Guide for Concrete Slabs that Receive Moisture-Sensitive Flooring Materials

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Dennis Phillips
John W. Rohrer[*]
Phillip A. Smith
Bruce A. Suprenant[‡]
Scott M. Tarr[*]
Gregory R. Taylor
Eldon G. Tipping

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[*] Member, Moisture Task Group.
[†] Secretary, Moisture Task Group.
[‡] Chair, Moisture Task Group, and principal author.

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. 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 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 the most current editions of both ACI 302.1R, "Guide for Concrete Floor and Slab Construction," and ACI 360R, "Design of Slabs-on-Ground," for general information. These two documents contain guidance on floor design and construction that is needed to achieve successful floor covering performance.

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

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CHAPTER 1—INTRODUCTION AND BACKGROUND

1.1—Introduction

Delamination, blistering, staining, mold growth, and other problems related to the installation and performance of moisture-sensitive flooring materials on concrete slabs are common. The problems include claims for total failure of the flooring system, construction-schedule delays caused by slow concrete drying, and lawsuits involving indoor air quality. It is currently up to architects, engineers, floor covering installers, flooring and adhesive manufacturers, concrete contractors, and concrete producers to solve these problems.

The objective of this document is to reduce the potential for moisture-related problems in both slabs-on-ground and suspended slabs. It provides basic information on the concrete drying process, moisture behavior in concrete, testing for pH and moisture, and vapor retarders/barriers. Based on this information, recommendations for the design and construction of concrete slabs that will receive moisture-sensitive or pH-sensitive flooring materials or coatings are presented.

1.2—Flooring moisture issues

Figures 1.1 to 1.4 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.

1.3—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, 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/barrier, 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 document supplements information contained in the ACI 360R and 302.1R guides 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.

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

In the last 10 to 15 years, there has been an increase in the number of reported flooring problems—for example, blisters, debonding, staining, and mold growth—caused by moisture originating within or moving through concrete slabs. Some

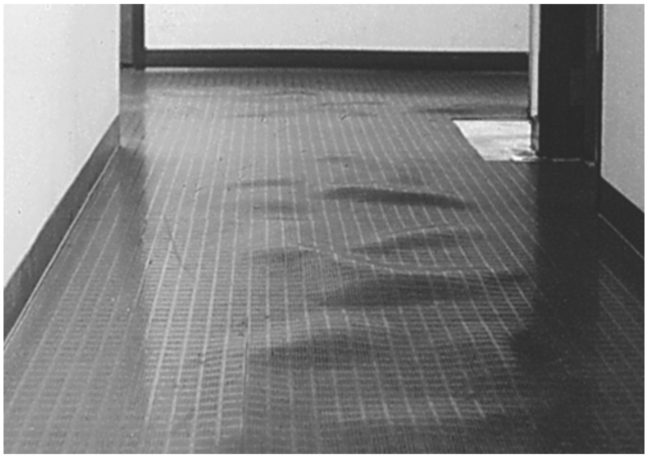


Fig. 1.1—Debonded sheet flooring due to moisture in the concrete slab. (Courtesy of Peter Craig and Herman Protze III.)

Fig. 1.2—Blisters due to moisture in concrete. (Courtesy of Peter Craig.)

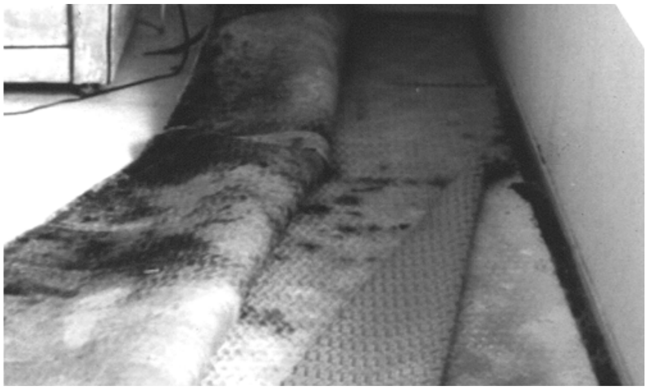


Fig. 1.3—Mold growth in carpet due to moisture in concrete. (Courtesy of Floor Seal Technology, Inc.)

Fig. 1.4—Adhesive degradation leading to debonded solid vinyl tile installed over asbestos tile. (Courtesy of Peter Craig.)

problems may be related to fast-track construction methods that allow less time for concrete drying. Other problems may result from changes in the composition of floor covering adhesives related to restrictions on the use of volatile organic compounds (VOCs).

1.5—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.

The foreword of 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 2002b,c). As shown in the examples by 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.

Time-dependent changes in floor profiles occur on every project, but the magnitude of the profile change can vary. ACI 117-90 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. Therefore, the design team should consider how changes in floor profiles with time might affect:

- The floor covering installers' ability to meet Division 9 specification requirements; and
- Long-term floor performance after the floor covering has been installed.

Figure 1.5 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 1.6 (a) through (c) show three possible approaches:

- **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

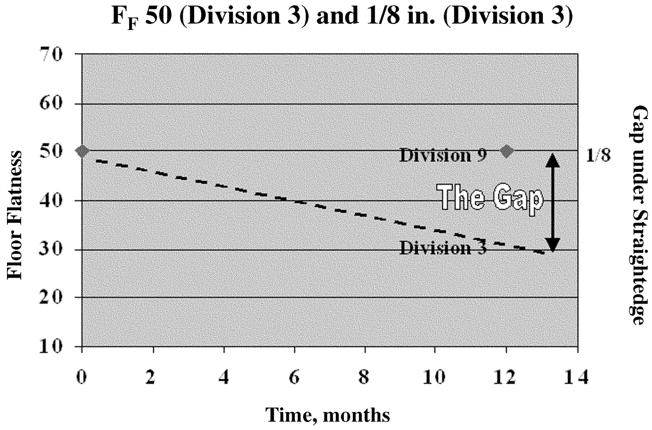


Fig. 1.5—When flatness of an unreinforced floor is measured initially, F-numbers may indicate a very flat floor. When flooring installers start their work, however, flatness may have changed, as indicated by the gap between Division 3 and Division 9 flatness (Suprenant 2003d).

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;

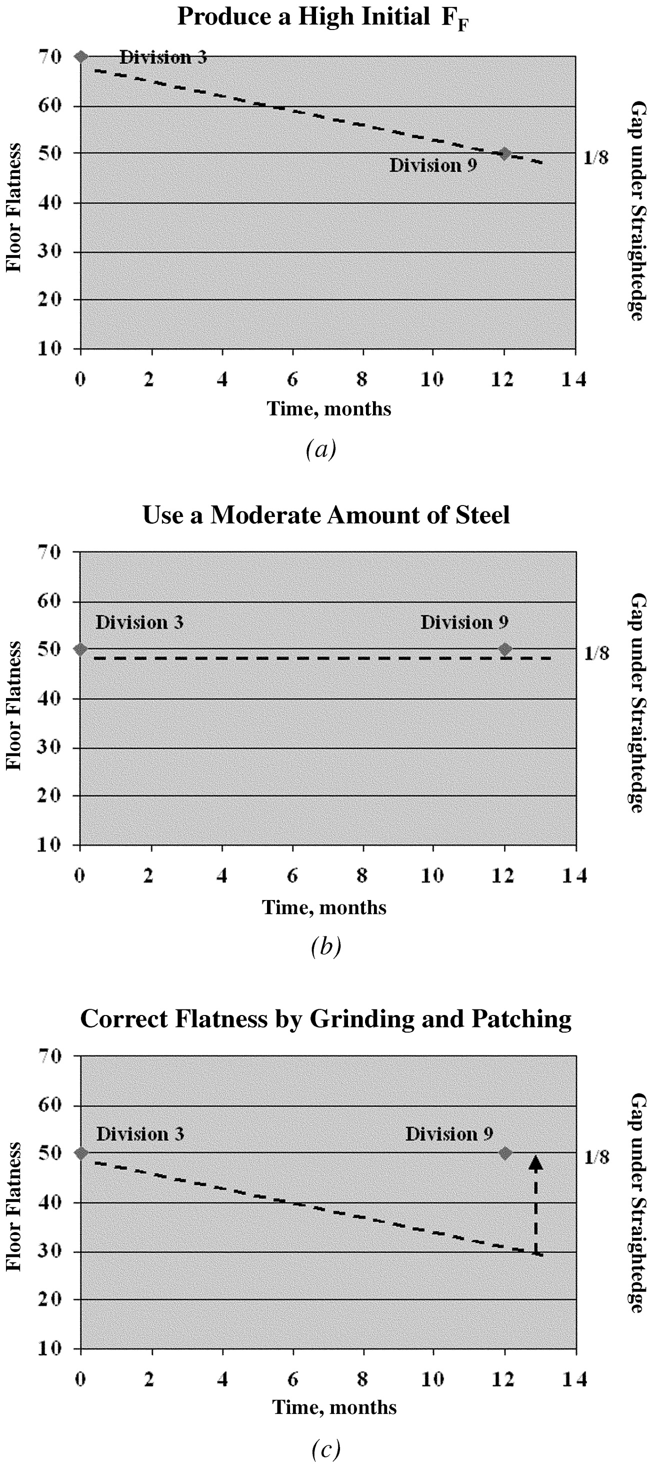
- **Use reinforcing steel.** The engineer selects a ratio of reinforcement area to gross concrete area—typically approximately 0.5% for Grade 60 steel—that minimizes curling. Refer to ACI 360R for more information; or
- **Correct flatness problems by grinding and patching.** The engineer designs a floor that is expected to curl, but requires the contractor or floor covering installer to include an allowance in the bid for repairing the curl (Suprenant and Malisch 1999b). Section 5.2.9 discusses various repair options.

1.6—Other considerations

Wide random cracks in slabs create problems when floor materials are placed over them. Floor covering manufacturers all require some form of crack repair for wide cracks. To minimize crack width and crack repair, steel reinforcement should be considered for use in the slab (Fig. 1.7), as recommended by Holland and Walker (1998). Other methods for reducing the potential for excessive cracking include proper concrete mixture proportioning and joint spacing or other types of reinforcement such as post-tensioning.

Contraction, construction, and column blockout joints are almost always visible under thin flooring materials. Because of this problem, Holland and Walker (1998) recommend using reinforcing bars to minimize crack widths, and eliminating contraction joints and the traditional diamond-shaped isolation joints at columns when floors will receive a covering. Instead of using diamond-shaped isolation joints, steel columns in a floor system should be wrapped for the full floor depth with 1/4 to 3/8 in. (6.4 to 9.5 mm) thick compressible isolation joint material (Fig. 1.8). Refer to ACI 360R for more information.

Carpeting and some other floor coverings can tolerate larger crack widths in the concrete floor without noticeable projection of the crack through the surface opening. 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.



(a)

(b)

(c)

Fig. 1.6—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).

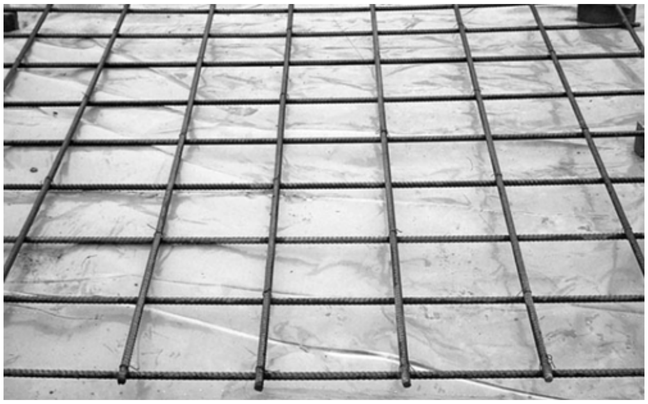


Fig. 1.7—Reinforcing bar in concrete slabs placed directly on vapor retarder help to control slab curling and cracking. Supported deformed bars no smaller than No. 4 (No. 13) should be used, and the bars spaced far enough apart so workers can step between them (Holland and Walker 1998).

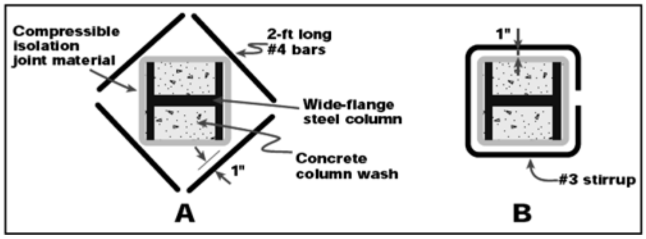


Fig. 1.8—Eliminate the normal isolation-joint boxouts at wide-flange steel columns by wrapping the column with compressible materials and using 2 ft (0.6 m) lengths of No. 4 bars (A) to control cracking at the re-entrant corners. To speed up steel placement at the columns, have the reinforcing bar supplier 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).

CHAPTER 2—CONCRETE MOISTURE BASICS

2.1—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 and finishing practices, evaporation during finishing, and curing methods. It is the changes in moisture distribution after the concrete hardens, however, that have the greatest effect on the performance of flooring materials. Understanding how water moves through hardened concrete is important in determining:

- Consequences of the moisture movement;
- Effectiveness of moisture testing methods; and
- Validity of flooring manufacturers' warranty recommendations.

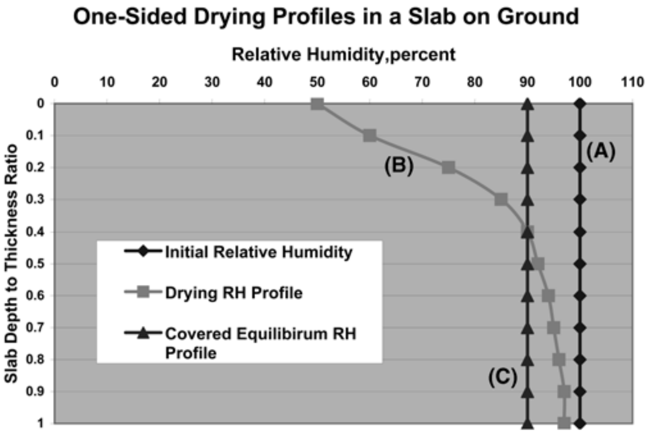


Fig. 2.1—One-sided drying profiles in a slab-on-ground showing initial, drying, and covered equilibrium relative humidity profiles (adapted from Hedenblad [1997]).

2.2—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).

2.2.1 *Drying of concrete slab-on-ground*—Figure 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% relative humidity (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 relative humidity lower at the top. The profile of the drying curve (Curve B) varies with the temperature and relative humidity at the concrete surface, the length of the drying period, and the concrete properties.

Drying ceases or slows when a floor covering is installed, depending on the permeability of the floor covering, and the internal moisture redistributes throughout the concrete before reaching an equilibrium level at which the RH is nearly uniform throughout the concrete. Figure 2.1 shows the new RH profile as a vertical line (uniform moisture) at 90% RH (Curve C). The absolute RH value at equilibrium varies depending on the initial moisture content, drying conditions, and length of the drying period (Hedenblad 1997).

2.2.2 *Drying of suspended concrete slab*—Figure 2.2 (adapted from Hedenblad) 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 mid-depth 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.

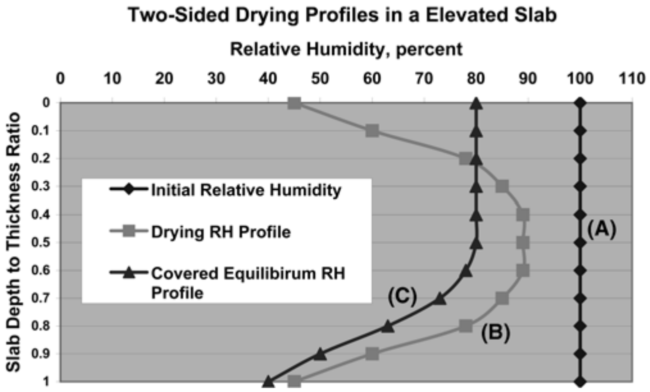


Fig. 2.2—Two-sided drying profiles in suspended slab showing initial, drying, and covered equilibrium relative humidity profiles (adapted from Hedenblad [1997]).

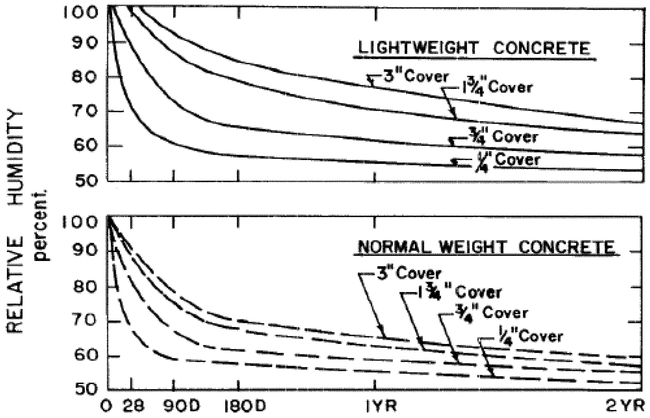


Fig. 2.3—Typical relative humidity distribution for lightweight and normalweight concrete in 6 x 12 in. (150 x 300 mm) concrete cylinders moist cured for 7 days, then dried (Hanson 1968). Cover refers to depth at which the relative humidity was measured. (Note: 1 in. = 25.4 mm.)

Drying at the top 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 2.2 shows the equilibrium 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.

2.2.3 *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/barrier, with an initially vertical RH profile and a drying curve similar to that shown in Fig. 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/barrier directly beneath it may have a final RH profile that does not benefit from any initial slab drying.

2.3—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 Section 2.2.

2.3.1 *Hanson (1968)*—Figure 2.3 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 2.3 shows that:

- Drying profiles differ for normalweight and lightweight concrete;
- Lightweight concrete takes longer to dry than normalweight concrete; and
- Normalweight concrete takes less than 90 days and lightweight concrete takes more than 180 days to reach 85% RH at the center of a 6 in. (150 mm) diameter specimen.

2.3.2 *Abrams and Orals (1965)*—The effect of moisture content on the fire resistance of concrete is well known. ASTM E 119 requires the concrete test specimen to be at a maximum RH of 75%. Fire investigators must measure the concrete's internal RH before fire testing the specimen. Figure 2.4 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 relative humidities of 10, 35, 50, and 75%. Specimens were dried to levels that produced relative humidities of 90 and 75% at the slab center. Figure 2.4 shows that:

- The concrete moisture profiles are curvilinear.
- 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; and
- 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.

2.3.3 *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 2.5 shows the results of these studies. The concrete drying profile for the pavement shows significant drying

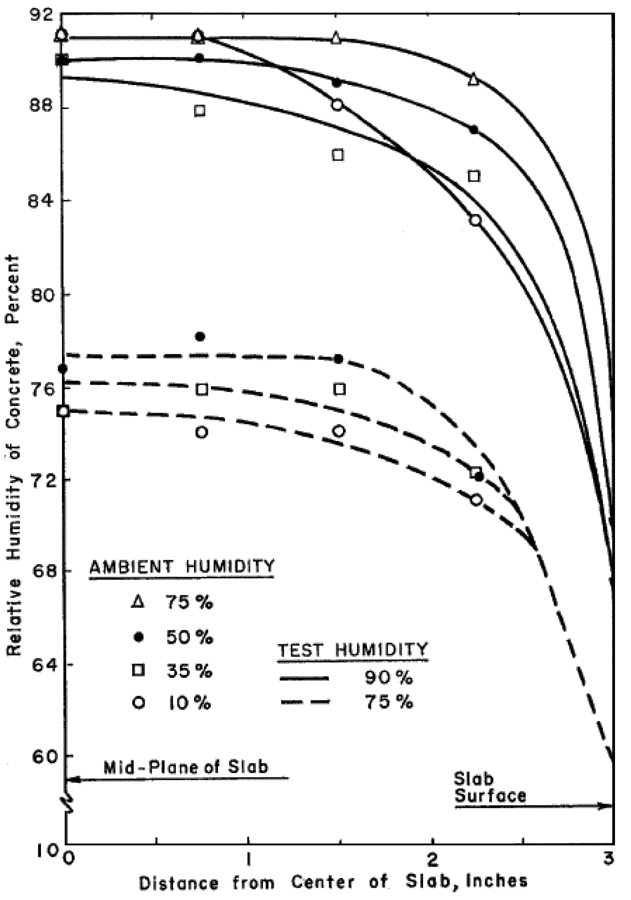


Fig. 2.4—Moisture profiles for slabs dried at differing ambient relative humidities (Abrams and Orals 1965). (Note: 1 in. = 25.4 mm.)

from the top only, while 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.

2.3.4 *Initial moisture profile*—Hanson's 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 (Hanson 1968). Table 2.1 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.

2.4—Effects of moisture movement

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

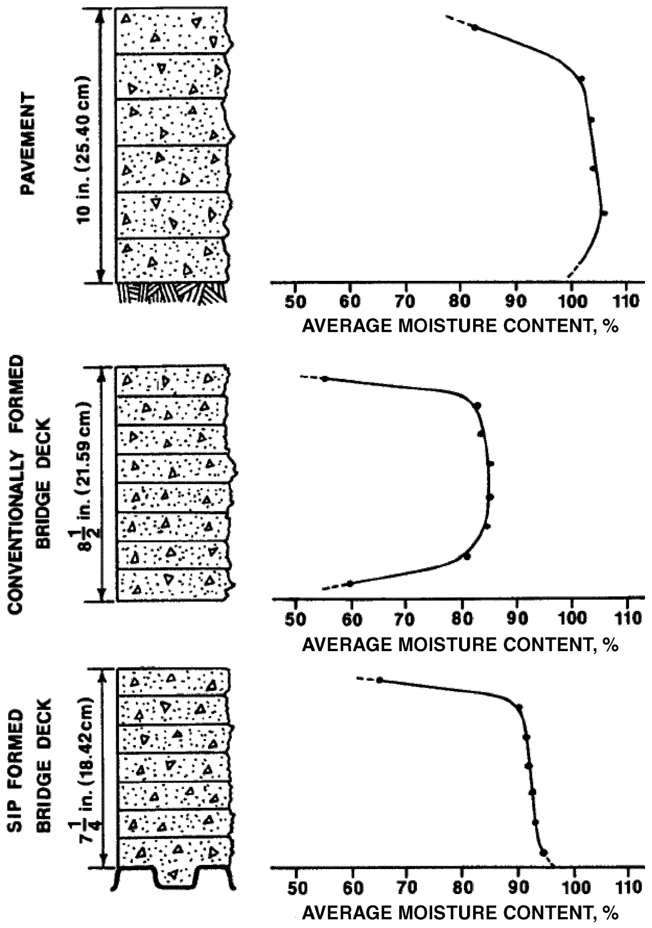


Fig. 2.5—Moisture profiles for concrete slab-on-ground drying from top only, suspended bridge deck drying from both top and bottom surfaces, and suspended deck placed on stay-in-place metal form drying from top only (Carrier and Cady 1975).

2.4.1 *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).

One possible consequence of changes in curling deflection is illustrated by the construction sequence described as follows (Fig. 2.6):

a. Concrete slab is placed and cured;

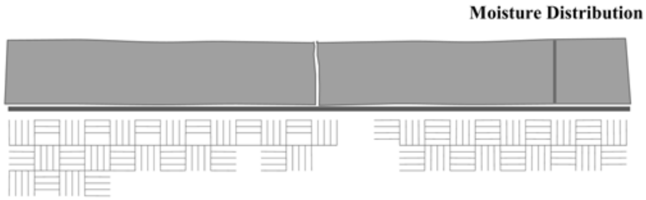
b. Concrete slab dries, causing the slab edges to curl upward;

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; and

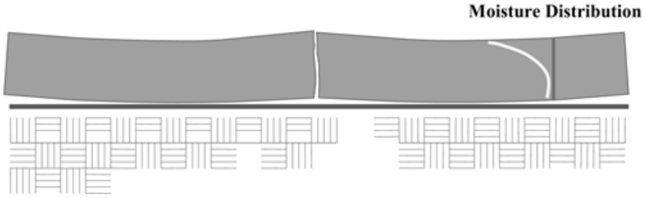
e. After some time, slab moisture redistributes to equilibrium, reducing slab curling deflection. Reduction in curling deflection along edges results in a slight dip where grinding occurred and extrusion of the joint filler material causing a visible ridge in the flooring (refer to Section 2.4.2). The dip or ridge along edges may require remedial work.

Concrete contractor places and cures slab, no curl.



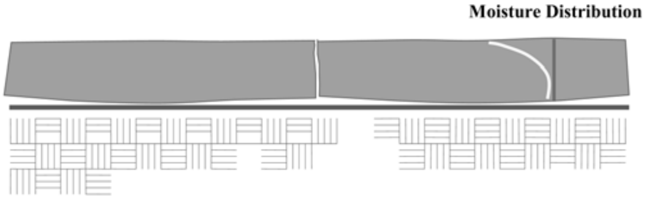
(a)

Concrete slab dries causing concrete to curl upward.



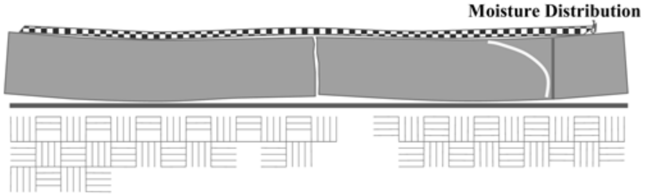
(b)

Floor covering installer checks flatness and grinds edges.



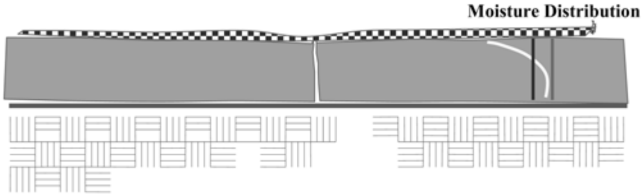
(c)

Floor covering installer applies floor covering.



(d)

Slab moisture redistributes, curl reduces, slight dip at edges.



(e)

Fig. 2.6—Slab curling sequence showing how moisture redistribution after floor covering placement can create a dip in floor cover at slab edges.

Table 2.1—Internal relative humidity distribution, % (Hanson 1968)

Depth, in. (mm)	0 days	3 days	7 days	14 days	28 days
Lightweight concrete (6 x 12 in. [150 x 300 mm] Cylinder 1), moist-cured 7 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

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.

2.4.2 *Joint bulging*—To minimize random cracking, contraction joints in floors must be cut before drying has occurred—usually either immediately after final finishing (with early-entry saws) or within about 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. 2.7 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. Sawcuts opens into V-shape as slab dries;
d. Sawcut is filled just before floor covering is placed; and

e. Moisture redistributes, concrete expands pushing joint filler up.

Slab curling can make this situation worse. If the slab curls after the joint is cut and then relaxes after the floor covering is placed, that movement can also cause the joint filler to bulge upward.

Most floor covering installers choose to repair this problem by removing the row (or strip) of covering directly above the joint bulge and using a razor blade 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.

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

- During drying, the surface moisture content will be lower than the moisture content measured at the midpoint, or at greater depths for slabs placed on vapor barriers/retarders;
- Relative humidity measurements taken with a surface-mounted hygrometer will be lower than measurements taken with an RH probe embedded in the slab;
- 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;
- Relative humidity measurements for slabs drying from one side only are typically taken at a depth of 40% of the slab depth from the top surface because that is approximately where the drying profile curve and the equilibrium curve intersect (Fig. 2.1). Thus, the RH measured during drying at that location will be approximately equal to the equilibrium RH for the slab (Hedenblad 1997; ASTM F 2170); and
- Relative humidity 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. 2.2). Thus, the RH measured during drying at that location will be approximately equal to the equilibrium RH measurement for the slab (Hedenblad, 1997; ASTM F 2170).

After the floor covering is placed, the surface moisture condition changes, 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 F 1869 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

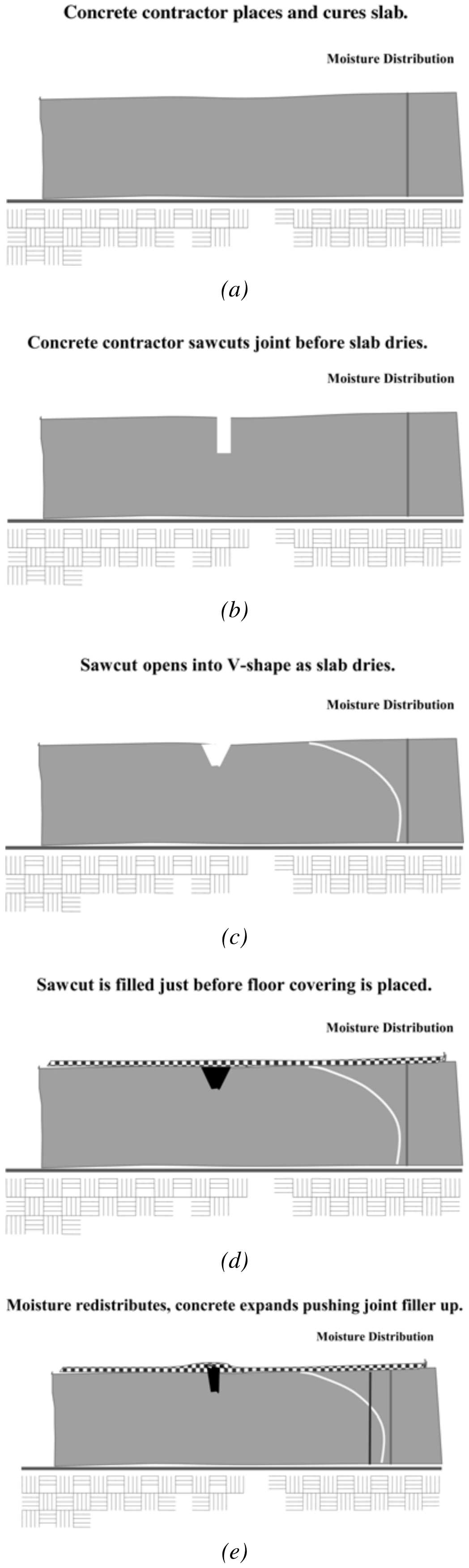


Fig. 2.7—Joint bulge sequence illustrating how moisture redistribution after floor covering is placed can create a joint filler bulge under installed floor covering.

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*Also private communication from P. Craig and W. C. McCall, 2004.

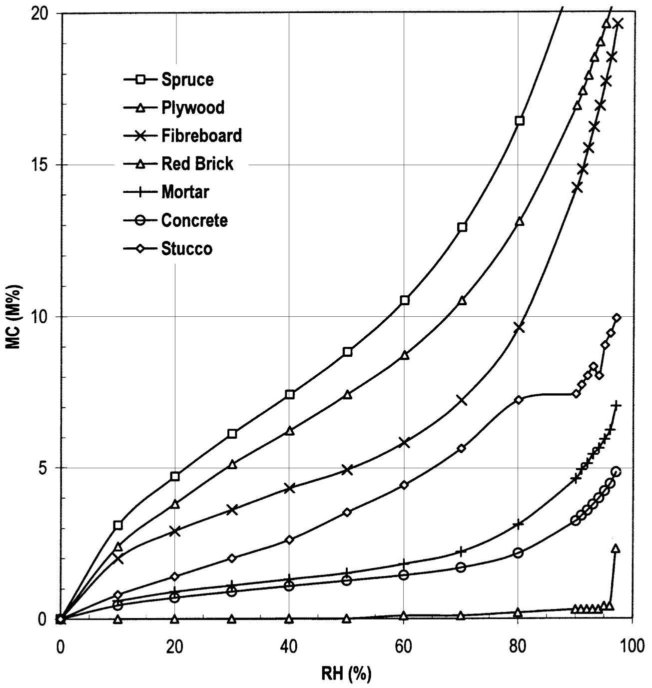

Fig. 2.8—Sorption isotherms for several common building materials (Straube 2000).

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.

2.5—Equilibrium moisture content

The equilibrium moisture content (EMC) concept used for wood products can also be applied to concrete. The moisture content (mass %) 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 from the United States Department of Agriculture Forest Products Laboratory shows how the EMC of wood in outdoor locations varies throughout the United States and worldwide (Simpson 1998). As is the case for wood, the equilibrium moisture content for a concrete slab drying while exposed to a high relative-humidity environment will not be the same as that for a slab in a low relative-humidity area. Figure 2.8 (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.

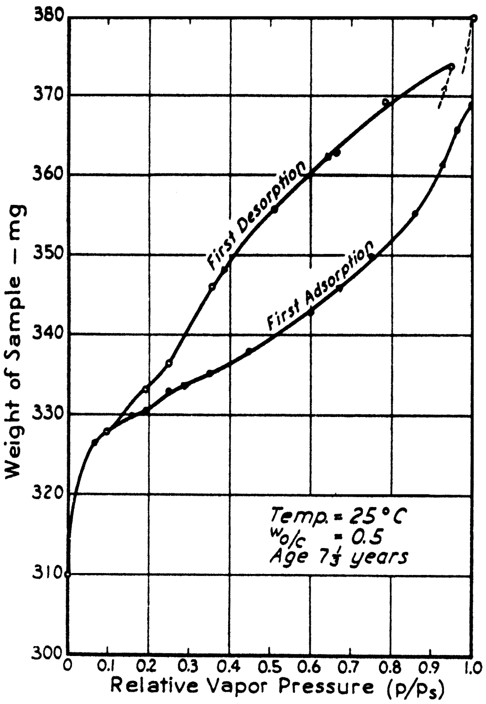

Fig. 2.9—Typical drying (desorption) and wetting (adsorption) curves showing that behavior is different and that concrete contains a different moisture content at the same relative humidity depending on whether it is drying or wetting (Powers and Brownyard 1947).

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:

- Exterior conditions (open building), or
- Interior conditions (building is enclosed and the heating, ventilation, or air conditioning system is operating).

2.6—Drying and wetting of concrete

2.6.1 *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 2.9 (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 showed that there are different drying and wetting 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 relative humidities (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 relative humidities vary. Conversely, at a fixed internal RH, the moisture content of different concretes can vary (Fig. 2.10).

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-wetting curves for lightweight concrete: 1) the water retained within the cement paste at normal ambient relative humidities is small when compared with the water absorbed by the aggregate; and 2) for some lightweight aggregates, the shape of the desorption-adsorption curves changes due to permanent weight changes that occur during drying and wetting.

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 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) provides a note before the foreword in *Drying of Construction Water in Concrete* that 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."

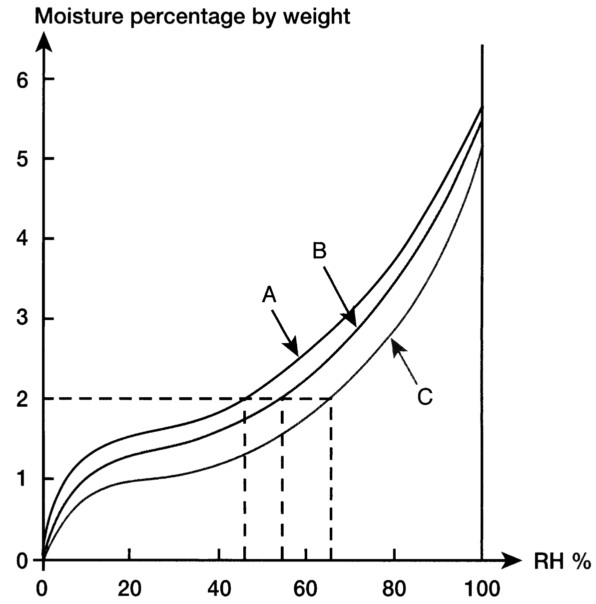

Fig. 2.10—Idealized wetting (adsorption) curves illustrating that at the same moisture content the concretes will have different measured internal relative humidity. Consider A, B, and C to be concretes with w/cm *of 0.4, 0.5, and 0.7, respectively (Kanare 2005).*

Figure 2.11 (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. Later research (Hedenblad 1993; Suprenant and Malisch 1999c) shows 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.

2.6.2 *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.

2.6.3 *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 with water. The effect of repeated wetting on the time required to reach a given moisture vapor emission rate is shown in Fig. 2.12 (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

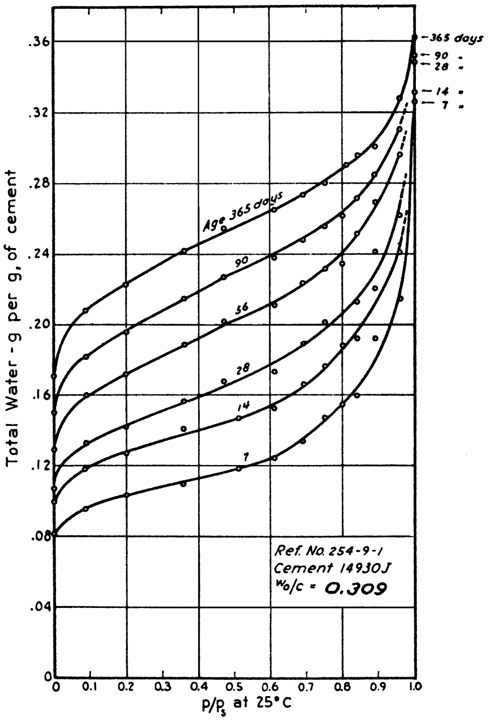

Fig. 2.11—Measured soprtion curves for samples at different ages. Note that the 365-day-old sample has approximately 50% more moisture than the 28-day-old sample at a relative humidity range from 80 to 90% (Powers and Brownyard 1947).

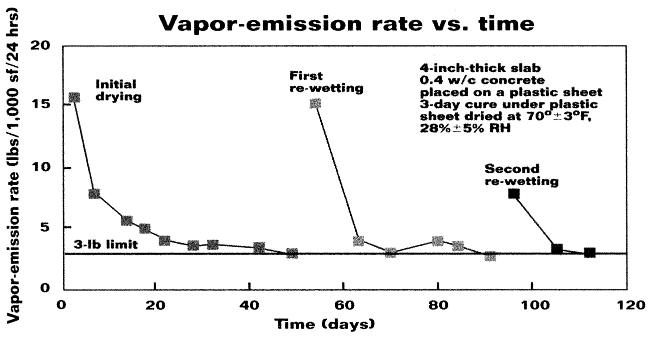

Fig. 2.12—Even with a low w/cm *and a 3-day cure under plastic sheeting, these slabs took approximately 7 weeks to dry to a 3 lb/1000 ft^2/24 h (1.5 kg/100 m^2/24 h) emission rate. After rewetting, the slabs took several weeks to again reach the 3 lb/1000 ft^2/24 h (1.5 kg/100 m^2/24 h) emission rate (Suprenant and Malisch 1998c).*

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.

2.7—Moisture loss during drying

Concretes used in floor construction usually have a *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 of 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, about 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's work (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 ft^2/24 h (1.5 kg/100 m^2/24 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 must lose approximately 0.6 lb/ft^2 (2.9 kg/m^2) 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 experiments must 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 3—CONCRETE MOISTURE TESTING

3.1—Introduction

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

- Standard test method, if applicable;
- Acceptable test methods;
- Frequency and location of testing;
- Environment (before and during the test);
- Surface preparation, if applicable;
- Responsible testing party;
- Acceptance criteria; and
- Interpretation of results.

3.2—Standard guides and test methods

Most ASTM standards for moisture testing were first developed in the mid- to late 1990s. The current ASTM standard guides and test methods are:

- ASTM E 1907, "Standard Guide to Methods of Evaluating Moisture Conditions of Concrete Floors to Receive Resilient Floor Coverings,"
- ASTM D 4263, "Standard Test Method for Indicating Moisture in Concrete by the Plastic Sheet Method,"
- ASTM F 1869, "Standard Test Method for Measuring Moisture Vapor Emission Rate of Concrete Subfloor Using Anhydrous Calcium Chloride,"
- ASTM F 2170, "Standard Test Method for Determining Relative Humidity in Concrete floor Slabs Using in situ Probes," and
- ASTM F 2420, "Standard Test Method for Determining

Relative Humidity on the Surface of Concrete Floor Slabs Using Relative Humidity Probe Measurements and Insulated Hood."

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.

3.3—Qualitative and quantitative tests

3.3.1 *Introduction*—ASTM E 1907 lists eight tests that might be used to evaluate the moisture condition of concrete. The tests 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 E 1907 are as follows:

Qualitative tests	**Quantitative tests**
Plastic sheet test (ASTM D 4263)	Electrical resistance test (No ASTM standard test method)
Mat test (No ASTM standard test method)	Electrical impedance test (No ASTM standard test method)
Qualitative calcium chloride test (No ASTM standard test method)	Quantitative calcium chloride test (ASTM F 1869)
Primer or adhesive strip test (No ASTM standard test method)	Relative humidity test (ASTM F 2170 and F 2420)

While not listed in ASTM E 1907, a quantitative calcium carbide test method used in Europe is occasionally specified in the United States.

3.3.2 *Plastic sheet test*—ASTM E 1907 and D 4263 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. 3.1).

Another option is the use of a moisture meter on the surface before and after placing the plastic sheet on the surface. It is also possible to measure through the plastic sheet and leave the sheet in place for an extended time to check for changes in moisture at the surface.

The plastic sheet test has been used for more than 50 years. When adhesive products were more moisture-resistant than they are now, the plastic sheet test may have been useful for predicting the moisture condition at which concrete slabs were ready to receive floor coverings. Now, however, the test has two limitations:

- Leaving the sheet in place for 16 hours does not provide enough time for the test to reflect results of moisture movement from the bottom to the top of the slab. Thus, it indicates only what is happening at the surface; and
- 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. 3.1—When moisture is present after the plastic sheet test has been conducted, the surface feels cooler and is often a darker color (Kanare 2005).

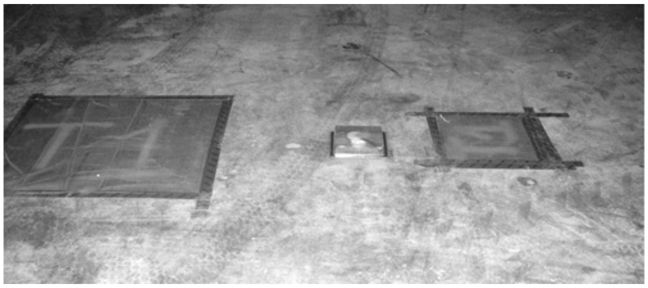

Fig. 3.2—Even though plastic sheet tests can show no evidence of moisture, calcium chloride tests conducted on adjacent concrete can indicate moisture vapor emission rates as high as 13 lb/1000 ft^2/24 h (6.3 kg/100 m^2/24 h) (Suprenant 2003b; Kanare 2005).

Figure 3.2 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 recognized as a standard practice for determining moisture-related acceptability of concrete floors by ASTM E 1907 and by some manufacturers, the plastic sheet test does not give a reliable indication of the floor moisture condition (Kanare 2005; Suprenant 2003b).

3.3.3 *Mat and primer tests*—In addition to a quantitative moisture test, some manufacturers also recommend a mat or primer test (Fig. 3.3), for which there is no ASTM standard test method. Using the specified adhesive and floor covering (or primer), a 2 ft (610 mm) square sample is applied to the concrete floor using the manufacturer's recommended adhesive (or primer) and installation procedure. The perimeter is sealed using 2 in. (51 mm) wide duct tape. After 72 hours, both visual and physical testing are performed. If the adhesive beneath the floor covering is partially or completely

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[*] Also, private communication from P. Craig and C. Lezell, 2005.

Fig. 3.3—Mat test performed on sample. (Courtesy of Scott Tarr.)

Fig. 3.4—Electrical resistance and impedance moisture meters. (Courtesy of Scott Tarr.)

dissolved, is still wet, or has little bond, there is too much moisture present to proceed with the floor covering installation. If the floor covering (or primer) is firmly bonded and removal of the covering with a putty knife or bar reveals good adhesion, the moisture level is considered to be sufficiently low to permit installation of the floor covering.

Because 72 hours is not long enough to allow the moisture from the bottom of a slab to move to the top, the mat and primer tests measure the short-term influence of the moisture in the concrete surface. 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 D 4263), the mat and primer test can falsely indicate that the floor is ready for covering but won't falsely indicate that the floor is *not* ready for covering. If the primer or mat is not well adhered, the floor moisture condition or surface preparation is problematic.

3.3.4 *Moisture meters*—Electrical resistance and impedance meters (Fig. 3.4) are used to measure moisture in concrete (neither test is described in an ASTM standard). Electrical resistance relates the moisture content to the measured electrical conductivity of concrete between the sensing pins or probes. Electrical impedance relates the moisture content to the measured electrical AC impedance. The electrical resistance meters measure moisture at the depth to which the probes or pins are pushed into the concrete surface. Electrical impedance meters measure moisture in unreinforced concrete to a depth of about 2 in. (51 mm).

Electrical impedance meters are useful for making a quick survey (similar to using a rebound hammer on concrete as described in ASTM C 805) 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 or at the location 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; however, these calibrations should be used with caution, if used at all. Check the manufacturer's calibration procedures that accompany the meter. Although the moisture meters "read" only to a depth of an inch or so, 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 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.

3.3.5 *Calcium chloride tests*—The qualitative anhydrous calcium chloride test is performed by pouring anhydrous calcium chloride on the concrete floor and then covering it with a plastic canopy sealed to the floor. After 72 hours, the canopy is removed, and the calcium chloride is observed for evidence of moisture (it gets darker or cakes when moisture is present). The quantitative test is the preferred method, and is much more widely used.

The test kit for the quantitative calcium chloride test (ASTM F 1869) consists of:

- A plastic dish containing approximately 16 g (0.56 oz) of anhydrous calcium chloride and covered with a lid that can be sealed around the circumference with pressure-sensitive tape; and
- A flanged clear plastic cover that has a preformed sealant strip attached to the flanges (Fig. 3.5 and 3.6).

To conduct the test, the surface is first prepared by abrasive cleaning to remove all foreign substances (Fig 3.7). 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 hole is cut in the 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,

Fig. 3.5—Typical calcium chloride test kit for measuring moisture vapor emission rates. (Courtesy of Calvin McCall.)

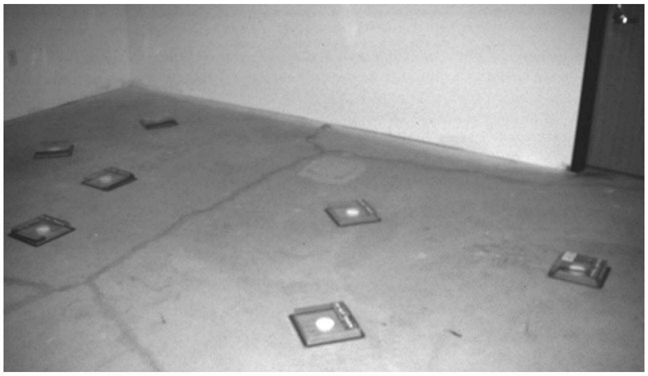

Fig. 3.6—Moisture vapor emission tests used to determine precision and bias statement (Suprenant and Malisch 2000a).

Fig. 3.7—Surface preparation using grinder before installing a moisture vapor emission test. (Courtesy of Peter Craig.)

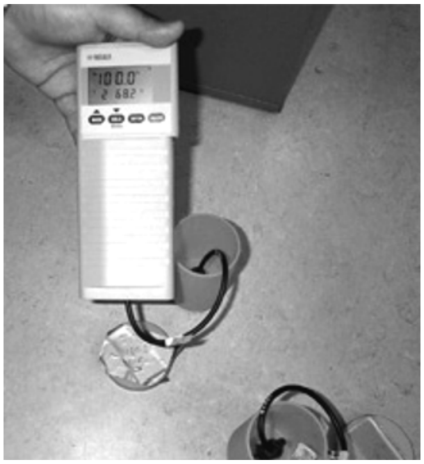

Fig. 3.8—Relative humidity measurement in a floor slab. (Courtesy of Peter Craig.)

the top of the cover can be pushed down. If the seal is tight, the cover will pop back up. If the seal is broken, 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), it is advisable to record both of these measurements at the start and completion of testing to enhance the interpretation of the test results.

3.3.6 *Relative humidity test*—To perform tests in accordance with ASTM F 2170, in-place RH meters (Fig. 3.8) are attached to a sensing probe that is inserted in a lined hole in 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, the bottom of the probe hole depth should be 40% of the slab thickness. For slabs drying from both sides (suspended concrete slabs not on metal decks), the probe hole depth should be 20% of the slab thickness. A depth gauge on the hammer drill is useful for determining the correct depth.

The holes are drilled dry, brushed, and vacuumed using a small-diameter nozzle capable of reaching the bottom of the drilled hole. A hole liner is inserted to the bottom of the hole, a stopper is placed in the top end of the liner, and a good seal between the liner and the concrete at the top of the hole is ensured. The hole liner isolates the sides of the hole so that only the bottom is exposed. An RH measurement is made after allowing 72 hours for the air in the hole to achieve equilibrium with the surrounding concrete. To make a measurement, the rubber stopper in the hole liner is removed and the probe is inserted. The probe is connected to the meter, and both the meter and probe are allowed to reach relative-humidity equilibrium with the surrounding concrete (Fig. 3.8 and 3.9). The time required to reach equilibrium depends on the type of instrument, condition of the concrete, and temperature stability. The meter measures RH to the nearest 1%, and the temperature in the hole is also recorded. Relative humidity measurements can be taken continuously or at selected intervals using the same holes.

3.4—Test parameters

3.4.1 *Test frequency*—ASTM E 1907, D 4263, F 1869, F 2170, and F 2420 all state the required number of tests. The required number of tests is as follows:

- D 4263 (plastic sheet test) requires one test area per 500 ft^2 (46 m^2) of surface area, or portion thereof, unless otherwise specified;

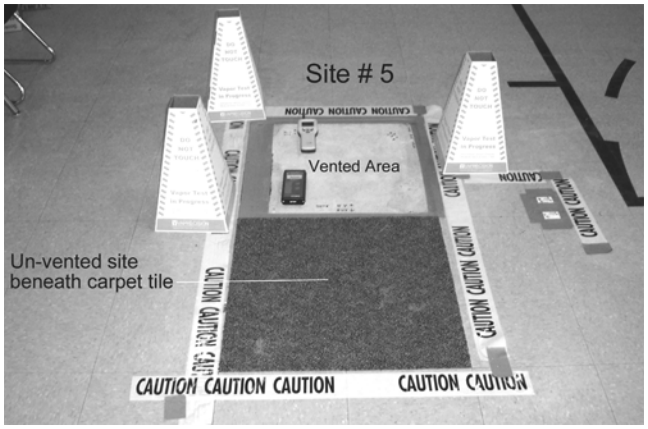

Fig. 3.9—Relative humidity measurements being taken in a vented area (no floor covering), and an unvented area (covered by carpet tile) using equipment described in ASTM F 2170. (Courtesy of Peter Craig.)

- F 1869 (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 ft^2 (93 m^2), and one additional test for each 1000 ft^2 (93 m^2) or fraction thereof;
- F 2170 (relative humidity test) requires three tests for the first 1000 ft^2 (93 m^2), and at least one additional test for each additional 1000 ft^2 (93 m^2);
- E 1907 (not a test method, but a guide that lists eight tests) recommends three sample locations for areas up to 500 ft^2 (46 m^2), and one additional sample location for each additional 500 ft^2 (46 m^2); and
- F 2420 (relative humidity probe with hood) requires three tests for the first 1000 ft^2 (93 m^2), and at least one additional test for each additional 1000 ft^2 (93 m^2).

Meeting the ASTM test frequency requirements for a 100,000 ft^2 (9290 m^2) floor would require from 102 to 202 tests. The rationale for the ASTM test frequency requirements given at a meeting of ASTM Committee F6 in 2003 was that a 10 yd^3 (7.6 m^3) truckload of concrete covers approximately 800 ft^2 (74 m^2) of a 4 in. (100 mm) thick floor. Thus, testing every truckload requires a moisture test every 500 to 1000 ft^2 (46 to 93 m^2). Some project specifications have even increased the required frequency to one test for every 300 ft^2 (28 m^2).

These test frequency requirements are rarely met in practice. Thus, most tests do not conform to all the requirements of the ASTM standard referenced in the project specifications. Moisture testing is typically a trial-and-error procedure because the construction schedule requires the contractor to start installing the floor covering as soon as possible. Thus, multiple tests are conducted to track the concrete moisture condition and determine when the appropriate acceptance criteria are attained. On some projects, the test frequency required by ASTM would call for many hundreds of tests, and the need to avoid disturbing tests in progress could hinder other construction activity.

Using a large number of tests does not guarantee an acceptable concrete moisture condition for floor covering. A basic understanding of concrete moisture and testing, along with intelligent 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 represents every truckload of concrete.

3.4.2 *Test location*—Choosing the proper test locations is important. ASTM E 1907 provides the following advice: “Locations shall not be concentrated and shall be distributed around the floor area. One location shall be near the center with others around the perimeter. Selection of locations shall include, but not be limited to, areas of potentially high moisture such as joints and areas closer than 5 ft (1.5 m) from the edge of the slab.” The standard also cautions that no tests should be placed in direct sunlight or near direct sources of heat.

Moisture meters are often used to locate areas of potentially high moisture where further testing is conducted. The meters can be used to quickly survey many test locations and check different concrete placements along joints, near exterior walls for slabs-on-ground, near water and drain lines under the slab, and other areas of potentially high moisture. The results of the initial survey should dictate the frequency for further testing. After an initial moisture survey, typically 30 tests could be used to further evaluate a 100,000 ft^2 (9300 m^2) slab.

3.4.3 *Test environment*—The test environment is very important for tests that evaluate concrete surface moisture condition, and less important for RH tests that are taken with probes inserted in holes at a depth of 40% of the slab thickness. For surface moisture tests, such as the calcium chloride test, if the environment changes—or more importantly, 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 recommended for at least 48 hours before starting the test and throughout the test duration (ASTM E 1907).

ASTM E 1907, F 2170, F 2420, and F 1869 all indicate an appropriate test environment, but only ASTM E 1907, F 2420, and F 2170 require that the measured temperature and RH be reported. To allow meaningful interpretation of ASTM F 1869 test results, the environmental conditions at the beginning and end of the test should be reported.

Test laboratories and floor covering installers are often asked by the general contractor or construction manager to test a concrete surface and sometimes even a specific location. The test environment is often not appropriate for the test. The tester, however, seldom controls the temporary HVAC, and must rely on the general contractor or construction manger to understand the need to turn on the HVAC. It is suggested that the specifier notify the general contractor in Division 1—General Requirements, Section 01500 Temporary Facilities and Controls (Construction Specifications Institute 2000), of the need for an appropriate environment during moisture testing, and thus allow that activity to be included in the bid.

3.4.4 *Surface preparation*—The plastic sheet, mat, primer or adhesive, and calcium chloride test results can be affected by the surface preparation. Coatings, curing compounds, finishes, or other substances (such as oil from spills) can affect the rate of moisture dissipation and the adhesion of the finishes. Calcium chloride tests placed over a surface coated with curing compound and over an adjacent area with the curing compound removed have yielded results that differed by 1 to 2 lb/1000 ft^2/24 h (0.5 to 1.0 kg/100 m^2/24 h) for readings in the 3 to 7 lb range (1.5 to 3.4 kg/100 m^2/24 h) (Suprenant 2003b).*

Although shotblasting is typically used to remove curing compounds and sealers prior to flooring installation, this method is often not available to the tester. Hand-held grinders are typically used to prepare the small surface areas required for testing (Fig. 3.7). ASTM F 1869 requires a minimum area of 20 x 20 in. (510 x 510 cm). 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.

3.4.5 *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 hasn't 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 laboratory take the moisture tests instead of the floor covering installer (World Flooring Covering Association 2001) because:

- An independent party provides an unbiased test result;
- A testing laboratory is typically more experienced in following ASTM test standards; and
- Test reports from the testing lab are more likely to be distributed to all parties, so all parties can consider the ramifications of the results.

The testing laboratory should not be made responsible for the decision to place or not place the flooring based on the moisture test. Typically, the laboratories are prohibited by the project specification 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 should also 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 are able to control the building environment during the testing.

Table 3.1—Typical limits for moisture vapor emission test (Resilient Floor Covering Institute 1995)

Moisture vapor emission rate	Floor covering materials
5 lb/1000 ft^2/24 h (2.4 kg/100 m^2/24 h)	Vinyl composition tile Felt-backed resilient sheet flooring Porous-backed carpet Linoleum
3 lb/1000 ft^2/24 h (1.5 kg/100 m^2/24 h)	Solid vinyl sheet flooring Vinyl-backed carpet Nonporous-backed carpet Cork Direct glue-down flooring

Table 3.2—Maximum value of relative humidity in concrete (Finish SusaRYL 2000)

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

Table 3.3—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

3.4.6 *Acceptance criteria*—Tables 3.1 to 3.3 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 MVER (Craig 2003). The selection of an emission rate of 5 or 3 lb/1000 ft^2/24 h (2.4 or 1.5 kg/100 m^2/24 h) appears to have been based on historical information and modified with field experience. No laboratory data from a floor covering or adhesive manufacturer has been presented to establish a rational basis for the 5 or 3 lb (2.4 or 1.5 kg) 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.

A report on recent testing that attempted to correlate moisture in the concrete with floor covering performance concluded

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*Also, private communication from P. Craig, 2004.

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” (The Concrete Society 2004).

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

3.4.7 *Using multiple test methods*—Most project specifications require that only one type of moisture test method be used or that flooring manufacturer’s recommendations for moisture testing be followed. 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.

3.4.8 *Modified surface testing*—Instead of measuring a surface moisture value that will change when the floor covering is placed, some tests require a 10 ft (3 m) square plastic sheet or 18 in. (460 mm) square carpet tiles to be taped to the concrete surface and left in place for 1 to 2 weeks. Leaving the plastic sheet or carpet tile in place simulates the effect of the floor covering and allows a more accurate estimation of the moisture condition to which the floor covering will be exposed when it is installed. When this is done, it is important to achieve and maintain uniform contact of the plastic sheet or carpet tile with the concrete surface. Moisture meter measurements can be taken directly over the plastic sheet, or holes can be cut in the plastic sheet or carpet tile to allow testing with calcium chloride test kits or with mat or primer tests (Suprenant and Malisch 1999c).

3.4.9 *Testing with no vapor retarder/barrier directly under concrete*—For any moisture test, the acceptable moisture condition is based on the assumption that no water enters the slab from the bottom. Even if water that is initially present in the concrete moves from the bottom to the top of the slab, the resulting equilibrium moisture content at the surface is still assumed to be low enough to prevent a flooring failure. The results, however, will be different if moisture can enter through the bottom of the concrete slab.

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 barrier/retarder is needed directly beneath the slab. Without an effective vapor retarder/barrier directly beneath the slab, the results of any moisture test can not be considered a true indicator of the moisture condition that will develop once the floor is covered.

Acceptance limits for surface moisture tests, such as the calcium chloride test, are established based on the assumption that a vapor barrier/retarder is present. Moisture in the capillary pores will redistribute after flooring is installed, but the supply of water will not be replenished from an external source.

For slabs not placed on a vapor retarder/barrier, the validity of any moisture test taken at the surface or with probes in the concrete should be questioned. The test result can not be used to estimate the amount of water that can move to the floor covering once it is installed because the amount of water entering the bottom of the slab is impossible to determine.

ACI 302.1R recommends that a concrete slab to receive a moisture-sensitive floor covering be placed directly on a vapor retarder/barrier. Previous versions of this document recommended placing a granular layer between the vapor retarder/barrier and the concrete. If a granular layer is placed between the vapor retarder/barrier and the slab, however, rainwater or water used to aid compaction can later pass through the slab in a liquid or vapor form and accumulate at the interface of the concrete and the floor covering.

Warning—*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/barrier.*

3.5—Underlayment testing

Underlayment products used to smooth or flatten a concrete slab should also be tested for moisture. Some product manufacturers recommend moisture tests for use with their products. These tests may or may not be ones that are suitable for use on concrete. For instance, most underlayment manufacturers do not recommend using the calcium chloride test. Internal RH tests are also difficult to perform if the underlayment thickness is less than 1 in. (25 mm) because it is difficult to tightly seal the probe at 40% of the underlayment depth. Some manufacturers recommend using a plastic sheet test, an electrical resistance moisture meter, or the calcium carbide test method.

Specifiers should verify that the underlayment products 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.

3.6—Comments on moisture vapor emission rate tests

The MVER test is widely used, and tests in accordance with ASTM F 1869 are typically required by the floor covering and adhesive manufacturer. Some specific issues investigated with respect to this test are:

- **Test duration effects**. ASTM F 1869 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 time period will typically yield

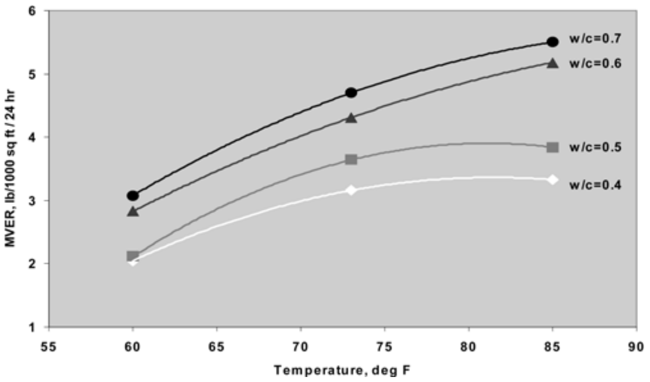


Fig. 3.10—Effect of temperature on calcium chloride emission tests for different concretes (Kanare 2005). (Note: 1 °F = [(°F – 32)/1.8] °C; 1 lb/1000 ft^2/24 h = 0.488 kg/100 m^2/24 h.)

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/barrier (*Concrete Repair Digest* 1997);

- **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);
- **Effect of moisture inside the plastic cover**. Some investigators have suggested that the initial RH inside the plastic cover has an effect on the test result. In one study, 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 relative humidities of 74 and 33%, respectively. This indicated that a correction factor might be required to account for moisture initially present in the air inside the plastic cover. Relative humidity 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);
- **Effect of the test environment**. Figure 3.10 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 ºF (18 to 29 ºC) temperature range that is permitted by ASTM F 1869. The effect is greatest for concretes with *w/c* larger than 0.5; and
- **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).

CHAPTER 4—CONCRETE pH TESTING

4.1—Introduction

Most flooring and adhesive manufacturers require pH testing of concrete surfaces because adhesives can degrade and lose strength when exposed to highly alkaline solutions such as concrete porewater.

The pH, a measure of hydrogen ion concentration, 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.

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.

In concrete terminology, carbonation is the reaction of carbon dioxide (CO_2) in the atmosphere with 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. 4.1).

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

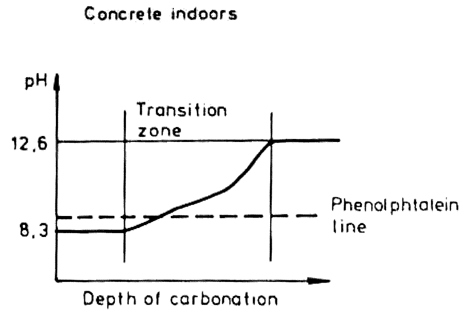


Fig. 4.1—Typical carbonation front showing carbonated concrete at pH of 8.3 and transition zone to uncarbonated concrete at pH of 12.6 (Tuutti 1982).

Fig. 4.2—pH indicators supplied with calcium chloride test kits. (Courtesy of Calvin McCall.)

year. Mean carbonation depths for concretes with *w/c* from 0.40 to 0.45, cured and stored as previously described, were not deeper than approximately 1/8 in. (3.2 mm) even after 10 years of exposure (ACI 222R).

4.2—Test methods

Figure 4.2 illustrates a number of commercially available pH test kits. There are two ASTM standards that deal with pH testing: ASTM D 4262 and F 710.

Testing for pH is typically accomplished by placing a few drops of water on the clean concrete surface, waiting for a given time interval, and then dipping pH paper into the water. The paper is removed, and immediately the color is compared to a chart to determine the pH reading. The readings, however, are very sensitive to the amount of time that the water is in contact with the concrete.

4.3—ASTM test differences

ASTM D 4262 does not require a specified waiting time before the pH is measured. As noted in Section 4.4.1, results from pH test methods that do not include a specific waiting time may vary. ASTM F 710 states: “A pH test shall be taken at every location and at each time a moisture test is performed. To perform a pH test, place several drops of distilled water on a clean concrete surface, forming a puddle of about 1 in. (25 mm) diameter. Wait 60 ± 5 seconds after the puddle has formed, then dip the pH paper into the water. Remove immediately, and compare the paper color to that on the chart to determine the pH reading. Report the pH reading with each moisture test result.”

Table 4.1—Effect of moisture contact time on pH reading

Contact times, seconds	pH measurement			
	pH paper No. 1	pH paper No. 2	pH paper No. 3	pH meter
50	8.0	11.0	7.0	9.8
60	9.0	11.5	8.0	10.2
70	9.0	11.5	9.0	10.5
180	12.0	12.5	9.0	11.6
300	12.0	12.5	9.5	11.8

4.4—Factors affecting pH test results

4.4.1 *Wetting time*—Pinelle et al. (2005) performed pH tests during which they varied the time that water was in contact with the concrete surface and used a pH meter to measure changes in pH. They found that the pH increased with contact time (Table 4.1).

4.4.2 *Test kit components*—Pinelle et al. (2005) also performed pH tests at different times with three different pH papers and a pH meter. The range in readings (shown in Table 4.1) indicates that variability attributable only to differences in pH papers used in the test might result in pH values not acceptable to the adhesive manufacturers. Manufacturers who recommend a maximum pH should specify the test method to be used for measuring pH. Pinelle et al. (2005) believe the pH meter is the most appropriate testing device.

4.4.3 *Carbonation*—ASTM F 710 summarizes surface pH changes with age: “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 inch [1.0 mm]).”

Because of carbonation, the surface pH should decrease with time unless the carbonated layer is removed.

4.4.4 *Surface preparation*—ASTM F 710 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 pH tests, waiting time, application of patching compound or underlayment, or a combination thereof, might be required after abrasive removal of the concrete surface.”

Test results by Suprenant (2003b) confirm this. He measured a pH of 9 on dried test slabs, then removed a thin layer of concrete surface by sandblasting. Measurements made immediately after the sandblasting yielded a pH of 12. Pinelle et al. (2005) have also presented test results indicating

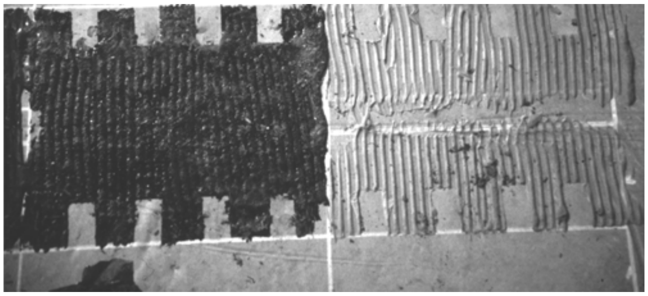


Fig. 4.3—pH tests conducted at various time intervals to determine the effect of adhesive water on pH. The concrete surface was initially at pH of 9, but rose quickly to 11.5 as adhesive water brought the alkalis into solution (Suprenant 2003c).

that the removal of the carbonated surface layer exposes a surface of higher pH.

A pH test made on concrete surfaces with a curing compound residue or sealer present will not yield a true pH value. If a drop of water on the surface beads up instead of being absorbed, a curing compound, sealer, or some other contaminant may be present where the test is being conducted.

4.4.5 *Adhesive water*—The water in water-based flooring adhesives can have an immediate effect on the pH of the concrete surface. Suprenant (2003c) investigated this effect 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. 4.3). 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. The effect of this immediate increase in pH is not known. Because water-based adhesives have been used on many successful projects, the short time exposure to a high pH caused by water from the adhesive may be tolerated by most adhesives without harmful effects.

4.4.6 *Number of tests*—ASTM F 710 requires a pH test at each location where a moisture test is conducted. Because the moisture state is more variable than the pH, the amount of data resulting from this requirement is probably more than is needed. The test duration is only 2 to 3 minutes, however, so pH testing is usually performed concurrently with moisture testing.

CHAPTER 5—FLOOR COVERING AND ADHESIVE MANUFACTURER'S RECOMMENDATIONS

5.1—Introduction

The architect and engineer should communicate to ensure that the requirements for floor coverings in Division 9 of Construction Specifications Institute (2000) specifications are compatible with Division 3 requirements for concrete in the same specification. Project specifications should provide specific information concerning the type of moisture tests to be performed as well as the required results and surface preparation requirements. The engineer should not design the slab-on-ground independently of the architect's selection of the floor covering, and the architect should not select the floor covering material independently of the engineer's choice of concrete materials and construction methods. 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.

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 conflict with best practices.

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.

5.2—Manufacturer's recommendations

Floor covering and adhesive manufacturers give specific requirements that must be met to maintain their product warranties. Some deal with design issues, such as the need for a vapor retarder or barrier. Others relate to surface preparation and subsequent concrete condition—usually MVER and pH—prior to flooring installation. The design team should consider these requirements when preparing the plans and specifications.

Manufacturers typically provide requirements related to:

- Vapor retarder/barrier;
- Concrete properties or materials;
- Curing;
- Surface finish;
- Floor flatness;
- Moisture limit;
- pH limit;
- Surface preparation; and
- Repair.

5.2.1 *Vapor retarder/barrier*—A number of flooring manufacturers and flooring industry guidelines require the use of a vapor retarder/barrier beneath concrete slabs.

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

- Properties of the vapor retarder (perm rating, puncture, and tensile strength);
- Minimum thickness of the vapor retarder;
- Location or placement of the vapor retarder (directly below the slab; and
- Installation of the vapor retarder (required laps, treatment at penetrations, repair of punctures).

5.2.2 *Concrete materials and properties*—Some floor covering and adhesive manufacturers provide guidance on concrete materials and properties. Unfortunately, some of the guidance is of little value. Some provide recommendations on concrete strength, slump limits, water content, and selection of materials. A few suggest following recommendations in ACI 302.1R. Following the current ACI 302.1R recommendations for concrete floors that will receive floor coverings does not provide any help because ACI 302.1R does not cover the topic. 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. The designer, however, balances multiple objectives that include: providing the needed workability, finishability, and strength; minimizing cracking, curling, and the time needed for drying; and using the most economical combination of concrete materials and construction methods.

5.2.3 *Curing*—Some floor covering manufacturers suggest curing concrete by ponding water on the slab for 28 days. Others require 28 days of curing, but use the term “curing” to mean time after placement, regardless of the curing environment. The design team must understand that nothing is technically relevant about 28 days of curing, and the longer the concrete is kept moist, the longer it will take to dry. Also, ponding or adding water to the top of the slab certainly does not help the mixture water to evaporate faster. Additionally, curing water will infiltrate cracks and joints, wetting the bottom of the slab and making excessive curling more likely.

Almost all manufacturers require that no curing compounds be used or that they be removed prior to adhesive application.

5.2.4 *Surface finish*—Most manufacturers call for a hard trowel finish. A few call for a light broom finish after hard troweling. Some choose their own references and ask for a “shark skin finish” or a “slight texture such as 100 grit abrasive paper.” The design team should consider the following when specifying a surface finish:

- Will the adhesive be placed directly on the specified surface finish or will surface preparation be required?
- If surface preparation is required, is the initial finish important?
- How many finishes will be required when more than one type of floor covering is to be installed in a building?
- 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?

5.2.5 *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 used in Division 3. Also, Division 3 specifications require the floor flatness to be measured within the first 72 hours, while the manufacturer’s floor flatness is measured when the flooring installer arrives on site. Manufacturers of very thin vinyl flooring require very flat floors, while carpet manufacturers seldom give a floor flatness requirement.

5.2.6 *Moisture condition*—The floor covering manufacturer provides a limit 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, is currently the most common test requirement. Some manufacturers, however, require relative humidity (RH) tests, moisture content tests using a moisture meter or calcium carbide test apparatus, the plastic sheet test, or others described in Chapter 3. It is difficult, if not impossible, to establish any correlation among results of these different test methods. Because of this, the design team must either use the manufacturer’s recommended test and test-result limits, or get approval from the manufacturer for using another test and test limit.

5.2.7 *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. Because several pH test methods are available and each method can yield different results, manufacturers should state which test method is applicable to their requirement.

Concrete surfaces can easily carbonate to reach a pH of 10, and even pH values of 9 are possible with a longer waiting time. A pH requirement less than 9, however, is unreasonable and a pH of 7 is impossible to achieve for normal concrete. The design team should decide, and manufacturers should also state, if the pH requirement applies to concrete before or after surface preparation. Most surface preparation will remove the carbonated concrete skin and result in a higher pH.

5.2.8 *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 and pH are achieved, removal of the dense, carbonated layer increases the MVER and the pH above that previously measured. As a general practice, moisture and pH 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.

Table 5.1—Concrete surface criteria (Suprenant 2003d)

Organization/document	Flooring type	Floor finish	Flatness	Levelness	Comments
American Concrete Institute ACI 302.1R-96, "Guide for Concrete Floor and Slab Construction"	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	Elevated slabs
American Concrete Institute ACI 301-99, "Specifications for Structural Concrete"	All flooring types	Troweled finish	F_F 20 5/16 in. in 10 ft	F_L 15	For slabs specified as troweled finish
ASTM International ASTM F 710-98, "Standard Practice for Preparing Concrete Floors to Receive Resilient Flooring"	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					
"Guide Specification for Bonded Terrazzo"	Bonded	Broom finish	1/4 in. in 10 ft	—	—
"Guide Specification for Sand Cushion Terrazzo"	Sand cushion	Float finish	1/4 in. in 10 ft	—	—
"Specification of Concrete Slab-on-Grade Substrates to Receive Epoxy Terrazzo"	Epoxy terrazzo	Light steel trowel	F_F 30/15	F_L 20/10	—
Resilient Floor Covering Institute "Addressing Moisture-Related Problems Relevant to Resilient Floor Coverings Installed over Concrete"	Resilient flooring	Hard trowel/smooth	5/16 in. in 10 ft	—	—
Carpet and Rug Institute CRI 104, "Standard for Installation Specification of Commercial Carpet"	Carpet	None	None	None	Has no requirements
Maple Flooring Manufacturers Association "Concrete Slab Flatness"	Gym floors	Troweled smooth	1/8 in. in 10 ft	—	—
Wood Flooring Manufacturers Association "Installation of Gymnasium Floors over a Concrete Slab"	Gym floors	Good float finish	1/4 in. in 10 ft	—	—

Note: 1 in. = 25.4 mm.

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.

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

- Crack repair;
- Spall repair;
- Curling repair;
- Joint filler repair;
- Joint stabilization;
- Surface grinding; and
- Underlayment 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.

5.3—Dealing with multiple floor covering requirements

Owners and architects often specify multiple floor covering products in facilities such as retail stores. Concrete surface-finish requirements, however, can be different for each product. Table 5.1 shows floor finish and tolerance requirements as recommended by ACI, ASTM International, 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. Often, 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 5.1 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 6—DRYING OF CONCRETE

6.1—Introduction

Concrete must partially dry before a floor covering is installed because moisture affects floor covering performance.

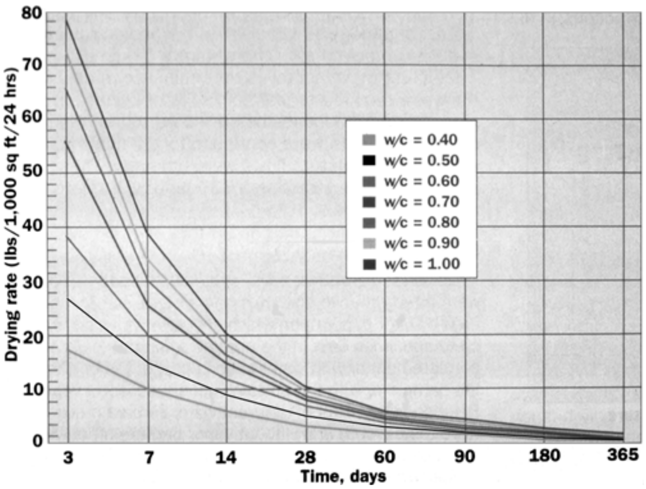


Fig. 6.1—Drying curves for concretes at different w/c *based on Brewer data on moisture vapor emission rates (Suprenant 1997). (Note: 1 lb/1000 ft^2/24 h = 0.488 kg/100 m^2/24 h.)*

Both designers and contractors are concerned with the performance of the floor covering once it is installed, but the construction team also considers the time needed for the concrete slab to dry to an acceptable level. Drying of concrete is thus a fundamental issue when the design team prepares specifications and when the construction team prepares schedules.

Concrete drying studies cited in this report 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.

6.1.1 *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 F 1869.

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. Relative humidity was measured at different depths in the slab while both sides were exposed to a temperature of 73 ± 2 °F (23 ± 1 °C) and relative humidities of 10, 35, 50, and 75%.

The details of Hedenblad's (1997) studies are not available in English, but a summary of his results has been printed in English. He used RH as a measure of moisture condition for concretes of varying ages and subjected to differing drying environments.

Further details regarding the work of each of these researchers can be found in the references.

6.2—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. 6.1. Brewer reported the drying rate in grains/ft^2/hour, but the data have been reformatted in lb/1000 ft^2/24 h, which is the most commonly used measure of moisture emission rate (Suprenant 1997). As indicated in Fig. 6.1, 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 or 5 lb/1000 ft^2/24 h (1.5 or 2.4 kg/100 m^2/24 h) emission rate is during the final drying stage.

As will be discussed in a following section, Brewer found that the *w/c* was the most important factor affecting time required to reach specified emission rate. Table 6.1 shows the drying time in days to reach 3 lb/1000 ft^2/24 h (1.5 kg/100 m^2/24 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 6.2 shows time needed for concretes with differing *w/c* and curing conditions to dry to an 85 or 90% internal RH level.

6.3—Concrete drying: exposed to moisture from below

Brewer's (1965) test also included concrete specimens that were exposed to vapor and liquid water at the bottom of the specimen. As Table 6.1 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 stopped taking measurements after 365 days, as indicated in the table by "> 365."

Table 6.2 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 ft^2/24 h (0.5 kg/100 m^2/24 h) after drying for 365 days. When in contact with water, concrete with the same *w/c* reached 2.5 lb/1000 ft^2/24 h (1.2 kg/100 m^2/24 h). This shows that uncovered concrete can dry to the lowest commonly specified emission rate (3 lb/1000 ft^2/24 h [1.5 kg/100 m^2/24 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 2, and performance of the floor covering might not be acceptable. Brewer calculated the percent saturation, amount of water in each specimen, under the given drying conditions. When dried from one side

Table 6.1—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

Table 6.2—Moisture vapor emission rate (MVER) and percent saturation after 1 year in 0.5 *w/c* concrete

Test condition	MVER, lb/1000 ft^2/24 h (kg/100 m^2/24 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

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.

6.4—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. 2.12, the MVER rose to around 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.

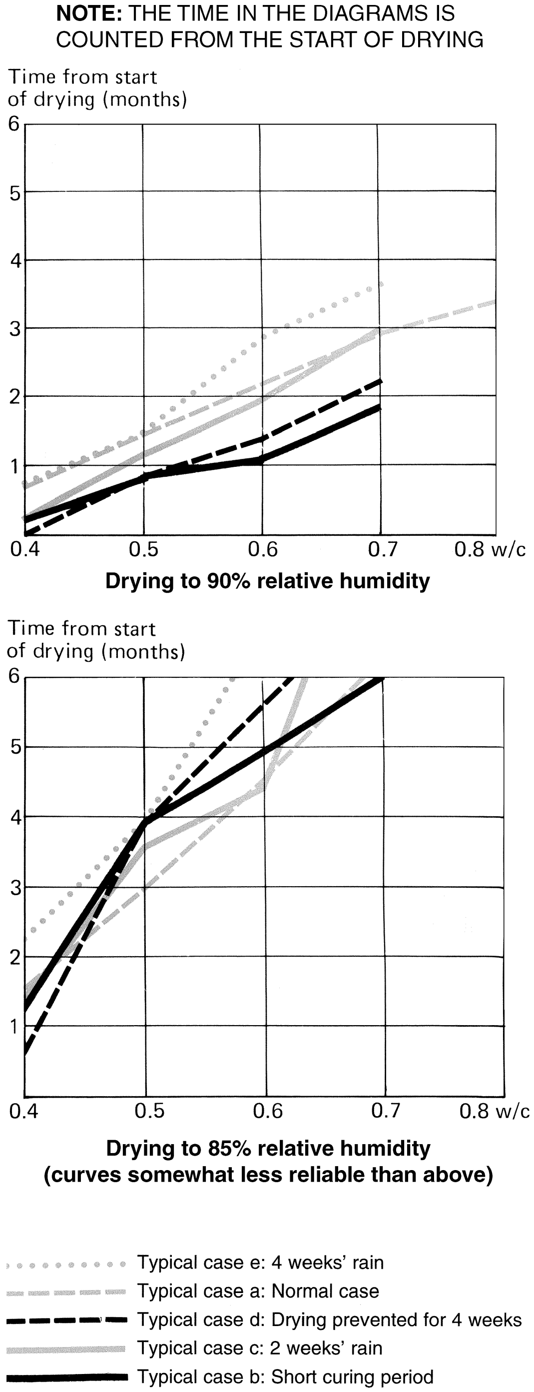


Fig. 6.2—Effects of w/c *and curing method on time needed to reach either 85% or 90% internal relative humidity at a depth of approximately 36 mm in a slab 180 mm thick. Slab dried from both sides in air at 18 °C and 60% relative humidity.*

6.5—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 6.3.

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 6.3—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

6.6—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):

- Cement content: 300 to 700 lb/yd^3 (178 to 415 kg/m^3);
- Cement types: Type I, I/II, and III;
- Class F fly ash and silica fume;
- Four different air-entraining agents;
- Chloride and nonchloride accelerators;
- Lignin and hydrocarboxcylic acid water reducers;
- High-range water reducers; and
- 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 drying curve for concrete with a *w/c* of 0.4 but using materials available in 1965 (portland cement and admixtures).

Hedenblad 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.

6.7—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:

- Slumps from 1-1/2 to 9-1/2 in. (38 to 240 mm);
- Air contents from 1 to 7%;
- Normalweight concretes with densities from 139 to 154 lb/ft^3 (2230 to 2470 kg/m^3);
- Compressive strengths from 1300 to 8000 psi (9.0 to 55 MPa); and
- *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.

6.8—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 6.4 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 or 5 lb/1000 ft^2/24 h (1.5 or 2.4 kg/100 m^2/24 h) maximum values, as shown in Table 6.5. 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 mid-depth 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. 6.4).

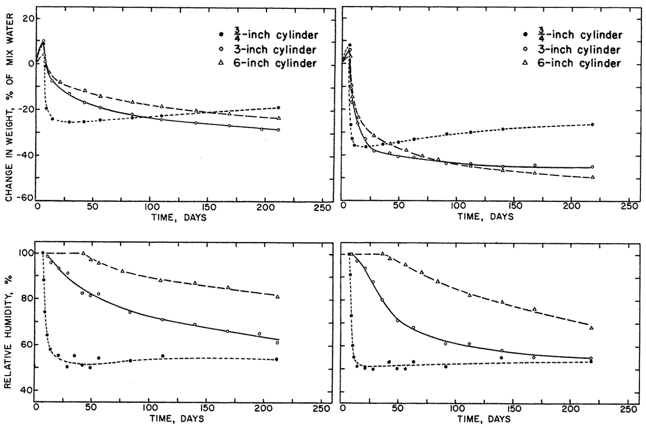
Although slab thickness has no effect on the time needed to reach a given MVER, thickness affects the time needed to reach a given RH within the slab.

6.9—Effect of curing

Monfore (1963) measured RH at the mid-depth 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 mid-depth. For the 3 and 6 in. (76 and 150 mm) diameter cylinders, however, the time to dry to a RH of 90% at the mid-depth after extended curing increased from 20 to 30 days and from 83 to 141 days, respectively. Figures 6.4 and 6.5 show that extended curing delays drying.

Hedenblad (1997) developed correction factors to account for the effect of curing conditions on concrete drying (Table 6.6). As shown by these correction factors, any curing period longer than 1 day can significantly extend drying times.

Determining the needed moist-curing regimen, 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 some 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 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.



(*a*) (*b*)

Fig. 6.4—Weight loss and internal relative humidity 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).*

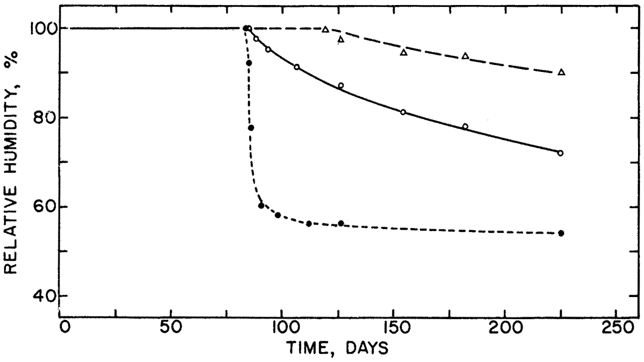


Fig. 6.5—Effect of extended curing (84 days) on relative humidity for concrete with a w/c *of 0.4. Compare to Fig. 6.4 for the same concrete that was cured for 7 days to show how extended curing increases drying time (Monfore 1963).*

6.10—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.

6.11—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 6.7 shows the effect of environmental humidity on drying time at a constant temperature of 70 °F (21 °C).

Table 6.4—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 6.5—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
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)

Table 6.6—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

As Table 6.7 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 relative humidities at mid-depth 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 relative humidities 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 6.8). 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

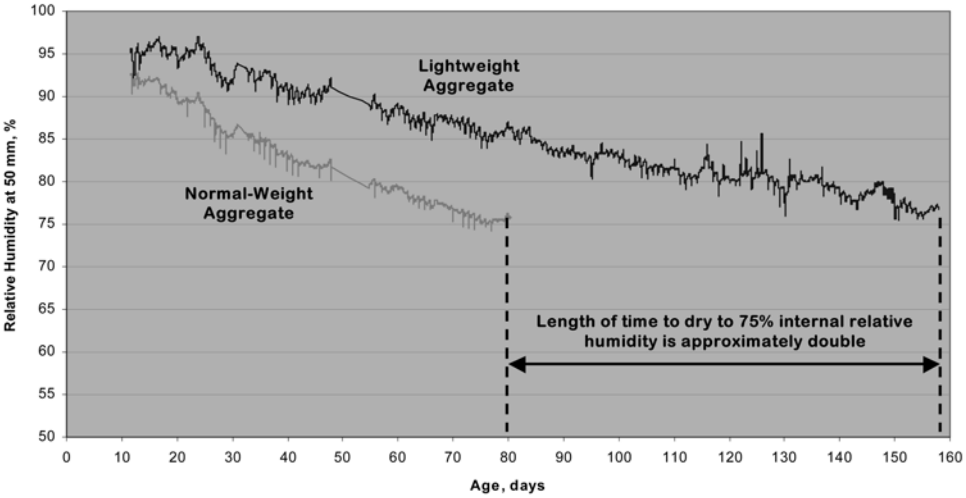


Fig. 6.6—Relative humidity measurements by Kanare (2005) showing that lightweight concrete takes longer to dry than normalweight concrete.

Table 6.7—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 relative humidity measured at mid-depth of 6 in. (150 mm) thick specimen.

Table 6.8—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

Table 6.9—Effect on 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% relative humidity.

the required concrete drying time by approximately 50%. Hedenblad's data indicate that concrete drying time is more sensitive to changes in temperature than it is to changes in RH.

6.12—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 6.9 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 the approximately the same as the measurements in other parts of the slab interior.

6.13—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). Using calcium chloride tests, Suprenant and Malisch 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 3 lb/1000 ft^2/24 h (1.5 kg/100 m^2/24 h) in 46 days, while the lightweight concrete dried to that level in 183 days.

Using RH measurements, Kanare (2005) found (Fig. 6.6) that normalweight concrete dried to an internal RH of 75% in approximately 80 days, while the lightweight concrete took about 160 days to reach that level.

CHAPTER 7—VAPOR RETARDER/BARRIER

7.1—Introduction

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

7.1.1 *Composition*—Most vapor retarder/barrier materials are plastic. There are many variations in the type and grade of resin used to create plastic vapor retarders/barriers. Some plastics are created from 100% virgin resin, while others are created with high percentages of reprocessed materials. Some plastics are low-density, while others are high-density.

In the past, 4, 6, 8, and 10 mil (0.10, 0.15, 0.20, and 0.25 mm) low-density polyethylene sheets have been used as below-slab vapor retarder material. Any material used as a below-slab vapor retarder/barrier, however, should conform to the requirements of ASTM E 1745, "Standard Specification for Water Vapor Retarders Used in Contact with Soil or Granular Fill Under Concrete Slabs."

7.1.2 *Vapor retarders and vapor barriers*—Historically, the construction industry used the term "vapor barrier" to describe a polyethylene-based material below a concrete slab. Polyethylene, however, does not completely stop the transmission of water vapor. These products only reduce or retard water vapor transmission. It was therefore considered more appropriate to call these products vapor retarders instead of vapor barriers.

ASTM E 1745 indicates that vapor retarders were formerly called vapor barriers, and does not define the term vapor barriers. In ASTM E 1745, vapor retarders are required to have a maximum rating of 0.3 perms. By definition, 1 perm equals 1 grain per ft^2/h per in. of mercury pressure. It is common to find many products for reducing moisture transmission through floors with perm ratings below 0.02 perms. Manufacturers and committees of standards-developing organizations are considering reinstating the term "vapor barrier," which would refer to some lower level of permeance than 0.3 perms.

7.2—Vapor retarder/barrier location

Some specifiers require concrete to be placed directly on the vapor retarder, and others require placement of a granular blotter layer between the concrete and the vapor retarder. 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).

7.2.1 *Benefits of concrete placed on 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 min. 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 require a granular blotter layer cite additional benefits that include less chance of:

- Puncturing the vapor retarder;
- Surface blistering or delaminations caused by an extended bleeding period;
- Settlement cracking over reinforcing steel;
- Slab curling during drying; and
- Cracking caused by plastic or drying shrinkage.

Many specifiers recommend using a 3 or 4 in. (76 or 100 mm) thick layer of trimmable, compactible, self-draining granular fill for the blotter layer. Although concrete sand is 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.

7.2.2 *Benefits of concrete placed directly on vapor retarder/barrier*—Research has 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 often-required MVER of 3 lb/1000 ft^2/24 h (1.5 kg/100 m^2/24 h) should be reached faster under these conditions. The uncovered vapor retarder may also act as a slip sheet, reducing slab restraint and, thus, reducing random cracking.

Placing concrete directly on a vapor retarder also eliminates a potential water reservoir in the blotter layer (Section 7.2.3). 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.

Specifiers who require concrete to be placed directly on the vapor retarder cite these advantages:

- Reduced costs because of less excavation and no need for additional granular material;
- Better curing of the slab bottom because the vapor retarder minimizes moisture loss;
- Less chance of floor moisture problems caused by water being trapped in the granular layer; and
- Less radon gas infiltration.

These specifiers recommend using a low-*w/c* concrete and water-reducing admixtures to reduce bleeding, shrinkage, and curling of concrete placed directly on the vapor retarder. They believe that higher-quality concrete and better curing reduce cracking and produce a better floor.

7.2.3 *Granular layer as water reservoir*—When a low-permeability floor covering will be installed on a concrete floor, care is needed during construction to control the moisture content of the subgrade, subbase, or granular layer (if used over the vapor retarder). Where granular fill layer is used, it is best to place the slab after the building is enclosed and the roof is watertight. On many projects, however, this isn't possible, and the granular layer can become 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. Rainwater can then enter the open column blockouts. Water can also penetrate joints and cracks, utility penetrations, and open closure strips, thus increasing the moisture content of the subgrade, capillary break, 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. ACI 302.1R recommends that the granular layer be dry at the time of concreting unless severe drying conditions exist.

Wet-curing methods, such as ponding or continuous sprinkling, allow water to enter joints, cracks, and other openings, again contributing to a higher-than-necessary moisture content beneath the floor 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 joint sawing and abrasive wet blasting or wet grinding, which may be needed to achieve a flatter floor profile. Sometimes power washing is used to clean debris or other contaminants from the floor. Most slabs are constructed using a strip-placement sequence that leaves portions of the granular layer exposed to rainwater.

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.

7.2.4 *ACI 302/360 Task Group recommendations on vapor retarder/barrier location*—A task group from ACI Committees 302 and 360 issued the following ACI update in *Concrete International* in April 2001:

> *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, compactible, 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.*
>
> *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 7.1 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.*

7.3—Vapor transmission through retarder/barrier

There are ways that water vapor can flow through a vapor retarder and barrier. Punctures in the vapor retarder/barrier 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.

7.3.1 *Perm rating*—ASTM E 1745 requires vapor retarders to have a maximum perm rating of 0.3. By definition, 1 perm equals 1 grain per ft^2/h/in. of mercury pressure differential. This can be converted to units of the commonly used MVER (lb/1000 ft^2/24h), by dividing by 7000 grains/lb of water, multiplying by 24 h, and then multiplying by 1000 ft^2.

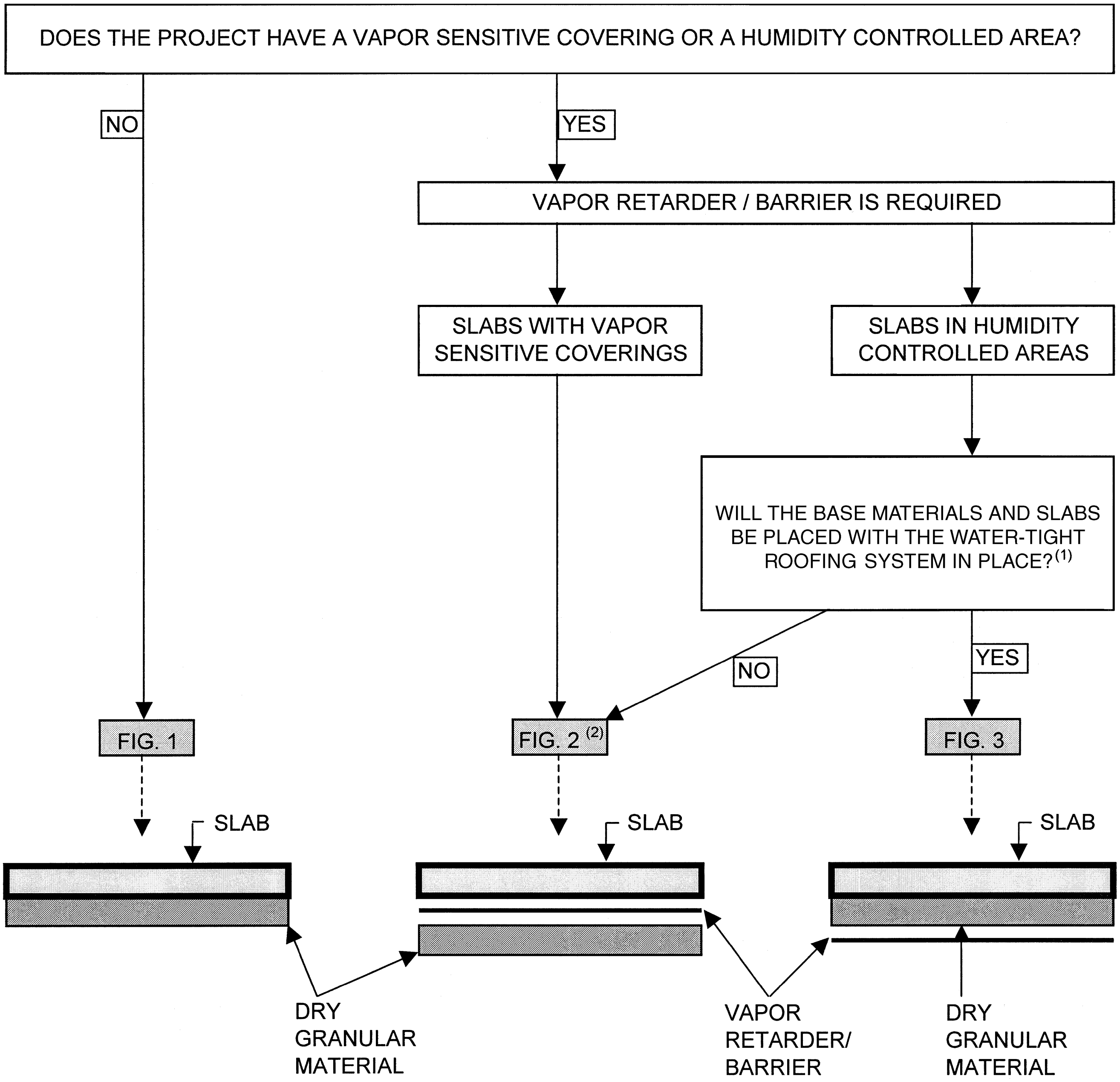
This yields a conversion factor of 3.4 lb/1000 ft^2/24 h per in. of mercury pressure. The flow through a 0.3 perm rating material is thus 3.4 × 0.3, or approximately 1 lb/1000 ft^2/24 h per inch of mercury pressure.

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 0.3 perm rating is approximately 0.4 lb/1000 ft^2/24 h (0.2 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 0.02 lb/1000 ft^2/24 h (0.01 kg/100 m^2/24 h).

Clearly, there is a substantial difference in water vapor transmission through a vapor retarder meeting the allowable ASTM E 1745 specification requirement of 0.3 perms and through a product with a maximum perm rating of 0.01 perms.

7.3.2 *Water vapor transmission through punctures*—Suprenant and Malisch (1998e) used calcium chloride tests (ASTM F 1869) to evaluate the MVER through punctures in vapor retarders and barriers. 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 C 33 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



NOTES:

(1) IF GRANULAR MATERIAL IS SUBJECT TO FUTURE MOISTURE INFILTRATION, USE FIG. 2.

(2) IF FIGURE 2 IS USED, A REDUCED JOINT SPACING, A LOW SHRINKAGE MIX DESIGN, OR OTHER MEASURES TO MINIMIZE SLAB CURL WILL LIKELY BE REQUIRED.

Fig. 7.1—Decision flow chart to determine if a vapor retarder/barrier is required and where it is to be placed (ACI 302.1R).

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 about 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, while 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.

7.3.3 *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-96 recommended a minimum 10 mil (0.25 mm) thick vapor retarder. Suprenant and Malisch showed this recommendation to be appropriate when the vapor retarder will be covered with base materials that are then compacted.

The ACI 302.1R-96 recommendation for minimum thickness was made in conjunction with a recommendation in the same document that vapor retarder/barriers be covered (and thus, protected) by a granular layer. ACI 302.1R-04 gives no recommendations regarding the thickness or strength of a vapor retarder or barrier placed directly under the concrete slab and exposed to construction traffic. Concrete-truck traffic, use of laser-guided screeds, presence of pump hoses, and reinforcing bar placement are just some of the activities that can cause punctures when concrete is placed directly on the vapor retarder/barrier. The specifier should consider these activities when selecting the appropriate vapor retarder/barrier. 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.

7.3.4 *Effectiveness of vapor retarder/barrier in reducing water vapor inflow*—Results by Suprenant and Malisch (1998e) 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:

- Compacted clay;
- Compacted clay covered with a gravel layer;
- Compacted clay covered with a vapor retarder; and
- Compacted clay covered with a gravel layer and vapor retarder.

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

Brewer started measuring moisture inflow approximately a 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 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 did not detect differences between 8 and 40 mil (0.20 and 1.0 mm) polyethylene.

7.3.5 *Construction concerns*—Contractors must 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/barrier.

Finally, the vapor retarder should be installed by following manufacturers' instructions that usually require:

- Lapping joints and sealing them, typically with duct tape;
- Sealing with duct tape around all penetrations;
- Lapping over footings, sealing with duct tape to foundation walls, or both;
- Protecting the vapor retarder during installation of reinforcing steel, utilities, and concrete placement; and
- Repairing vapor retarder damage.

CHAPTER 8—FLOOR COVERING MATERIALS

8.1—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. In addition, optimizing the concrete floor and floor finish provides the best performance at the lowest cost. It may not be economical or practical to resolve any moisture-related substrate performance requirements by simply requiring concrete to reach a desired moisture state in a very short time, or by requiring floor covering and adhesive systems to tolerate a high moisture content at the concrete-flooring interface. The design should seek concrete and floor covering materials that are robust enough to accommodate the variations inherent to construction.

8.2—Communication between architect and engineer

The architect and engineer should communicate to ensure that the Construction Specifications Institute Division 9 specification requirements for floor coverings are compatible with 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, taking into consideration that one or more of the following Division 9 specification sections will have to be addressed by the floor design team:

- Section 09402 Epoxy Terrazzo;
- Section 09620 Specialty Flooring;
- Section 09621 Fluid-Applied Athletic Flooring;
- Section 09622 Resilient Athletic Flooring;
- Section 09640 Wood Flooring;
- Section 09651 Resilient Tile Flooring;
- Section 09652 Sheet Vinyl Floor Coverings;
- Section 09654 Linoleum Floor Coverings;
- Section 09671 Resinous Flooring;
- Section 09677 Static-Control Resilient Floor Covering;
- Section 09680 Carpet;
- Section 09681 Carpet Tile;
- Section 09960 High-Performance Coatings; and
- Section 09963 Elastomeric Coatings.

As stated in Chapter 5, 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.

8.3—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. Some of the floor covering associations and their website addresses are as follows:

- Carpet & Rug Institute: **www.carpet-rug.org**;
- Tile Council of America: **www.tileusa.com**;
- Resilient Floor Covering Institute: **www.rfci.com**;
- World Floor Covering Association: **www.wfca.org**;
- National Wood Flooring Association: **www.nwfa.org**;
- The Wood Flooring Manufacturers Association: **www.nofma.org**;
- Maple Flooring Manufacturers Association: **www.maplefloor.org**;
- Polymer Coatings & Surfacings Institute; and
- National Terrazzo & Mosaic Association: **www.ntma.com.**

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.

8.4—Floor adhesives and coverings

8.4.1 *Adhesives*—There are ASTM standards for various floor coverings and ASTM standard test methods for adhesives, but there are no ASTM standard specifications for flooring adhesives. Thus the design team has few nationally accepted guidelines for selecting adhesives. Adhesives typically vary from a solids-water content of 80-20% to 60-40%. Adhesives with higher water contents are usually less expensive, but may have more stringent requirements for the substrate moisture state prior to installation of the flooring. For instance, the adhesive manufacturer may require a MVER of 3 lb/1000 ft^2/24 h (1.5 kg/100 m^2/24 h) instead of the less restrictive 5 lb (2.4 kg) rate. Adhesives with the higher solids content and lower water content cost more and usually have less stringent moisture-state criteria for adhesive application.

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 alternate adhesive costs 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. The inspector should verify that the specified adhesive was placed, and placed at the proper rate.

8.4.2 *Floor coverings*—Because moisture vapor can pass readily through some carpeting, the concrete substrate doesn't have to be as dry as it does for more moisture-sensitive

Fig. 8.1—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).

coverings. The carpet backing, however, determines the ease with which moisture passes through the carpet. If moisture vapor cannot pass through the backing, more stringent requirements for concrete moisture state may be needed.

Vinyl composition tile (VCT) and sheet vinyl flooring with and without backing may require differing moisture states for the substrate. VCT is generally produced in 12 x 12 in. (300 x 300 mm) tiles, which allows some moisture to escape at the relatively closely spaced joints. Seams in sheet vinyl flooring are often welded or sealed, allowing no moisture to pass. Although both VCT and sheet goods are made with vinyl, the required moisture state for the substrate before flooring installation may differ.

Terrazzo-tile floors differ from concrete terrazzo. The polymer matrix of a 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.

8.5—Effect of moisture in flooring adhesives

Flooring adhesives are usually spread on the concrete surface and then left uncovered (open) for 15 to 30 minutes before the floor covering is installed. During this open time, some of the water or solvent in the adhesive evaporates, but some is absorbed by the concrete. To measure the water lost by evaporation, Suprenant (2003c) applied several different flooring adhesives to nonporous plastic plates (Fig. 8.1), 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 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 on the surface may also affect the pH. To investigate the immediate effect of water-based adhesives on surface pH, Suprenant spread a water-based adhesive on a previously dried concrete slab that had an initial pH of 9. Flat plastic 1 x 2 in. (25 x 51 mm) strips were placed on the surface before applying the adhesive, then removed to leave bare concrete surfaces after the adhesive was applied (Fig. 4.2). At 15-second intervals, the pH of the concrete on the bare surfaces was measured using pH indicator strips. Only a few minutes after the adhesive had been applied, the surface pH rose from 9 to 11.5. This indicated that moisture from the adhesive had penetrated the concrete, and that alkalis had been brought into solution quite quickly (Suprenant 2003e). This means that a newly placed adhesive could be exposed to a high pH environment not created by concrete mixing water or external moisture sources other than the water in the adhesive. In adhesives with a low solids-water content, the water that does not evaporate during the open time might be absorbed by the concrete, dissolve alkalis near the surface, and have an adverse effect on adhesive performance.

The influence of adhesive moisture content on flooring performance is recognized by some adhesive manufacturers. A minimum solids-water content of 75 to 25%, or no more than 25% water, is recommended for adhesives used to install wood flooring. Adhesives with higher water contents are believed to affect the behavior of the wood flooring. The wood's moisture changes can then adversely affect the performance. Thus, while wood warping is often blamed on moisture in the concrete, the adhesive can provide the necessary 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.

8.6—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. 8.2). 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

Fig. 8.2—Pulloff testing for vinyl composition tile placed on concrete slab with known moisture vapor emission rate (Suprenant 2003c).

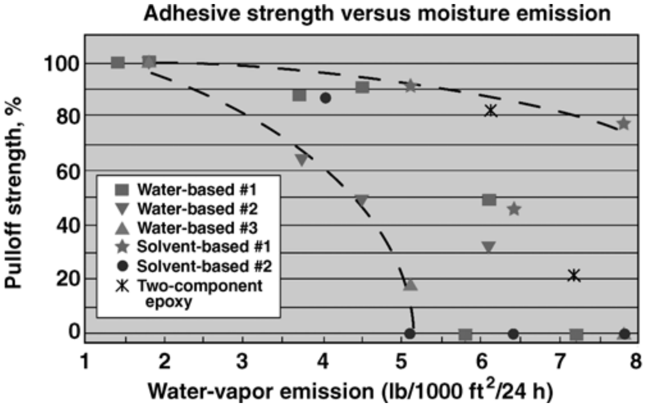


Fig. 8.3—Pulloff test results for different adhesives on concrete slabs with different moisture vapor emission rates (Suprenant and Malisch 1999a). (Note: 1 lb/1000 ft^2/24 h = 0.488 kg/100 m^2/24 h.)

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.

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:

- Average strength for the epoxy-based adhesive was 128 psi (882 kPa);
- Average strengths for two solvent-based adhesives were 11.0 and 29.5 psi (76 and 203 kPa); and
- Average strengths for six water-based adhesives ranged from 7.0 to 38.5 psi (48 to 265 kPa).

Figure 8.3 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 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 9—DESIGN AND CONSTRUCTION RECOMMENDATIONS

9.1—Introduction

These design and construction recommendations are based on the information presented in the previous chapters. Figures 9.1 and 9.2 illustrate the effects of several variables on drying time and pH. Specifications will usually include clauses related to:

- Testing;
- Moisture mitigation systems;
- Vapor retarder/barrier;
- Concrete materials and properties;
- Curing;
- Protection;
- Surface preparation;
- Repair materials; and
- Floor covering 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.

9.2—Testing

The following testing recommendations should be considered:

- Qualified, accredited independent agencies should perform moisture tests as specified in Construction Specification Institute (CSI) Section No. 1400,

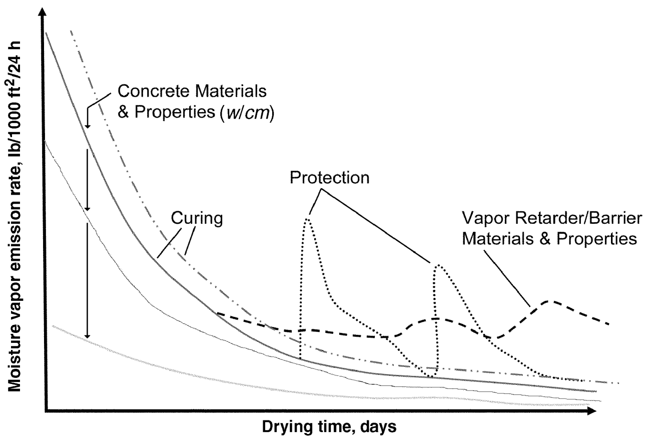


*Fig. 9.1—Water-cementitious material ratio (*w/cm*) is the primary concrete property affecting MVER. The lowest curve represents the lowest* w/cm*. At the same* w/cm*, wet curing (highest curve) increases the time needed to reach a required MVER. If concrete is left unprotected, each rewetting increases MVER. If there is no vapor retarder/barrier, or if the retarder/barrier is breached by poor laps or punctures, MVER does not reach an equilibrium point.*

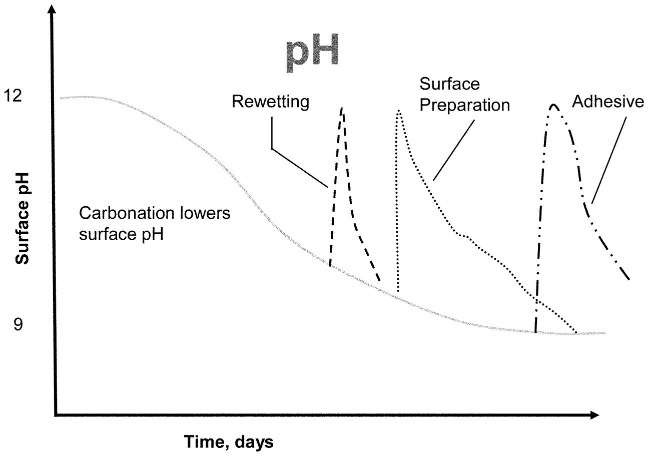


Fig. 9.2—Although carbonation of the surface reduces pH, rewetting can dissolve more alkalis, raising the pH. Abrasive blasting or other surface preparation methods can remove all or part of the carbonated layer, increasing the pH. Water contained in the adhesive can also increase the pH of the surface.

“Quality Requirements;”

- For quality control, the flooring installer should also perform moisture tests as specified in the floor covering specifications;
- One or more of the following test methods should be specified: ASTM F 1869, F 2170, E 1907, or F 2420 (refer to Section 10.1);
- 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;
- The number of tests should be reduced to fewer than the number required by ASTM standards (refer to Section 3.4 of this guide). A minimum of 10 and a maximum of 30 tests should be considered for determining whether flooring should be placed. No fewer than three final tests should be used on each concrete placement, however, regardless of how many total tests are required. Thus, if there were 20 concrete placements, 60 tests would be needed to verify that the slab complied with moisture criteria specified. If there were four concrete placements, a minimum of 12 tests would be required; and
- In CSI Section No. 1500 of the specification, “Temporary Facilities and Controls,” 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.

9.3—Vapor retarder/barrier

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

- For floor covering or coating applications, concrete slabs should be placed directly on the vapor retarder/barrier;
- The vapor retarder/barrier should conform to ASTM E 1745. This standard requires the specifier to choose Class A, B, or C or, alternatively, specific performance requirements for each of the properties (water vapor permeance, tensile strength, and puncture resistance). Class A, B, and C vapor retarders all have the same 0.3 perm water vapor permeance but have to meet differing tensile strength and puncture-resistance requirements. Class A has the highest strength and puncture resistance, and Class C has the lowest. The choice should be based on conditions expected during construction. Such conditions might include exposure to puncture or tearing by angular subbase particles, use of laser-guided self-propelled screeds with tires in contact with the vapor retarder, or reinforcing steel laying on the surface;
- In accordance with ASTM E 1745, the specifier should choose performance requirements, if any, for special conditions (flame spread, permeance after soil poison petroleum vehicle exposure, and permeance after exposure to ultraviolet light);
- It should be determined whether a vapor retarder with a 0.3 perm rating (passes 0.5 lb/1000 ft^2/24 h [0.24 kg/100 m^2/24 h]) is sufficient protection for the flooring material to be installed. If not, a vapor barrier with a perm rating of 0.01 or less (passes 0.02 lb/1000 ft^2/24 h [0.01 kg/100 m^2/24 h]) should be specified. 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 relative humidity [RH]) will benefit from the use of a vapor retarder material with a permeance level well below the current ASTM minimum requirement;
- 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-04 recommends a minimum 10 mil (0.25 mm) vapor retarder thickness when the retarder is protected with a granular fill. When the vapor retarder is not protected by a fill, some specifiers require a 15 mil (0.38 mm) thickness or greater;

- Installation should be in accordance with ASTM E 1643;
- Referencing ASTM E 1643 requires the contractor to follow the manufacturer's instructions for placement (including laps and sealing around penetrations and foundation walls), protection, and repair. ASTM E 1643 requires the contractor to use reinforcement supports that do not puncture the vapor retarder and to repair any damaged areas; and
- Inclusion of some of the construction items mentioned in ASTM E 1643 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.") Construction-related requirements included only in cited standards are more difficult for the contractor to find and comply with.

9.4—Concrete materials

As discussed in Section 6.6, there is no reason to include or exclude the use of any 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. Lightweight concrete provides other benefits, however, so the specifier may choose lightweight concrete and consider means for dealing with the increased drying time. Such means may include selection of floor coverings or adhesive that can be placed on concretes at higher interior RH values or MVERs.

9.5—Concrete properties

As discussed in Section 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.

9.5.1 *Selecting a* w/cm—ASTM F 710 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 adhesives or floor coverings, or both, to fail due to high moisture permeability.

"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 resilient flooring industry standard MVER). The importance of using a moderate to moderately low water-cement ratio for floors to receive resilient flooring cannot be overemphasized."

Using a water-cementitious material ratio (*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 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.

A concrete drying time of approximately 3 months can be accommodated in the schedule for many construction projects, and the desired moisture state can often be achieved within 3 months 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 or mid-range water-reducing admixtures can be used to produce such a concrete.

If the concrete is exposed to wetting (waterproof roof and walls not present during construction of the concrete slab), 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). The committee suggests specifying 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 aren't reliable enough for use in assuring that the specified value has been achieved.

9.6—Surface finish

When floors will receive coverings, most specifiers require a power-trowel finish. Some specifiers choose a troweled surface with a light broom texture. A burnished finish (produced by repeated hard troweling) should not be specified if a broom texture is needed because the resulting surface will be too dense to be marked with a broom. Also, expect some wearing of the broom finish by the time the floor covering is applied.

Different floor coverings often require different finishes. The Ceramic Tile Institute prefers a hard-troweled finish with a broom texture as a substrate for their products. The Resilient Flooring Institute prefers a hard-troweled, very smooth surface with the broom texture being unacceptable.

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 surface preparation. Many surface preparation treatments such as shotblasting, scarifying, or grinding will make the choice of the original surface floor finish moot.

9.6.1 *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 5.1 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 Section 5.3, 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 5.1 recommendations, a compromise for use in Division 9 of the specifications 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 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-04 for suspended 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.

9.7—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 (1999c) recommend 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.

Many specifiers require water curing for floors—sometimes for as long as 28 days. This practice is counterproductive for floors that must dry before flooring materials are installed. It 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 water curing or curing durations longer than 7 days for any curing method.

ASTM F 710, "Standard Practice for Preparing Concrete Floors to Receive Resilient Flooring," provides the following commentary:

"Membrane-forming curing compounds meeting Specification C 309 are commonly spray-applied to the top surface of the slab immediately after finishing to retard moisture evaporation. Spray, roller, or brush applied cure-and-seal compounds are sometimes used instead of membrane-forming compounds. All of these compounds aid in retaining some moisture in the concrete, thus retarding the rate of drying. Resilient flooring and adhesive manufacturer's specifications often prohibit the use of such compounds as they can interfere with the bond of the adhesive to the concrete.

"Such agents, in many cases, form a surface film of oil, wax, resins, or a combination thereof, that tend to obstruct the bond between the and the adhesive or may trap moisture in the concrete which will be released at a future date, or both, causing adhesive failure or other problems related to excess water vapor between the flooring and the slab. In all cases where curing compounds have been used, the resilient flooring or adhesive manufacturer, or both, shall be consulted."

Based on the information presented, the following is recommended:

- Slabs should not be cured by adding water (for example, ponding or wet burlap);
- Curing compounds or cure-and-seal materials should not be used unless such use is approved in writing by the adhesive and floor covering manufacturer. The curing product manufacturer's conformance to ASTM C 1315 is not a substitute for the adhesive and floor covering manufacturers' approval. Using a curing compound will slow the initial drying, resulting in longer drying times, and will typically have to be removed before the floor covering adhesive can be placed; and
- The slab should be cured by being covered with waterproof paper, plastic sheets, or a combination of the two for 3 to 7 days.

9.8—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 F 710 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 pH tests, 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 and pH 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 is needed for the surface to meet pH or moisture requirements. Historically, most floors perform well when they are tested, prepared, and then covered, so additional testing might not be necessary.

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 C 811, D 4258, D 4259, D 4260, D 5295, and F 710 (refer to Section 10.1).

These additional publications can also provide guidance:

- "Concrete Surface Preparation: Treating Surface Irregularities, Cleaning, and Profiling," *The Fundamentals of Cleaning and Coating Concrete* (The Society for Protective Coatings 2001);
- "Selecting and Specifying Concrete Surface Preparation for Sealers, Coatings, and Polymer Overlays" (International Concrete Repair Institute 1997); and
- "Preparing Surfaces for Epoxy Compound Application," Chapter 5 of ACI 503R, "Use of Epoxy Compounds with Concrete," (American Concrete Institute 1993);

9.9—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.

9.10—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/barrier 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.

9.11—Moisture mitigation

Because waiting for a slab to dry can delay completion of the building, some architects incorporate a specification section that deals with moisture mitigation systems. Such moisture mitigation systems are externally applied to the concrete surface to produce a moisture state that allows the adhesive to bond to the concrete surface. 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 can not wait for the concrete to dry.

CHAPTER 10—REFERENCES

10.1—Referenced standards and reports

The standards and reports listed below were the latest editions at the time this document was prepared. Because these documents are revised frequently, the reader is advised to contact the proper sponsoring group if it is desired to refer to the latest version.

American Concrete Institute (ACI)

117	Specifications for Tolerances for Concrete Construction and Materials
222R	Protection of Metals in Concrete Against Corrosion
302.1R	Guide for Concrete Floor and Slab Construction
318/318R	Building Code Requirements for Structural Concrete and Commentary
360R	Design of Slabs-on-Ground
503R	Use of Epoxy Compounds with Concrete

ASTM International

C 33	Standard Specification for Concrete Aggregates
C 805	Standard Test Method for Rebound Number of Hardened Concrete
C 811	Standard Practice for Surface Preparation of Concrete for Application of Chemical-Resistant Resin Monolithic Surfacings
C 1315	Standard Specification for Liquid Membrane-Forming Compounds Having Special Properties for Curing and Sealing Concrete

D 4258	Standard Practice for Surface Cleaning Concrete for Coating
D 4259	Standard Practice for Abrading Concrete
D 4260	Standard Practice for Liquid and Gelled Acid Etching of Concrete
D 4262	Standard Test Method for pH of Chemically Cleaned or Etched Concrete Surfaces
D 4263	Standard Test Method for Indicating Moisture in Concrete by the Plastic Sheet Method
D 5295	Standard Guide for Preparation of Concrete Surfaces for Adhered (Bonded) Membrane Waterproofing Systems
E 119	Standard Test Methods For Fire Tests of Building Construction and Materials
E 1643	Standard Practice for Installation of Water Vapor Retarders Used in Contact with Earth or Granular Fill Under Concrete Slabs
E 1745	Standard Specification for Water Vapor Retarders Used in Contact with Soil or Granular Fill under Concrete Slabs
E 1907	Standard Guide to Methods of Evaluating Moisture Conditions of Concrete Floors to Receive Resilient Floor Coverings
F 710	Standard Practice for Preparing Concrete Floors to Receive Resilient Flooring
F 1869	Standard Test Method for Measuring Moisture Vapor Emission Rate of Concrete Subfloor Using Anhydrous Calcium Chloride
F 2170	Standard Test Method for Determining Relative Humidity in Concrete Floor Slabs Using in situ Probes
F 2420	Standard Test Method for Determining Relative Humidity on the Surface of Concrete Floor Slabs Using Relative Humidity Probe Measurement and Insulated Hood

ICRI

03732	Selecting and Specifying Concrete Surface Preparation for Sealers, Coatings, and Polymer Overlays

These publications may be obtained from the following organizations:

American Concrete Institute
P.O. Box 9094
Farmington Hills, MI 48333-9094
www.concrete.org

ASTM International
100 Barr Harbor Drive
West Conshohocken, PA 19428-2959
www.astm.org

International Concrete Repair Institute
3166 South River Road, Suite 132
Des Plaines, IL 60018
www.icri.org

10.2—Cited references

Abrams, M. S., and Monfore, G. E., 1965, "Application of a Small Probe-Type Relative Humidity Gage to Research on Fire Resistance of Concrete," *Journal of the PCA Research and Development Laboratories*, V. 7, No. 3, pp. 2-12.

Abrams, M. S., and Orals, D. L., 1965, "Concrete Drying Methods and Their Effect on Fire Resistance," ASTM STP No. 385, pp. 52-73.

Anderson, T., and Roper, H., 1977, "Influence of an Impervious Membrane Beneath Concrete Slabs on Grade," *Symposium on Concrete for Engineering*, Institute of Engineers, Brisbane, Australia, pp. 51-56.

ASCC, 2005, "Misuses of the Moisture Vapor Emission Test," *Concrete International*, V. 27, No. 3, Mar., p. 95

Brewer, H. W., 1965, "Moisture Migration—Concrete Slab-on-Ground Construction," *Bulletin* D89, Portland Cement Association, Skokie, Ill., May, 24 pp.

Carrier, R. E.; Pu, D. C.; and Cady, P. D., 1975, "Moisture Distribution in Concrete Bridge Decks and Pavements," *Durability of Concrete*, SP-47, American Concrete Institute, Farmington Hills, Mich., pp. 169-192.

Concrete Repair Digest, 1997, "Perspectives on Repair Options for Floor Moisture Problems," Dec. 1996/Jan. 1997, pp. 289-293.

The Concrete Society, 2004, "Moisture in Concrete and the Performance of Impermeable Floor Coverings," *CS 130*, The Concrete Society, UK, 32 pp.

"Concrete Surface Preparation: Treating Surface Irregularities, Cleaning, and Profiling," 2001, *The Fundamentals of Cleaning and Coating Concrete*, The Society for Protective Coatings, 380 pp.

Construction Specifications Institute, 2000, *Manual of Standard Practice*, Alexandria, Va.

Craig, P., 2003, "Survey of Floor Covering Manufacturers Moisture Guidelines," ACI 302-360 Task Group.

Craig, P. A., 2004, "Vapor Barriers: Nuisance or Necessity?" *Concrete Construction*, Mar., pp. 32-37.

Finish SisaRYL, 2000, "Code of Building Practice."

Hanson, J. A., 1968, "Effects of Curing and Drying Environments on Splitting Tensile Strength of Concrete," ACI JOURNAL, *Proceedings* V. 65, No. 7, July, pp. 535-543.

Harriman, L., 1995, "Drying Concrete," *Construction Specifier*, V. 48, No. 3, Mar., pp. 55-64.

Hedenblad, G., 1993, *Drying Times for Concrete after Water Damage*, The Swedish Council for Building Research, Stockholm, Sweden, 31 pp. (English translation provided by Hedenblad)

Hedenblad, G., 1997, *Drying of Construction Water in Concrete*, Swedish Council for Building Research, Stockholm, Sweden, 54 pp.

Holland, J. A., and Walker, W., 1998, "Controlling Curling and Cracking in Floors to Receive Coverings," *Concrete Construction*, July, pp. 603-605.

Jackson, F. H., and Kellerman, W. F., 1939, "Tests of Concrete Curing Materials," ACI JOURNAL, *Proceedings*, V. 36, June, p. 481.

Kanare, H., 2005, *Concrete Floors and Moisture*, Portland Cement Association, Skokie, Ill., 156 pp.

Kercheval, R., 1999, "Concrete-Moisture-Vapor-Emission Mechanisms," *ASCE Practice Periodical on Structural Design and Construction*, Aug., pp. 96-104.

Landgren, R., 1964, "Water-Vapor Adsorption-Desorption Characteristics of Selected Lightweight Concrete Aggregates," *Bulletin* 178, Portland Cement Association, Skokie, Ill., pp. 830-845.

Mindess, S., and Young, F., 1981, *Concrete*, Prentice-Hall, Inc., Englewood Cliffs, N.J., pp. 103-105.

Monfore, G. E., 1963, "A Small Probe-Type Gage for Measuring Relative Humidity," *Journal of the PCA Research and Development Laboratories*, V. 5, No. 2, pp. 41-47.

Pinelle, D. J.; O'Keefe, J.; and Craig, P., 2005, "Evaluation of Test Method for Measuring pH of a Concrete Subfloor Prior to Installation of Floor Finishes," *Moisture Testing Mitigation Seminar*, International Concrete Repair Institute, Boston, Mar.

Powers, T. C., and Brownyard, T. L., 1947, "Studies of the Physical Properties of Hardened Portland Cement Paste," ACI JOURNAL, *Proceedings* V. 43, Oct. 1946-Apr. 1947, 356 pp.

Resilient Floor Covering Institute, 1995, "Addressing Moisture Related Problems Relevant to Resilient Floor Coverings Installed Over Concrete," Nov., 10 pp.

Rollings, R. S., 1995, "Retail-Grocery—Floor Failure," *Journal of the Performance of Constructed Facilities*, V. 9, Issue 2, American Society of Civil Engineers, May, pp. 137-145.

Sika, 2003, *Acoubond Installation Guidelines*, Eiger International, Telluride, Colo., 16 pp.

Simpson, W. T., 1998, "Equilibrium Moisture Content of Wood in Outdoor Locations in the United States and Worldwide," *Research Note* FPL-RN-0268, Forest Products Laboratory, Madison, Wis., 11 pp.

Straube, J., 2000, "Moisture Properties of Plaster and Stucco for Strawbale Buildings," *Report for Canada Mortgage and Housing Corporation*, June, 53 pp.

Suprenant, B. A., 1992, "Vapor Barriers Under Concrete Slabs," *Concrete Construction*, Apr., pp. 292-296.

Suprenant, B. A., 1997, "Moisture Movement through Concrete Slabs," *Concrete Construction*, Nov., pp. 879-885.

Suprenant, B. A., 2002a, "Bird Baths: Expectations vs. Reality," *Concrete International*, V. 24, No. 2, Feb., pp. 67-69.

Suprenant, B. A., 2002b, "Why Slabs Curl: Part I: A Look at the Curling Mechanism and the Effect of Moisture and Shrinkage Gradients on the Amount of Curling," *Concrete International*, V. 24, No. 3, Mar., pp. 56-61.

Suprenant, B. A., 2002c, "Why Slabs Curl: Part II: Factors Affecting the Amount of Curling," *Concrete International*, V. 24, No. 4, Apr., pp. 59-64.

Suprenant, B. A., 2003a, "Design of Slabs that Receive Moisture-Sensitive Floor Coverings, Part I: A Design Guide for Architects and Engineers," *Concrete International*, V. 25, No. 3, Mar., pp. 84-88.

Suprenant, B. A., 2003b, "Design of Slabs that Receive Moisture-Sensitive Floor Coverings, Part 2: Guide to Specification Issues for Architects and Engineers," *Concrete International*, V. 25, No. 4, Apr., pp. 85-91.

Suprenant, B. A., 2003c, "Effects of Adhesives on Moisture-Sensitive Floor Covering Performance," *Concrete International*, V. 25, No. 6, June, pp. 59-62.

Suprenant, B. A., 2003d, "The Concrete Floor Tolerance-Floor Covering Conundrum," *Concrete International*, V. 25, No. 7, July, pp. 89-94.

Suprenant, B. A., 2003e, "Use and Misuse of Moisture-Vapor Emission Tests for Concrete Slabs," *Concrete International*, V. 25, No. 12, Dec., pp. 82-87.

Suprenant, B. A., and Malisch, W. R., 1998a, "Quick-Dry Concrete: A New Market for Ready-Mix Producers," *The Concrete Producer*, May, pp. 330-333.

Suprenant, B. A., and Malisch, W. R., 1998b, "Where to Place the Vapor Retarder," *Concrete Construction*, May, pp. 427-433.

Suprenant, B. A., and Malisch, W. R., 1998c, "Are Your Slabs Dry Enough for Floor Coverings?" *Concrete Construction*, Aug., pp. 671-677.

Suprenant, B. A., and Malisch, W. R., 1998d, "Qualifying Quick-Dry Concrete," *The Concrete Producer*, Sept., pp. 619-620.

Suprenant, B. A., and Malisch, W. R., 1998e, "Do Not Puncture the Vapor Retarder," *Concrete Construction*, Dec., pp. 1071-1075.

Suprenant, B. A., and Malisch, W. R., 1999a, "Effect of Water-Vapor Emissions on Floor-Covering Adhesives," *Concrete Construction*, Jan., pp. 27-33.

Suprenant, B. A., and Malisch, W. R., 1999b, "Repairing Curled Slabs," *Concrete Construction*, May, pp. 58-65.

Suprenant, B. A, and Malisch, W. R., 1999c, "Why Won't the Concrete Dry?" *Concrete Construction,* July, pp. 29-33.

Suprenant, B. A., and Malisch, W. R., 2000a, "Are Moisture Tests on Target?" *Concrete Construction,* Jan. pp. 61-69.

Suprenant, B. A., and Malisch, W. R., 2000b, "Examining Puncture Resistance," *Concrete Construction*, July, pp. 53-55.

Suprenant, B. A., and Malisch, W. R., 2000c, "Long Wait for Lightweight," *Concrete Construction*, Nov., pp. 48-49.

Tarr, S. M.; Craig, P. A.; and Kanare, H. M., 2006, "Concrete Slab Repair: Getting Flat is One Thing, Staying Flat is Another," *Concrete Repair Bulletin*, V. 19, No. 1, Jan.-Feb., pp. 12-15.

Tuutti, K., 1982, *Corrosion of Steel in Concrete*, No. 4, Swedish Cement and Concrete Research Institute, Stockholm, 469 pp.

World Floor Covering Association, 2001, "Floor Covering Industry White Paper Position Statement on Moisture Emission Testing," Oct., 5 pp. (www.wfca-pro.org)

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/barrier 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—Postconstruction 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/barrier 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).