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Concrete Slabs that Receive Moisture-Sensitive Flooring Materials—Guide

Reported by ACI Committee 302

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Concrete Slabs that Receive Moisture-Sensitive Flooring Materials—Guide

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Concrete Slabs that Receive Moisture-Sensitive Flooring Materials—Guide

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

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

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CHAPTER 1—INTRODUCTION AND SCOPE

1.1—Introduction

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

1.2—Scope

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

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

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



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



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

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

1.3—Flooring moisture issues

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

1.4—Concrete slabs that receive flooring materials

This document focuses on the behavior of moisture in concrete slabs and the effect of the concrete moisture condition on the performance of applied flooring materials. Reaching a desired moisture state, however, should not be



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



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



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

the only acceptance criterion for a concrete slab that will be coated or covered. Floor flatness, surface texture and finish, cracking, curling, structural capacity, jointing requirements, and the potential for the slab to stay acceptably dry should also be considered. The goal is installation of a flooring system—subgrade, subbase, vapor retarder, concrete slab (and possibly reinforcement), coating or flooring adhesive, and floor covering—that satisfies performance requirements.

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

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

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

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

1.6—Floor flatness changes with time

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

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

Time-dependent changes in floor profiles occur on every project, but the magnitude of the profile change can vary. ACI 117 states, “Since neither deflection nor curling will significantly change a floor’s F_F value, there is no time

limit on the measurement of this characteristic.” Flatness measurements on given floors at different ages, however, indicate that this statement is not true (Suprenant 2003d), and ACI 117-06 requires flatness measurements within 72 hours after finishing. Therefore, the design team should consider how changes in floor profiles with time might affect:

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

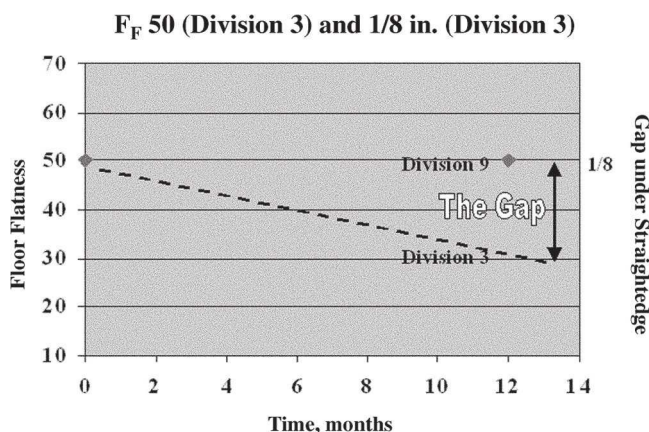


Fig. 1.6a—When flatness of an unreinforced floor is measured initially, F-numbers may indicate a very flat floor. When flooring installers start their work, however, flatness may have changed, as indicated by the gap between Division 3 and Division 9 flatness (Suprenant 2003d).

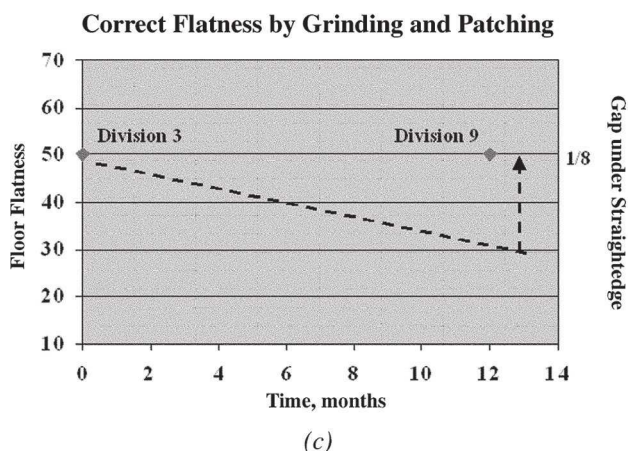
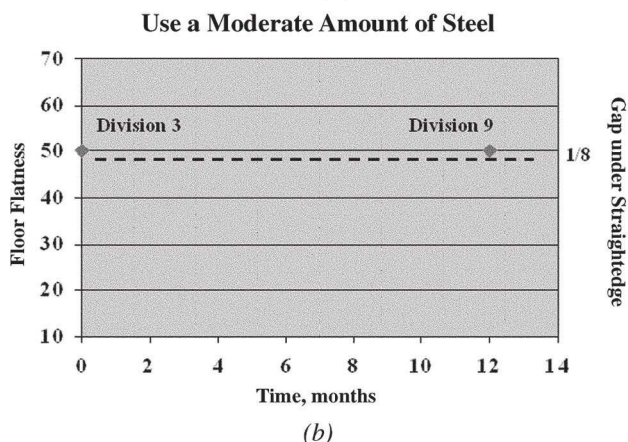
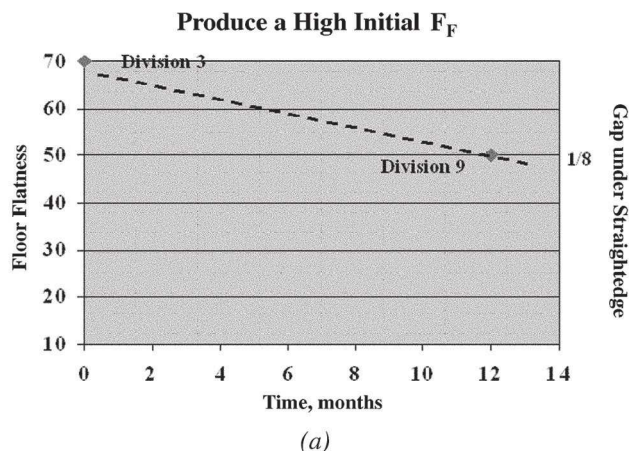


Fig. 1.6b—Approaches to providing a floor that meets the needs of the floor covering installer: (a) produce a higher initial F_F ; (b) use reinforcing steel to reduce curling; and (c) correct flatness problems by grinding and patching (Suprenant 2003d).

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

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

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

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

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

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

1.7—Other considerations

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

Contraction, construction, and column isolation joints often visibly telegraph through thin flooring materials. Because of this problem, [Holland and Walker \(1998\)](#) recommend using continuous reinforcing bars to minimize crack widths, and eliminate sawcut contraction joints and the traditional diamond-shaped isolation joints at columns when floors will receive a covering. Instead of using diamond-

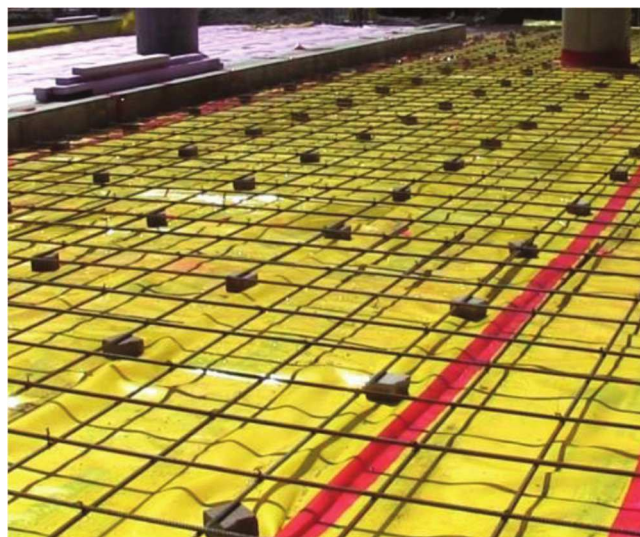


Fig. 1.7a—Proper sized and supported reinforcing bars help control slab curling and the width of cracking in slabs placed directly on a vapor retarder.

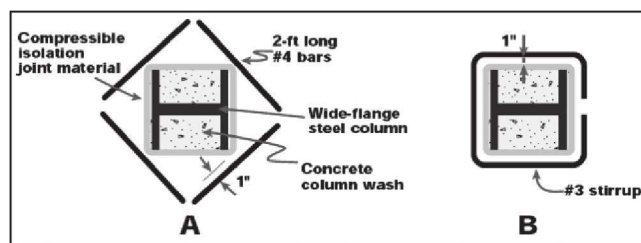


Fig. 1.7b—Eliminate the normal isolation-joint boxouts at wide-flange steel columns by wrapping the column with compressible materials and using 2 ft (0.6 m) lengths of No. 4 (No. 13) bars (A) to control cracking at the reentrant corners. To speed up steel placement at the columns, have the reinforcing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

shaped isolation joints, columns in a floor system should be wrapped for the full floor depth with 1/2 in. (12.7 mm) thick compressible isolation joint material (Fig. 1.7b). Refer to [ACI 360R](#) for more information.

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

CHAPTER 2—DEFINITIONS

2.2—Definitions

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

CHAPTER 3—CONCRETE MOISTURE BASICS

3.1—Introduction

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

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

3.2—Moisture movement

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

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

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

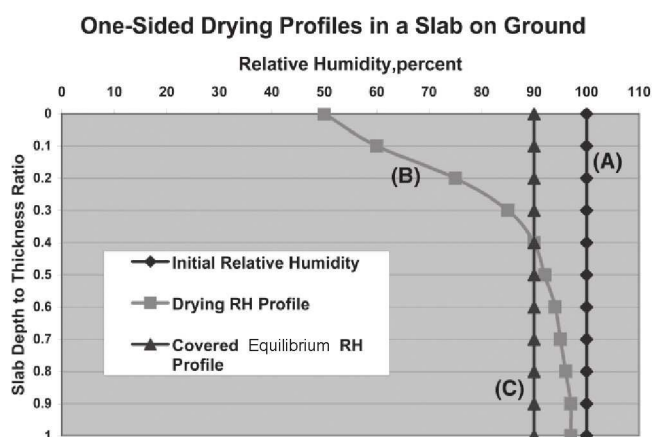


Fig. 3.2.1—One-sided drying profiles in a slab-on-ground showing initial, drying, and covered equilibrium RH profiles (adapted from Hedenblad [1997]).

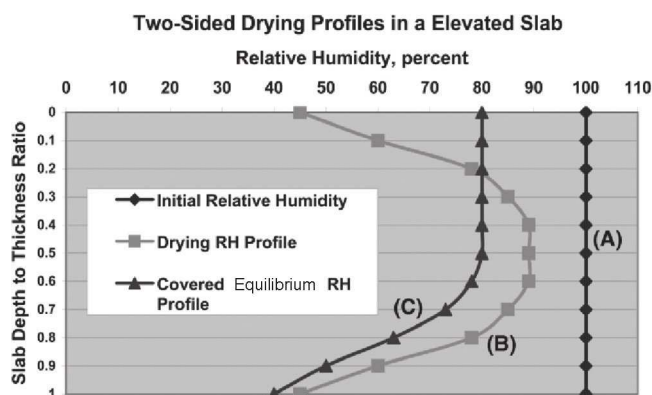


Fig. 3.2.2—Two-sided drying profiles in suspended slab showing initial, drying, and covered equilibrium RH profiles (adapted from Hedenblad [1997]).

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

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

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

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

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

3.3—Concrete drying profiles

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

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

- (a) Drying profiles differ for normalweight and lightweight concrete.
- (b) Lightweight concrete took longer to dry than normalweight concrete.

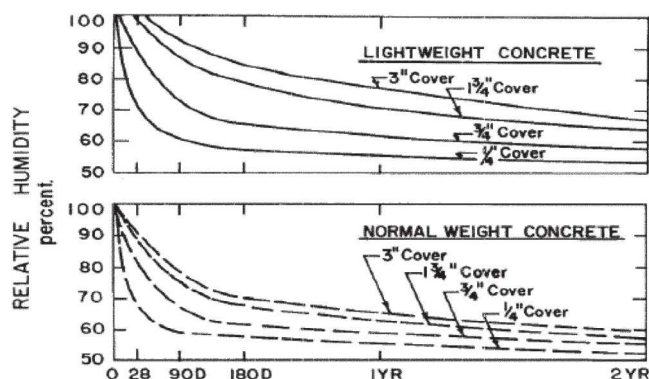


Fig. 3.3.1—Typical RH distribution for lightweight and normalweight concrete in 6 x 12 in. (150 x 300 mm) concrete cylinders moist cured for 7 days, then dried (Hanson 1968). Cover refers to depth at which the relative humidity was measured. (Note: 1 in. = 25.4 mm.)

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

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

- (a) The concrete moisture profiles are curvilinear.
- (b) Differences in RH of up to 65% (10 versus 75% RH) at the drying surface resulted in small (approximately 3%) RH differences at a depth of 3 in. (76 mm) from the drying surface.
- (c) Even when the surface was exposed to a very dry environment (10% RH), concrete at a depth of 3 in. (76 mm) reached only 75% RH.

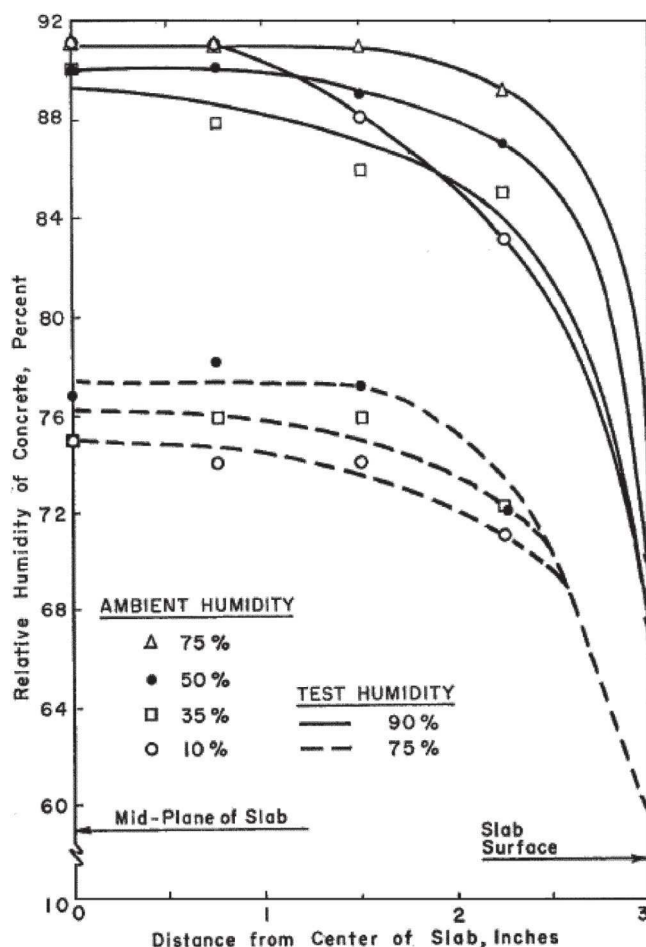


Fig. 3.3.2—Moisture profiles for slabs dried at differing ambient RH (Abrams and Orals 1965). (Note: 1 in. = 25.4 mm.)

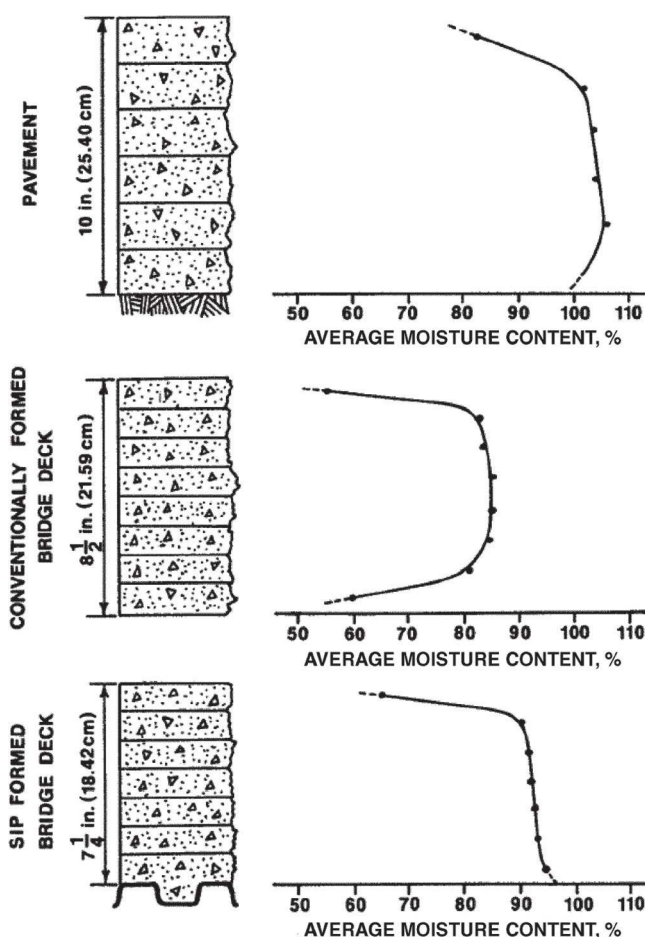


Fig. 3.3.3—Moisture profiles for concrete slab-on-ground drying from top only, suspended bridge deck drying from both top and bottom surfaces, and suspended deck placed on stay-in-place metal form drying from top only (Carrier et al. 1975).

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

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

3.3.4 Initial moisture profile—Hanson's (1968) internal RH measurements on normalweight and lightweight concrete 6 x 12 in. (150 x 300 mm) cylinders also verify the assumption that the moisture distribution in concrete after curing is initially reasonably uniform throughout the member thickness. Table 3.3.4 shows RH test results for two

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

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

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.

3.4—Effects of moisture movement

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

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

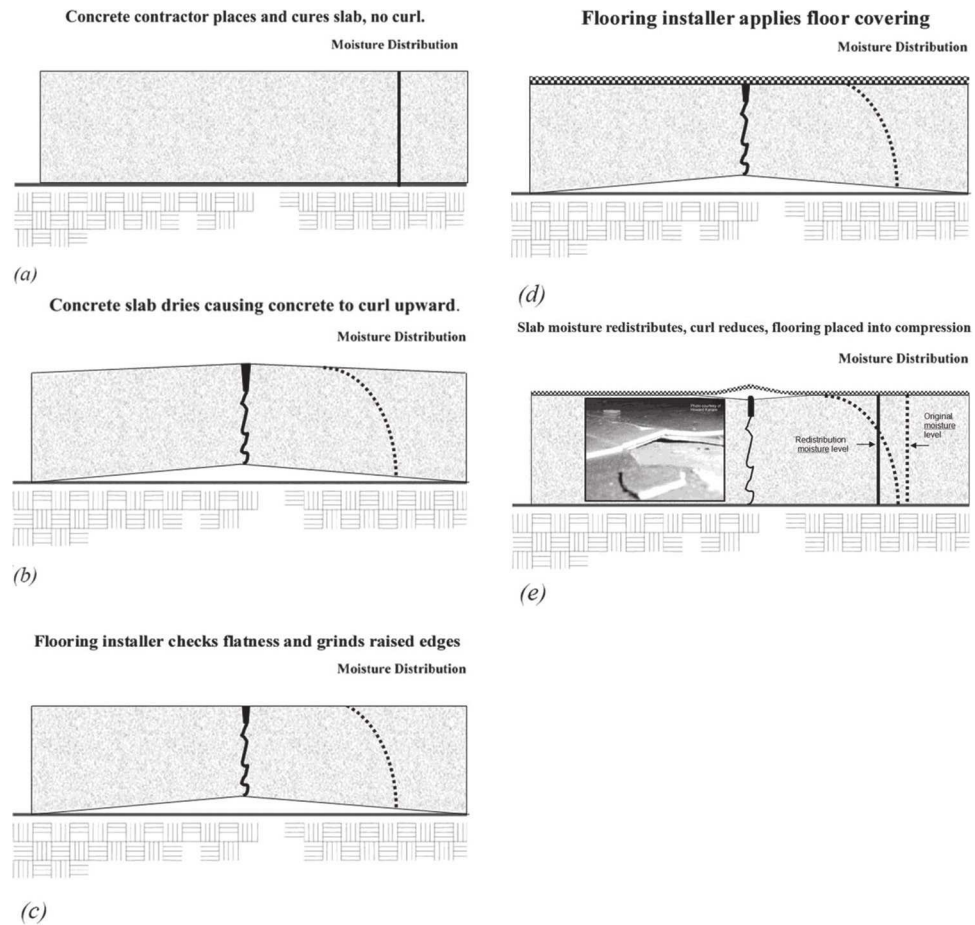


Fig. 3.4.1—Sequence showing how moisture redistribution after floor covering placement can place flooring and underlayment materials into compression over curled joints.

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

- (a) Concrete slab is placed and cured
- (b) Concrete slab dries, causing the slab edges to curl upward
- (c) The floor covering installer checks concrete flatness and grinds the curled edges of some concrete panels to provide a level surface.
- (d) Installer applies floor covering
- (e) After some time, slab moisture redistributes to equilibrium, reducing slab curling deflection. A reduction in edge curl can cause a joint filler material, leveling compound, or the flooring material itself, to be placed in compression and create a visible ridge in the flooring (refer to 3.4.2). When this occurs, additional remedial work is typically required.

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

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

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

- (a) Concrete contractor places and cures slab
- (b) Concrete contractor sawcuts joint before slab dries
- (c) Sawcut opens and a V-shape geometry is formed from the top down as the slab dries
- (d) Sawcut is filled just before the floor covering is installed. Moisture redistributes upward in the slab causing the top portion of the slab to expand, which places the filler material into compression, which can force many types of joint filler materials upward.

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

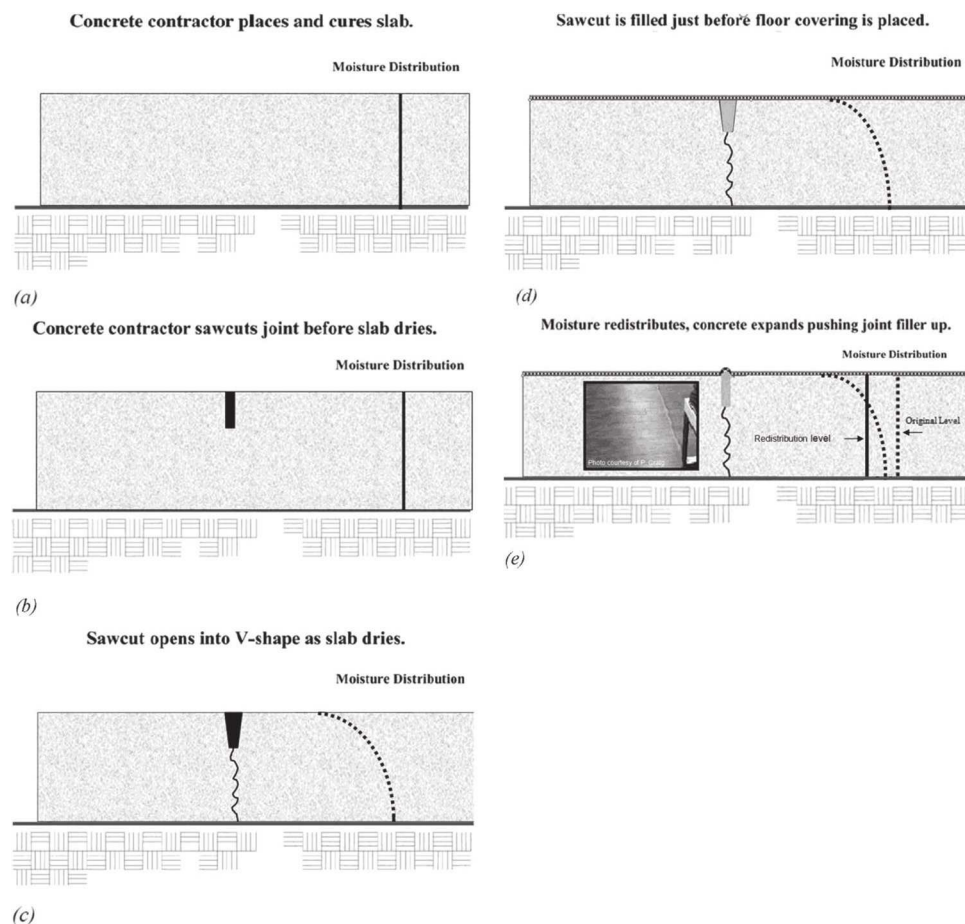


Fig. 3.4.2—Joint bulge sequence illustrating how moisture redistribution after floor covering is placed can create a joint filler bulge under installed floor covering.

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

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

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

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

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

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

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

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

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

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

Measurements in accordance with ASTM F1869 on these floors or laboratory specimens indicated that the MVER increased significantly (a 1 to 2 lb/1000 ft²/24 h [0.5 to 1.0 kg/100 m²/24 h] increase for floors initially in the 3 to 5 lb/1000 ft²/24 h [1.5 to 2.4 kg/100 m²/24 h] MVER range). These tests showed that the surface moisture condition had changed after the floor covering was placed but did not indicate the time at which it reached equilibrium.

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

3.5—Equilibrium moisture content

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

Data (Simpson 1998) show how the EMC of wood in outdoor locations varies throughout the United States and worldwide. As is the case for wood, the equilibrium moisture content for a concrete slab drying while exposed to a

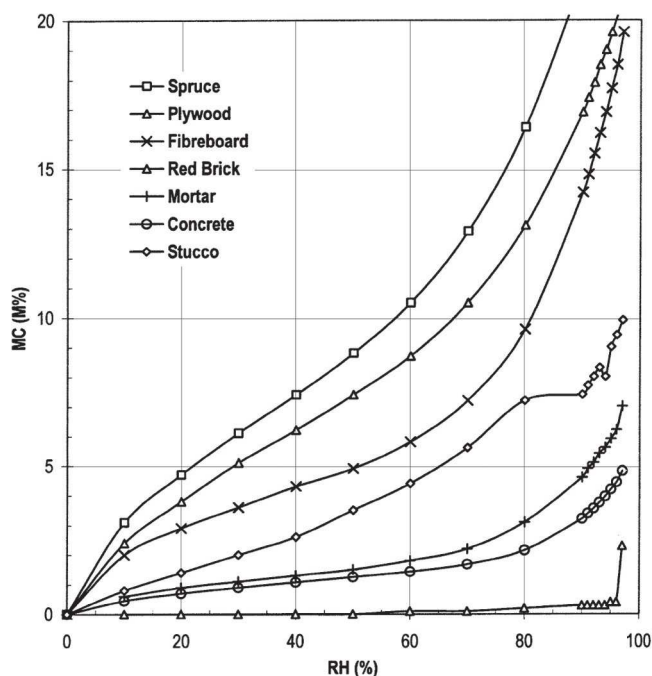


Fig. 3.5—Sorption isotherms for several common building materials (Straube 2000).

high RH environment will not be the same as that for a slab in a low RH environment. Figure 3.5 (Straube 2000) shows that if the average RH to which the concrete is exposed is above 80%, the moisture content will never fall below 2% (by mass). Similarly, if the average RH is below 40%, the moisture content can reach 1% or lower.

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

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

3.6—Drying and wetting of concrete

3.6.1 Adsorption and desorption effects—When concrete dries, the moisture loss is referred to as desorption, and when it is wetted, the moisture gain is referred to as adsorption. Figure 3.6.1a (Powers and Brownard 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 Brownard (1947) showed that there are different drying and wetting

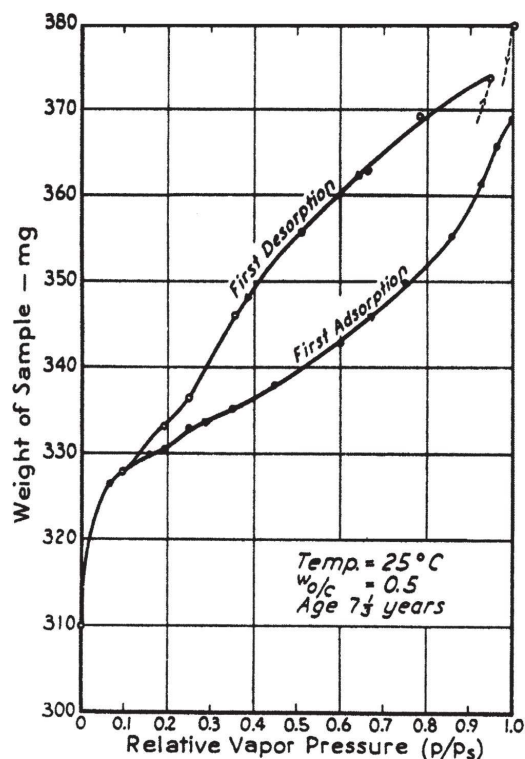


Fig. 3.6.1a—Typical drying (desorption) and wetting (adsorption) curves showing that behavior is different and that concrete contains a different moisture content at the same RH depending on whether it is drying or wetting (Powers and Brownard 1947). (Note: °C = 5/9 × [°F - 32].)

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

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

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

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

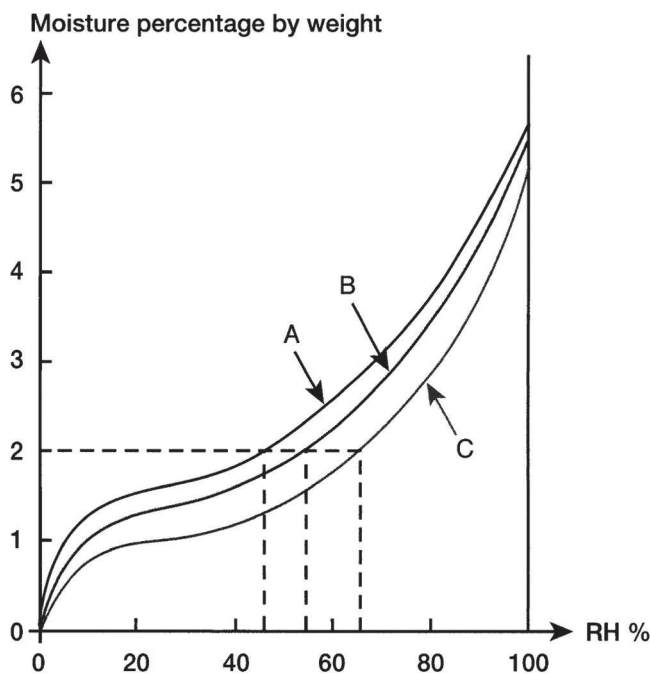


Fig. 3.6.1b—Idealized wetting (adsorption) curves illustrating that at the same moisture content the concretes will have different measured internal relative humidity. Consider A, B, and C to be concretes with w/cm of 0.4, 0.5, and 0.7, respectively (Kanare 2005).

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

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

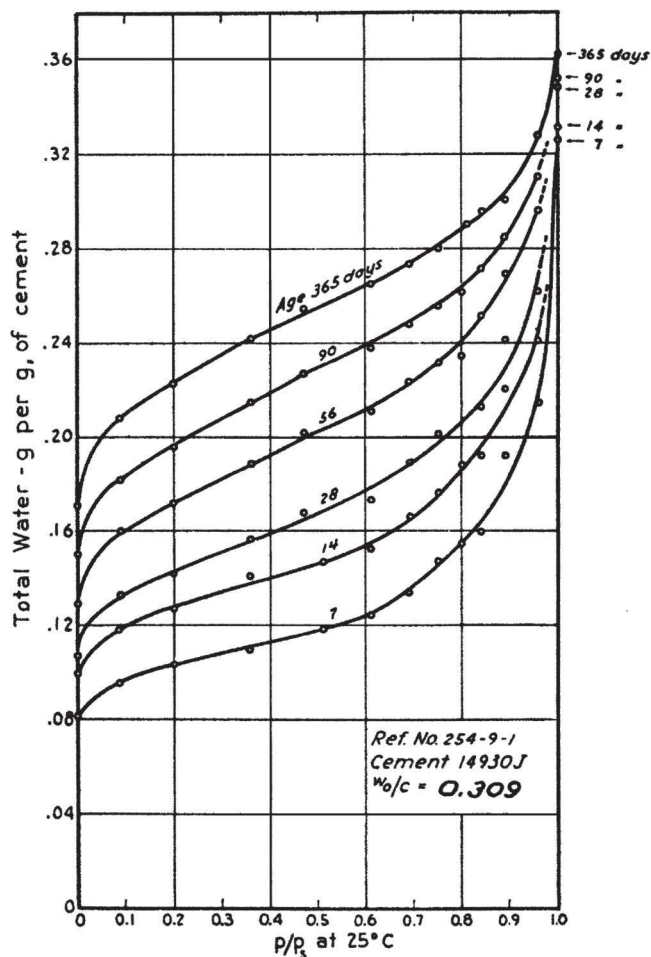


Fig. 3.6.1c—Measured sorption curves for samples at different ages. Note that the 365-day-old sample has approximately 50% more moisture than the 28-day-old sample at a RH range from 80 to 90% (Powers and Brownnyard 1947).

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

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

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

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

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

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

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

3.7—Moisture loss during drying

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

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

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

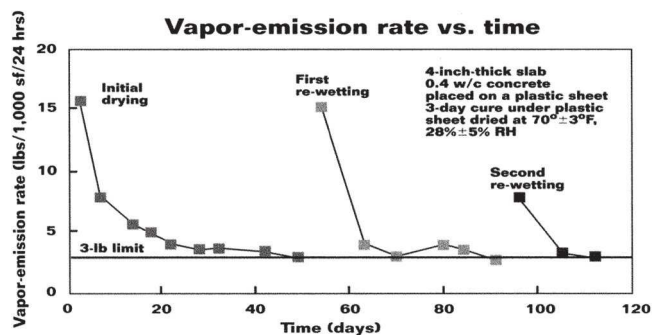


Fig. 3.6.3—Even with a low w/cm and a 3-day cure under plastic sheeting, these slabs took approximately 7 weeks to dry to a 3 lb/1000 ft²/24 h (1.5 kg/100 m²/24 h) emission rate. After rewetting, the slabs took several weeks to again reach the 3 lb/1000 ft²/24 h (1.5 kg/100 m²/24 h) emission rate (Suprenant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

CHAPTER 4—CONCRETE MOISTURE TESTING

4.1—Introduction

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

- Standard test method, if applicable
- Acceptable test methods
- Frequency and location of testing