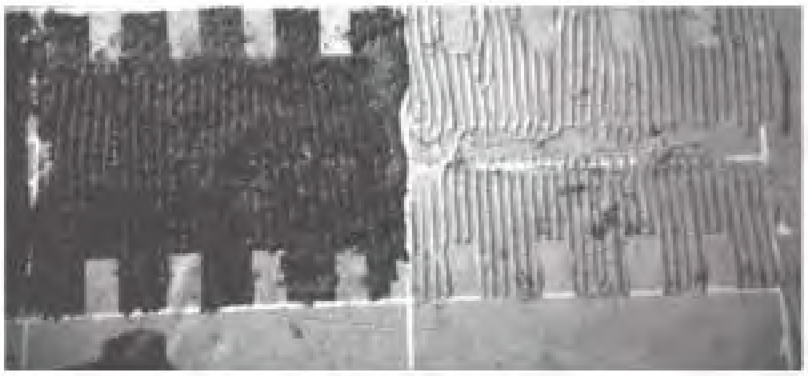

Fig. 5.3—pH tests conducted at various time intervals to determine the effect of adhesive water on pH. The concrete surface was initially at pH of 9 but rose quickly to 11.5 as adhesive water brought the alkalis into solution (Suprenant 2003c).

not deeper than approximately 1/8 in. (3.2 mm) even after 10 years of exposure (ACI 222R).

5.3—Adhesive water

Water in a water-based flooring adhesive can have an immediate effect on a pH measurement of the concrete surface (Suprenant 2003). This effect was studied by spreading a water-based adhesive on a dry concrete slab that had an initial pH of 9. Flat plastic strips, 1 x 2 in. (25 x 51 mm), were placed on the surface before applying the adhesive, then removed to leave bare concrete surfaces after the adhesive was applied (Fig. 5.3). At 15-second intervals, the pH of the bare concrete surface was measured with pH indicator strips. A few minutes after the adhesive had been applied, the surface pH rose from 9 to 11.5. This indicated that alkalis had been brought into solution quite quickly, exposing the adhesive to a high pH environment that was unrelated to concrete mixing water or external moisture sources other than the adhesive. Because water-based adhesives have been used successfully on many projects, the short-term exposure to a high-pH solution appears to be well tolerated by most adhesives, especially if the surface of the concrete is porous and the internal relative humidity of a slab placed directly over an effective vapor retarder is 85% or lower.

CHAPTER 6—FLOOR COVERING AND ADHESIVE MANUFACTURER'S RECOMMENDATIONS

6.1—Introduction

The architect and engineer should communicate to ensure that the Division 3 requirements for concrete floor slabs are compatible with the Division 9 requirements for floor coverings. Project specifications should provide specific information concerning the type of below-slab vapor retarder, its location beneath the slab, slab curing method, what types of moisture tests are to be performed, and the required results and the concrete subfloor surface preparation requirements. The engineer should not design a slab-on-ground or a suspended slab without considering the type of floor covering to be used and its requirements. Ideally, the design team will also include a flooring consultant and the floor covering manufacturer. The project team may need input from several floor covering manufacturers to allow for differences in product requirements.

When preparing specifications for different flooring applications, it is not advisable to rely solely on phrases such as: "Prepare the concrete surface and install flooring in accordance with the manufacturer's instructions." In some cases, flooring manufacturers' instructions do not cover all the requirements necessary to ensure a successful installation.

Because some floor covering warranty requirements have multiple disclaimers or exclusions, the design team should get written approval of their final specifications from all adhesive and floor covering manufacturers that are included in the project specifications.

6.2—Manufacturer's recommendations

Floor covering and adhesive manufacturers give specific requirements that should be met to obtain their product warranties. Some deal with design issues, such as the need for a vapor retarder or barrier. Others relate to slab moisture and pH levels and concrete surface preparation. The design team should review the specific requirements for the flooring and adhesive products specified and consider in advance if these requirements can realistically be met within the project schedule. If the schedule, location, or other anticipated influences make it unreasonable to expect the concrete to dry naturally to the required level, a preemptive, or contingency moisture mitigation strategy should be included in the project specifications and bid process.

Manufacturers typically provide requirements related to:

(a) Vapor retarder
(b) Concrete properties or materials
(c) Curing
(d) Surface finish
(e) Floor flatness
(f) Moisture limit
(g) pH limit
(h) Surface preparation
(i) Repair

6.2.1 *Vapor retarder*—Most flooring manufacturers and flooring industry guidelines require the use of a vapor retarder beneath concrete slabs to receive moisture-sensitive finishes.

The design team may need to provide the following information to the manufacturer of the flooring materials to determine whether the proposed vapor retarder and installation is appropriate for use with the flooring material(s) specified:

(a) Properties of the vapor retarder (perm rating, puncture resistance, and tensile strength)

(b) Minimum thickness of the vapor retarder

(c) Location or placement of the vapor retarder

(d) Installation of the vapor retarder (required laps, treatment at penetrations, repair of punctures)

6.2.2 *Concrete materials and properties*—Some floor covering and adhesive manufacturers provide guidance on concrete materials and properties. Unfortunately, in some cases, this information does not always reflect what is known to be best concrete practice. Some manufacturers provide recommendations on concrete strength, slump limits, water content, and selection of materials. A few suggest following recommendations in ACI 302.1R. However, while ACI 302.1R does provide valuable information, the document does not cover the topic in detail. Other recommendations on concrete materials and properties often conflict with data provided by others (Brewer 1965; Hedenblad 1997; Kanare 2005; Suprenant 2003a,b).

The majority of floor covering and adhesive manufacturers provide recommendations for concrete materials and properties that are based on one concern: drying. However, the designer should consider and balance multiple objectives that include providing the needed concrete workability, finishability, strength, curing, minimizing cracking and curling, surface tolerance, and the time needed for drying.

6.2.3 *Curing*—Curing is essential to the proper development of concrete strength and surface integrity. However, how the finished concrete surface is cured can have a significant effect on drying time and surface preparation costs. Membrane-forming curing compounds have been used for years as a practical, inexpensive means of curing a concrete slab surface. However, curing compounds delay the start of slab drying and most flooring manufacturers, and ASTM F710, require that any type of curing compound be removed prior to the flooring material being installed. Depending on the type of curing compound used, the cost and effort needed to remove the material from the concrete surface can be significant. Because of this concern, when floor coverings are involved, cover curing methods are often employed. Cover curing methods include dry wet-strength curing paper, layflat polyethylene, or fabric-backed polyethylene if a wet-curing method is called for.

6.2.4 *Surface finish*—Most flooring manufacturers prefer a smooth but nonburnished concrete finish, free of trowel marks or ridges. The design team should consider the following when specifying a surface finish:

(a) Will the adhesive be placed directly on the specified surface finish or will surface preparation be required?

(b) How will the finish affect the drying time?

(c) If surface preparation is required, is the initial finish important?

(d) How many finishes will be required when more than one type of floor covering is to be installed in a building?

(e) To minimize costly, small, multiple placements, can a single surface finish be applied to a large concrete placement and be compatible with the requirements for most of the floor coverings to be installed on that placement?

6.2.5 *Floor flatness*—Floor covering manufacturers generally specify a floor flatness requirement. In Division 9, that flatness is usually specified as a gap under a straightedge, which is not consistent with the F-number specification or measuring system that may be called for in Division 3. F-number specifications require the floor flatness be measured within the first 72 hours after placement (ASTM E1155) whereas the manufacturer's floor flatness is typically measured when the flooring installer arrives on site. The design team should consider the type of flooring to be installed, its required floor tolerance, and how that tolerance is to be achieved and maintained. The floor covering installer should be advised that the concrete contractor is responsible only for meeting the tolerance requirements specified for the concrete work. The specifier should establish an allowance in the floor covering installer's contract to address any tolerance differences that exist between the Division 3 and Division 9 specifications.

6.2.6 *Moisture condition*—The floor covering manufacturer provides limits on the moisture condition of the slab prior to installation of the covering. A maximum value for the MVER, as measured by the calcium chloride test, and a limit of the concrete's internal relative humidity (RH) (ASTM F2170) are the most common requirements. On occasion, other types of moisture tests are called for. These tests may include testing using an electronic moisture meter (ASTM F2659), calcium carbide test, or the plastic sheet test method (ASTM F4263). It is not possible to establish any correlation among results of these different test methods. Because of this, the design team should use the manufacturer's recommended test methods and test-result limits, and, if necessary, supplement these tests with others to provide adequate information upon which to base an installation decision.

6.2.7 *pH*—Most adhesive manufacturers require a maximum value or range for the pH of a concrete surface to receive a floor covering. Typical limits are between 9 and 10, with a few at 7 and a few above 10. The requirement for pre-installation pH testing has, however, been removed from the mandatory content of ASTM F710-21. In the non-mandatory Appendix section of F710-21, it states "If the design team, or manufacturer of a flooring material, adhesive, or underlayment has a requirement for pH testing their method of testing and their acceptance levels are to be described in their sub-floor evaluation specifications and their method is to be followed."

Concrete surfaces can easily carbonate to reach a pH of 10, and a pH value of 9 is possible with a longer waiting time. A pH requirement less than 9, however, is unreasonable and a pH of 7 is impossible to achieve on an untreated or uncontaminated bare concrete surface. The design team should decide, and manufacturers should also state, if the pH requirement applies to concrete before or after surface prep-

aration. Most surface preparation will remove the carbonated concrete skin and result in a higher pH.

6.2.8 *Surface preparation*—Some flooring or adhesive manufacturers' instructions require removing all contaminants (dust, solvent, scaly paint, wax, oil, grease, asphalt, sealing compounds, and old adhesive) plus curing, hardening, and bond-breaking compounds by mechanical methods such as abrasive blasting. Still others recommend power sanding the surface, or power washing it to remove contaminants and roughen the surface. Some manufacturers recommend neutralizing the surface with acid, then flushing it thoroughly with water. Any preparation procedure that adds water to the floor, such as power washing or acid etching, changes the moisture condition and increases the time needed to reach a given moisture limit.

If the concrete surface is shotblasted after a desired moisture emission rate is achieved, removal of the dense, carbonated layer may increase the MVER above that previously measured. As a general practice, moisture tests should be taken on a concrete surface that reflects the final prepared stage before installation of the flooring material or smoothing or leveling compound. When the concrete surface is opened by grinding or shotblasting, additional drying time for the concrete surface will likely be required to allow the concrete surface to carbonate to an acceptable pH level.

Acid etching should not be used to prepare a surface for flooring because too much water is needed to neutralize the acid. Although it is occasionally recommended as a technique for lowering the pH, the pH will increase with time.

6.2.9 *Repairs*—Almost every floor requires some repair before floor covering installation, including:

(a) Crack repair
(b) Spall repair
(c) Curling repair
(d) Joint filler repair
(e) Joint stabilization
(f) Surface grinding
(g) Underlayment leveling or smoothing application

Underlayments are particularly important, as they are used on most projects. They should be compatible with the concrete surface, adhesive, and floor covering. The moisture limits and pH requirements for underlayments should not be more restrictive than those for the surrounding concrete, or they may delay the construction schedule.

The design team should ask the floor covering and adhesive manufacturer to review their floor repair procedures and products to make sure they are compatible and that the warranty is still in effect over the repaired areas.

6.3—Dealing with multiple floor covering requirements

Owners and architects often specify multiple floor covering products in facilities such as retail stores, schools, and clinical facilities. Concrete surface-finish requirements, however, can be different for each product. Table 6.3 shows

Table 6.3—Concrete surface criteria

Organization/document	Flooring type	Floor finish	Flatness	Levelness	Comments
ACI 302.1R	Thick-set tile	—	F_F 20	F_L 15	All concrete slabs
	Carpet	—	F_F 25	F_L 20	All concrete slabs
	Thin-set flooring	—	F_F 35	F_L 25	Slabs-on-ground
	Thin-set flooring	—	F_F 20	F_L 15	Suspended slabs
ACI 301	All flooring types	Troweled finish	F_F 20 5/16 in. in 10 ft	F_L 15	For slabs specified as troweled finish
ASTM F710	Resilient flooring	—	3/16 in. in 10 ft	None	Requires no defects that telegraph through
Tile Council of America ANSI A 108	Thin-set tile	Hard trowel/broom	1/4 in. in 10 ft 1/16 in. per ft	—	—
	Thick-set tile	None required	1/4 in. in 10 ft	—	—
National Terrazzo and Mosaic Association NTMA 09 66 13.19: 2012	Bonded	Broom finish	1/4 in. in 10 ft	—	—
National Terrazzo and Mosaic Association NTMA 09 66 13.13:2012	Sand cushion	Float finish	1/4 in. in 10 ft	—	—
National Terrazzo and Mosaic Association NTMA 09 66 23.16:2019	Epoxy terrazzo	Light steel trowel	F_F 30/15	F_L 20/10	—
Resilient Floor Covering Institute (1995)	Resilient flooring	Hard trowel/smooth	5/16 in. in 10 ft	—	—
Carpet and Rug Institute CRI 104	Carpet	None	None	None	Has no requirements
Maple Flooring Manufacturers Association (2015)	Gym floors	Troweled smooth	1/8 in. in 10 ft	—	—
National Wood Flooring Association (NWFA/NOFMA) "Wood Flooring Installations Guidelines"	Solid and engineered wood floors	CSP1-CSP4	1/8 in. in 6 ft or 3/16 in. in 10 ft	NA	—

Note: 1 in. = 25.4 mm; 1 ft = 0.3 m.

floor finish and tolerance requirements as recommended by ACI, ASTM, and various flooring organizations. If only one product is used, Division 9 specifications can match that product's requirements. The issue, however, isn't that simple if multiple products are used.

To get the best price for owners and to meet their schedule on larger contracts, contractors generally place 25,000 ft^2 (2300 m^2) or more of concrete per day. It is not feasible to have the concrete contractor meet separate floor tolerances and finish requirements for every area where a different floor covering product will be used. In some cases, the owner hasn't made the flooring product choices for different locations before the concrete slab is placed. The architect and engineer should balance the floor finish and tolerance needs of the floor covering products.

Based on Table 6.3 recommendations, a compromise for use in Division 9 might be to specify a 1/4 or 3/16 in. (6.4 or 4.8 mm) gap under a 10 ft (3 m) straightedge, and a hard trowel finish. For floor covering products that require a different flatness or finish, the specialty floor covering contractor might be instructed to patch, grind, or shotblast the floor as needed. This instruction would need to be covered in Division 9 under the scope of work.

CHAPTER 7—DRYING OF CONCRETE

7.1—Introduction

Concrete slabs should dry to a prescribed level before a floor covering, adhesive, or coating material can be installed. Both designers and contractors are concerned with the performance of the floor covering once it is installed and should consider the time and conditions that will be needed to enable the concrete slab to dry to an acceptable level. Drying of concrete is therefore a fundamental issue when the design team prepares specifications and when the construction team prepares schedules.

The normalweight concrete drying studies cited in this document include those by Brewer (1965), Abrams and Orals (1965), Hedenblad (1997), and Suprenant and Malisch (1998a). Results of these studies are used to illustrate the drying behavior of concrete.

7.1.1 *Study summaries*—Brewer (1965) tested 141 specimens made from 29 different concrete mixtures that were moist-cured for 7 days. The *w/c* by weight ranged from 0.4 to 1.0. The 4 in. (100 mm) thick concrete specimens, exposed to 50% relative humidity (RH) and 70°F (21°C) temperature at the top, were weighed as they dried with the following exposures: bottom sealed, bottom exposed to water vapor, and bottom in contact with water.

Suprenant and Malisch (1998a) tested 2, 4, 6, and 8 in. (51, 100, 150, and 200 mm) thick, 3 ft (910 mm) square concrete slabs made with *w/cm* of 0.31, 0.37, and 0.40 and cured under plastic sheeting for 3 days. The slabs were stored indoors at a RH of 28 ± 5% and a temperature of 70 ± 3°F (21 ± 2°C). They measured water-vapor emission in accordance with ASTM F1869.

Abrams and Orals (1965) tested 3 ft (1 m) square concrete slabs that were 6 in. (150 mm) thick and made with a *w/c* of 0.6. RH was measured at different depths in the slab while both sides were exposed to a temperature of 73 ± 2°F (23 ± 1°C) and RH of 10, 35, 50, and 75%. Hedenblad's (1997) used RH as a measure of moisture condition for concretes of varying ages and subjected to differing drying environments.

7.2—Concrete drying with no external source of moisture

Brewer's (1965) results for concrete specimens dried from one side only and with the bottom sealed are shown in Fig. 7.2a. Brewer reported the drying rate in grains/ft^2/h (grains/m^2/h), but the data have been reformatted in lb/1000 ft^2/24 h (kg/100 m^2/24 h), which is the most commonly used measure of moisture emission rate (Suprenant 1997). As indicated in Fig. 7.2a, concrete dries initially at a rapid rate, as shown by the steep downward slope of the curves, but the slope then flattens markedly. Because the drying curve flattens markedly, much of the waiting time for concrete to reach the commonly specified 3 to 5 lb/1000 ft^2/24 h (1.5 to 2.4 kg/100 m^2/24 h) emission rate is during the final drying stage.

Brewer (1965) found that the *w/c* was the most important factor affecting time required to reach specified emission rate. Table 7.2 shows the drying time in days to reach

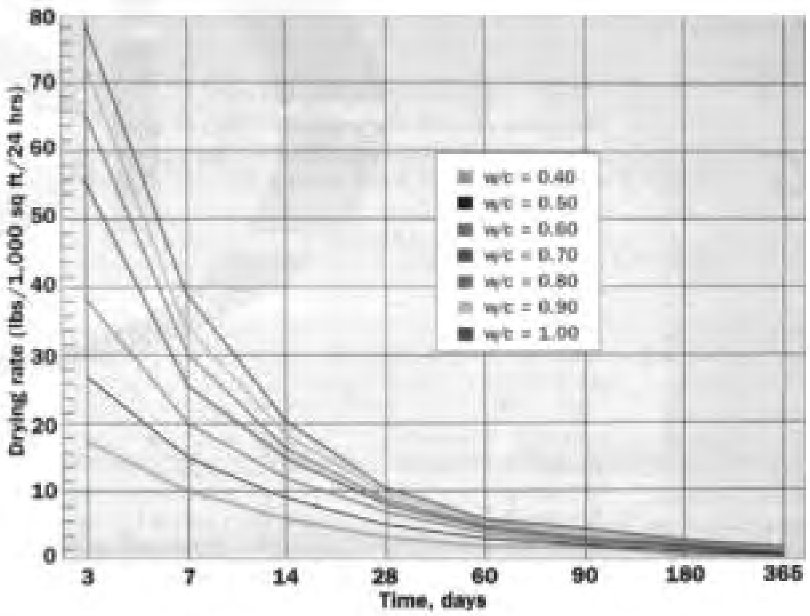

Fig. 7.2a—Drying curves for concretes at different w/c based on Brewer (1965) data on moisture vapor emission rates (Suprenant 1997). (Note: 1 lb/1000 ft²/24 h = 0.488 kg/100 m²/24 h.)

Table 7.2—Drying time to reach 3 lb/1000 ft^2/24 h (1.5 kg/100 m^2/24 h), days

w/c	Drying—one side	Exposed to vapor	In contact with water
0.4	46	52	54
0.5	82	144	199
0.6	117	365	>365
0.7	130	>365	>365
0.8	148	>365	>365
0.9	166	>365	>365
1.0	190	>365	>365

3 lb/1000 ft²/24 h (1.5 kg/100 m²/24 h). Concrete with a *w/c* of 0.5 (approximately a 4000 psi [28 MPa] strength level) took 82 days to reach a 3 lb (1.5 kg) rate. Concrete with a *w/c* of 0.6 (approximately a 3000 psi [21 MPa] strength level) took 117 days to dry to reach the 3 lb (1.5 kg) rate. Note that these results were for laboratory specimens drying at 50% RH and 70°F (21°C). In the field, under conditions of varying temperature and humidity, drying times would vary. Figure 7.2b shows time needed for concretes with differing *w/c* and curing conditions to dry to an 85 or 90% internal RH level.

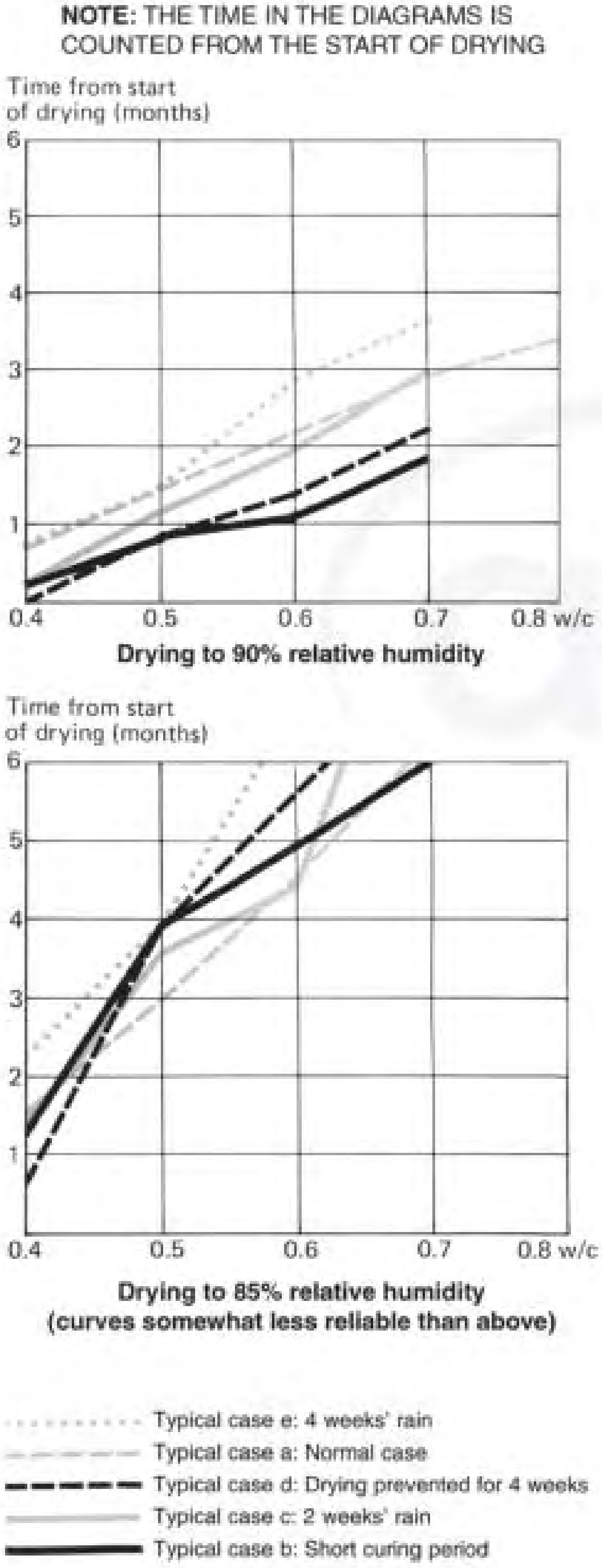

Fig. 7.2b—Effects of w/c *and curing method on time needed to reach either 85 or 90% internal RH at a depth of approximately 1.4 in. (36 mm) in a slab 7 in. (180 mm) thick. Slab dried from both sides in air at 64°F (18°C) and 60% RH.*

7.3—Concrete drying: exposed to moisture from below

Brewer's (1965) test included concrete specimens that were exposed to vapor and liquid water at the bottom of the specimen. As Table 7.2 shows, the time needed to reach a given emission rate increases when moisture can enter the bottom of the concrete specimen. For a *w/c* of 0.5, the required drying time increased from 82 days with no external water exposure to 144 days with exposure to water vapor, and to 199 days with water contact. The results for a *w/c* of 0.6 were even more dramatic, as it took specimens 117 days to dry with no exposure to water, and 365 days when exposed to water vapor. Brewer (1965) stopped taking measurements after 365 days, as indicated in Table 7.2 by > 365.

Table 7.3 shows Brewer's (1965) 1-year results for concrete with a *w/c* of 0.5. With no external water source, this concrete reached an emission rate of 1.0 lb/1000 ft²/24 h (0.5 kg/100 m²/24 h) after drying for 365 days. When in contact with water, concrete with the same *w/c* reached 2.5 lb/1000 ft²/24 h (1.2 kg/100 m²/24 h). This shows that uncovered concrete can dry to the lowest commonly specified emission rate (3 lb/1000 ft²/24 h [1.5 kg/100 m²/24 h]) even while in contact with water. When a floor covering is applied, however, redistribution of the moisture can be expected, as discussed in Chapter 3, and performance of the floor covering might not be acceptable. Brewer (1965) calculated the percent saturation, amount of water in each specimen, under the given drying conditions. When dried from one side only (vapor retarder on the bottom), the concrete had an approximately 50% saturation level. Concretes exposed to vapor or in contact with water had a higher saturation level of approximately 80%. Thus, when a floor covering is installed, the amount of water that can be redistributed to the top surface is much greater for concrete exposed to vapor or in contact with water. Although the emission rate might be considered acceptable when the floor covering is installed, the increased amount of water stored in the concrete is likely to affect floor covering performance after installation.

Table 7.3—Moisture vapor emission rate (MVER) and percent saturation after 1 year in 0.5 *w/c* concrete

Test condition	MVER, lb/1000 ft²/24 h (kg/100 m²/24 h)	Percent saturation
Water in contact with concrete	2.5 (1.2)	81
Water vapor in contact with concrete	2.3 (1.1)	76
Water in contact with 4 mil (0.10 mm) polyethylene	1.5 (0.73)	53
Water in contact with 32 mil (0.81 mm) ABS plastic	1.1 (0.54)	51
Drying only	1.0 (0.49)	50

7.4—Concrete drying: exposed to moisture from above

Suprenant and Malisch's (1998a) concrete specimens with *w/cm* of 0.40 or less took only 46 days to reach the 3 lb/1000 ft^2/24 h (1.5 kg/100 m^2/24 h) emission rate required for many floor coverings. To study the effect of rewetting, they (Suprenant and Malisch 1998c) ponded 12.5 lb (5.7 kg) of water on the 4 in. (100 mm) thick slab that had a *w/cm* of 0.40. They removed the water after 2 hours and measured it. The slab had absorbed 4.6 lb (2.1 kg) of water, and as shown in Fig. 3.6.3, the MVER rose to approximately 15 lb (6.8 kg). It required approximately 5 more weeks of drying to again reach the 3 lb/1000 ft^2 24 h (1.5 kg/100 m^2/24 h) rate. At that point, they again wetted the slab with 12.5 lb (5.7 kg) of water, this time for 6 hours, and measured the amount of water absorbed. The absorption decreased to 2.8 lb (1.3 kg), and this time the emission rate rose to only 8 lb (3.9 kg) before returning to 3 lb (1.5 kg) in approximately 2 weeks.

Clearly, the time needed for concrete to dry to a predetermined MVER cannot be determined based only on the placement date or the end of moist curing. The date of the last rewetting should also be considered.

7.5—Concrete drying from both sides

Some suspended structural slabs dry from both the top and the bottom. Hedenblad (1997) developed relative factors for drying from one and two sides for different *w/c*, as shown in Table 7.5.

As the table shows, drying from only one side takes at least twice as long as drying from both sides to reach the same internal RH criteria. Note that the one-sided drying takes longer for higher *w/c*.

Table 7.5—Relative factors for one- or two-sided drying

	w/c			
Drying	**0.4**	**0.5**	**0.6**	**0.7**
One side	2.0	2.3	2.6	3.2
Two sides	1.0	1.0	1.0	1.0

7.6—Effect of concrete-making materials

The following ranges in material types and amounts were used in the drying studies of Brewer (1965), Abrams and Orals (1965), Hedenblad (1997), and Suprenant and Malisch (1998a):

(a) Cement content: 300 to 700 lb/yd^3 (178 to 415 kg/m^3)
(b) Cement types: Type I, I/II, and III
(c) Class F fly ash and silica fume
(d) Four different air-entraining agents
(e) Chloride and nonchloride accelerators
(f) Lignin and hydrocarboxcylic acid water reducers
(g) High-range water reducers
(h) One butyl stearate waterproofing admixture

Brewer's (1965) conclusion was "on the basis of concretes with equal water-cement ratios, the admixtures used neither contributed to, nor detracted from the measured flow to any appreciable degree." Hedenblad (1997) concluded "drying of concrete containing a superplasticizer largely occurred in the same way as for concrete without a superplasticizer admixture and with the same *w/c* ratio." Suprenant and Malisch (1998a), using concrete materials and admixtures available in 1998 (nonchloride accelerator, fly ash, and high-range water-reducing admixture) at a *w/cm* of 0.40, reasonably matched Brewer's (1965) drying curve for concrete with a *w/c* of 0.4 but using materials available in 1965 (portland cement and admixtures).

Hedenblad (1997) found that using 5 and 10% silica fume by weight of cement decreased drying time by 2 and 4 weeks, respectively.

Based on the published data, there is no reason to include or exclude any concrete materials, with the exception of the addition of silica fume, in an attempt to reduce needed drying time for concrete with a given *w/cm*. Much work is currently being done to investigate the use of materials that will reduce the time needed for concrete to dry to a moisture condition that permits flooring to be applied.

7.7—Effect of fresh and hardened concrete properties

Concretes with the following ranges in properties have been used in the work of the four researchers previously cited:

(a) Slumps from 1-1/2 to 9-1/2 in. (38 to 240 mm)
(b) Air contents from 1 to 7%
(c) Normalweight concretes with densities from 139 to 154 lb/ft^3 (2230 to 2470 kg/m^3)
(d) Compressive strengths from 1300 to 8000 psi (9.0 to 55 MPa)
(e) *w/cm* from 0.30 to 1.0

The only variable found to correlate with drying time is the *w/cm*. If a change in slump or air content causes a change in the *w/cm*, the drying time is affected. If a concrete strength change is due to a change in the *w/cm*, the drying time changes. Thus, the design team needs to specify only the *w/cm* if concrete drying time is a primary concern.

7.8—Effect of thickness

Hedenblad (1997) developed correction factors for slab thickness effects on time required to reach a given RH in holes drilled to a depth equal to 20% of the slab thickness. Table 7.8a is modified from its original form to have a 4 in. (100 mm) thick slab as the base reference. Based on this data, drying times double as the concrete slab increases from 4 to 6 in. (100 to 150 mm), and triple as the slab thickness increased from 4 to 8 in. (100 to 200 mm).

Suprenant and Malisch (1998a) found that slab thickness had no influence on the time needed for MVER to reach the commonly specified 3 to 5 lb/1000 ft^2/24 h (1.5 to 2.4 kg/100 m^2/24 h) maximum values, as shown in Table 7.8b. Based on their data and other work, MVER results reflect the moisture condition near the top concrete surface only, and are unaffected by slab thickness.

Monfore's (1963) RH measurements at the middepth of 3/4, 3, and 6 in. (19, 76, and 150 mm) diameter concrete cylinders show that the time required to dry to a given RH increases with distance from the drying surface (Fig. 7.8).

Table 7.8a—Relative effect of thickness on drying time*

Thickness, in. (mm)	*w/c*			
	0.4	0.5	0.6	0.7
4 (100)	1.0	1.0	1.0	1.0
6 (150)	2.0	2.0	2.0	1.8
7 (180)	2.5	2.5	2.5	2.5
8 (200)	2.8	2.8	2.8	3.0
10 (250)	3.3	3.5	3.8	4.5

*Modified from Hedenblad (1997).

Table 7.8b—Moisture emission rates for different thicknesses of concrete (*w/cm* = 0.40)

Days	2 in. (51 mm)	4 in. (100 mm)	6 in. (150 mm)	8 in. (200 mm)	Average, in. (mm)
3	13.2 (6.44)	15.9 (7.76)	15.5 (7.57)	13.4 (6.54)	14.5 (7.08)
7	7.4 (3.61)	7.9 (3.86)	7.8 (3.81)	9.6 (4.69)	8.2 (4.00)
14	5.4 (2.64)	5.7 (2.78)	5.2 (2.53)	5.5 (2.69)	5.5 (2.69)
18	4.4 (2.15)	5.1 (2.49)	5.1 (2.49)	4.8 (2.34)	4.9 (2.39)
22	4.7 (2.29)	4.1 (2.00)	3.9 (1.90)	4.3 (2.10)	4.3 (2.10)
28	3.5 (1.71)	3.7 (1.81)	3.5 (1.71)	4.2 (2.05)	3.7 (1.81)
32	3.3 (1.61)	3.7 (1.81)	3.5 (1.71)	3.6 (1.76)	3.5 (1.71)
42	3.7 (1.81)	3.5 (1.71)	3.4 (1.66)	3.6 (1.76)	3.5 (1.71)
49	2.8 (1.37)	3.0 (1.46)	3.1 (1.51)	2.3 (1.12)	2.8 (1.37)

Although slab thickness has no effect on the time needed to reach a given MVER, thickness affects the time needed to reach a given RH within the slab.

7.9—Effect of curing

Monfore (1963) measured RH at the middepth of 3/4, 3, and 6 in. (19, 76, and 150 mm) diameter concrete cylinders having 0.4 and 0.6 *w/c* and moist cured for 7 and 84 days before they were dried. For the 3/4 in. (19 mm) diameter cylinder, an extended curing time had little effect on the time to dry to a RH of 90% at middepth. For the 3 and 6 in. (76 and 150 mm) diameter cylinders, however, the time to dry to a RH of 90% at the middepth after extended curing increased from 20 to 30 days and from 83 to 141 days, respectively. Figures 7.8 and 7.9 show that extended curing delays drying.

Hedenblad (1997) developed correction factors to account for the effect of curing conditions on concrete drying (Table 7.9). As shown by these correction factors, any curing period longer than 1 day can significantly extend drying times.

Determining the curing method, and especially the curing time, requires consideration of the curing effects on desired drying times and concrete surface properties. In the absence of any concentrated floor loading, surface strength requirements for concrete should at least equal the strength of the adhesive used for flooring. Suprenant and Malisch (1999a) tested adhesives that failed in pulloff tests at stresses ranging from 30 to 50 psi (0.21 to 0.34 MPa). Based on this data, a moist-curing time of 1 to 3 days should provide adequate

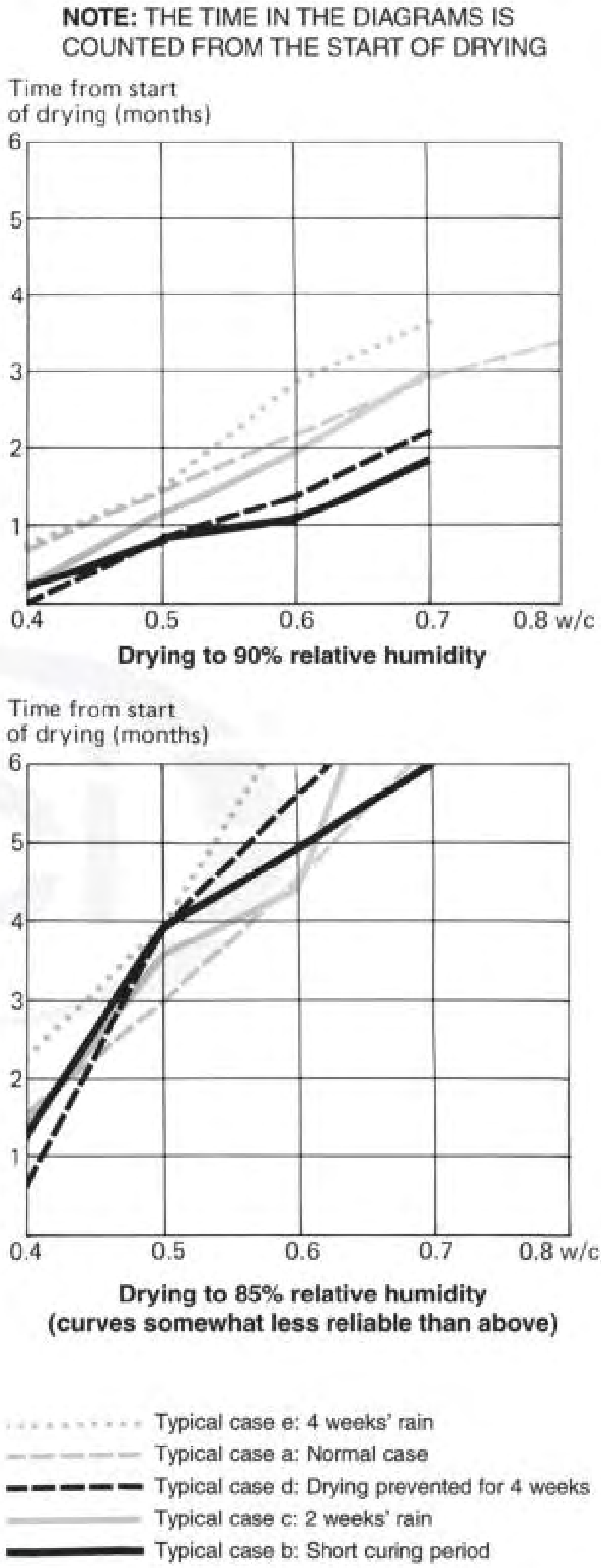

Fig. 7.8—Weight loss and internal RH at 3/4, 3, and 6 in. (19, 76, and 150 mm) cylinders for concretes with w/c of: (a) 0.4; and (b) 0.6 (Monfore 1963). (Note: 1 in. = 25.4 mm.)

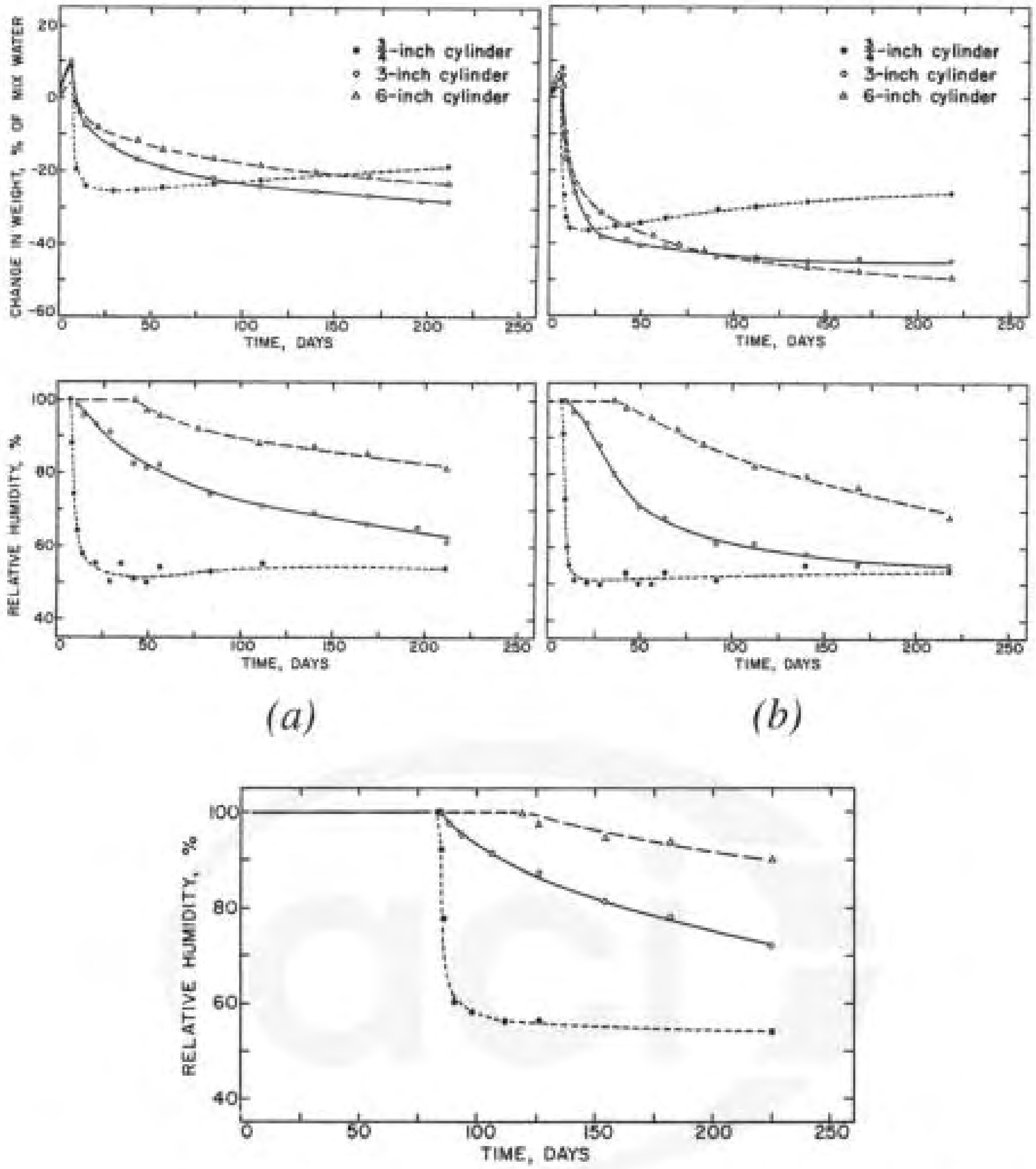

Fig. 7.9—Effect of extended curing (84 days) on RH for concrete with a w/c of 0.4. Compare to Fig. 7.8 for the same concrete that was cured for 7 days to show how extended curing increases drying time (Monfore 1963).

Table 7.9—Relative factors for effect of curing on concrete drying time

Curing conditions	*w/c*					
	0.5		**0.6**		**0.7**	
Drying concrete to RH of:	85%	90%	85%	90%	85%	90%
1 day of curing	2	1	2	1	2	1.4
4 weeks of moist air	2	1	2	1.4	2	1.6
2 weeks of rain 2 weeks of moist air	2	2	2	2	2	2
4 weeks of rain	2.8	2	2.8	2.6	2.8	2.6

surface strength, especially when the surface preparation removes any weak top surface skin. For higher-strength coatings, such as epoxy, 3 to 7 days of moist curing might be needed. Manufacturers' data on adhesive strength would be helpful in setting the optimum curing time.

7.10—Drying of mature concrete

Because fresh concrete loses moisture more slowly after a longer moist-curing period, mature concrete might be expected to dry slowly after rewetting. Hedenblad (1993) studied the drying behavior of well-hydrated concrete specimens that were more than a year old. After rewetting, the mature concrete specimens of different thicknesses and *w/c* were allowed to dry at 50% RH and 70°F (21°C). He

measured the internal RH at a depth of 40% of the slab thickness for one-sided drying, and 20% of the slab thickness for two-sided drying. Rewetted mature concrete with a *w/c* of 0.70, and drying from one side, took 515 days to reach 85% internal RH. To reach the same RH level, newly placed concretes with the same *w/c* took 184 days when cured for 1 day, and 258 days when cured for 4 weeks.

7.11—Effect of drying environment

Abrams and Orals (1965) subjected 3 ft (910 mm) square by 6 in. (150 mm) thick slabs, drying from both sides, to RH environments of 10, 35, 50, and 75%. They measured RH at mid-depth of the slab. Table 7.11a shows the effect of environmental humidity on drying time at a constant temperature of 70°F (21°C).

As Table 7.11a shows, the lower the internal RH target, the longer it takes to reach that target at a given environmental RH. At an environmental RH of 35%, it took 1.0, 3.7, and 8.0 months to reach internal RH at middepth of 90, 75, and 50%, respectively. Lowering the environmental RH allowed the specimens to dry faster, with the greatest effects being for a lower targeted internal RH. The dashes in the table indicate that specimens had not reached the targeted internal RH after 28 months of drying.

In the field, concrete is likely to be exposed to ambient RH ranging from 35 to 75%, depending on geographical location and time of year. A considerable difference in drying rates should thus be expected for concrete slabs built in different locations and during different seasons.

Hedenblad (1997) developed relative factors for concrete drying time based on the exposure environment (Table 7.11b). Note that at 50% RH, reducing the temperature from approximately 85 to 50°F (29 to 10°C) doubles the time required to reach a RH target. At approximately 85°F (29°C), increasing the RH of the exposure environment from 50 to 80% increases the required concrete drying time by approximately 50%. Hedenblad's (1997) data indicate that concrete drying time is more sensitive to changes in temperature than it is to changes in RH.

Table 7.11a—Effect of environmental humidity on drying time, months

Environmental relative humidity, %	Drying time for different internal relative humidity, months		
	95%	75%	50%
10	0.6	2.7	20.5
35	1.0	3.7	28.0
50	1.2	8	—
75	1.2	—	—

Note: Two-sided drying and internal RH measured at middepth of 6 in. (150 mm) thick specimen.

Table 7.11b—Relative factors for drying time due to exposure environment

Relative humidity of the air, %	Air temperature, °F (°C)			
	50 (10)	64 (18)	77 (25)	86 (30)
50	2.00	1.50	1.17	1.00
60	2.17	1.67	1.33	1.17
70	2.33	1.83	1.33	1.17
80	2.83	2.00	1.67	1.50

7.12—Drying at exposed edge

Using RH probes at two different levels in a 6 in. (150 mm) thick slab, Abrams and Monfore (1965) showed how edge drying affects RH measurements on the slab interior. Table 7.12 shows that the extent of the edge drying effect is limited to approximately the thickness of the slab. The RH measurements 6 in. (150 mm) away from the edge are approximately the same as the measurements in other parts of the slab interior.

7.13—Drying of lightweight concrete

Studies of lightweight concrete drying time indicate that it dries more slowly than normalweight concrete (Kanare 2005; Suprenant and Malisch 2000c; Craig and Wolfe 2012). Using calcium chloride tests, Suprenant and Malisch (2000c) compared MVERs of normalweight and lightweight concretes with a *w/c* of 0.4 and exposed to the same drying environment. The normalweight concrete dried to

Table 7.12—Effect of edge drying on relative humidity in a 6 in. (150 mm) thick slab

Distance from exposed edge, in. (mm)	Relative humidity, %					
	80 days		130 days		175 days	
	2 in. (51 mm)	3 in. (76 mm)	2 in. (51 mm)	3 in. (76 mm)	2 in. (51 mm)	3 in. (76 mm)
2 (51)	79	82	72	77	63	68
4 (100)	84	87	77	82	70	75
6 (150)	85	88	78	83	71	76
8 (200)	86	88	80	83	72	75
10 (250)	86	89	81	83	73	76
12 (300)	86	88	80	82	73	75
16 (410)	86	—	80	—	71	—
20 (510)	87	89	81	84	73	75

Note: Drying from both sides and edge exposed to 73°F (23°C) and 10% RH.

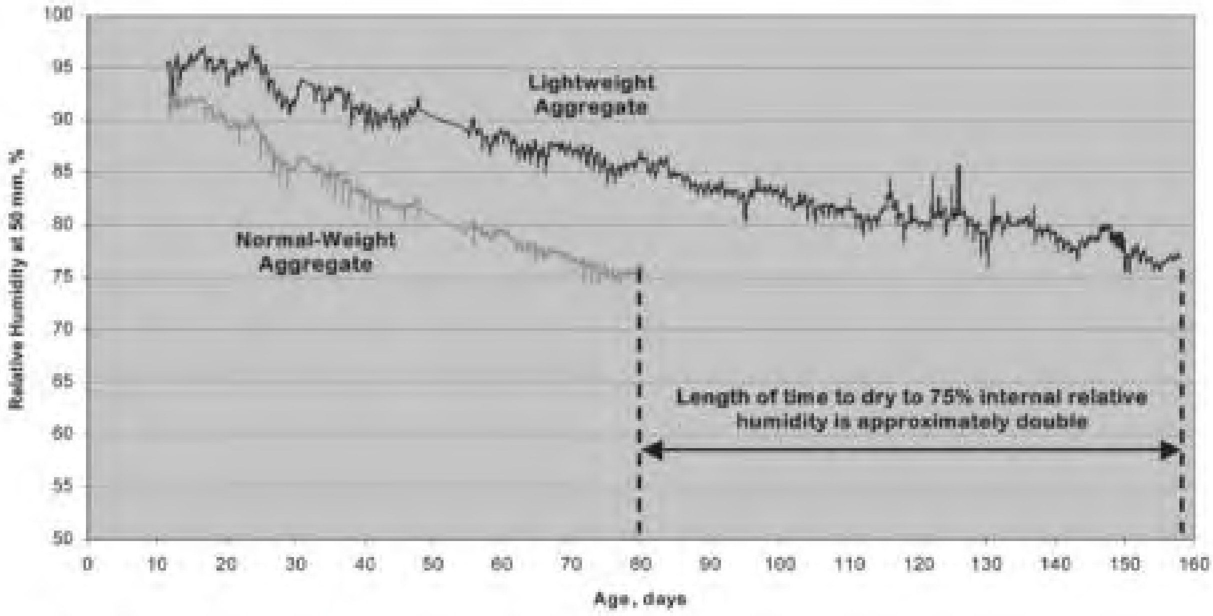

Fig. 7.13—RH measurements by Kanare (2005) showing that lightweight concrete takes longer to dry than normalweight concrete.

3 lb/1000 ft^2/24 h (1.5 kg/100 m^2/24 h) in 46 days whereas the lightweight concrete dried to that level in 183 days.

Using RH measurements, Kanare (2005) found that normalweight concrete dried to an internal RH of 75% in approximately 80 days whereas the lightweight concrete took approximately 160 days to reach that level (Fig. 7.13).

In a noncontrolled, watertight environment where ambient temperatures ranged from 47.6 to 99.5°F (8.7 to 37.5°C) and ambient RH levels ranged from 21.4 to 84.3%, Craig and Wolfe (2012) found that it took 216 days for normalweight concrete (*w/c* of 0.50) to dry to a 2.6 lb (1.2 kg) MVER. At the same time, the lightweight concrete (*w/c* of 0.50) MVER was at 3.2 lb (1.5 kg). At 180 days, the internal RH of the normalweight concrete was 85.5% whereas the lightweight concrete measured 90.7%. At 273 days, the normalweight internal RH was 80.2% whereas the lightweight concrete measured 86.6%. The conclusion of this study was that the time necessary for concrete to dry to an acceptable level is greatly affected by ambient conditions and it can be a challenge for both normalweight and lightweight concrete to dry to an acceptable level in a short period of time in non-climate-controlled conditions.

CHAPTER 8—VAPOR RETARDER

8.1—Introduction

Below-slab vapor retarders are intended to limit water vapor from entering concrete slabs in contact with the ground. Vapor retarder products are typically plastic in sheet or roll form. Multi-layered composite materials and fluid applied membranes have also been used for certain applications.

8.1.1 *Composition*—Most materials used for below-slab moisture protection are plastic. There are many variations in the type and grade of resin used to create plastic vapor retarders. Some plastics are created from 100% virgin resin whereas others are created with high percentages of reprocessed materials. Some plastics are low-density whereas others are high-density.

Previously, 4, 6, 8, and 10 mil (0.10, 0.15, 0.20, and 0.25 mm) low-density polyethylene sheeting was used as a below-slab vapor barrier material. However, currently any material used as a below-slab vapor barrier should conform to the minimum requirements of ASTM E1745.

8.1.2 *Vapor retarders and vapor barriers*—Historically, the construction industry used the term "vapor barrier" to describe a wide range of polyethylene-based materials placed below concrete slabs-on-ground. However, because polyethylene does not completely stop the transmission of water vapor, it was considered more appropriate to call these products "vapor retarders" instead of "vapor barriers".

ASTM E1745 does not use or define the term "vapor barrier". In ASTM E1745, vapor retarders are required to have a maximum permeance of 0.1 perms. By definition, 1 perm equals the transmission of 1 grain of water vapor per ft^2/h per in. of mercury pressure. There are, however, numerous floor flooring and coating materials with permeance levels below 0.1 perm. To provide a higher level of below-slab moisture protection than 0.1 perm, there are today numerous vapor retarder materials with permeance levels 10 times lower than 0.1 perm. For critically sensitive flooring and coating installations owners, designers, engineers, manufacturers, and contractors can reference ASTM E1745 and obtain a greater level of moisture protection by modifying the acceptable permeance level to 0.01 perm as measured both before and after the conditioning tests required in E1745. At the 0.01 perm level, there are industry professionals who believe that the term "vapor barrier" could be reconsidered for use to help differentiate between the two acceptance levels.

8.2—Vapor retarder location

For many years, specifiers called for a granular blotter layer to be placed between the concrete and the vapor retarder rather than to place concrete in direct contact with the plastic. As with many engineering decisions, the location of a vapor retarder is often a compromise between minimizing water vapor movement through the slab and

providing the desired short- and long-term concrete properties (Suprenant 1992; Suprenant and Malisch 1998b). While there are numerous concrete-related benefits to placing a granular blotter layer over the vapor retarder, it is generally accepted that the benefits do not outweigh the risks when a moisture-sensitive flooring material is to be installed over the slab.

8.2.1 *Benefits of concrete placed on a granular layer*—Finishers prefer that concrete be placed on a granular base because the base absorbs mixing water, shortens the bleeding period, and allows floating to start earlier. Australian researchers noted that 4-1/2 in. (110 mm) slump concrete placed on a granular base lost its bleedwater sheen approximately 2 hours faster than the same concrete placed directly on a vapor barrier (Anderson and Roper 1977).

Base conditions also affect concrete stiffening. In tests performed by Suprenant and Malisch (1998b), 2-1/2 in. (64 mm) slump concrete was used for two 4 x 4 ft (1.2 x 1.2 m), 4 in. (100 mm) thick slabs. One slab was placed directly on a vapor retarder, and the other on a crushed stone base. Technicians periodically set a steel-shot-filled rubber boot weighing 75 lb (34 kg) on the surface and measured the footprint indentation. Concrete on the stone base had stiffened enough after 90 minutes to allow a 1/4 in. (6.4 mm) footprint indentation—an indication that floating could begin. Concrete placed directly on the vapor retarder required 45 more minutes of stiffening time before it was ready for floating.

Specifiers who had required a granular blotter layer cited additional benefits that include less chance of:

(a) Puncturing the vapor retarder

(b) Surface blistering or delaminations caused by an extended bleeding period

(c) Settlement cracking over reinforcing steel

(d) Slab curling during drying

(e) Cracking caused by plastic or drying shrinkage

(f) Dominant (extremely wide) joint development that occurs when concrete is placed directly on a low-friction vapor retarder and all the joints do not activate

Specifiers that in the past had recommended using a granular blotter layer called for a 3 or 4 in. (76 or 100 mm) thick layer of trimmable, compactable, self-draining granular fill for the blotter layer. Although concrete sand was sometimes used, sand does not provide a stable working platform. Concrete placement and workers walking on the sand can disturb the surface enough to cause irregular floor thickness and create sand lenses in the concrete.

8.2.2 *Risks of placing a granular layer over a vapor retarder*—When a granular blotter layer is placed over a vapor retarder, care is needed during construction to control the moisture content of the granular layer. In most cases, the only way of accomplishing this is to place the slab after the building is enclosed and the roof is watertight. On most projects, this is not possible, which places the granular layer at risk of becoming a water reservoir.

To provide unrestricted floor access for construction activities such as tilt-up panel forming and casting, columns sometimes aren't erected and column blockouts aren't filled until months after floor placement. If the building is not closed in and watertight, rainwater can enter the granular layer through these open blockouts. Rainwater can also penetrate joints, cracks, utility penetrations, and open closure strips and increase the moisture content of the subgrade or granular layer. Workers sprinkling the granular layer with too much water before concrete placement can also create a moisture reservoir that will delay drying of the concrete floor.

Wet-curing methods, such as ponding, continuous sprinkling, or water-saturated fabric allow water to enter joints, cracks, and other openings, which will contribute to a higher-than-necessary moisture content in a granular layer beneath the slab. Water from construction operations on a newly placed slab also can increase the granular-layer moisture content by entering joints, cracks, or slab openings. Such operations include wet sawing, wet abrasive blasting, wet grinding, or wet cleaning.

Rollings (1995) determined that a tile floor failure was caused by rainwater accumulating in a 3 in. (76 mm) thick sand layer placed between a 5 in. (130 mm) thick concrete slab and a polyethylene vapor retarder. One portion of the slab had not been placed along with the others, thus exposing the sand layer to rain and turning it into a reservoir of trapped water.

8.2.3 *Benefits of concrete placed directly on vapor retarder*—Brewer (1965) demonstrated that concrete specimens isolated from a moisture source at the bottom of the specimen dry faster than specimens exposed to water or water vapor at the bottom (Brewer 1965). Floor covering and coating installations can thus proceed sooner and at less risk of failure where the concrete slab is placed directly on a vapor retarder. If the vapor retarder effectively reduces moisture inflow from external sources, only water in the concrete pores needs to exit the slab. The slab moisture level requirements should be reached faster under these conditions. A vapor retarder directly below the slab to be covered may also act as a slip sheet, reducing slab restraint and, thus, reducing random cracking without necessarily increasing long-term curling.

Placing concrete directly on a vapor retarder also eliminates a potential water reservoir in the blotter layer (8.2.3). Because more subgrade soil is removed to accommodate the additional 3 to 4 in. (76 to 100 mm) thick blotter layer, that layer is more likely to be placed below the finished-grade level, thus increasing the chance of its holding water and to act as a conduit for water vapor that enters the granular layer through tears, punctures or unsealed edges.

Placing concrete in direct contact with the vapor retarder provides the following advantages:

(a) Reduced costs because of less excavation and no need for additional granular material

(b) Faster drying of the slab

(c) More positive moisture protection to the flooring system

(d) Better curing of the slab bottom because the vapor retarder minimizes moisture loss

(e) Less chance of floor moisture problems caused by water being trapped in or entering the granular layer

(f) Less radon gas infiltration

(g) Conformance with ASTM F710

When concrete is placed directly on a vapor retarder, a low shrinkage concrete mixture and continuous reinforcement can be used to help control shrinkage, cracking, curling, and dominant joint activity (Holland and Walker 1998).

8.2.4 *ACI 302/360 Task Group recommendations on vapor retarder location*—In April of 2001, a task group from ACI Committees 302 and 360 issued the following ACI update in *Concrete International*, which included a flowchart to help guide the decision-making process.

The report of ACI Committee 302, "Guide for Concrete Floor and Slab Construction (ACI 302.1R-96)" states in Section 4.1.5 that "if a vapor barrier or retarder is required due to local conditions, these products should be placed under a minimum of 4 in. (100 mm) of trimmable, compactable, granular fill (not sand)." ACI Committee 302 on Construction of Concrete Floors and Committee 360 on Design of Slabs-on-Ground have found examples where this approach may have contributed to floor covering problems.

Based on the review of the details of problem installations, it became clear that the fill course above the vapor retarder can take on water from rain, wet-curing, wet-grinding or cutting, and cleaning. Unable to drain, the wet or saturated fill provides an additional source of water that contributes to moisture vapor emission rates from the slab well in excess of the 3 to 5 lb/1000 ft^2/24 h (1.5 to 2.4 kg/100 m^2/24 h) recommendation of the floor covering manufacturers.

As a result of these experiences, and the difficulty in adequately protecting the fill course from water during the construction process, caution is advised as to the use of the granular fill layer when moisture-sensitive finishes are to be applied to the slab surface.

The committees believe that when the use of a vapor retarder or barrier is required, the decision whether to locate the material in direct contact with the slab or beneath a layer of granular fill should be made on a case-by-case basis.

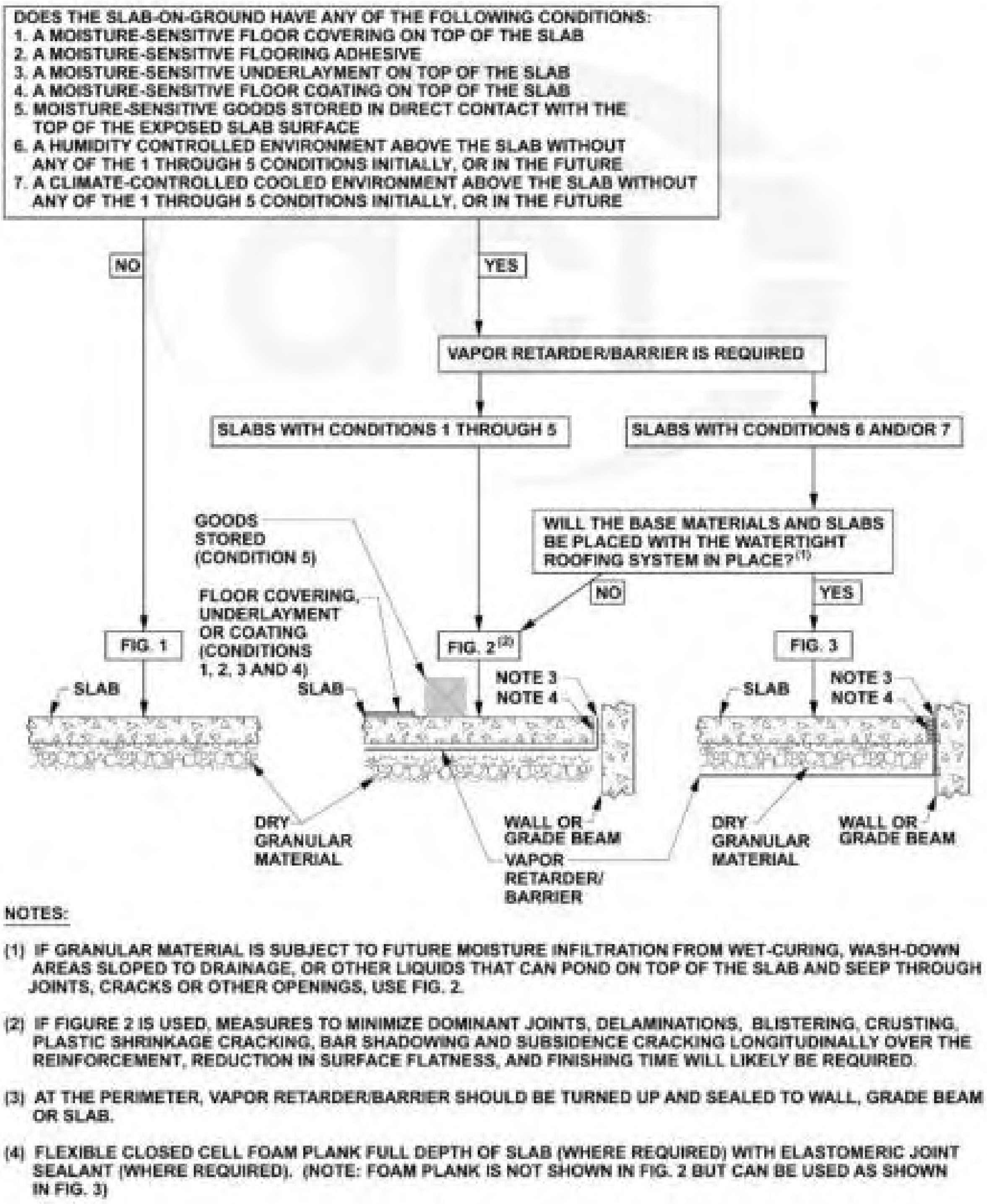

Fig. 8.2.4 - Decision flow chart to determine if a vapor retarder/barrier is required and where it is to be placed (ACI 302.1R).

Fig. 8.2.4—Decision flow chart to determine if a vapor retarder is required and where it is to be placed (ACI 302.1R).

Each proposed installation should be independently evaluated to consider the moisture sensitivity of subsequent floor finishes, anticipated project conditions, and the potential effects of slab curling and cracking.

Figure 8.2.4 can be used to assist in deciding where to place the vapor retarder. The anticipated benefits and risks associated with the specified location of the vapor retarder should be reviewed with all appropriate parties before construction.

Since the update was published in 2001, the position of ASTM F710, "Standard Practice for Preparing Concrete Floors to Receive Resilient Flooring," concerning the location of the vapor retarder below a concrete floor slab has changed from that of being non-mandatory information to being a requirement. In the 2008, 2011, 2019, and 2021 versions of ASTM F710, it is a requirement that the vapor retarder is to be installed in direct contact with the underside of the slab. The original flowchart was updated to reflect this requirement in ACI 302.1R in 2015. The current version is now shown.

8.3—Vapor transmission through retarder

There are ways that water vapor can flow through a vapor retarder. Punctures in the vapor retarder or gaps at the laps of adjacent sheets can allow water to penetrate the concrete. The perm rating of the material establishes the basic flow rate through an uncompromised vapor retarder or barrier.

8.3.1 *Perm rating*—ASTM E1745 requires vapor retarders to have a maximum perm rating of 0.1. By definition, 1 perm equals the transmission of 1 grain of water vapor per ft^2/h/in. of mercury pressure differential. This can be converted to units of the commonly used MVER (lb/1000 ft^2/24 h), by dividing by 7000 grains/lb of water, multiplying by 24 hours, and then multiplying by 1000 ft^2.

This yields a conversion factor of 3.4 lb/1000 ft^2/24 h per in. of mercury pressure. The flow through a 0.1 perm rating material is thus 3.4 × 0.1, or approximately .34 lb/1000 ft^2/24 h per inch of mercury pressure.

For a slab exposed to a 70°F (21°C) and 50% relative humidity (RH) environment at the top and 50°F (10°C) and 100% RH at the bottom, the vapor pressure difference is approximately 0.2 psi (0.0014 MPa), or approximately 0.4 in. (10 mm) of mercury pressure. Under these conditions, the water vapor flow through a vapor retarder with a 0.1 perm rating is approximately 0.14 lb/1000 ft^2/24 h (0.062 kg/100 m^2/24 h). The same calculation for a vapor barrier with a perm rating of 0.01 yields a water vapor flow through a vapor barrier under a concrete slab of 0.014 lb/1000 ft^2/24 h (0.006 kg/100 m^2/24 h).

Clearly, there is a substantial difference in water vapor transmission through a vapor retarder meeting the allowable ASTM E1745 requirement of 0.1 perms and through a product with a maximum perm rating of 0.01 perms.

8.3.2 *Water vapor transmission through punctures*—Suprenant and Malisch (1998d) used calcium chloride tests (ASTM F1869) to evaluate the MVER through punctures in vapor retarders. They performed the tests over intact and punctured vapor retarders placed over a sand subbase at two moisture contents. They also varied vapor retarder thickness and the size of the punctures.

ASTM C33/C33M concrete sand was placed in twelve 16 in. (410 mm) diameter, 3.75 in. (95 mm) deep metal pans. To simulate saturated sand, water was poured into eight of the pans until the water level was visible just below the top of the pan. They weighed the sand in the other four pans and added 8% water by weight to simulate a typical optimum compaction moisture content for a granular subbase. Four of the saturated sand samples were covered with 8 mil (0.20 mm) thick polyethylene sheeting and the other four with 40 mil (1.0 mm) thick polyethylene, using duct tape to secure the overhanging sides to the pan and prevent moisture loss.

A similar procedure was used to cover the four pans containing lower-moisture-content sand with an 8 mil (0.20 mm) thick polyethylene sheet. In each of the three sets of four pans, one vapor retarder was intact, one had a 1/8 in. (3.2 mm) diameter nail hole, one had a 5/8 in. (16 mm) diameter stake hole, and one had an opening cut to the size of the lid for the calcium chloride test kit.

Moisture vapor emission rates were measured for all 12 specimens, using calcium-chloride cup test kits that were left in place for 3 days. After the first test, the filled pans were stored in the laboratory for approximately 10 weeks and then retested for vapor emissions. For the retest, no additional water was added to the sand.

A 1/8 in. (3.2 mm) diameter nail hole allowed an average MVER of 1.3 lb/1000 ft^2/24 h, (0.63 kg/100 m^2/24 h) and a 5/8 in. (16 mm) diameter stake hole increased the average MVER to 3 lb/1000 ft^2/24 h (1.5 kg/100 m^2/24 h). Because a 3 lb (1.5 kg) rate is often the maximum allowed for installation of moisture-sensitive floor coverings, stake holes of this size could conceivably cause localized floor covering failures or delay floor covering installation. The measured MVER through the lid-sized opening was approximately the same regardless of the sand moisture content, and the rate did not decrease after more than 2 months of drying. This suggests that when a granular layer is placed between a concrete slab and a vapor retarder, any trapped moisture, whether from rain, workers sprinkling the layer, or compaction, could provide a significant amount of moisture to the concrete slab.

After the retests were completed, the moisture content of the sand in the three pans with lid-sized openings in the polyethylene was measured. The moisture contents of the saturated sand were 18.8 and 15.6% for the 8 and 40 mil (0.20 and 1.0 mm) polyethylene, respectively, whereas the moisture content of the 8% sand had dropped to 2.5%. Surprisingly, even the granular base with a 2.5% moisture content emitted water vapor at approximately the same rate as the wetter subbases.

8.3.3 *Puncture resistance*—Suprenant and Malisch (2000b) performed tests on 6, 8, 10, and 20 mil (0.15, 0.20, 0.25, and 0.51 mm) vapor retarders to determine puncture resistance when these materials were placed under a granular fill. ACI 302.1R formerly recommended a minimum 10 mil (0.25 mm) thick vapor retarder. Suprenant and Malisch

(2000b) showed this recommendation to be appropriate when the vapor retarder will be covered with base materials that are then compacted.

The ACI 302.1R recommendation for minimum thickness was made in conjunction with a recommendation in the same document that vapor retarder be covered (and thus, protected) by a granular layer.

The thickness and strength of a vapor retarder or barrier for placement directly under the concrete slab and exposed to construction traffic should be considered carefully. Concrete truck traffic, use of laser-guided screeds, presence of pump hoses, and reinforcing bar placement are some of the activities that can cause punctures when concrete is placed directly on the vapor retarder. The specifier should consider these activities when selecting the appropriate vapor retarder material. While use of a less expensive vapor-retarding material might seem reasonable, the added cost of repairing punctures and tears could exceed the cost of using a product more suitable for heavy-duty wear. Most ASTM E1745 Class A materials have demonstrated adequate performance when subjected to construction traffic.

8.3.4 *Effectiveness of vapor retarder in reducing water vapor inflow*—Results by Suprenant and Malisch (1998d) show that the effects of intact vapor retarders are similar to those from earlier tests by Brewer (1965). Brewer measured moisture inflow from the subbase into 4 in. (100 mm) thick concrete specimens with a *w/c* of 0.70 and placed directly on:

(a) Compacted clay
(b) Compacted clay covered with a gravel layer
(c) Compacted clay covered with a vapor retarder
(d) Compacted clay covered with a gravel layer and vapor retarder

Brewer (1965) used two different vapor retarders: 4 mil (0.10 mm) polyethylene and 55 lb (25 kg) roofing felt.

Brewer (1965) started measuring moisture inflow approximately 1 month after the concrete had been placed. At this time, the inflow for concrete placed directly on compacted clay (converted to units of the commonly specified MVER) was approximately 20 lb/1000 ft^2/24 h (9.8 kg/100 m^2/24 h). Moisture inflow for the clay covered with a vapor retarder was approximately 7 lb/1000 ft^2/24 h (3.4 kg/100 m^2/24 h). Thus, an intact vapor retarder over a clay subgrade reduced moisture inflow by approximately 13 lb/1000 ft^2/24 h (6.3 kg/100 m^2/24 h).

Moisture inflow for concrete placed directly on a gravel layer over compacted clay was approximately 14 lb/1000 ft^2/24 h (6.8 kg/100 m^2/24 h). Covering the clay and gravel with a vapor retarder had reduced inflow to approximately 6 lb/1000 ft^2/24 h (2.9 kg/100 m^2/24 h). Thus, an intact vapor retarder over a gravel subbase reduced moisture inflow by approximately 8 lb/1000 ft^2/24 h (3.9 kg/100 m^2/24 h).

Brewer's (1965) values are in the same range as Suprenant and Malisch's (2000b) initial and retest values of approximately 9 and 11 lb/1000 ft^2/24 h (4.4 and 5.4 kg/100 m^2/24 h), respectively, for intact vapor retarders placed over a wet sand subbase. Brewer wasn't able to detect vapor emission differences between 4 mil (0.10 mm) polyethylene and 55 lb (25 kg) roofing felt, and Suprenant and Malisch (2000b) did not detect differences between 8 and 40 mil (0.20 and 1.0 mm) polyethylene. It should be noted that many below-slab vapor retarder materials today have considerably lower permeance levels than the low-density polyethylene used in the Brewer and Supernant and Malisch studies, or the 0.1 perm minimum requirement shown in ASTM E1745. These modern-day low-permeance vapor retarders would be expect to result in considerably lower moisture inflow levels than those reported above.

8.3.5 *Construction concerns*—Contractors should avoid damaging the vapor retarder. Some form manufacturers make supports for slab edge forms that do not require puncturing the vapor retarder with stakes. Many contractors use job-built edge-form supports with wide bearing pads to avoid puncturing the plastic with edge-form stakes. Brick-type reinforcing bar supports or large pad supports can position the steel while reducing the possibility of puncturing the vapor retarder. Finally, the vapor retarder should be installed by following manufacturers' instructions and ASTM E1643.

These practices include:

(a) Lapping joints 6 in. (150 mm) and sealing them with the manufacturers recommended sealing tape
(b) Sealing around all penetrations
(c) Extending the vapor retarder over footings and sealing the material to foundation walls, grade beams, or the face of the slab
(d) Selecting a vapor retarder material capable of withstanding potential construction site damage
(e) Repairing vapor retarder damage

CHAPTER 9—FLOOR COVERING MATERIALS

9.1—Introduction

There are a variety of floor coverings and adhesives. A basic knowledge of floor covering materials and the specific substrate requirements for these materials is essential in designing a concrete floor that is compatible with the floor covering materials. If the project is fast-track in nature, or constructed in a climate or time period where ambient relative humidity (RH) levels are consistently high, the design team should anticipate that conventional concrete may not be able to dry to the level required within the project schedule. In these specific cases, a preemptive moisture mitigation strategy can be incorporated into the project specifications and implemented either the beginning of the project or included as a contingency for use only if the required concrete moisture limits are not attained by the time flooring needs to be installed.

9.2—Communication between architect and engineer

The architect and engineer should communicate to ensure that the most recent Construction Specifications Institute requirements for floor coverings are compatible with the Division 3 requirements for concrete. Slab-on-ground design should be coordinated with the selection of the floor covering, and vice versa. Ideally, the design team will also include a

flooring consultant and the floor covering manufacturer. The team may need input from several floor covering manufacturers to allow for differences in product requirements. As stated in Chapter 6, when the specifications are prepared for different flooring applications, it is not advisable to rely only on the manufacturer's installation instructions. The design team should carefully review floor covering and adhesive manufacturers' instructions and recommendations plus the applicable ASTM standards related to floor covering installation. Because some floor covering warranty requirements contradict best practices, the design team should get written approval of their specifications from the adhesive and floor covering manufacturer. No single design team member can ensure a successful slab design without the input and cooperation of the other parties. Reducing the potential for a moisture problem and meeting the owner's expectations requires a team effort.

9.3—Floor covering technical resources

When selecting floor covering materials and writing specifications for substrate preparation and flooring installation, design and construction teams can take advantage of many technical resources such as reference manuals, handbooks, and recommended work practices published by flooring-related organizations. Flooring manufacturer's requirements for substrate preparation may not match the concrete industry requirements for floor finishes. Conflicting requirements should be dealt with during the design stage rather than the construction stage. Some specifiers, for instance, address conflicting requirements by adding the following statement to the specifications: When the specifications conflict, the contractor shall perform the most restrictive provision.

Choosing the applicable provision should not be left to general contractors or concrete contractors, who may not have the expertise to make such decisions. The design team should evaluate the flooring manufacturer's installation requirements and the concrete industry requirements and decide how to deal with conflicts.

9.4—Floor adhesives and coverings

9.4.1 *Adhesives*—There are longstanding ASTM standards for various floor coverings. However, until the introduction of ASTM D8397 in 2022, there were no ASTM standards specifications for flooring adhesives. The solids-to-water ratio of water-based adhesives can vary, which makes surface porosity of the slab an important issue. If free water in the adhesive cannot be absorbed into the surface of the concrete or underlayment, the adhesive may not reach the cured state necessary for a successful flooring installation. ASTM F3191 can be used to make this determination.

Because some adhesives are more moisture-tolerant than others, project delays while waiting for the concrete to dry can sometimes be avoided by choosing a more moisture-tolerant adhesive. Even though the more moisture-tolerant adhesive may cost more, using it may be more economical than delaying project completion, using desiccant drying, or applying a moisture mitigation system to the floor.

Because moisture tolerance and other adhesive properties vary from product to product, substitutions for the specified adhesive should be carefully scrutinized. It should be verified that the specified adhesive was used, and placed at the proper rate.

9.4.2 *Floor coverings*—The sensitivity to moisture-related conditions varies from one type of floor covering and adhesive to another. Carpet that allows moisture to pass through it may perform successfully on a slab where a welded sheet vinyl, linoleum, or rubber flooring system would have problems. However, the risk of installing breathable carpet over a slab with a suspended moisture level is that mold may develop where a nonbreathing material such as a file cabinet or plastic desk chair pad is placed over the carpet.

With water-based adhesives, the moisture limits for individual tiles may vary from sheet flooring materials. The frequent spacing of joints, and the ability with water-based adhesives to allow more of the water to evaporate before individual tiles are installed, allows many tile products to have a higher moisture installation limit than many welded or sealed sheet flooring installations.

Polymer terrazzo-tile floors differ from concrete terrazzo. The matrix of a polymer terrazzo tile does not breathe and is not as moisture-tolerant as concrete terrazzo. Terrazzo tile manufacturers typically place very restrictive moisture limits for substrates to be covered by their tile.

9.5—Effect of moisture in flooring adhesives

Flooring adhesives are usually spread on the concrete surface and then left uncovered for varying time periods before the floor covering is installed. During this open time, some of the water or solvent in the adhesive evaporates, and some may be absorbed by the concrete. To measure the water lost by evaporation, Suprenant (2003c) applied several different flooring adhesives to nonporous plastic plates (Fig. 9.5), then monitored weight loss during and after the open time recommended by the adhesive manufacturer. Only a small percentage (approximately 10%) of the water/solvent evaporated during the open time. The other 90% of the water/solvent could presumably either remain in the adhesive below the flooring or be absorbed by the concrete substrate after the floor covering was placed. In the study, the amount of water lost to evaporation differed greatly for the adhesives used. Some adhesives lost twice as much water as others.

Any moisture that remains within an adhesive after the flooring is installed may temporarily affect the surface pH level (Section 5.3). In adhesives with a low solids-to-water content, the water that does not evaporate during the open time may be absorbed by the concrete, dissolve alkalis near the surface, and may alone have a temporary effect on the surface pH level (Section 5.3).

The influence of adhesive moisture content on flooring performance is recognized by some adhesive manufacturers. In the past, a minimum solids-water content of 75 to 25%, or no more than 25% water was recommended for adhesives used to install wood flooring. While a 25% limit on water in a wood flooring adhesive may still apply, today, many wood

Fig. 9.5—Adhesives placed on nonporous plastic plates and allowed to dry. The plates were weighed during the drying process to determine the water loss during the open time and then the subsequent amount of water that the concrete would absorb if an impermeable floor covering was placed over the adhesive (Suprenant 2003c).

flooring adhesives are no longer water-based. Water in an adhesive can change the wood moisture content, which in turn can adversely affect the performance of the flooring. Thus, while wood warping is often blamed on moisture in the concrete, the adhesive can also provide sufficient moisture to cause the wood to warp. Specifiers should be very specific about the adhesive they require and not allow substitutions unless they are sure of the performance of the alternate.

9.6—Effect of concrete moisture on adhesive performance

Suprenant and Malisch (1999a) tested the pulloff strength of several different flooring adhesives that were applied to concrete slabs with varying MVERs. Low emission rates (1.4 and 1.8 lb/1000 ft^2/24 h [0.68 and 0.88 kg/100 m^2/24 h]) were for a 20-year-old existing floor, while higher rates (3.7 to 7.8 lb/1000 ft^2/24 h [210 to 440 kg/m^2/24 h]) were for test slabs that were more than 6 months old.

Three 4 x 12 in. (100 x 300 mm) vinyl composition strips were core-drilled to produce three 2 in. (51 mm) diameter tile plugs. This allowed three pulloff tests for each adhesive tested (Fig. 9.6a). Adhesive manufacturer's recommendations were followed for adhesive thickness, trowel size, and open time when spreading each adhesive to cover an area on the concrete surface approximately the size of the tile strip. After waiting until the recommended open time had been reached, the 4 x 12 in. (100 x 300 mm) strips were placed on the adhesives and pounded into place. The 2 in. (51 mm) diameter plugs were then placed into the drilled holes and pounded down.

Fig. 9.6a—Pulloff testing for vinyl composition tile placed on concrete slab with known moisture vapor emission rate (Suprenant 2003c).

After the adhesive cured for 3 days, a fast-setting epoxy was used to attach a 2 in. (51 mm) diameter steel disc that had a 1/2 in. (13 mm) diameter threaded rod welded to the top. A 500 lb (2.2 kN) capacity hydraulic ram was attached to the threaded rod and used to pull the tiles off the floor.

Pulloff strength test results for the existing floor (MVER of 1.4 and 1.8 lb/1000 ft^2/24 h [0.68 and 0.88 kg/100 m^2/24 h]) showed that:

(a) Average strength for the epoxy-based adhesive was 128 psi (882 kPa)

(b) Average strengths for two solvent-based adhesives were 11.0 and 29.5 psi (76 and 203 kPa)

(c) Average strengths for six water-based adhesives ranged from 7.0 to 38.5 psi (48 to 265 kPa)

Figure 9.6b shows the pulloff strength test results for concrete slabs with different MVERs. There is a trend toward decreasing strength with increasing emission rate, as shown by the dashed lines, but there are some anomalies. Also note the wide spread between the top and bottom dashed

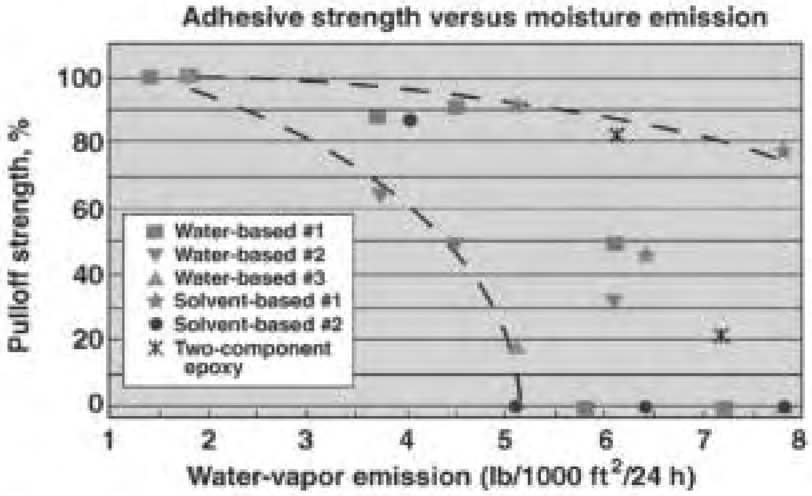

Fig. 9.6b—Pulloff test results for different adhesives on concrete slabs with different moisture vapor emission rates (Suprenant and Malisch 1999a). (Note: 1 lb/1000 ft^2/24 h = 0.488 kg/100 m^2/24 h.)

lines. Some adhesives performed much better than others, but performance wasn't necessarily related to the generic adhesive class. For instance, the water-based No. 1 adhesive outperformed the solvent-based No. 2 adhesive, but the solvent-based No. 1 adhesive outperformed the water-based No. 2 adhesive.

More data on the relationship between adhesive properties, such as tensile or shearing strength and performance of the adhesives on concrete substrates, are needed.

CHAPTER 10—DESIGN AND CONSTRUCTION RECOMMENDATIONS

10.1—Introduction

These design and construction recommendations are based on the information presented in the previous chapters. Figures 10.1a and 10.1b illustrate the effects of several variables on drying time and pH. Specifications will usually include clauses related to:

(a) Moisture testing
(b) Moisture mitigation systems
(c) Below-slab vapor retarder
(d) Concrete materials and properties
(e) Curing
(f) Protection
(g) Surface preparation
(h) Repair materials
(i) Floor covering materials and adhesives

Because conditions for a project can be unique, the design team should review general recommendations regarding the items listed, decide which to incorporate, then rephrase them in specification (mandatory) language. The resulting specification should also be reviewed by the floor covering and adhesive manufacturers before it is issued as part of the project documents. If manufacturers of these flooring or adhesive products do not agree with requirements in the project specifications, either the specifications or products should be changed. This helps ensure that the warranty for flooring or adhesive products remains valid. For special flooring applications, a prebid review by several flooring installers might also help the design team work out any disagreements before construction begins. The importance of evaluating the effects of changes in specifications or scope of work is illustrated by two case studies described in the Appendix.

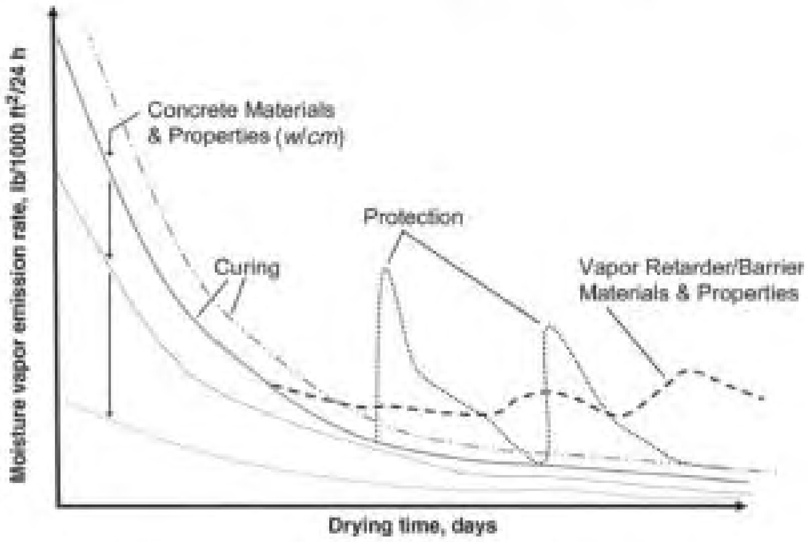

Fig. 10.1a—Water-cementitious material ratio (w/cm) is the primary concrete property affecting MVER. The lowest curve represents the lowest w/cm. At the same w/cm, wet curing (highest curve) increases the time needed to reach a required MVER. If concrete is left unprotected, each rewetting increases MVER. If there is no vapor retarder, or if the retarder is breached by poor laps or punctures, MVER does not reach an equilibrium point.

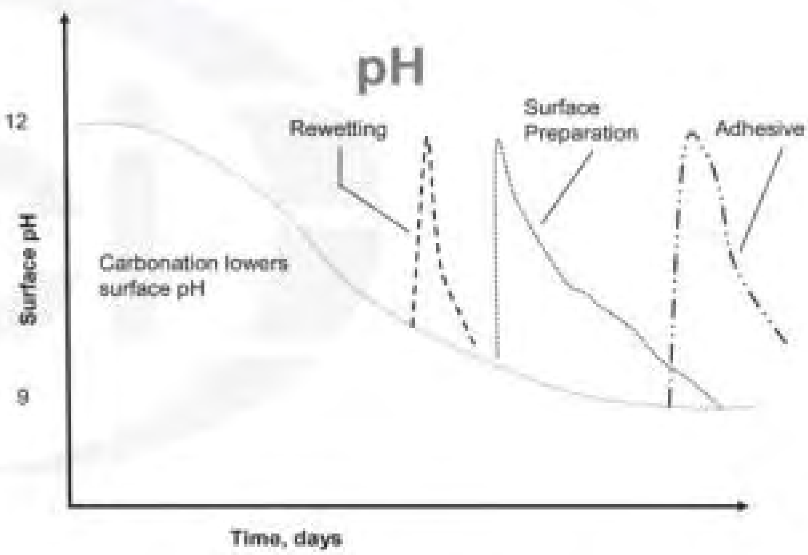

Fig. 10.1b—Although carbonation of the surface reduces pH, rewetting can dissolve more alkalis, raising the pH. Abrasive blasting or other surface preparation methods can remove all or part of the carbonated layer, increasing the pH. Water contained in the adhesive can also temporarily increase the pH of the surface.

10.2—Moisture testing

The following moisture testing recommendations should be considered:

(a) Moisture testing should be performed by a qualified, independent agency (World Flooring Covering Association 2001).

(b) Those performing moisture tests should hold a current ICRI Moisture Testing Technician Grade 1 Certification.

(c) If the flooring or adhesive manufacturer only requires testing by ASTM F1869, require that in-place concrete internal relative humidity (RH) tests (ASTM F2170) also be performed.

(d) For repair materials or underlayments, a moisture content of the repair material should be specified and measured with either a specific meter or a calcium carbide test, whichever is recommended by the manufacturer of the repair material or underlayment.

(e) On large projects, prior to performing the full number of moisture tests currently required by the ASTM standards, a lesser number of pilot tests can first be performed on each concrete placement. No fewer than six pilot tests should be performed on each concrete placement. If the pilot tests do not show that the slab is at the required moisture level, there is no reason to expect that a greater number of tests would provide different results. However, if the pilot tests do pass, the full ASTM-compliant number of tests should be performed to comply with the ASTM standards and the floor covering and adhesive manufacturers requirements.

(f) In Construction Specifications Institute (2000), Section No. 1500, the general contractor or construction manager should be advised that environmental controls will be required during moisture testing as per the designated ASTM standard selected for the test.

10.3—Vapor retarder

Vapor retarder location is a critical decision, but composition, permeance, thickness, and installation methods for the retarder should also be considered. Recommendations include:

(a) For floor covering or coating installations, concrete slabs are to be placed directly on the vapor retarder.

(b) Vapor retarders should conform to the minimum requirements of the most current version of ASTM E1745. This standard shows physical property requirements divided into three classes: A, B, or C. Class A, B, and C vapor retarders all have the same 0.1 perm water vapor permeance requirement but differing tensile strength and puncture-resistance requirements. Class A has the highest strength and puncture resistance, and Class C has the lowest. The choice in physical properties should be based on conditions expected during construction. Such conditions might include exposure to puncture or tearing by angular subbase particles, traffic from concrete trucks, laser screeds, or concrete buggies directly on the vapor retarder or over reinforcing steel laying on the surface of the retarder.

(c) The specifier should examine the performance properties after the conditioning tests called for in ASTM E1745. Such properties include flame spread, permeance, puncture resistance, tensile strength, wetting, drying, soaking, heat conditioning, low temperature conditioning, soil organism exposure, soil poison petroleum vehicle exposure, and exposure to ultraviolet light.

(d) It should be determined whether a vapor retarder with a 0.1 perm rating is sufficient protection for the flooring material to be installed. If not, a vapor retarder with a much lower permeance than 0.1 perms should be specified. Below-slab vapor retarder materials with permeance levels well below 0.1 perm before and after conditioning tests are available. Low-permeance flooring materials or floor coverings with low moisture requirements (3 lb/1000 ft^2/24 h [1.5 kg/100 m^2/24 h], 75% internal RH) will benefit from the use of a vapor retarder material with a permeance level well below the current ASTM minimum requirement.

(e) It should be considered whether the published material properties specified are sufficient or if a minimum thickness of the vapor retarder should be specified. ACI 302.1R recommends that the thickness of an ASTM E1745-compliant material be selected on the basis of protective needs and durability during and after construction. When the vapor retarder is subjected to traffic, it should meet the ASTM E1745 class A requirements. Some specifiers and contractors have observed slab placement traffic tearing 10 mil vapor retarders and require that the vapor retarder thickness be 15 mil (0.38 mm) or greater.

(f) Installation should be in accordance with ASTM E1643.

(g) Referencing ASTM E1643 requires the contractor to follow the manufacturer's instructions for placement (including laps and sealing around penetrations and foundation walls), protection, and repair. ASTM E1643 requires the contractor to use reinforcement supports that do not puncture the vapor retarder and to repair any damaged areas.

(h) Inclusion of some of the construction items mentioned in ASTM E1643 in the text of the project specifications should be considered (for example, "Place vapor retarder sheeting with the longest dimension parallel with the direction of the concrete pour". Lap joints a minimum of 6 in. (150 mm) or as instructed by the manufacturer". "Seal laps in accordance with the manufacturer's recommendations". Construction-related requirements included only in cited standards are more difficult for the contractor to find and comply with.

10.4—Concrete materials

As discussed in 7.6, there is no reason to include or exclude the use of water-reducing admixtures, cements, or supplementary cementitious materials as a means for influencing concrete drying or moisture emission rates. There is evidence that concretes containing silica fume dry faster than concretes without silica fume. Silica fume, however, is rarely used in concrete slabs that receive floor coverings.

Lightweight concrete does not dry as fast as normalweight concrete. Specifiers who choose to use lightweight concrete will need to consider means for dealing with the increased drying time. Such means may include the selection of floor coverings or adhesives that can be placed on concretes at higher moisture levels, or the application of a moisture mitigation system conforming to ASTM F3010.

10.5—Concrete properties

As discussed in 6.7, concrete drying time is related to the *w/cm*, independent of whether the *w/cm* was adjusted by varying the cement or water content. Both Brewer (1965) and Hedenblad (1997) showed that concretes with the same

w/cm took the same time to dry to a given state, whether a water-reducing admixture was present or not.

10.5.1 *Selecting a* w/cm—ASTM F710-21 contains statements concerning *w/c* in the Appendix (nonmandatory information):

"Moderate to moderately low water-cement ratios (0.40 to 0.45) can be used to produce floor slabs that can easily be placed, finished, and dried, and which will have acceptable permeability to moisture. Floor slabs with water-cement ratios above 0.60 take an exceedingly long time to dry and cause adhesive or floor coverings, or both, to fail due to high moisture permeability. Floor slabs with water-cement ratios above 0.50 take longer to dry and often result in the project having to install a topical moisture mitigation system to meet the floor covering and adhesive requirements.

"A 4 inch (100 mm) thick slab, allowed to dry from only one side, batched at a water-cement ratio of 0.45, typically requires approximately 90 to 120 days to achieve a moisture vapor emission rate (MVER) of 3 lb/1000 ft^2 per 24 h (1.5 kg/100 m^2/24 h). The importance of using a moderate to moderately low water-cement ratio for floors to receive resilient flooring cannot be overemphasized."

Using a *w/cm* of 0.40 to 0.45 will typically produce concretes with compressive strengths between 4500 and 5000 psi (31 to 34 MPa). Concrete with these strengths due to higher cementitious content are likely to have an increased potential for shrinkage, curling, and cracking. If a short concrete drying time is critical, a *w/cm* of 0.40 to 0.45 may be appropriate. Suprenant and Malisch (1998a) found that concretes with a *w/cm* less than 0.40 reached a given MVER at the same time as concrete with a *w/cm* of 0.40.

In regions of the country where ambient RH levels are consistently below 50%, it is possible for the desired moisture state to be reached within 90 to 120 days of the building being totally closed in, watertight, and brought to an interior temperature of at least 70°F (21°C) using concrete with a 0.50 *w/cm*. Such a concrete is more economical and has enough paste to permit the finishing steps needed to produce the specified surface finish and flatness. Water-reducing admixtures, a nonburnished concrete finish, and cover curing methods can be used to produce concrete that, when exposed to favorable drying conditions, can dry to an acceptable level within 90 to 120 days. For projects where ambient RH levels are consistently high, or the project schedule cannot accommodate an extended drying time after the building is closed in, a rapid drying concrete mixture or a topical moisture mitigation system can be used.

If a concrete slab is exposed to re-wetting from rainwater, or other sources, drying will be delayed. Using a low-*w/cm* concrete to reduce the time needed for slab drying is of doubtful value if the slab will be exposed to weather for 3 to 9 months after placement. The required concrete drying time is as much related to the time of the last wetting as it is to the original *w/cm*.

Specifying a *w/cm* of 0.50 is typically equivalent to requiring a specified compressive strength f_c' of 4000 psi (28 MPa). Specify both *w/cm* and the corresponding compressive strength. ACI 318 code requirements do not usually govern design and construction of soil-supported slabs, but the following quote from the code commentary is noted in support of this suggestion: "Selection of an f_c' that is consistent with the water-cementitious materials ratio selected for durability will help ensure that the required water-cementitious materials ratio is actually obtained in the field."

This indicates that compressive strength tests can be used indirectly to verify the *w/cm*. Field measurements of *w/cm* for fresh concrete are not reliable enough for use in assuring that the specified value has been achieved.

10.6—Surface finish

Most floor covering manufacturers prefer that the concrete surface be brought to a smooth, but non-burnished, finish free of trowel marks and ridges. A burnished finish (produced by repeated hard troweling) does not readily absorb free water from the flooring adhesive and can slow down the release of free water in the slab, which will extend the drying time. The desired final finish can be difficult to achieve under certain circumstances. Mechanical surface preparation may be required to open the finished surface for many types of flooring materials. The specifier should establish an allowance in the floor covering installers contract to address changes that may be necessary to achieve the degree of surface porosity needed for certain types of floor covering installations.

Different floor coverings often require different finishes. Facilities built with only one type of floor covering are rare. For economical concrete finishing, it is better to specify one finish and have the floor covering installers use the surface preparation methods required to produce the finishes they need. When specifying the surface finish, keep in mind the required method of subsequent surface preparation. Many surface preparation treatments such as shotblasting, scarifying, or grinding will make the choice of the original surface floor finish moot.

10.6.1 *Floor flatness*—Owners and architects often specify different floor covering products for use in different parts of facilities such as retail stores. Concrete surface-finish requirements, however, are unique for each product. Table 6.3 shows floor finish and tolerance requirements as recommended by ACI, ASTM, and various flooring organizations. Where only one product is used, Division 3 and Division 9 specifications can exactly match that product's requirements. The issue, however, is not that simple where multiple products are used.

As discussed in 6.3, it is not feasible to have the concrete contractor meet separate floor tolerances and finish requirements for every area where a different floor covering product will be used. Based on Table 6.3 recommendations, F-numbers can be specified in Division 9. For floor covering installations where higher F numbers are required, the specialty or floor covering contractor would be instructed to patch, grind, or shotblast the floor as needed. This instruction would then be covered in Division 9 under the scope of work.

F-number specification requirements should be in accordance with the recommendations in ACI 302.1R for suspended slabs and slabs-on-ground. An overall floor flatness F_F greater than 35 should not be specified because changes in flatness after F_F is measured (curling of slabs-on-ground and deflections of suspended slab) can decrease the flatness.

10.7—Curing

Experimental work by Hedenblad (1997) and Jackson and Kellerman (1939) shows that shorter curing durations result in faster drying of the concrete. Hedenblad's experimental work indicates that moist curing for 28 days instead of 1 day increased the time required to reach a desired moisture state by approximately 1 month. Suprenant and Malisch (1999b) recommended using a sheeting material to cure the concrete for 3 days. This provides a compromise between improving the concrete properties and decreasing the time required to reach a desired moisture state.

Some specifiers have required that new slabs be water cured for as long as 28 days. This practice is counterproductive for floors that need to dry before flooring materials are installed. Extended wet curing delays the start of drying, adds water that must later exit the concrete, and constricts the path through which the water must exit. If drying time is critical to the schedule, the specifier should not require extended water curing or curing durations for any curing method for longer than 7 days.

ASTM F710-21 requires that the surface of concrete floors to receive resilient flooring shall be free of: film-forming curing compounds; silicate-penetrating curing compounds; and sealing, hardening, or parting compounds that might affect the rate of moisture dissipation from the concrete. These surface treatments can lengthen the drying time of the concrete and can inhibit the bond between the concrete surface and flooring adhesives, patching, or underlayment materials. They may also trap moisture in the concrete, which can lead to future problems with flooring materials installed over them. In all cases where curing compounds of any type have been used, the manufacturers of the flooring materials to be installed should be consulted and the requirements of ASTM F710 followed.

Based on the information presented, the following is recommended:

(a) Slabs to receive floor coverings should not be cured by continuous wet curing methods such as sprinkling or burlap that is kept wet continuously.

(b) Non-dissipating curing compounds or cure-and-seal materials that conform to ASTM C309 or ASTM C1315 should not be used unless such use is approved in writing by the underlayment, adhesive, and floor covering manufacturer. The curing product manufacturer's conformance to ASTM C309 or ASTM C1315 is not a substitute for the underlayment adhesive and floor covering manufacturers' approval. Using a curing compound will slow the initial drying, resulting in longer drying times, and to conform with ASTM F710 will need to be removed before the floor covering adhesive can be applied.

(c) As an alternative to continuous wet curing, or membrane cures, cover curing materials such as lay-flat, non-staining waterproof paper, lay-flat plastic sheeting, or saturated, fabric-backed poly, that conform to ASTM C171 can be considered.

(d) Reactive type surface hardeners/densifiers should not be used as a form of curing on slabs to receive moisture-sensitive flooring materials or adhesives.

10.8—Surface preparation

Regardless of the floor covering or adhesive manufacturer's instructions, no surface preparation should be allowed without authorization of the architect or engineer. ASTM F710 states that "abrasive removal (shotblasting, sanding, or grinding) of a thin layer of concrete can remove [the] carbonated layer and expose more highly alkaline concrete below. Additional waiting time, application of patching compound or underlayment, or a combination thereof, might be required after abrasive removal of the concrete surface."

Surface preparation requirements and the testing requirements should be specific. Generally, once the moisture test results are satisfactory, surface preparation should begin, and the floor covering should be placed without further testing. Tests required after surface preparation should be specified. When tests are conducted after surface preparation, some additional time may be needed for the surface to meet the moisture requirements.

Power washing or acid etching should not be allowed as part of the surface preparation. The adhesive and floor covering manufacturer should agree that the specified surface preparation methods are compatible with their product requirements. Shotblasting is often the preferred method of surface preparation.

The specifier should determine whether any of the following ASTM standards should be referenced as part of the surface preparation in the project specifications: ASTM C811/C811M, D4258, D4259, D4260, D5295, and F710. The Society for Protective Coatings (2001) and ICRI 310.2R will also provide guidance.

10.9—Repairs

Some grinding or patching might be needed to repair cracks or to bring floors into compliance with specifications for floor flatness. The effects of such repairs on moisture and pH should be considered. Grinding should be done dry, with a vacuum attachment. If wet grinding is used, additional drying time is required. It should be ensured that patching materials are compatible with the flooring adhesive to be used. Also, it should be ensured that the moisture state of patching materials is checked prior to flooring placement. Some manufacturers supply quick-drying underlayments for use before floor coverings are placed. Be wary of using or-equal products of this type. It should be confirmed that the adhesive and floor covering manufacturers' warranties are still valid with the chosen repair product.

10.10—Protection

When drying time is critical to the schedule, it is important to protect the slab from external moisture sources such as rainwater; runoff from adjacent slopes; landscaping water; water from curing; or wet grinding, sawing, and cleaning.

When drying time is critical and the moisture-sensitive floor covering is an important feature of the facility, the slabs should be constructed after the building is enclosed and the roof is watertight. Typically, this extends the construction schedule and increases costs (ACI 302.1R), but these disadvantages should be weighed against a 1- or 2-month schedule delay if the floors are rained on.

Protection is the most difficult design and construction item to incorporate into the project. Placing the concrete slab directly on the vapor retarder eliminates the possible moisture reservoir that can form under the slab, but the slab surface doesn't begin its final drying until the structure is enclosed and protected from rain. Owners may object to placing the concrete slab under a watertight roof because of the increased cost and schedule delay. Requiring the contractor to keep an exposed slab dry (by protecting it from rain or other external moisture sources), however, is likely to be unaffordable to the owner and not feasible for the contractor.

Unless the structure is enclosed before the floor slab is placed, all parties should accept the fact that the slab will undergo alternate wetting-and-drying cycles. It is inappropriate for specifiers to ask contractors to state the required drying times and critical schedule dates, and to specify the needed protection methods. Decisions by the owner, design team, and contractor can all have an influence on the anticipated concrete drying time.

10.11—Moisture mitigation

Because waiting for a slab to dry can delay completion of the building, some architects incorporate a specification section that deals with slab moisture mitigation. Such systems are topically applied to the concrete surface to protect the flooring and adhesive from moisture and moisture-induced high-pH condition. Adding such a specification section brings potential floor drying problems to the attention of the owner and contractor, allows the owner to get a bid as an alternate to waiting, and then facilitates decision-making when concrete is not drying fast enough. This informs all parties of the possible issues and remedies and the costs if the schedule cannot wait for the concrete to dry.

CHAPTER 11—REFERENCES

Committee documents are listed first by document number and year of publication followed by authored documents listed alphabetically.

American Concrete Institute

ACI 117-10 (15)—Specification for Tolerances for Concrete Construction and Materials and Commentary

ACI 222R-19—Guide to Protection of Metals in Concrete against Corrosion

ACI 301-20—Specifications for Concrete Construction

ACI 302.1R-15—Guide for Concrete Floor and Slab Construction

ACI 318-19—Building Code Requirements for Structural Concrete and Commentary

ACI 360R-10—Guide to Design of Slabs-on-Ground

ASTM International

ASTM C33/C33M-18—Standard Specification for Concrete Aggregates

ASTM C171-20—Standard Specification for Sheet Materials for Curing Concrete

ASTM C309-19—Standard Specification for Liquid Membrane-Forming Compounds for Curing Concrete

ASTM C805/C805M-18—Standard Test Method for Rebound Number of Hardened Concrete

ASTM C811-98(2008)—Standard Practice for Surface Preparation of Concrete for Application of Chemical-Resistant Resin Monolithic Surfacings (Withdrawn 2012)

ASTM C1315-19—Standard Specification for Liquid Membrane-Forming Compounds Having Special Properties for Curing and Sealing Concrete

ASTM D4258-05(2017)—Standard Practice for Surface Cleaning Concrete for Coating

ASTM D4259-18—Standard Practice for Preparation of Concrete by Abrasion Prior to Coating Application

ASTM D4260-05(2017)—Standard Practice for Liquid and Gelled Acid Etching of Concrete

ASTM D4262-05(2018)—Standard Test Method for pH of Chemically Cleaned or Etched Concrete Surfaces

ASTM D4263-83(2018)—Standard Test Method for Indicating Moisture in Concrete by the Plastic Sheet Method

ASTM D5295/D5295M-18—Standard Guide for Preparation of Concrete Surfaces for Adhered (Bonded) Membrane Waterproofing Systems

ASTM D8397-22—Standard Specification for Acrylic and Reactive Adhesives for Installation of Vinyl and Rubber Floor Coverings

ASTM E119-20—Standard Test Methods for Fire Tests of Building Construction and Materials

ASTM E1643-18a—Standard Practice for Installation of Water Vapor Retarders Used in Contact with Earth or Granular Fill Under Concrete Slabs

ASTM E1745-17—Standard Specification for Water Vapor Retarders Used in Contact with Soil or Granular Fill under Concrete Slabs

ASTM F710-21—Standard Practice for Preparing Concrete Floors to Receive Resilient Flooring

ASTM F1869-16a—Standard Test Method for Measuring Moisture Vapor Emission Rate of Concrete Subfloor Using Anhydrous Calcium Chloride

ASTM F2170-19a—Standard Test Method for Determining Relative Humidity in Concrete Floor Slabs Using in situ Probes

ASTM F2659-10(2015)—Standard Guide for Preliminary Evaluation of Comparative Moisture Condition of Concrete, Gypsum Cement and Other Floor Slabs and Screeds Using a Non-Destructive Electronic Moisture Meter

ASTM F3191-16—Standard Practice for Field Determination of Substrate Water Absorption (Porosity) for Substrates to Receive Resilient Flooring

ASTM F3311-19—Standard Practice for Mat Bond Evaluation of Performance and Compatibility for Resilient Flooring System Components Prior to Installation

International Concrete Repair Institute

ICRI 310.2R—Selecting and Specifying Concrete Surface Preparation for Sealers, Coatings, and Polymer Overlays

National Terrazzo and Mosaic Association

NTMA 09 66 13.19: 2012—Guide Specification for Bonded Terrazzo Flooring

NTMA 09 66 13.13:2012—Guide Specification for Sand Cushion Terrazzo Flooring

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APPENDIX—TWO CASE STUDIES OF MOISTURE-RELATED FLOORING PROBLEMS

A.1—Value engineering results in flooring failure

A 6 in. (150 mm) thick, 4000 psi (28 MPa) concrete slab was to receive an epoxy coating. The original design called for the 3 ft (910 mm) thick mat foundation to be covered by 6 in. (150 mm) of compacted granular fill, with a 10 mil (0.25 mm) thick vapor retarder laid on the fill, and the concrete slab placed on the vapor retarder. During a value engineering meeting, participants decided to raise the mat foundation elevation and use the top of the foundation as the floor surface, with the epoxy coating applied directly to the mat foundation. This saved the cost of the 6 in. (150 mm) thick concrete slab, 6 in. (150 mm) of granular fill, and the vapor retarder, while also requiring less excavation.

The result of this value engineering was a debonded epoxy coating. The project participants shared in the cost of repairing the failure, with the engineering firm contributing $100,000 because they did not specify placement of a vapor retarder below the 3 ft (910 mm) thick mat foundation. Based on the previous information in other chapters of this guide, the moisture in a 3 ft (910 mm) thick mat foundation would have been enough to cause a problem with the epoxy coating regardless of whether or not a vapor barrier had been in place. It is unlikely that water from below the mat foundation played a role in debonding of the epoxy coating. Given the thickness of the concrete, however, a very long time would have been required for the concrete to reach the desired moisture state and remain there after the coating had been applied. Recommendations provided in this chapter could have been used in the original design to ensure that the concrete slab was able to receive a moisture-sensitive floor covering. At the value engineering meeting, the cost of covering the surface of the mat foundation with a moisture mitigation system should have been included. The value-engineering alternative might not have been chosen if this cost had been included.

A.2—Post-construction trench drains results in flooring failure

An engineering company was called to investigate the flooring failure of a very small 5000 ft^2 (460 m^3) office. The flooring had been in place for 3 years and, in some areas, the floor covering was not adhering to the floor. During the investigation, the floor covering was removed, and calcium chloride and internal relative humidity (RH) tests were conducted. In addition, concrete cores were removed from the slab-on-ground to determine the moisture content of the granular fill and subgrade and the location of the vapor barrier.

Investigators found that after completion of the original floor, a new owner had required installation of additional underslab utilities. To install the new utilities, concrete was removed, trenches were dug, utilities were installed, fill was placed and compacted, and new concrete was placed. Unfortunately, the contractor who placed the utilities did not place a vapor retarder under the concrete and did not seal the joints where the new concrete abutted the old concrete. This system passed more moisture than the old concrete on top of the vapor retarder, thus creating localized failures at the trenches. Because the trenches were extensive and the floor covering area limited, a moisture mitigation system was applied to the entire 5000 ft^2 (460 m^2).

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