Why Slabs Curl

Part I: A look at the curling mechanism and the effect of moisture and shrinkage gradients on the amount of curling

BY BRUCE A. SUPRENANT

Most slabs on grade curl. Sometimes the curl is considered objectionable, sometimes it's not. When the curl is considered objectionable, we consider the causes. Sometimes we understand what caused the curl, sometimes we don't. When we believe we know what caused the curl, we are ready to attribute blame and seek remedy. Sometimes we're right, sometimes we're wrong.

Some research has been done over the years to determine why slabs curl and how curling can be reduced or controlled. Unfortunately, because much of that work is so scattered, it hasn't received the attention it deserves nor has it contributed to a better understanding of why slabs curl. The following is a summary of the research and what it may mean to designers, specifiers, and contractors.

Mechanics of curling

Slab curling is caused primarily by differences in moisture content or temperature between the top and bottom of the slab. The slab edges curl upward when the surface is drier and shrinks more, or is cooler and contracts more than the bottom. Curling is most noticeable at construction joints, but it can also occur at sawcut joints or random cracks. The curl can result in a loss of contact between the slab and subbase. Generally, the length of lost subbase contact is about 10% of the slab length (measured between joints) at joints that have load transfer (doweled or sawcut joints), and about 20% at joints with no load transfer. However, these values are also a function of joint spacing, concrete properties, slab thickness, and subbase stiffness. Upward curl at slab corners can be as high as 1 in. (25 mm), but is typically about 1/4 in. (6 mm).

The term *curling* is used to refer to upward vertical deflections in slabs caused by moisture-content differences and the associated shrinkage. The term *warping* is sometimes used to refer to upward vertical deflections caused by temperature differences between the top and bottom slab surfaces. In practice, a measured vertical slab deflection is a combination of both temperature and moisture differences, so the resulting upward deflections from both sources are typically referred to as curling. Both the temperature and shrinkage differences apply an upward curling moment to the slab that causes the upward deflections.

The curling moment that lifts the slab is greater near the ends of a slab and then decreases to almost zero at the slab center. Due to gravity forces, the internal stresses caused by curling are smallest near the slab end and highest over a large center area.[1]

Moisture and shrinkage gradients

To assess the relationship between moisture and shrinkage gradients in concrete and the amount of curling that occurs, several researchers measured moisture and shrinkage gradients in specimens exposed to various drying conditions. Here are their findings:

Moisture and shrinkage gradient at constant drying environment

In 1934, Carlson obtained experimental data showing moisture contents and shrinkage gradients for slabs drying only from the top.[2] He tested 6-in. (300 mm) concrete cubes cast in copper forms and exposed the tops of the cubes to a drying environment of 80 °F (27 °C) and 50% relative humidity. He used concrete mixtures made with varying combinations of three different cements and two aggregate types.

Figure 1 shows the moisture loss and shrinkage in the specimens at 600 days, measured at various distances from the exposed concrete surface. Greater moisture loss and shrinkage occurred near the top, and exposed concrete surface and less moisture loss and shrinkage occurred near the bottom. This shrinkage gradient due to moisture-content differences applies a curling moment to the slab, causing it to deflect upward. The larger the shrinkage gradient, the greater the difference between top and bottom shrinkage, and the larger the applied curling moment. The larger the applied curling moment, the greater the upward deflections.

It's interesting to note that the shrinkage gradients provided by Carlson are different for different cements. We typically use the drying-shrinkage potential of concrete when evaluating the amount of curl, but we don't consider the effects of the concrete ingredients on the shrinkage gradient because not enough test data are available. Carlson's work showed that differences in measured shrinkage due to changing cements or aggregates were small near the concrete cube's surface but could be much larger near the bottom.

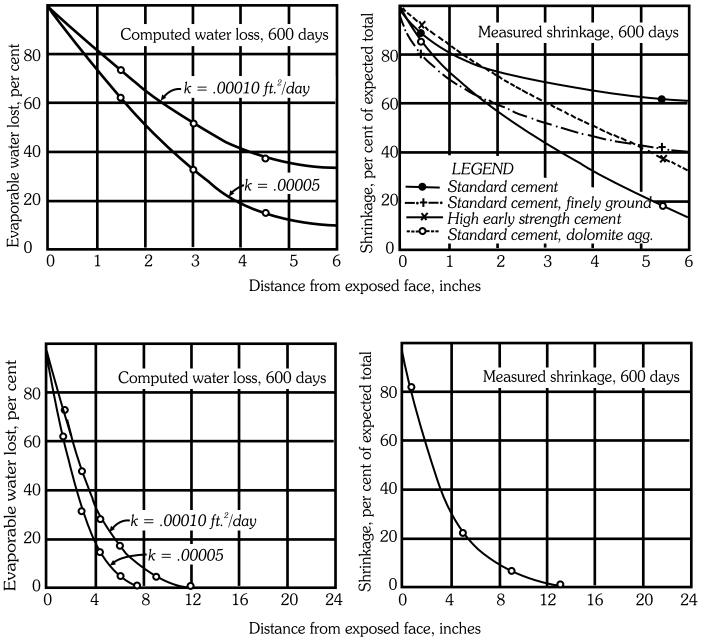

Fig. 1: Comparison between computed distribution of drying and measured distribution of shrinkage in 6-in. (152 mm) cubes of concrete drying from one face only (From Reference 2)

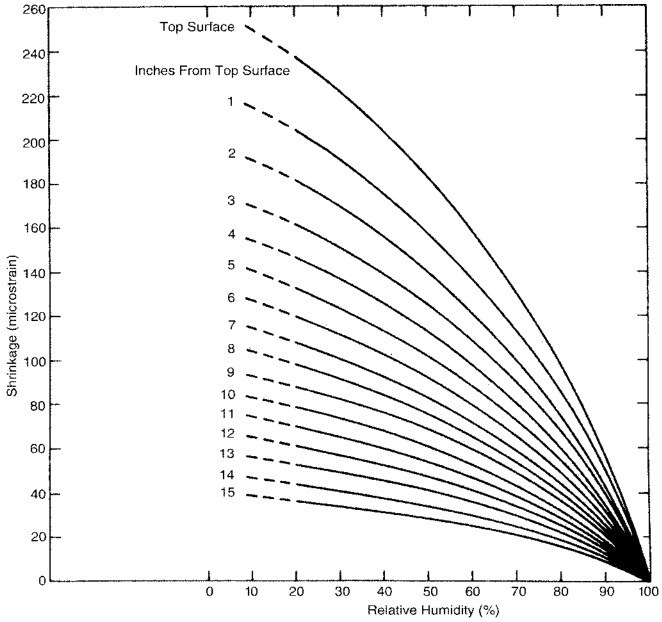

Fig. 2: One year of shrinkage data for a 15-in.-thick (380 mm) slab as a function of relative humidity with only the top surface exposed to drying (From Reference 3)

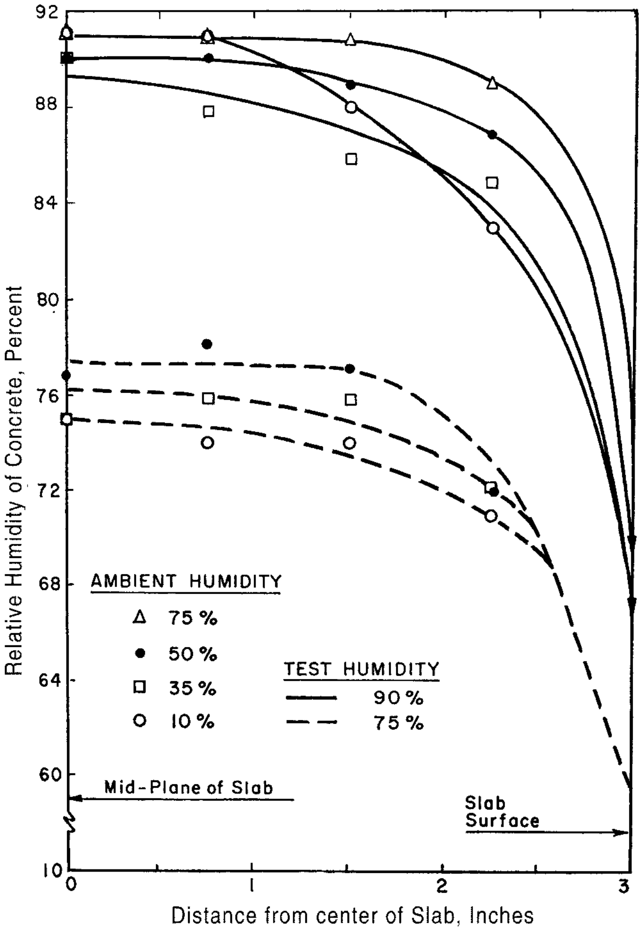

Fig. 3: Effect of ambient humidity on humidity gradient through slab sections (From Reference 4)

Shrinkage gradients at different drying conditions

Research shows that the relative humidity of the drying environment can change the shrinkage gradient. Concrete loses more water at a lower relative humidity, resulting in more shrinkage. Data from Keeton, shown in Fig. 2, provide shrinkage profiles for relative humidities from 20 to 100%.[3] As the relative humidity decreases, the shrinkage gradient increases, thus causing a greater applied curling moment and greater upward slab curling.

Work at the Portland Cement Association by Abrams and Orals[4] and Abrams and Monfore[5] also shows that moisture-content gradients in concrete depend on the relative humidity of the drying environment, with concrete losing more moisture and at a faster rate at a lower relative humidity (Fig. 3).

Because slabs that are exposed to a lower relative humidity will lose moisture faster, they will curl sooner than slabs exposed to a higher relative humidity. Thus, a slab placed in Phoenix is likely to curl sooner than a slab placed in Houston (assuming similar concreting materials, mixture proportions, subbase stiffness, and placing and curing methods are used) because the relative humidity in Phoenix is lower.

Moisture gradients in the field

Researchers at Penn State University used a stacked disc technique to measure the moisture contents of a pavement and two bridge decks.[6] One of the bridge decks was placed on stay-in-place metal forms and the other deck was placed on plywood forms, which were removed after the concrete was placed and cured. Figure 4 shows the moisture-content gradients associated with each of the structures. These full-scale field tests verify moisture-gradient profiles found in other researchers' labs.

Janssen also measured moisture-content differences in pavements in the field.[7] Using lab measurements, he then calculated shrinkage strain and stress in the pavement. Figure 5 shows his estimate of moisture distribution in an 8-in.-thick (200 mm) pavement and the resulting stress distribution due to differential shrinkage. I added the arrows to better illustrate the applied upward curling moment, which Janssen calculated as 2500 in.-lb/in. (11,125 N-mm/mm) of slab width.

Depth of moisture loss

Note that in Fig. 1 through 5, the moisture loss is significant only in the top 2 in. (50 mm) of the specimens, regardless of the specimen size. An often-used rule of thumb for the time needed to dry concrete floors to be covered with a moisture-sensitive covering is 1 month for each inch (25 mm) of slab thickness. However, when Suprenant and Malisch measured moisture-emission rates for concrete slabs during a 3-month-long drying period, they found that reduction in the emission rate with time was about the same for slabs 2-, 4-, 6-, and 8-in. (50, 100, 150, and 200 mm) thick.[8] These measurements were repeated with four different concrete mixtures, and again reduction in emission rate was unaffected by slab thickness.

Slabs of all thicknesses reached about the same emission rate at the same drying time. This too seems to show that moisture loss is significant only in the top 2 in. (50 mm) of the specimens or less, regardless of the specimen size.

Effect of subbase conditions

Nagataki tested three sets of 4 x 4 x 20-in. (100 x 100 x 508 mm) concrete specimens cured for 7 days and then exposed to a drying environment of 75 °F (24 °C) and 50% relative humidity.[9] He tested one specimen with all sides exposed to drying, one specimen drying only from the top, and the final specimen with only the top exposed to drying and the bottom on wet sand at a 10% moisture content. Figure 6 shows the shrinkage gradients he measured.

As would be expected, Specimen I (dried from all four sides) had only a slight shrinkage gradient. Specimen II (dried only from the top) had a much larger shrinkage gradient and, therefore, would have a larger applied curling moment. Note that the bottom of Specimen II still dried some as there was a resulting shrinkage. Specimen III had the largest shrinkage gradient because the bottom expanded when exposed to the moist sand subgrade.

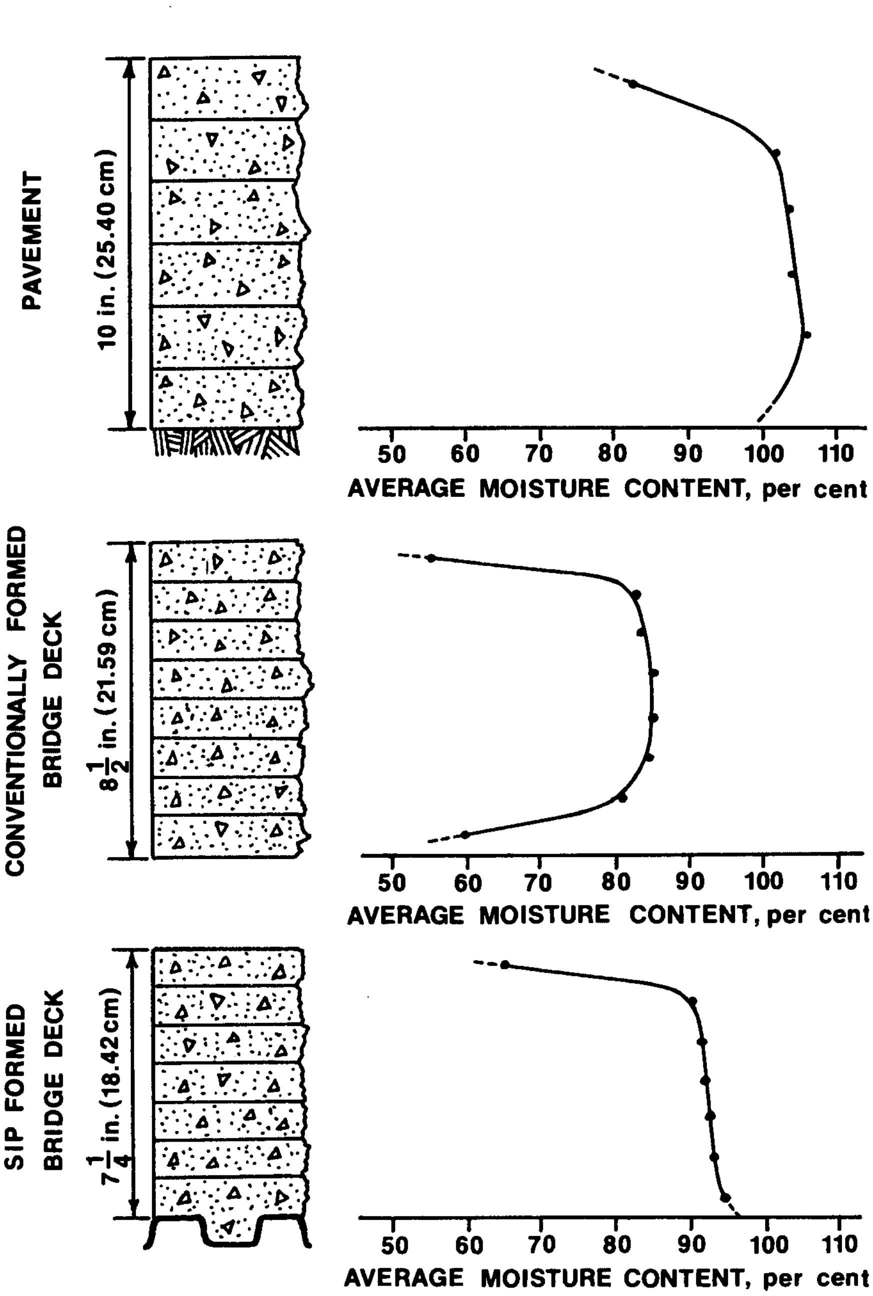

Fig. 4: Moisture distribution in a pavement and in bridge decks (From Reference 6)

In practice, it's often difficult to explain differences in the amount of slab curl for floors that are built with similar materials, mixture proportions, and construction methods, and then exposed to similar drying environments. It's likely that the subbase moisture condition plays an important role in determining the shrinkage gradient and, therefore, the applied curling moment when all other factors are nearly the same. ACI Committee 302, Construction of Concrete Floors, suggests that for slabs to receive moisture-sensitive floor coverings, it may be best to place concrete directly on a vapor retarder because a wet subbase can adversely affect floor-covering performance.[10]

Specimen II from Nagataki's work represents a shrinkage gradient typical for slabs placed on a vapor retarder. He didn't include a dry subbase in his comparison. Suprenant and Malisch, however, measured the moisture content of a 1- and 2-in.-thick (25 and 50 mm) sand layer beneath freshly placed concrete.[11] The initial moisture content was less than 1%. In the first hour, the moisture content of the sand increased to 5 or 6%, but during the second hour, it decreased to 2 to 3% as the water was reabsorbed back into the concrete. Because the reabsorption process occurred quickly, it's difficult to say whether a dry subbase would produce a moisture gradient different than what would occur when concrete is placed directly over a vapor retarder.

In another experiment, Nagataki placed a 10-in.-thick (254 mm) concrete pavement 34 ft 4 in. long (10.5 m) by 2 ft 8 in. wide (0.8 m) on a heavy sheet of paper. He then covered the pavement with wet burlap for 10 days.

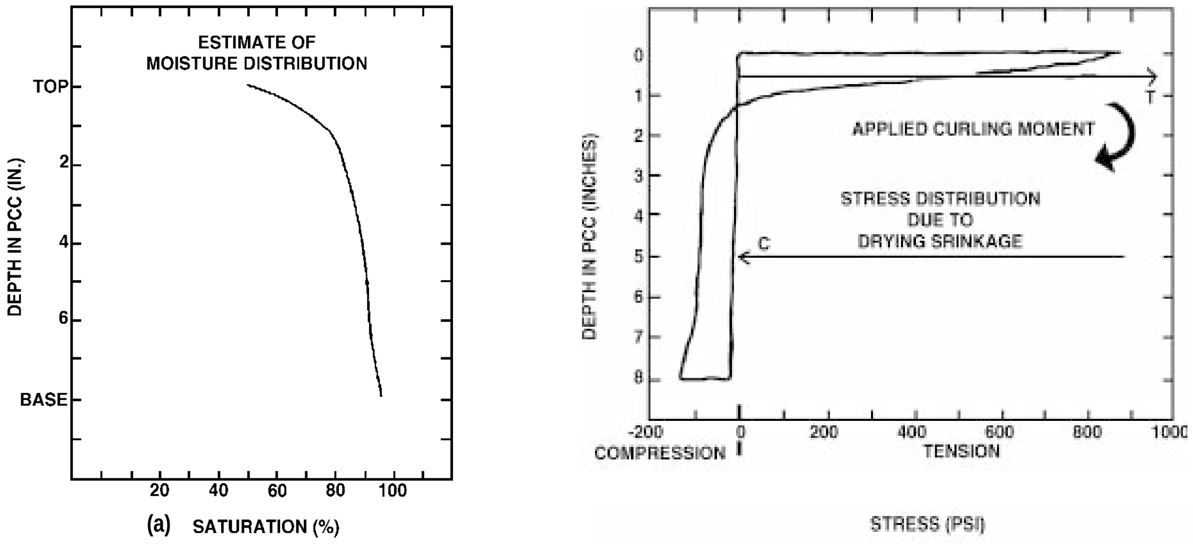

Fig. 5: (a) Estimate of moisture distribution for an 8-in.-thick (200 mm) pavement; (b) The stress distribution due to the moisture gradient. Arrows show the resulting applied curling moment (Modified from Reference 7)

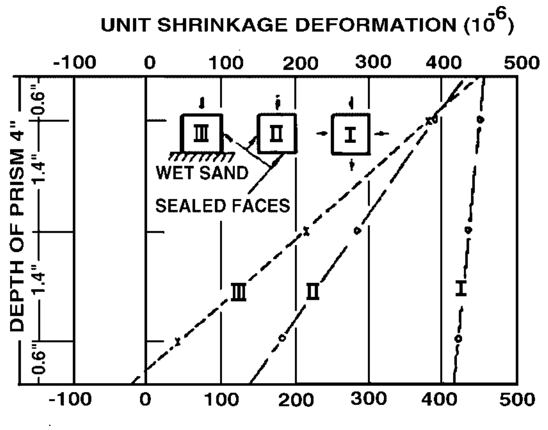

Fig. 6: Distribution of unit shrinkage deformation in prisms under different drying conditions (From Reference 9)

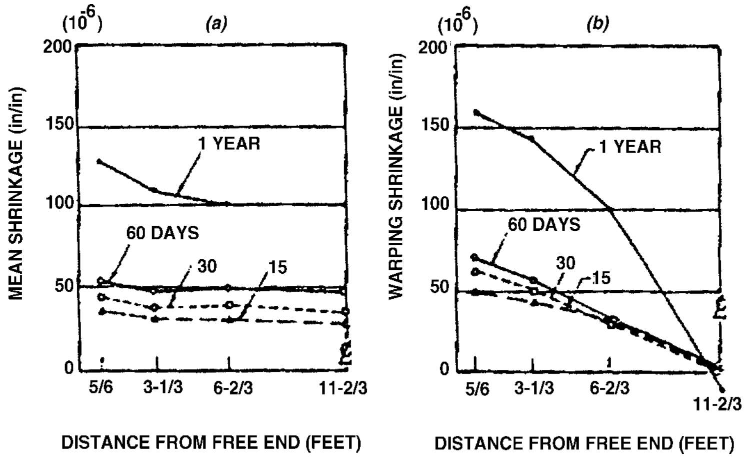

Fig. 7: (a) Mean shrinkage through the depth of pavement sections; and (b) warping shrinkage at the surface of each section (From Reference 9)

Carlson-type strain gages were placed throughout the concrete pavement. He took strain readings at different depths, at different locations in the pavement, and at a time to minimize the temperature gradient in the pavement. As shown in Fig. 7, Nagataki was able to plot the shrinkage gradients at various distances from the free end of the pavement. The mean shrinkage through the depth of the section is almost the same because the paper-covered subgrade offered little resistance to horizontal sliding. The shrinkage gradient is higher at the free end then decreases nearly linearly in proportion to the distance from the free end.

Work by Nicholson is cited to prove that concrete placed directly on a vapor retarder will curl more than when placed on a granular subbase.[12] For instance, ACI 360R-92, "Design of Slabs on Grade," includes the statement that "Nicholson showed that serious shrinkage cracking and curling can occur when concrete slabs are cast on an impervious base."[13] This statement is incorrect. Nicholson didn't measure curling or any other flatness-related property in his research.

Shrinkage-gradient effects

The cited research results indicate that:

- Curling is the result of nonuniform drying that establishes the moisture gradient, the resulting stress distribution, and applied curling moment and thus the amount of curl;
- The drying takes place in the top few inches regardless of the slab thickness or external environment;
- For a given moisture gradient, differing concreting materials can cause differing shrinkage gradients within a slab, with the differences likely to be greater near the bottom of the slab;
- Placing a concrete slab on a wet subbase increases

the shrinkage gradient and the applied curling moment, and thus the amount of curl;

- Whether concrete curls more when placed directly on a vapor retarder or on a granular subbase depends on the moisture content of the subbase;
- Slabs exposed to low relative humidities develop greater shrinkage gradients that can increase the applied curling moment and cause more upward deflection at joints or cracks than higher relative humidities; and
- The same concrete may exhibit different amounts of curl due to the different final environments.

Factors related to the slab's final environment—temperature and relative humidity at the surface, and moisture content in the subbase or subgrade if it's in contact with the concrete—can affect the amount of curl as much as the concrete properties. However, we usually attempt to control curling by modifying the concrete.

In Part II of this article, I'll discuss other factors affecting the amount of curling.

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Why Slabs Curl

Part II: Factors affecting the amount of curling

BY BRUCE A. SUPRENANT

Slabs curl due to differences in moisture distribution that create a shrinkage gradient. This induces an applied curling moment within the slab. The amount of curling for a given moisture distribution may, however, not be unique. Some research and field experience helps us estimate the amount of curling deflection as affected by differences in:

- Amount of drying shrinkage;
- Modulus of subgrade reaction;
- Concrete compressive strength and modulus of elasticity;
- Reinforcement ratio;
- Slab thickness;
- Joint spacing; and
- Curing.

Not all of these factors affect curling deflection to the same degree.

Drying shrinkage

Drying shrinkage is considered to be one of the most important factors affecting the amount of curling deflection. Many references suggest ways to minimize drying shrinkage,[1-3] but the exact relationship between drying shrinkage and curling deflection is unclear.

Tremper and Spellman[4] developed a figure that related slab-curling deflections of full-size test slabs to the shrinkage of laboratory specimens made with the test-slab concrete. Although this figure provides information on only one project, their paper includes data on slab curling versus drying shrinkage for two other projects. The data for all three projects are shown in Table 1 and arranged in the order of the percent of drying shrinkage, from lowest to highest.

The table shows that it's difficult to relate drying shrinkage to curling deflection for projects with differing variables such as subgrade or subbase stiffness and drying environments. However, Fig. 1, which graphs the Tremper and Spellman data by project, suggests that a relationship exists on a project-by-project basis. As the graph shows, curling deflection increases as drying shrinkage increases, though the ratio of drying shrinkage to curling is unique for each project. As Table 1 shows, the average curl, in inches, is three times the drying shrinkage, in percent. Thus, in some cases, reducing drying shrinkage by a given percent would result in a much greater percentage decrease in curling deflection.

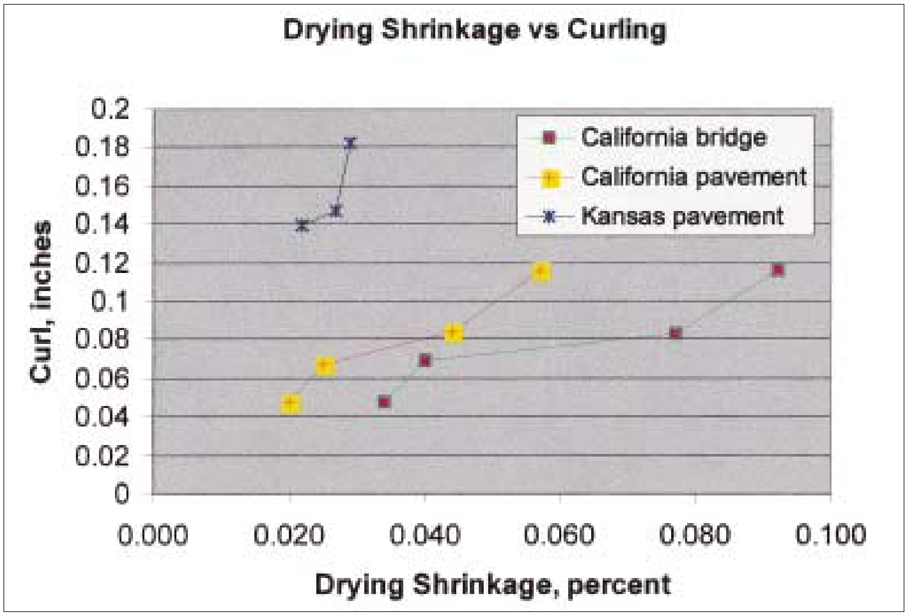

Fig. 1: Relationship between drying shrinkage of test specimens and the amount of curling deflection of full-size test slabs for three different slabs

TABLE 1:
DRYING SHRINKAGE OF SPECIMENS VERSUS CURLING OF FULL-SIZED SLABS

Drying shrinkage of prisms, %	Slab curling, in.	Ratio of curl, in., to shrinkage, %	Tremper and Spellman reference
0.020	0.048	2.4	California pavement
0.022	0.139	6.3	Kansas pavement
0.025	0.067	2.7	California pavement
0.027	0.147	5.4	Kansas pavement
0.029	0.182	6.3	Kansas pavement
0.034	0.048	1.4	California bridge
0.040	0.069	1.7	California bridge
0.044	0.084	1.9	California pavement
0.057	0.116	2.0	California pavement
0.077	0.083	1.1	California bridge
0.092	0.116	1.3	California bridge
		Avg. 3.0	

Modulus of subgrade reaction

The modulus of subgrade reaction, or soil stiffness, controls the depth to which a slab sinks into the subgrade as it curls. The contact area of the bottom of the slab decreases with an increase in soil stiffness. Al-Nasra and Wang[5] showed a maximum 30% increase in curling deflections when the modulus of subgrade reaction *k* increased from 50 to 800 lb/in.^{3} (14 to 216 MPa/m). Leonards and Harr[6] performed calculations for three slabs but at *k* values of 200 and 700 lb/in.^{3} (54 and 189 MPa/m). Their calculations showed slight to no increase in curling deflection with an increase from 200 to 700 lb/in.^{3} At the same two *k* values, Al-Nasra and Wang showed about a 5% increase in curling deflection.

While there is little to no change in curling deflection as *k* values increase beyond 200 lb/in.^{3} (54 MPa/m), there is a small change when *k* increases from values lower than 200 lb/in.^{3}. Under normal job site soil conditions, *k* values typically range from 100 to 200 lb/in.^{3} (27 to 54 MPa/m). Based on the Al-Nasra and Wang research, increasing *k* from 100 to 200 lb/in.^{3} would increase curling deflection less than 10%.

Concrete strength and modulus of elasticity

Leonards and Harr and Al-Nasra and Wang both showed that curling deflections increased as concrete strength increased, primarily because the modulus of elasticity also increases. As Al-Nasra and Wang note, because the applied curling moment is proportional to the modulus of elasticity, the applied curling moment increases as the modulus of elasticity increases, which, in turn, increases the amount of curling.

Calculations by Leonards and Harr showed a 60% increase in curling deflections when the concrete strength increased from 3000 to 7500 psi (21 to 52 MPa). This strength increase resulted in an increased modulus of elasticity from 3,000,000 to 5,000,000 psi (21,000 to 35,000 MPa). Al-Nasra and Wang's calculations showed only a 35% increase in curling deflections for the same change in strength and modulus of elasticity.

From a designer's perspective, it seems reasonable to estimate that increasing the required concrete strength by 1000 psi (6.9 MPa) increases curling deflections by about 10%. Stated differently, increasing the modulus of elasticity by about 10% increases curling deflection by about 10%.

Reinforcement

Many publications[7-10] recommend placing reinforcement near the top surface of the slab to restrain shrinkage and reduce curling. But most don't tell designers how much steel is needed to reduce curling. ACI Committee 302 recommends using 1% reinforcement that extends perpendicularly about 10 ft (3 m) from the slab edge or construction joint toward the center. For a 6-in.-thick (150 mm) slab, 1% reinforcement is equal to a 0.72-in.^{2} area (465 mm^2) of steel, or No. 8 bars spaced 12 in. (about 300 mm) on center.

Experiments by Abdul-Wahab and Jaffar[11] provide data for estimating the effect of amount of reinforcement on curling. They made 4 x 6 x 60-in. (100 x 150 x 1520-mm) beams using concrete with a water-cement ratio (*w*/*c*) of 0.50. The beams were reinforced on only one face and allowed to dry only from the top. Time-deflection curves were used to show the reduction in curling for a given amount of reinforcement. Table 2 shows the results.

As the table shows, ACI Committee 302's recommendation of 1% reinforcement might decrease curling deflection by about 60 to 80%. Unfortunately, some specifiers believe that the shrinkage and temperature reinforcement commonly used to keep cracks from opening will also reduce curling. The small area of steel in light-gage welded-wire fabric or small-diameter bars spaced at 18 in. (about 460 mm) on centers isn't sufficient to reduce curling.

Slab thickness

ACI Committee 360 summarizes the work by Childs and Kapernick[12] regarding slab thickness: "Curling is greatest at corners of slabs, and corner curling is reduced as slab thickness increases. For example, corner curling vertical deflections of 0.05 in. and 0.11 in. (1.3 and 2.8 mm) were measured for 8- and 6-in.-thick (200 and 150 mm) slabs, respectively, after 15 days of surface drying." For the full-scale tests cited, a 2-in. (50 mm) increase in slab thickness reduced corner curling by more than 50% during the time it was measured.

An analysis performed by Leonards and Harr[6] showed that as slab thickness increases, upward corner deflections decrease. They used differential thermal contraction to simulate differential drying shrinkage, and assumed a constant effective temperature difference of 30 °F (17 °C) between the top and bottom slab surfaces, irrespective of thickness. A finite-element parametric study by Al-Nasra and Wang[5] gives conflicting results, indicating that curling deflection increases as slab thickness increases. However, the authors used an effective temperature gradient of 6 °F (3 °C) per inch. Therefore, as the slab thickness increased, the effective curling moment increased.

Based on measured moisture profiles and moisture emissions, the Leonards and Harr assumption of a reasonably constant curling moment due to moisture loss is more realistic than the Al-Nasra and Wang assumption that the curling moment increases with thickness. The Leonards and Harr analysis also matches the full-scale test data developed by Childs and Kapernick.

TABLE 2:
EFFECT OF REINFORCEMENT ON CURLING DEFLECTION

Reinforcement, %	Reduction in deflection (compared with unreinforced)
0.46	30%
0.92	60%
1.38	100%
1.74	Negative deflection (opposite direction)

Joint spacing

Industry publications advocate reducing joint spacing as one method of reducing the amount of curling deflection. Although field experience is in general agreement with this recommendation, there aren't any experimental data or analytical results to support it. Ytterberg[13] used Leonards and Harr data to show that reducing the joint spacing from 20 ft (6.1 m) to 15 ft (4.6 m) decreases the amount of upward deflection, but not by 25% or more, as might be expected.

An analytical study would be quite useful, because, as suggested by Ytterberg, it's likely that beyond a certain joint spacing, say 25 to 30 ft (7.6 to 9.1 m), curling would not increase with an increase in spacing. And reducing the joint spacing to 6 to 8 ft (1.8 to 2.4 m) is unlikely to reduce the amount of curling deflection much below that produced by a joint spacing of 10 ft (3.0 m). Ytterberg also states that smaller joint spacings produce more potential curling sites. Because more curling sites are likely to increase maintenance costs, an analytical study to determine optimum joint spacing for a variety of variables would be helpful.

Curing

When a slab curls, inadequate curling is often cited as a cause. This incorrect assumption is based on a belief that moist curing reduces total shrinkage and minimizes shrinkage differences between the top and bottom of the concrete slab, thereby minimizing curling. However, as test data show, curing doesn't provide either of these expected benefits. Curing has no effect on whether a slab will curl or how much it will curl. But the duration of curing may influence *when* a slab will curl.

Carlson[14] reported that the duration of moist curing had little effect on shrinkage. Lyse[15] found that increasing the duration of moist curing up to 7 days increased

Will thickened edges help?

ACI 360R-92, "Design of Slabs on Grade," includes this advice regarding thickened edges:

"Edge curling can be reduced by thickening slab edges at floor construction joints. The thickened edge contributes added weight and also reduces the surface area exposed to drying relative to the volume of concrete, both of which help to reduce upward curling. It is recommended that free slab edges at construction joints be thickened 50 percent with a gradual 1 in 20 slope. Providing the subgrade is smooth with a low coefficient of friction as detailed in Sec 9.8, then thickened edges should not be a crack-producing restraint."

I believe thickening slab edges sounds good in theory, but it isn't a practical way to reduce curling deflection. The following anecdotal evidence gives my reasoning.

For a 6-in.-thick (150 mm) slab, an edge thickened in accordance with ACI Committee 360 recommendations—thickened 50% with a gradual 1 in 20 slope—adds less than 100 lb/ft of slab edge. To assess the severity of curling, slab movement at curled joints can be measured to the nearest 0.001 in. (0.025 mm) before and after forklift loading. A loaded forklift weighs considerably more than 100 lb/ft of slab edge (1460 N/m) and can cause curled-slab edge movements between 0.01 and 0.30 in (0.25 and 7.6 mm). With the same measurement instrumentation in place, I've stood on curled joints and jumped on them without causing any measured movement, even though my body weight contributes more than 100 lb/ft of slab edge (1460 N/m). Thus, I don't think the extra weight of a thickened edge makes a measurable contribution to reduction in curling deflection.

Measured moisture emissions and profiles indicate that the slab top surface dries to about the same depth regardless of the slab thickness. Thus, the increased volume and reduced drying shrinkage indicated by ACI Committee 360 is also likely to be more theoretical than realistic.

Finally, I know of a company that adds more than 15 million ft^2 (1.4 million m^2) of large industrial distribution floors to its facilities each year. The company's construction manager tried using thickened-edge floors for about 2 years at an average estimated extra cost of $50,000 per building. On projects throughout the United States, thickened edges didn't eliminate curling deflections. The thickened edges may have reduced the deflections, but no measurements were made. On these projects, I've noted an increased incidence of cracking between the thickened-edge and the adjacent contraction joint, which is probably due to restraint caused by the thickened edge. The company has since discontinued this curling-control method.

shrinkage. Keene[16] showed that shrinkage in concrete cured in moist air for 7 days was greater than that of concrete that was never cured. Tests conducted in California[4] show substantially the same shrinkage in concrete moist cured for 7, 14, and 28 days. Perenchio[17] reported unpublished data showing that the lowest 1-year drying shrinkage occurred for concretes cured for either 1 day or 90 days.

In the last 40 years, four published papers have summarized factors that affect drying shrinkage. Surprisingly, curing doesn't even rate a mention in three of the papers. Both Tremper and Spellman[4] and Powers[18] provided tables listing the effects of various factors on concrete shrinkage, but curing wasn't even included. Ytterberg[19] didn't provide any comments on curing except to reference Meininger's work. And Meininger[20]—the only author to mention curing as a factor—indicated that the reduction in shrinkage for concretes cured 7 days instead of 3 days was only 5%.

Despite evidence spanning 65 years and showing that curing has little effect on drying shrinkage, the belief still persists that inadequate curing increases shrinkage and thus leads to increased curling.

The work of Childs and Kapernick[12] provides the most convincing evidence that curing doesn't eliminate curling. In a controlled environment, they placed two 12 x 18-ft, 8-in.-thick (3.7 x 5.5 x 0.2 m) concrete slabs and joined them using 1-in.-diameter (25 mm) round dowels. They cured the test slabs for 7 days under wet burlap, and then ponded them with water for another 4 to 5 weeks. At the end of this total curing period of 5 to 6 weeks, the water was removed and the slabs dried from the top. Corner and edge curling were measured within 2 weeks after the ponding water was removed. The researchers repeated these full-scale tests three times, and found the same results each time.

After one test, Childs and Kapernick added water, then heat, and then hot water to the slab surface to bring the slab back to a level, uncurled position. However, when the water and heat were removed, the slabs curled again to the same vertical deflections as before. ACI Committee 360[3] summarizes the work of Childs and Kapernick by succinctly stating: "Extended curing only delays curling, it does not reduce curling."

Can controlled curing help?

The Institution of Civil Engineers has published a design and practice guide for concrete industrial ground floors that helps to explain why the factors affecting curling are so difficult to sort out in practice.[21] The guide includes the following statement:

"If the rate of moisture migration is carefully controlled then the creep relaxation of this stress will enable the slab to maintain its integrity such as ultimately to absorb all potential drying shrinkage and provide a stress-free entity with little change in length."

Many curling problems that I've observed or heard about became apparent only after slabs were subjected to sudden drying by removal of ponded curing water, or by turning on the HVAC system after removing curing paper, burlap, or other coverings. Both of these result in rapid moisture loss. If a slower rate of moisture loss could occur, stress relaxation due to creep can dissipate the tensile stress and strain that might otherwise result in a larger curling deflection or a crack in the middle of the slab. The Portland Cement Association's new publication, *Concrete Floors on Ground,* indicates that relaxation reduces curling over a period of months.[22] Thus, curling deflection is likely to be smaller in slabs on which a curing compound slowly dissipates, reducing the rate of moisture loss and allowing more time for stress relaxation.

In elastic analysis, we often use an age-adjusted modulus of elasticity to account for creep effects. ACI 209R-92, "Prediction of Creep, Shrinkage, and Temperature Effects in Concrete Structures," provides information on calculating and using an age-adjusted modulus of elasticity for analysis.[23] Some simple assumptions can be used to calculate an age-adjusted modulus of elasticity that is 20 to 70% less than the elastic modulus. Based on data presented previously, reducing the elastic modulus by 50% could decrease curling deflections by about 50%. One of the most significant factors affecting curling deflections might be the rate of moisture migration and the resulting benefits of stress relaxation.

What the research tells us

We can conclude that some factors thought to have a major effect on the amount of curling deflection do indeed reduce it. Other factors have little or no effect.

- For any given project, (relatively small differences in modulus of subgrade reaction and environmental conditions), reducing drying shrinkage by a given percent may result in a much greater percentage decrease in curling deflection. As a rough rule of thumb: the average curl, in inches, is three times the drying shrinkage, in percent;
- Increasing the modulus of subgrade reaction within a narrow range, between 100 to 200 lb/in.^{3} (27 to 54 MPa/m), increases curling deflection no more than 10%. Increasing the modulus of subgrade reaction past 200 lb/in.^{3}, to as much as 800 lb/in.^{3} (216 MPa/m), has little effect on curling deflection;
- Increasing the concrete compressive strength by 1000 psi (6.9 MPa) or the modulus of elasticity by 10% increases curling deflection by about 10%;
- Adding reinforcing bars in the top third of the slab thickness and perpendicular to the slab edge or joint can significantly reduce curling, with a 1% reinforcement ratio potentially decreasing curling by 60 to 80%. The amounts of distributed steel (about 0.1 to 0.15%), commonly used for crack-width control, don't significantly reduce curling;
- Increasing slab thickness decreases the amount of curling deflection. In one case, increasing thickness from 6 in. (150 mm) to 8 in. (200 mm) reduced corner curling by 50%. Thickened edges haven't been proven to provide any measurable benefits;
- Decreasing joint spacing may reduce curling deflection, but I've found little field data and few analytical studies that relate curling deflection to joint spacing. Because increasing the number of joints increases the joint maintenance required, designers need to balance these opposing effects when choosing a joint spacing; and
- Longer moist-curing periods have little effect on drying shrinkage or curling, other than delaying the onset. The rate of moisture migration and the resulting relaxation of the concrete may be the most significant factor affecting curling deflections.

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