Part 1 of a 3-part series

Control of shrinkage and curling in slabs on grade

By **Robert F. Ytterberg**

Shrinkage problems: Causes and cures

Shrinkage cracking and upward curling, which result from shrinkage differentials, are common troubles for enclosed industrial slabs on grade. The most important factor contributing to shrinkage is the amount of water per unit volume of concrete. Understanding this, designers should select materials and specify concrete to minimize shrinkage and therefore reduce curling and cracking.

Industrial slabs are not covered with carpet or tile. Since the concrete surface is the wearing surface, cracking and curling seriously reduce their productive and aesthetic value. This article deals primarily with shrinkage and upward curling of these industrial slabs on grade that are under roofs and inside buildings where they are not exposed to the sun. Most of the principles, however, also apply to other flatwork. For example, highway and airport pavements, exposed to the sun, are subject to both moisture and temperature gradients. For simplicity, the moisture gradients are expressed in equivalent degrees per unit of slab thickness.

Concepts developed here do not apply to slabs on grade for tilt-up construction until after the panels have been raised and the roof constructed. To improve floor slabs for tilt-up buildings, cast the wall panels on waste slabs rather than on the finished floor slab.

Shrinkage cracking and upward slab edge curling are common in enclosed industrial floor slabs on grade. These problems can be caused by:

- Moist subgrades
- Dry air on the upper slab surface
- Excess water needed to make concrete workable but not needed to hydrate the cement

Evaporation of moisture from the upper surface of the slab causes drying shrinkage. Slab edges curl upward because the top of the slab dries to a lower moisture content than the bottom of the slab, and therefore shrinks more than the bottom.

Designers often overlook the effects of shrinkage and curling due to moisture loss from slab surfaces because of the great emphasis placed on compressive strength and slump testing and because of the lack of information on curling. But owners expect floor slabs to be relatively free of shrinkage cracks and free of curled edges at control and construction joints.

Designers specify control joints at closer spacings today mostly because of the Portland Cement Association (PCA) recommendations given in Reference 1, first published in 1978. The additional joints recommended by that publication reduce shrinkage cracking. But curling and breakdown of joint edges, at the increased number of joints, is often a bigger maintenance problem than the shrinkage cracks eliminated by the extra joints.

Unfortunately, enclosed slabs on grade made with portland cement concrete have worse shrinkage and curling problems today than 25 years ago for several reasons:

Shrinkage is neglected. Basic recommendations in References 1 and 2 fail to emphasize the need for low-shrinkage concrete for floor slabs on grade. They imply that if slump is low, then almost everything possible has been done to minimize shrinkage. Shrinkage testing should be every bit as important as compressive strength testing for enclosed slabs on grade.

Compressive strength is overemphasized. The commonly specified 28-day compressive strength has been increased to as much as 5000 psi to permit the reduction of calculated slab thickness. Despite a lower water-cement ratio, these higher 28-day-strength concretes usually have a higher total water content and thus have increased shrinkage. This required *early* strength development, which aggravates the problem, is supported by the American Concrete Institute (ACI) 302 requirement for a minimum of 1800 psi at 3 days (Ref. 2).

Clean, low-shrinkage aggregates are less available today than 25 years ago because environmental considerations restrict quarry operations.

Floor slabs are being built on higher-moisture-content subgrades as the cost of good industrial land has risen. Moist subgrades increase the moisture gradient through the slab, and this increases upward curling at free edges.

Defining drying shrinkage

In this article *drying shrinkage* of concrete is defined as the reduction in concrete volume resulting from a loss of water from the concrete after hardening. Drying shrinkage is believed (Ref. 3) to be caused principally by the contraction of the calcium silicate gel component of the cement paste when the moisture content of the gel is decreased.

All practical portland cement concrete shrinks about 0.04% to 0.08% due to drying (Ref. 4), but restraint by reinforcement can reduce drying shrinkage by up to one-half.

Effects of aggregate size

To provide the workability needed for placement, practical concrete mixes always contain more water than is needed to hydrate the cement. When this excess water evaporates, the cement paste shrinks. To fully restrain shrinkage of the cement paste, concrete should contain the maximum practical amount of an incompressible and clean aggregate.

If the dry-rodded volume of an incompressible and clean coarse aggregate was equal to the concrete volume, then the coarse aggregate would fully restrain cement-paste shrinkage. That is never the case, though, for conventional floor slab concrete because such a stony concrete mix would be totally unworkable.

In actual practice, the dry-rodded volume of the coarse aggregate is only 50% to 60% of the concrete volume if ½-inch-maximum size aggregate is used, but can be as high as 75% of the concrete volume if 1½-inch-maximum size aggregate is used (Ref. 5). Therefore, using a larger maximum size coarse aggregate will reduce shrinkage if the aggregate itself is low in shrinkage.

Selecting the best mix

Water demand of the separate materials used in concrete is the major determinant of concrete shrinkage. Variations in water demand caused by the separate concrete ingredients have a far greater effect on concrete shrinkage than does the common concern over the variation in slump.

Research on shrinkage (Ref. 6) shows there is a **cumulative** effect on shrinkage of making poor choices in the selection of material to be used. One study (Ref. 7) of eight factors that influence the water content of concrete concluded that their influence on shrinkage could total 400% (Table 1).

Table 1. Cumulative Effect of Adverse Factors on Shrinkage
(from Reference 7, Tremper and Spellman)

Effect of departing from use of best materials and workmanship	Equivalent increase in shrinkage %	Cumulative effect
Concrete temperature at discharge allowed to reach 80° F, whereas with reasonable precautions, temperature of 60° F could have been maintained	8	1.00 × 1.08 = 1.08
Used 6- to 7-inch slump where 3- to 4-inch slump could have been used	10	1.08 × 1.10 = 1.19
Excessive haul in transit mixer, too long a waiting period at jobsite, or too many revolutions at mixing speed	10	1.19 × 1.10 = 1.31
Use of ¾-inch-maximum size aggregate under conditions where 1½-inch could have been used	25	1.31 × 1.25 = 1.64
Use of cement having relatively high shrinkage characteristics	25	1.64 × 1.25 = 2.05
Excessive "dirt" in aggregate due to insufficient washing or contamination during handling	25	2.05 × 1.25 = 2.56
Use of aggregates of poor inherent quality with respect to shrinkage	50	2.56 × 1.50 = 3.84
Use of admixture that produces high shrinkage	50	3.84 × 1.50 = 5.00
Total increase	Summation = 183%	Cumulative = 400%

Concrete made with ¾-inch-maximum size aggregate will shrink about 30% more than concrete with 1½-inch-maximum size aggregate. But concrete placing costs may increase slightly when larger aggregate is used. Designers, therefore, should specify that the maximum size coarse aggregate be slightly less than one-third the slab thickness, with the understanding that the small increase in cost will be offset through lower shrinkage and a better floor slab.

However, the designer often has to make tradeoffs. For example, as will be discussed later, slab warping increases as the modulus of elasticity *E* of concrete increases. Unfortunately, low-shrinkage aggregates usually have a high modulus of elasticity and aggregate is the main determinant of the concrete's modulus. Designers must compromise between specifying low-modulus concrete and low-shrinkage concrete. To select the best possible mix, specify that shrinkage tests be made of several concrete mixes, each with different aggregates and cements, to obtain concrete with the lowest shrinkage for a particular job.

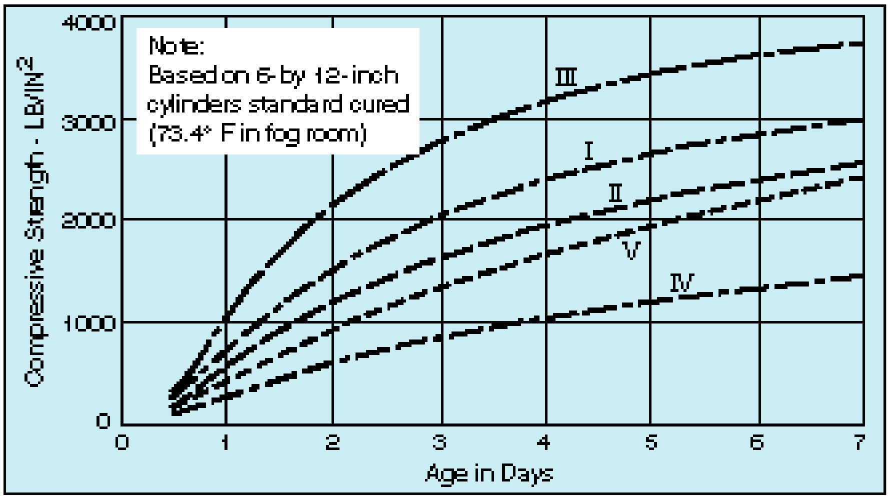
Water reducers and shrinkage

Frequently it is assumed that high-range water reducers (HRWRs) or superplasticizers will reduce shrinkage in proportion to their ability to reduce water. This is not the case. Few designers and specifiers realize that ASTM C 494, "Standard Specification for Chemical Admixtures for Concrete," (Ref. 8) allows concrete made with admixtures to have shrinkage 35% greater than the same concrete without the admixture. This permitted increase in shrinkage when admixtures are used means that the reduction in water achieved by using water reducers is no guarantee that concrete shrinkage also will be reduced. The only way to know if a particular water reducer will result in lower shrinkage is to test it with a particular mix design.

Slump and shrinkage

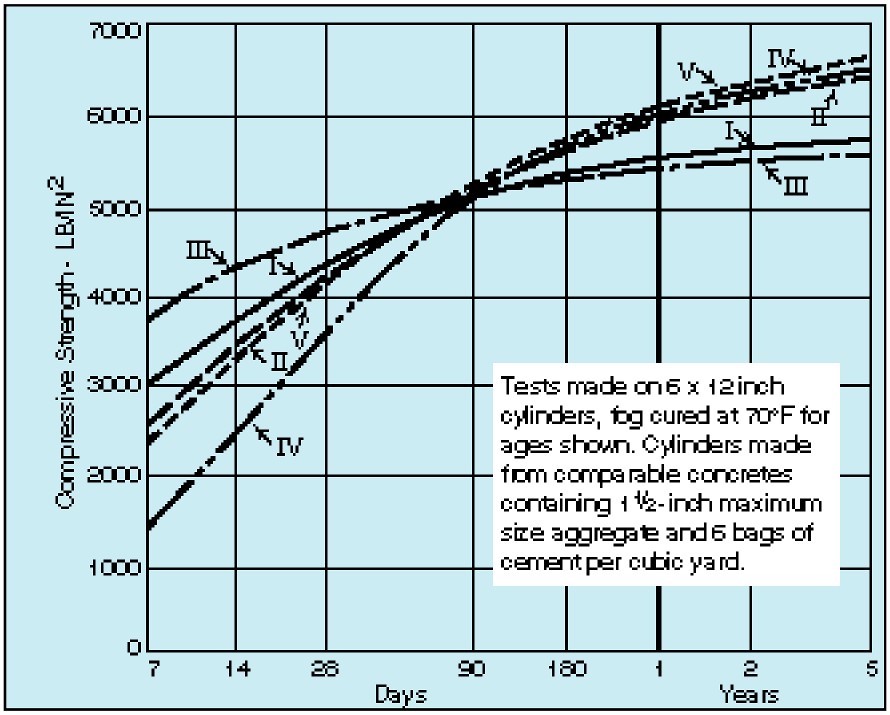
ACI and PCA literature emphasize low-slump concrete, thereby implying that low slump is the key to low shrinkage. PCA's "Concrete Floors on Ground" (Ref. 1, page 19) states: "Slabs made of low-slump concrete properly cured in a moist environment, with or without reinforcement, will have minimum shrinkage and few cracks." The reader is left to assume that if slump is kept low, then everything necessary for low shrinkage has been accomplished. However, substantial research evidence (Ref. 6) shows that slump control is only a small factor in the shrinkage equation.

Instead of expecting slump to control shrinkage, designers should effect real shrinkage reduction by specifying low-shrinkage, stony concrete mixes with large maximum size coarse aggregate.



Note:
Based on 6- by 12-inch cylinders standard cured (73.4° F in fog room)

Figure 1. *Concrete made from different types of cement gains early-age strength at different rates. (From the U.S. Bureau of Reclamation* Concrete Manual*)*



Tests made on 6 x 12 inch cylinders, fog cured at 70°F for ages shown. Cylinders made from comparable concretes containing 1 ½-inch maximum size aggregate and 6 bags of cement per cubic yard.

Figure 2. *At about 60 to 80 days, concrete made with Type II cement reaches the same strength as concrete made with Types I and III. (From the U.S. Bureau of Reclamation* Concrete Manual*)*

Early strength and shrinkage

Since shrinkage of cement paste is the primary cause of concrete shrinkage, it seems appropriate to choose a cement that produces a hardened paste with low shrinkage in order to reduce slab-on-grade shrinkage.

Researchers have emphasized (Ref. 6) coarseness of grind and low C_3A content of cement as important to low-shrinkage concrete. However, in an effort to obtain the 1800-psi 3-day strengths formerly required by ACI 302, Types I and III cements are frequently specified (Figure 1). Since they are finer and have relatively high C_3A content, they contribute to undesirable shrinkage. The designer who wants to limit shrinkage should specify Type II cement, which is coarser-ground and with less C_3A, so long as the amount of traffic on the slab can be controlled at early ages. Figure 2 shows that Type II cement concrete catches up in strength with Types I and III at 60 to 80 days and goes on to surpass them.

ACI 302 should require a minimum 3-day concrete strength only for formed, elevated structural slabs or for tilt-up slabs on ground, where early strength really is needed. I believe that ACI 302 should restrict the C_3A content of cements to 8% or 10% to reduce slab-on-grade shrinkage.

28-day strength and shrinkage

In addition to the 3-day minimum strength requirement, ACI 302's 28-day minimum strength requirement of 4000 and 4500 psi for Class 4, 5, and 6 industrial floor slabs on grade magnifies shrinkage problems.

ACI 302's mix proportioning Method A (but not Method B) protects the owner-user of floors from concrete floors made with too little cement to properly finish or to provide minimum strength for normal construction loads. This protection is in the form of minimum cement requirements adopted many years ago (see Table 2).

The usual way concrete suppliers meet ACI 302's 3- and 28-day strength requirements is to use a high-early-strength cement, add a water reducer, or add more cement. We have already discussed how these measures adversely increase shrinkage.

What is the logic behind a 4000- and 4500-psi 28-day strength requirement for industrial single-course floors when ACI 302 requires only a 3500-psi 28-day strength for almost all other floors, including Class 7, the base for two-course industrial floors? The argument most frequently heard is that the higher 28-day strengths will assure greater surface abrasion resistance for Class 4, 5, and 6 single-course industrial floors. This is untrue, as will be explained. Also, this higher 28-day strength requirement may lead to increased shrinkage.

Abrasion resistance

ACI 302 recognizes the importance of proper surface troweling and aggregate hardness to good surface abrasion resistance and even specifies them. Surface abrasion resistance largely depends on the quality and amount of troweling and on the application of cement-coated mineral hardeners to the floor surface. In other words, abrasion resistance is a function of the water-cement ratio at the surface of the floor, and of the quantity and quality of aggregate, not of the compressive strength of the concrete as measured from a 6x12-inch cylinder.

Since Chapter 7 of ACI 302 specifies the minimum acceptable amount of troweling, the 4000- and 4500-psi 28-day strength requirements should be reduced to 3500 psi because 6x12-inch cylinder strength does not correlate with floor surface abrasion resistance. Also, the higher strength can cause increased shrinkage. Figure 3 shows how abrasion resistance of slabs made from the same concrete can vary, depending on the finishing method.

Calculating slab thickness

Controlling compressive strength in slabs on grade assures that the slab is thick enough to carry the imposed loads. Designers calculate and specify slab-on-grade thickness using a square root function of design compressive strength to convert it to modulus of rupture, which is then reduced by a factor of safety and used to find the required slab thickness from various published design aids (Ref. 9). When calculating slab-on-grade thickness, the designer should consider using the 90-day concrete strength rather than the 28-day strength, if the slabs will not be subjected to design loads during the first 90 days of their life. A typical slab on grade with 3500-psi 28-day strength concrete will reach 4200 psi at 90 days, an increase of 20%. Slabs on grade should continue to gain strength past 28 days because, when cast, they contain twice as much water as is required for cement hydration and because moisture is retained by surface curing sealers. For applications other than tilt-up slabs, the designer might use the higher strength in calculating slab thickness, but only if design loads will not be applied to the slab during its first 3 months of life.

Table 2. Minimum Cement Requirements

Nominal maximum size of aggregate, inches	Cement content, pounds per cubic yard
1½	470
1	520
¾	540
½	590
⅜	610

Instead of using a high design strength to minimize slab design thickness, designers might better consider other alternatives. For example, using 8x8-inch base plates for post loads instead of 4x4-inch plates would make it possible to reduce slab thickness by more than 1 inch, according to PCA design aids (Ref. 10).

In view of the accumulated evidence (Ref. 6) that increased strength often is obtained at the cost of increased shrinkage, it is doubtful that a saving of about 7% in slab thickness (typically about ½ inch) by specifying a 4500-psi instead of a 3500-psi 28-day design strength is worth the risk of increased shrinkage.

Shrinkage testing

The designer should use shrinkage tests of both cement and concrete to guide the selection of concrete materials and mixes. Standardized shrinkage tests have been the subject of considerable study and debate (Ref. 6). The ASTM C 157 method (Ref. 11) is a laboratory test that does not always correlate well with field experience. I believe ASTM should adopt

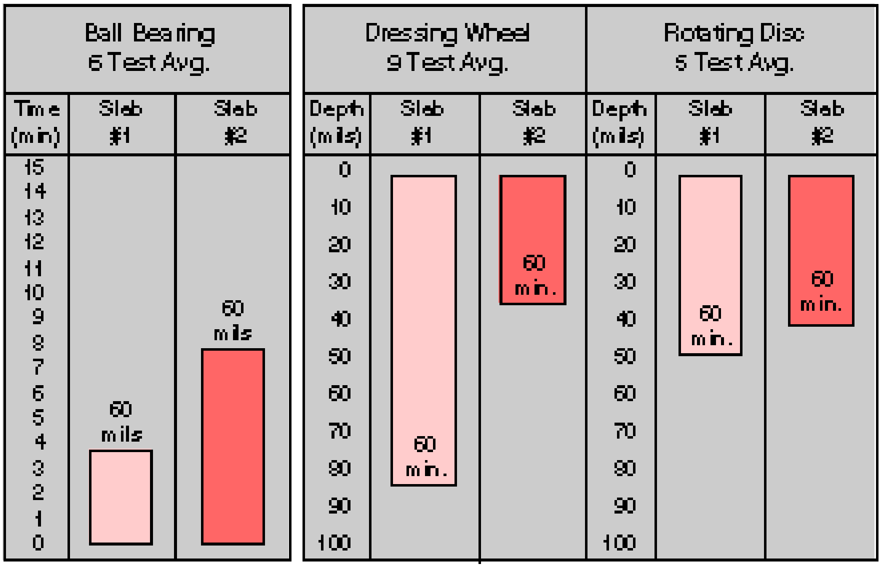


Figure 3. *Comparison of surface abrasion resistance of two slabs made from the same concrete mix, having the same compressive strengths. Slab 1 was a common, commercially finished slab, and Slab 2 had a hard-trowel, surface-hardened finish. Three different ASTM C 799 abrasion test machines were used. The ball bearing machine reports the time it takes to reach a depth of 60 mils; the other two report abrasion depth after a 60-minute test period. (Adapted from work by*

both a new laboratory shrinkage test using cylindrical specimens that remain in their molds until the start of shrinkage measurements, and a field shrinkage test as well. Detailed suggestions were presented in Reference 6.

Bazant's cylinder mold shrinkage test (Ref. 12) that gives meaningful results in 3 weeks should be specified for initial shrinkage testing. Kraii's test (Ref. 13) that determines the cracking potential of a given concrete mix within 24 hours should be used daily to detect any changes in the concrete as a job progresses. Kraii's test method should be supplemented with concrete cylinder shrinkage specimens made each day on slabs requiring more than 1,000 cubic yards of concrete.

Editor's note: This three-part series has been condensed and updated from Ref. 6. Parts two and three will appear in December and January.

References

1. *Concrete Floors on Ground, 2nd ed.,* Portland Cement Association (PCA), 1983.
2. ACI 302.1R-89, "Guide for Concrete Floor and Slab Construction," American Concrete Institute (ACI), 1989.
3. George W. Washa, "Volume Changes and Creep," *Significance of Tests and Properties of Concrete and Concrete Aggregates,* STP-169, ASTM, 1955, pp. 115-128.
4. *Volume Changes of Concrete,* PCA, 1967.
5. ACI 211.1-81, Revised 1984, "Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete," ACI, 1984.
6. Robert F. Ytterberg, "Shrinkage and Curling of Slabs on Grade" (published in three parts), *Concrete International,* April 1987, pp. 23-31; May 1987, pp. 54-61; and June 1987, pp. 72-81.
7. Bailey Tremper and D. L. Spellman, "Shrinkage of Concrete—Comparison of Laboratory and Field Performance," *Highway Research Record No. 3,* 1963, pp. 30-61.
8. ASTM C 494-90, Standard Specification for Chemical Admixtures for Concrete, *1991 Annual Book of ASTM Standards,* ASTM, Vol. 04.02, pp. 254-269.
9. ACI 360.1R-92, "Design of Slabs on Grade," ACI, 1992.
10. Robert G. Packard, *Slab Thickness Design for Industrial Concrete Floors on Grade,* PCA, 1976.
11. ASTM C 157-89, Standard Test Method for Length Change of Hardened Hydraulic Cement Mortar and Concrete, *1991 Annual Book of ASTM Standards,* ASTM, Vol. 04.01, pp. 101-106.
12. Z. P. Bazant, F. H. Wittmann, J. K. Kim, and F. Alou, "Statistical Extrapolation of Shrinkage Data—Part I: Regression," *ACI Materials Journal,* January-February 1987, pp. 20-33.
13. Paul Kraii, "A Proposed Test to Determine the Cracking Potential Due to Drying Shrinkage of Concrete," *Concrete Construction,* September 1985, pp. 775-778.

For More Information

For additional information about slabs on grade, consult Designing Floor Slabs on Grade, by Boyd C. Ringo and Robert B. Anderson.

This comprehensive book provides a single-source answer for selecting the most cost-effective approach for each job in order to achieve superior crack control, stability, flatness, and overall strength. The book features step-by-step procedures, as well as charts, tables, and equations. For more information and to order, see the advertisement on page 843 of this issue.

Robert F. Ytterberg is president of Kalman Floor Co., Evergreen, Colo., a national subcontractor specializing in construction of exposed concrete floors for industrial and warehouse use. He is a member and former chairman of the American Concrete Institute Committee 360, Design of Slabs on Grade, and a former member of Committee 302, Concrete Floor Construction.

PUBLICATION #C920825