

Guide for Concrete Slabs that Receive Moisture-Sensitive Flooring Materials

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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. 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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CONTENTS

Chapter 1—Introduction and background, p. 302.2R-2

- 1.1—Introduction
- 1.2—Flooring moisture issues
- 1.3—Concrete slabs that receive flooring materials
- 1.4—Changes in construction methods and materials that affect floor systems
- 1.5—Floor flatness changes with time
- 1.6—Other considerations

Chapter 2—Concrete moisture basics, p. 302.2R-5

- 2.1—Introduction
- 2.2—Moisture movement
- 2.3—Concrete drying profiles
- 2.4—Effects of moisture movement
- 2.5—Equilibrium moisture content
- 2.6—Drying and wetting of concrete
- 2.7—Moisture loss during drying

Chapter 3—Concrete moisture testing, p. 302.2R-12

- 3.1—Introduction
- 3.2—Standard guides and test methods
- 3.3—Qualitative and quantitative tests
- 3.4—Test parameters
- 3.5—Underlayment testing
- 3.6—Comments on moisture vapor emission rate tests

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Chapter 4—Concrete pH testing, p. 302.2R-19

- 4.1—Introduction
- 4.2—Test methods
- 4.3—ASTM test differences
- 4.4—Factors affecting pH test results

Chapter 5—Floor covering and adhesive manufacturer's recommendations, p. 302.2R-21

- 5.1—Introduction
- 5.2—Manufacturer's recommendations
- 5.3—Dealing with multiple floor covering requirements

Chapter 6—Drying of concrete, p. 302.2R-23

- 6.1—Introduction
- 6.2—Concrete drying with no external source of moisture
- 6.3—Concrete drying: exposed to moisture from below
- 6.4—Concrete drying: exposed to moisture from above
- 6.5—Concrete drying from both sides
- 6.6—Effect of concrete-making materials
- 6.7—Effect of fresh and hardened concrete properties
- 6.8—Effect of thickness
- 6.9—Effect of curing
- 6.10—Drying of mature concrete
- 6.11—Effect of drying environment
- 6.12—Drying at exposed edge
- 6.13—Drying of lightweight concrete

Chapter 7—Vapor retarder/barrier, p. 302.2R-28

- 7.1—Introduction
- 7.2—Vapor retarder/barrier location
- 7.3—Vapor transmission through retarder/barrier

Chapter 8—Floor covering materials, p. 302.2R-32

- 8.1—Introduction
- 8.2—Communication between architect and engineer
- 8.3—Floor covering technical resources
- 8.4—Floor adhesives and coverings
- 8.5—Effect of moisture in flooring adhesives
- 8.6—Effect of concrete moisture on adhesive performance

Chapter 9—Design and construction recommendations, p. 302.2R-35

- 9.1—Introduction
- 9.2—Testing
- 9.3—Vapor retarder/barrier
- 9.4—Concrete materials
- 9.5—Concrete properties
- 9.6—Surface finish
- 9.7—Curing
- 9.8—Surface preparation
- 9.9—Repairs
- 9.10—Protection
- 9.11—Moisture mitigation

Chapter 10—References, p. 302.2R-39

- 10.1—Referenced standards and reports
- 10.2—Cited references

Appendix—Two case studies of moisture-related flooring problems, p. 302.2R-41

- A.1—Value engineering results in flooring failure
- A.2—Postconstruction trench drains results in flooring failure

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

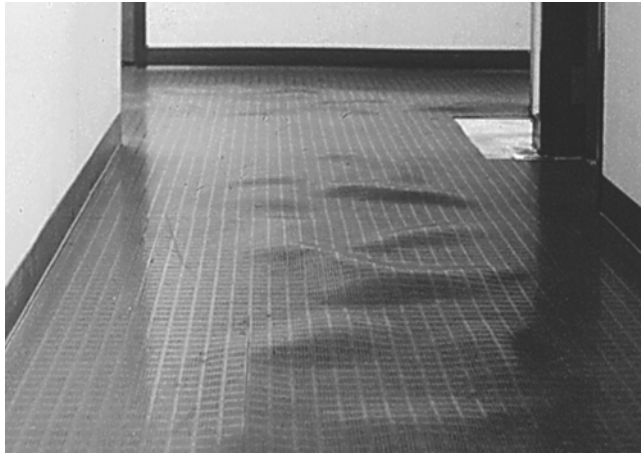


Fig. 1.1—Debonded sheet flooring due to moisture in the concrete slab. (Courtesy of Peter Craig and Herman Protze III.)



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

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



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.)

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 required by the floor covering installer. Making the estimate is difficult

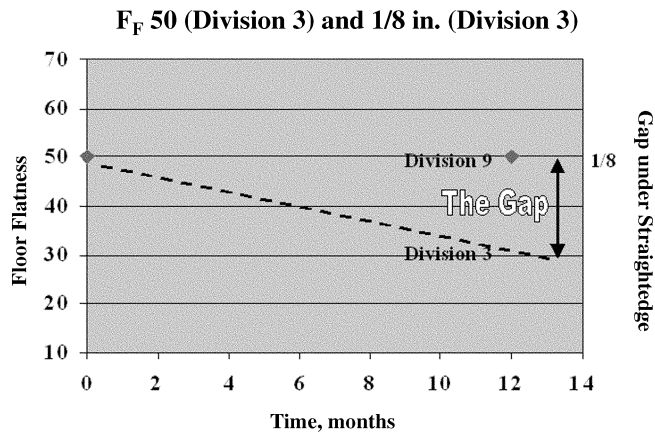


Fig. 1.5—When flatness of an unreinforced floor is measured initially, F_F numbers may indicate a very flat floor. When flooring installers start their work, however, flatness may have changed, as indicated by the gap between Division 3 and Division 9 flatness (Suprenant 2003d).

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;

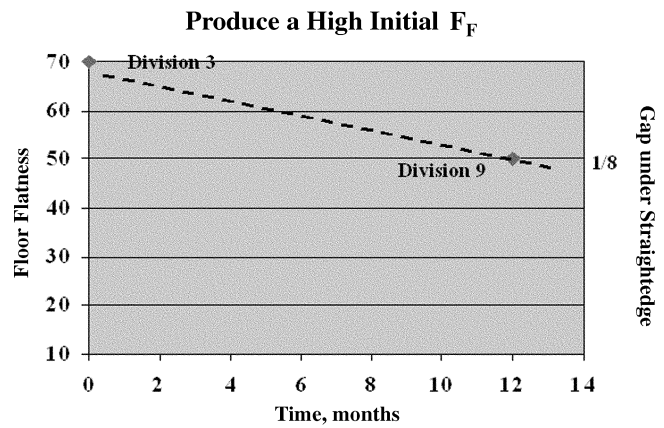
- **Use reinforcing steel.** The engineer selects a ratio of reinforcement area to gross concrete area—typically approximately 0.5% for Grade 60 steel—that minimizes curling. Refer to ACI 360R for more information; or
- **Correct flatness problems by grinding and patching.** The engineer designs a floor 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

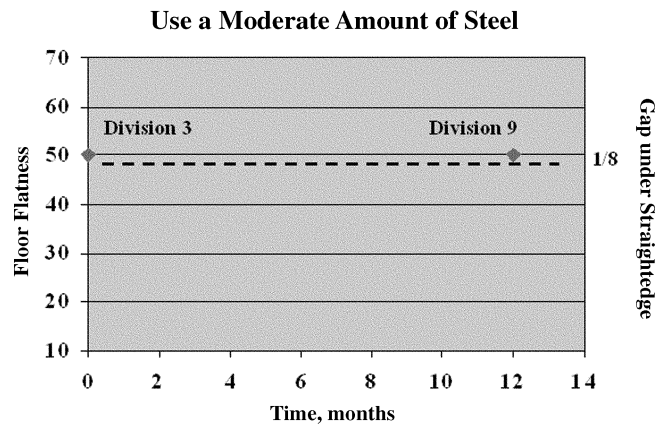
Wide random cracks in slabs create problems when floor materials are placed over them. Floor covering manufacturers all require some form of crack repair for wide cracks. To minimize crack width and crack repair, steel reinforcement should be considered for use in the slab (Fig. 1.7), as recommended 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.

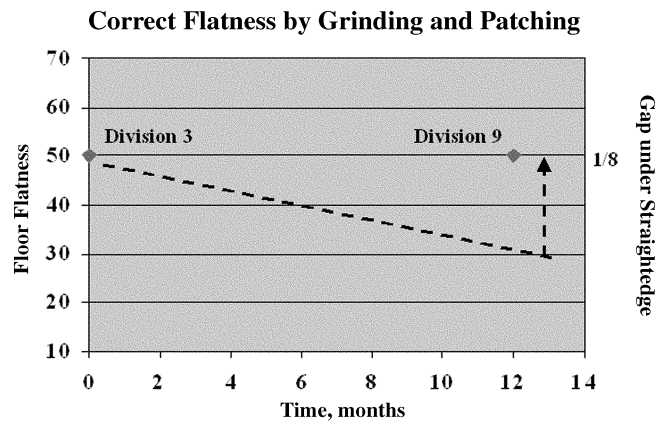
Carpeting and some other floor coverings can tolerate larger crack widths in the concrete floor without noticeable



(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).

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.



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).

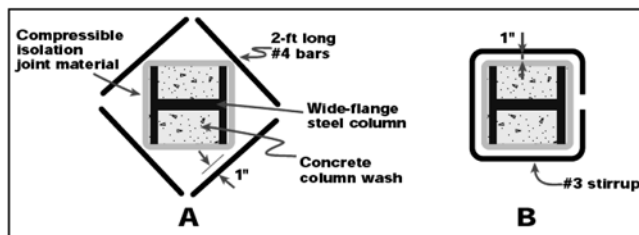


Fig. 1.8—Eliminate the normal isolation-joint boxouts at wide-flange steel columns by wrapping the column with compressible materials and using 2 ft (0.6 m) lengths of No. 4 bars (A) to control cracking at the re-entrant corners. To speed up steel placement at the columns, have the reinforcing bar supplier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

One-Sided Drying Profiles in a Slab on Ground

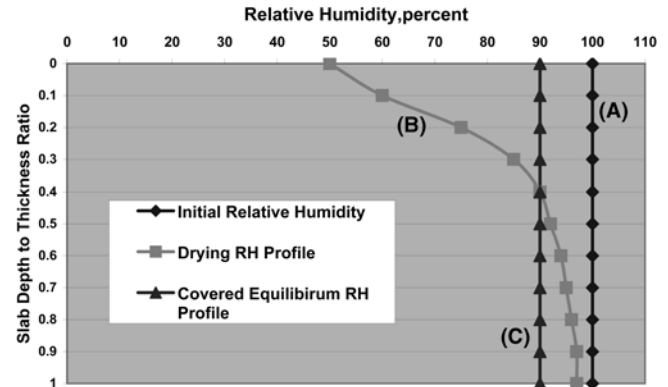


Fig. 2.1—One-sided drying profiles in a slab-on-ground showing initial, drying, and covered equilibrium relative humidity profiles (adapted from Hedenblad [1997]).

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.

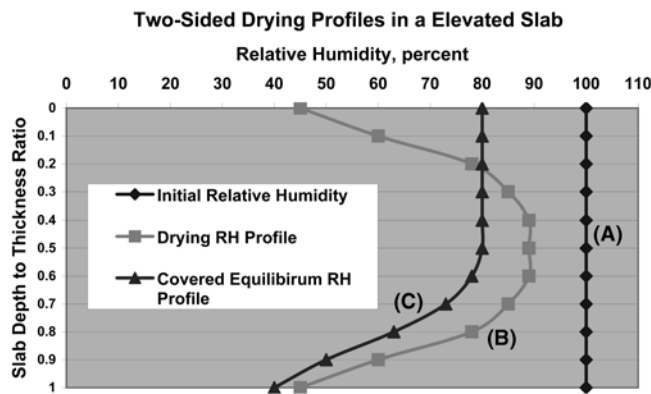


Fig. 2.2—Two-sided drying profiles in suspended slab showing initial, drying, and covered equilibrium relative humidity profiles (adapted from Hedenblad [1997]).

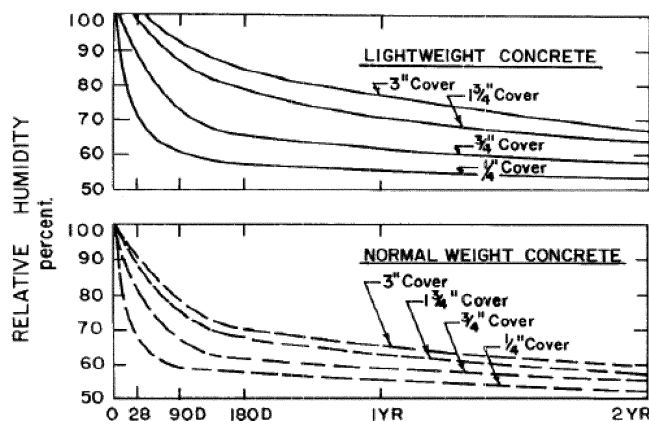


Fig. 2.3—Typical relative humidity distribution for lightweight and normalweight concrete in 6 x 12 in. (150 x 300 mm) concrete cylinders moist cured for 7 days, then dried (Hanson 1968). Cover refers to depth at which the relative humidity was measured. (Note: 1 in. = 25.4 mm.)

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

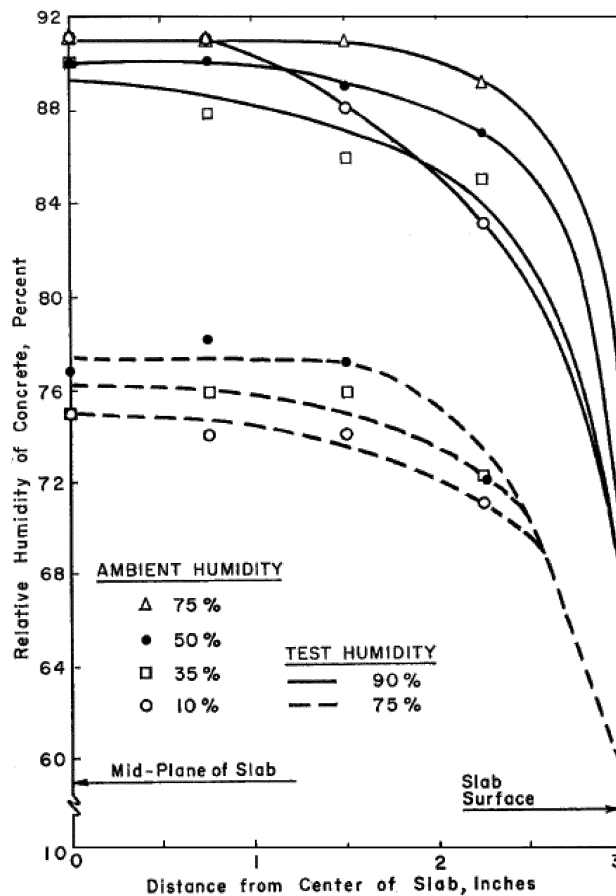


Fig. 2.4—Moisture profiles for slabs dried at differing ambient relative humidities (Abrams and Orals 1965). (Note: 1 in. = 25.4 mm.)

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.

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

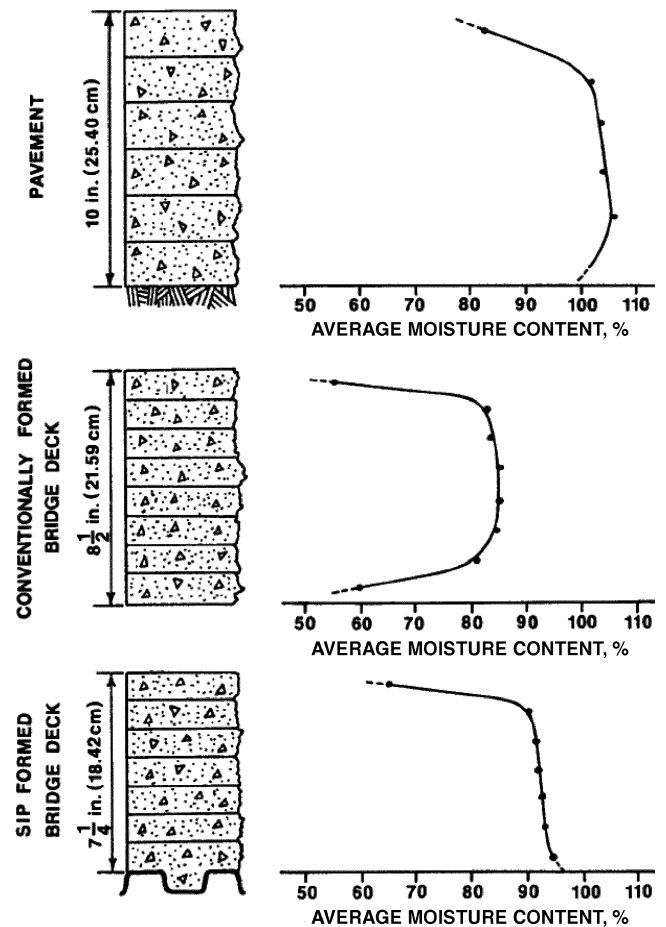


Fig. 2.5—Moisture profiles for concrete slab-on-ground drying from top only, suspended bridge deck drying from both top and bottom surfaces, and suspended deck placed on stay-in-place metal form drying from top only (Carrier and Cady 1975).

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):

- Concrete slab is placed and cured;
- Concrete slab dries, causing the slab edges to curl upward;
- The floor covering installer checks concrete flatness and grinds the curled edges of some concrete panels to provide a level surface;
- Installer applies floor covering; and
- 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 2.4.1). The dip or ridge along edges may require remedial work.

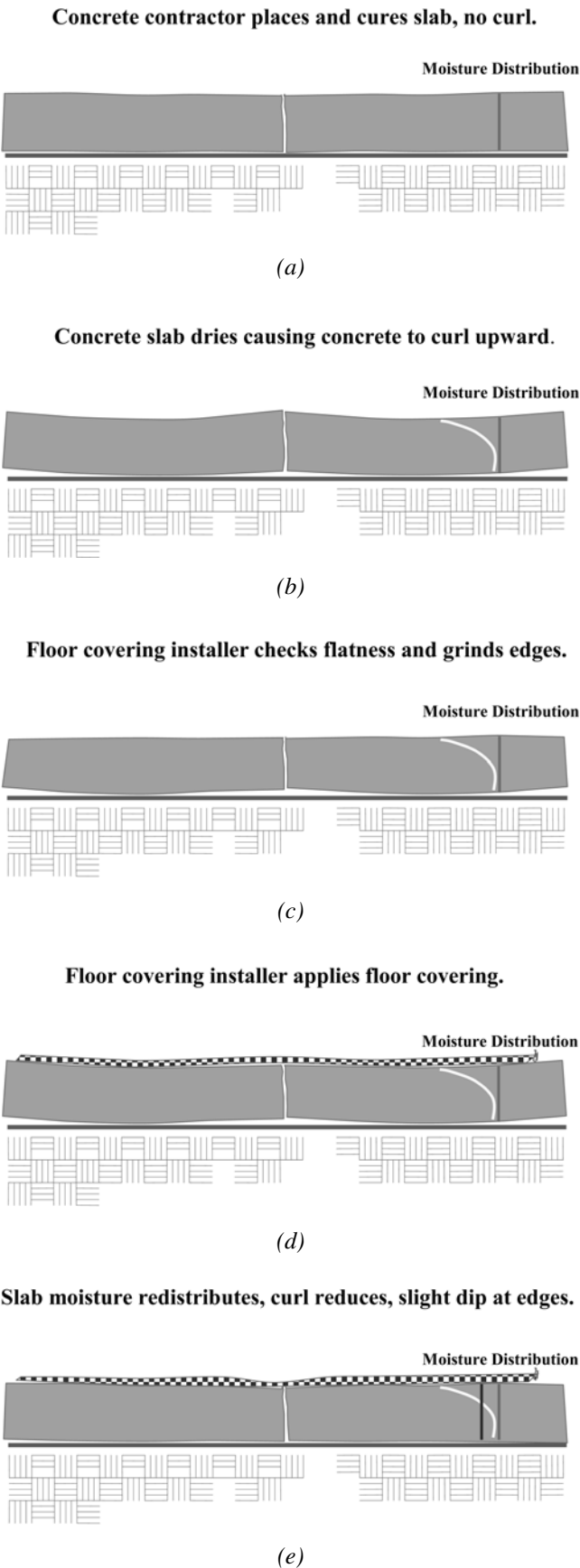


Fig. 2.6—Slab curling sequence showing how moisture redistribution after floor covering placement can create a dip in floor cover at slab edges.

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

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

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 ft²/24 h [0.5 to

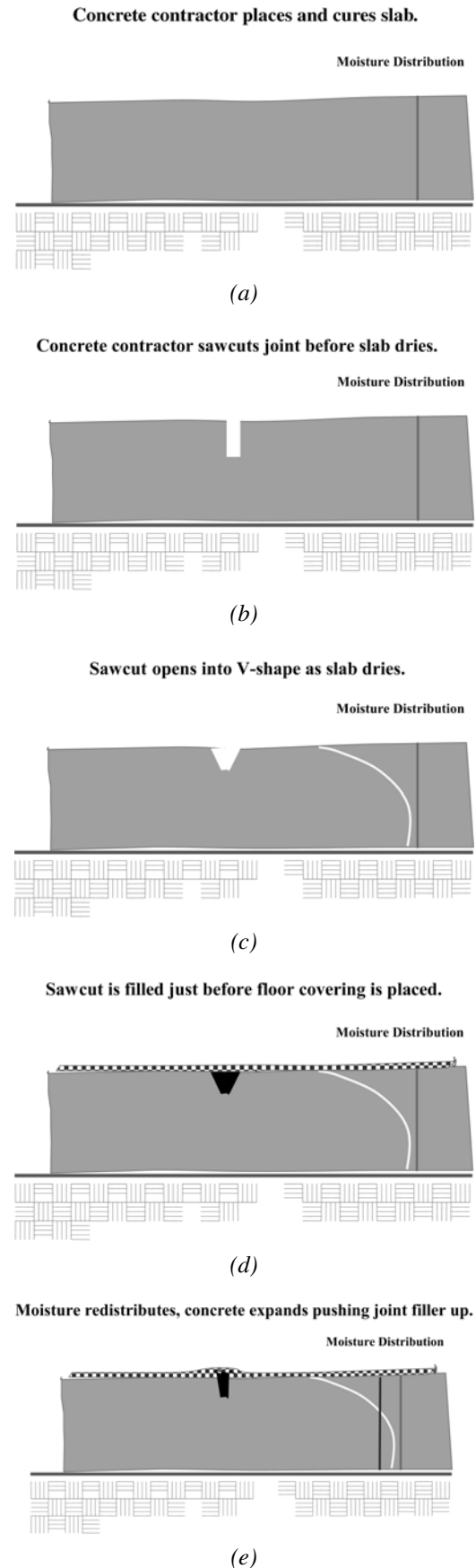


Fig. 2.7—Joint bulge sequence illustrating how moisture redistribution after floor covering is placed can create a joint filler bulge under installed floor covering.

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

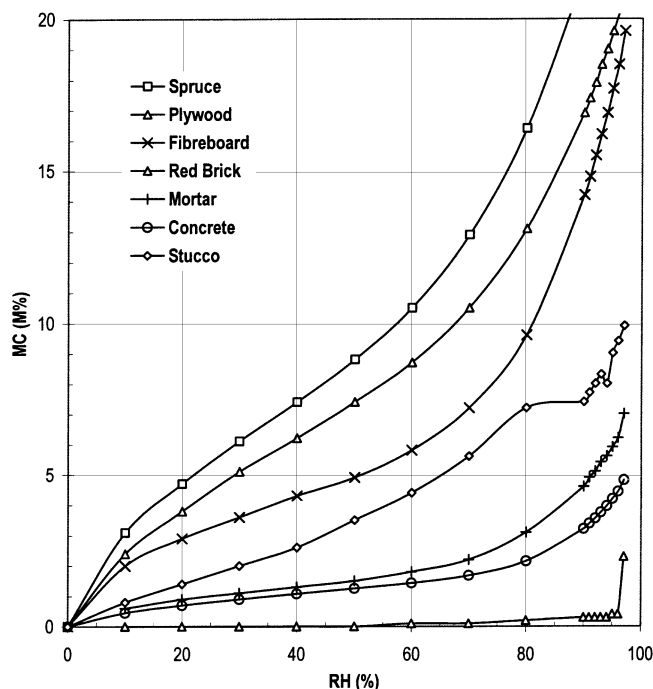


Fig. 2.8—Sorption isotherms for several common building materials (Straube 2000).

1.0 kg/100 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.

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

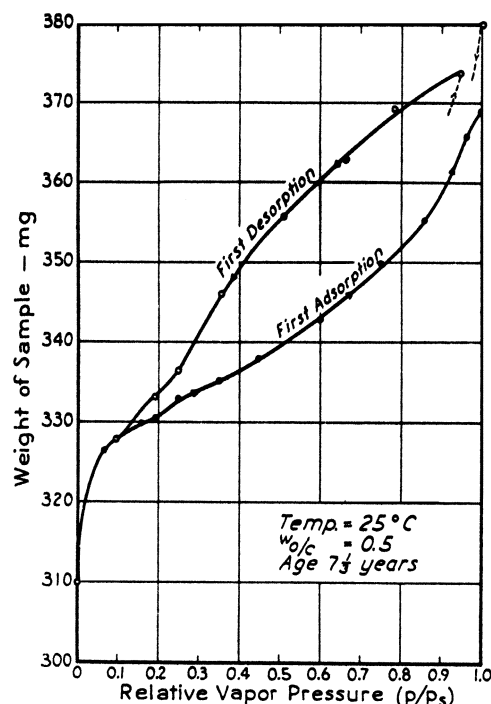


Fig. 2.9—Typical drying (desorption) and wetting (adsorption) curves showing that behavior is different and that concrete contains a different moisture content at the same relative humidity depending on whether it is drying or wetting (Powers and Brownyard 1947).

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:

- 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 Brownard 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 Brownard (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."

Figure 2.11 (Powers and Brownard 1947) illustrates measured wetting (adsorption) curves for samples of different ages. The 365-day-old sample has approximately

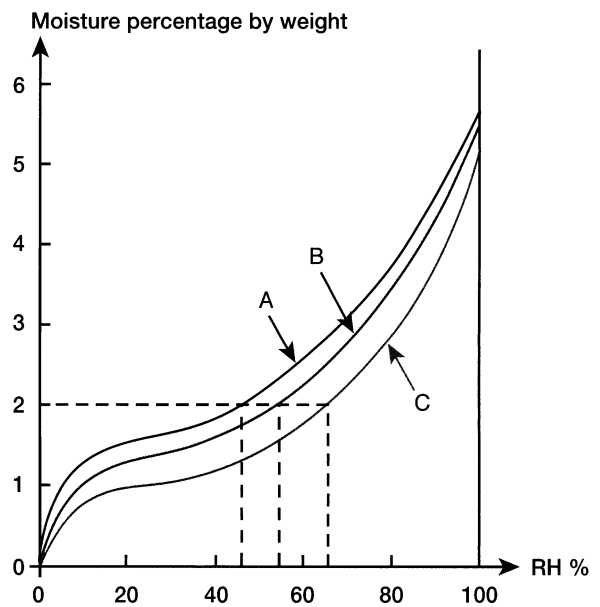


Fig. 2.10—Idealized wetting (adsorption) curves illustrating that at the same moisture content the concretes will have different measured internal relative humidity. Consider A, B, and C to be concretes with w/cm of 0.4, 0.5, and 0.7, respectively (Kanare 2005).

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

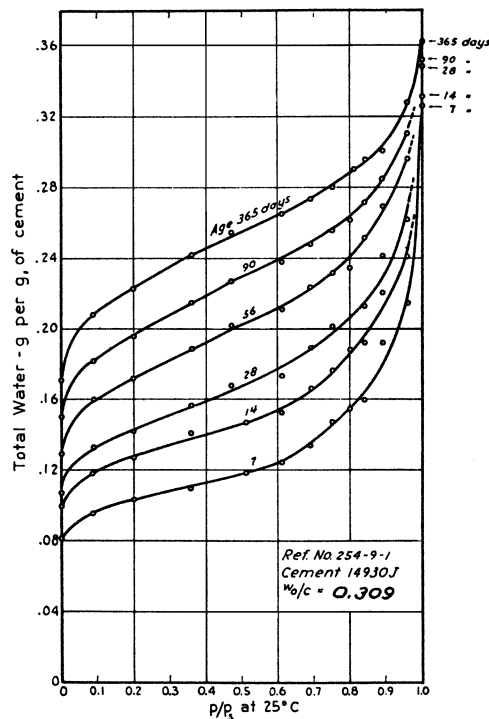


Fig. 2.11—Measured sorption curves for samples at different ages. Note that the 365-day-old sample has approximately 50% more moisture than the 28-day-old sample at a relative humidity range from 80 to 90% (Powers and Brownyard 1947).

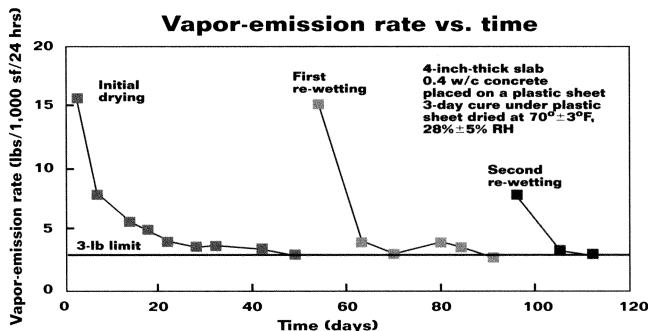


Fig. 2.12—Even with a low w/c and a 3-day cure under plastic sheeting, these slabs took approximately 7 weeks to dry to a 3 lb/1000 ft²/24 h (1.5 kg/100 m²/24 h) emission rate. After rewetting, the slabs took several weeks to again reach the 3 lb/1000 ft²/24 h (1.5 kg/100 m²/24 h) emission rate (Suprenant and Malisch 1998c).

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/c 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 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 must 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 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

Plastic sheet test
(ASTM D 4263)
Mat test
(No ASTM standard test method)
Qualitative calcium chloride test
(No ASTM standard test method)
Primer or adhesive strip test
(No ASTM standard test method)

Quantitative tests

Electrical resistance test
(No ASTM standard test method)
Electrical impedance test
(No ASTM standard test method)
Quantitative calcium chloride test
(ASTM F 1869)
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



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 ft²/24 h (6.3 kg/100 m²/24 h) (Suprenant 2003b; Kanare 2005).

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.

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 ft²/24 h (6.3 kg/100 m²/24 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

^{*}Also, private communication from J. Craig and C. Lovell, 2005.