The First Commandment for floor slabs:

Thou Shalt Not Curl Nor Crack...(hopefully)

by Wayne W. Walker and Jerry A. Holland

ALL FLOOR SLABS CURL, except under unusual conditions or when special designs are utilized. In spite of what many people think, it is not a matter of whether a particular slab has curled or not, but whether or not it has curled to an objectionable degree. Similarly, all floor slabs shrink eventually and since it is extremely difficult to eliminate significant restraints, the potential for undesirable cracking is always present.

What is curling?

Curling occurs when the upper part of the floor tries to occupy a smaller volume than the lower portion; this can happen with differences between the upper and lower portions with respect to shrinkage, temperature, moisture content, and other variables. For the slab to stay intact its edges must lift up. These edges can consist of the discontinuous end of the slab, a construction joint, a contraction (control) joint, or a sufficiently wide crack. For vertically unrestrained slab corners, the panel corners must lift higher than the edges further away if no cracking is to occur.

Both slabs on ground and suspended slabs curl, but for a number of reasons, slabs on ground usually curl more. Many slabs on ground have edges that actually lift off the subgrade; uplifted curled joints that move under vehicle traffic have often been misdiagnosed as having a soft, underlying subgrade. As the slab's edges are trying to curl up, gravity and concrete creep are having the opposite effect but can only partially offset the curl. The amount of curl and the curl profile depend on many complex factors. These include concrete shrinkage potential, strength, subgrade support, moisture and temperature conditions, slab thickness, joint spacings, and others.

Why is significant curling a problem?

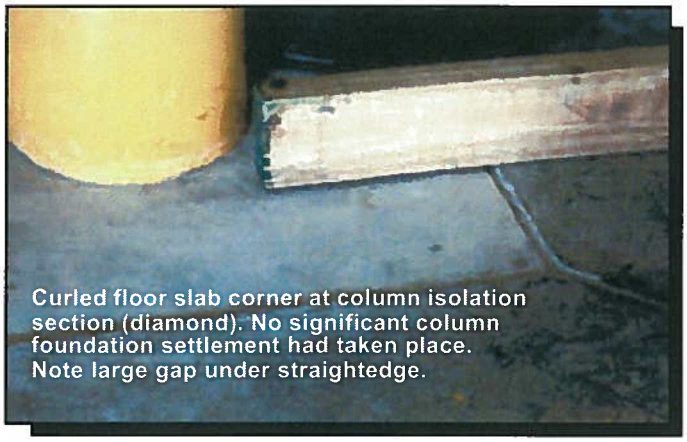
Significant curling is undesirable for a number of reasons. Substantial tensile stresses occur in the top of the slab from the edges curling up as gravity (and any loads or vertical restraints) tries to pull them down; this, plus linear shrinkage, can produce cracking. The great majority of the floor cracks that are attributed to shrinkage are actually due to a combination of curling and linear shrinkage stresses, typically with the curling stresses far greater than the linear shrinkage stresses These cracks can spall due to wheeled traffic, allow liquid penetration, be unsightly, or cause other difficulties.


Straightedge across a floor slab crack that was wide enough to have curled substantially. Note pen under straightedge and dark polymer applied in attempt to repair crack.

Wheels rolling across curled joint edges (without proper dowel load transfer) can cause one edge to deflect first, then the other, contributing to joint spalling, failure of joint filler or sealant, and other problems. Curling, especially differential curling at a joint or crack, also can cause distress in the floor materials covering the slab. Substantially curled joints and cracks can reduce the vehicle rideability of a floor or pavement, leading to driver discomfort, vehicle problems, and reduced productivity.

Which is more of a concern, shrinkage or curling?

Curling and linear shrinkage are intimately related and cannot be considered completely independent of each other. Almost anything that affects shrinkage will affect curl as well, positively or negatively. However, unless a slab on ground is cast directly on a substrate that causes significant restraint (such as a very uneven subgrade or an open-graded stone base), curling stresses typically far exceed linear shrinkage stresses. In fact, according to our analysis, on good planar substrates with a reasonably low coefficient of friction, the linear shrinkage stresses usually are no more than 10 to 50 psi (0.1 to 0.4 MPa), whereas the curling stresses can easily be 200 to 400 psi (1.4 to 2.8 MPa) or more. Thus, the term "shrinkage crack" is not truly appropriate for most slab on ground cracks; "curling crack" or "curling and shrinkage crack" is really far more accurate. Comparing these stresses with the typical range of concrete flexural stress capacity



Curled floor slab corner at column isolation section (diamond). No significant column foundation settlement had taken place. Note large gap under straightedge.

(modulus of rupture) of 450 to 650 psi (3.1 to 4.5 MPa) indicates the significance of curling. Obviously, the slab's load-carrying capacity can be reduced dramatically by high curling stresses.

Why are curl and shrinkage more of a problem today?

Floor curling and shrinkage have always been of concern, but their severity and cost implications have increased dramatically over the last 20 to 30 years. There are a number of reasons for this, and part of the problem is that many people do not realize that the rules of the game have changed. What has worked in the past could cause you to be sued in the future. Concrete mix designs, materials, details, practices, and other things have all changed.

Floor concrete compressive strengths have increased. In the 1960s, design strengths of 2000 to 3000 psi (17 to 26 MPa cube strength)* were typical, but now 4000 to 5000 psi (34 to 43 MPa cube strength) are common. Higher strength concretes generally (but not always) shrink more and always have a higher modulus of elasticity. The modulus of elasticity is a very significant factor because the higher the modulus the more curl will occur and the less the curled edges will relax downward over time due to creep.

Cement and aggregates

More cement and cementitious materials are being used now in mixes, and the cement has changed both chemically and physically. For example, many cements have a higher tricalcium aluminate content, and almost all cements are much finer. Many of the changes in cement have produced desirable qualities for certain situations (such as high early strength); however, one of the disadvantages is that many cements now shrink more than in the past (and some more so than others).

Aggregates have changed in different ways. The most significant change has been increased gap-grading when considering both coarse and fine aggregates combined. If a combined sieve analysis is made of the percentage by weight retained on each sieve from the 1-1/2 inch to No. 100 (37.5mm to 150 μm) sieves, some sieves can have as little as 0.1 percent and as much as 33 percent retained of the total amount of aggregates (coarse and fine) and still conform to ASTM C 33. (Doesn't it seem strange to realize that one or more sieves could have practically nothing retained on them and another could have 1/3 of the total aggregates in a mix?) Even typical aggregate ranges in North America are from 1 percent to 4 percent retained at the low end and 26 percent to 31 percent at the high end. The lowest percent retained is usually the No. 4, 8, and/or 16 (4.75, 2.36 and/or 1.18 mm) sieves. The main reason for this is that these "middle sizes" are used a great deal by the asphalt industry and thus are "scalped" from the coarse aggregates produced. Gap-grading is not a significant problem for concrete strength, but it negatively affects many other properties, including shrinkage and curl.

The recent increase in the number of specifications requiring combined aggregate constraints, such as the 8 percent minimum and 18 percent maximum retained on any sieve, is a step in the right direction. However, specifiers should be flexible in their requirements and work with the local concrete supplier to produce the best mix feasible with the available materials. For example, a mix with a minimum of 5 percent and a maximum of 25 percent is still a significant improvement over what we commonly see; the 8-18 percent is only an ideal gradation and is seldom achieved in actual practice without extensive effort.

Admixtures and water-cement ratio

Thirty years ago many concrete mixes for floors had no admixtures at all. If an admixture was used for floors, it was one of the early low-range water reducers or an air-entraining admixture for exterior flat work.

However, today it is rare for a concrete mix not to have an admixture, and many mixes have more than one (in fact, some mixes have so many admixtures that they are almost "chemical soups"). The introduction of new and better admixtures has been one of the best things to happen in the industry. However, not all admixtures are created equal, and some can increase shrinkage and curl. For instance, not many people are aware that ASTM C 494-98, Standard Specification for Chemical Admixtures in Concrete (water-reducing, retarding, or accelerating admixtures), allows up to 35 percent more shrinkage in test specimens with the admixture than that of the control specimens. This does not mean that when you put a water reducer (whether low-, mid-, or high-range) in a concrete mix that it will necessarily shrink 35 percent more than if you did not. However, the quality of admixtures varies significantly, and some of the more mediocre ones can increase shrinkage close to 35 percent (which would require a huge reduction in water to offset this large amount of admixture-related shrinkage).

Many designers are now specifying very low water-cementitious material ratios *(w/cm)* for floors, such as 0.45 or lower. Sometimes this is done for valid reasons, such as increasing durability or decreasing permeability. However, many times it is done in the mistaken belief that this will always reduce shrinkage by lowering the water content. The aggregates will have a certain water demand based on their size, shape, texture, and gradation (see below); thus, the water content is not likely to be reduced much, if at all. However, to meet the specified low *w/cm* the concrete supplier adds enough cementitious material to conform.

Most people in the concrete industry know that more water

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*The metric conversions for concrete compressive strengths are labeled as cube strengths because they incorporate the commonly used 25 percent increase in test strength for standard cubes as compared to standard cylinders made with the same concrete.

in a given mix will increase shrinkage, but many do not know that more cementitious material can have the same result (although to a lesser extent). On the other hand, if a poor mid- or high-range water reducer is used to keep the same cementitious material content and workability but reduce the water content, the resulting expected shrinkage decrease can actually end up being an increase instead. Furthermore, the increased compressive strength (and resulting higher modulus of elasticity) of either method of achieving the lower *w/cm* will increase curl. Thus, using this practice, the designer can unintentionally increase the chances of having significant shrinkage and curling.

Other changes

Buildings themselves have changed over the years. Many more buildings have air conditioning and increased heating requirements, both of which tend to lower humidity and increase curl and shrinkage. Coolers and freezers are commonplace and exhibit the same problems to an even greater degree (especially when the temperature is lowered at too fast a rate).

Building sites have changed in some ways. More buildings have landscaping and irrigation systems, which can increase moisture under the floors. Many floors have high humidity directly underneath but no vapor barrier or vapor retarder; others have either a mediocre vapor retarder or one that has been poorly installed and/or damaged during construction.

Another problem that has developed over the last 20 years is improper use of an aggregate blotter layer (as recommended by ACI Committee 302, Construction of Concrete Floors) over a required vapor barrier/retarder. Tests and experience have shown that the blotter can reduce curling and cracking if properly installed. However, if the blotter contains too much moisture (whether from rain or spraying water on the blotter just before placing concrete), curling and cracking can be exacerbated (not to mention increasing the chances for problems that the designer was trying to eliminate by using the vapor barrier/retarder in the first place). The authors believe that if the blotter cannot be kept reasonably dry, it is better to place the concrete directly on the vapor barrier/retarder and minimize curling and shrinkage by the other methods discussed herein.

Who is responsible?

Whose fault is it that floor curl and shrinkage problems have been increasing? Is it the contractor (who usually gets the most blame), the concrete supplier (who usually gets the next-most blame), the engineer/architect, or another of the design/construction team? In fact, all team members have contributed to the problems in general, some much more than others on specific projects. Conversely, each team member can do their part to minimize these problems as well. Even the owner must contribute by learning as much as feasible, insisting on quality, and being willing to pay appropriate construction costs and design fees (you get what you pay for in a floor, whether low or high quality, more so than for almost any other part of a facility). Finally, there must be close teamwork, rather than the more typical adversarial relationships that have existed in the past.

> ***"Whose fault is it that floor curl and shrinkage problems have been increasing?"***

What are the causes and what can be done to help?

In addition to the factors noted previously, almost anything that will increase or decrease shrinkage will have the same effect on curl. Many factors are involved in the shrinkage potential of a concrete mix. Furthermore, these factors have a synergistic, cumulative effect (not just an additive effect) as more and more factors are involved negatively or positively. For example, note the factors shown in Table 1; the additive summation of the adverse factors on shrinkage is 183 percent, but the cumulative effect is 400 percent.

Water and bleeding

Any increase in concrete mix water content will increase shrinkage, whether from making the concrete too "soupy," too gap-graded, or too finely graded. The latter two reflect the importance of having as large and as evenly-graded aggregate particles as possible. The water demand of a mix at

Table 1 — Cumulative effect of adverse factors on shrinkage[2]

Poor practices that can cause increased shrinkage in floor slabs	Equivalent increase in shrinkage, percent	Cumulative effect
Temperature of concrete at discharge allowed to reach 80F (27C), whereas with reasonable precautions, a temperature of 60F (16C) could have been maintained	8	1.00 × 1.08 = 1.08
Use of 6 to 7 in. (150 to 180 mm) slump where 3 to 4 in. (75 to 100 mm) slump could have been used	10	1.08 × 1.10 = 1.19
Excessive haul in transit mixer, too long a waiting period at job site, or too many revolutions at mixing speed	10	1.19 × 1.10 = 1.31
Use of 3/4 in. (19 mm) maximum size aggregate under conditions where 1-1/2 in. (38 mm) aggregate could have been used	25	1.13 × 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 an admixture that produces high shrinkage	30	3.84 × 1.30 = 5.00
TOTAL INCREASE (percent)	Summation = 183	Cumulative = 400

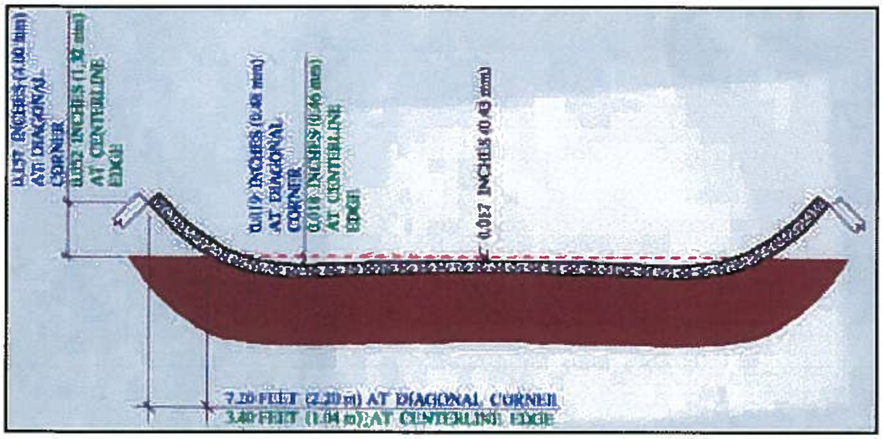

Fig. 1 — Slab curled shape for a 6 in. (150 mm) thick slab with a joint spacing of 24 ft (7.3 m): f'_c = 4500 psi (39 MPa cube), K = 80 pci (22,000 kN/m3), T = 30F (17C), K = Modulus of subgrade reaction

a given temperature is primarily a function of the ratio of the surface area per unit volume of each of the millions of particles that must be coated with paste (water and cementitious materials). The smaller the particle or the more elongated and flat it is, the greater the ratio and, thus, the greater the amount of water and cementitious materials required; therefore, shrinkage is increased.

For instance, 100 lb (45 kg) of average graded No. 4 stone (1-1/2 to 3/4 in. [38 to 19 mm]) has about 70 ft^2 (6.5 m^2) of surface area, but 100 lb (45 kg) of average graded sand will have close to 2000 ft^2 (185 m^2).[1] Obviously, dirty aggregates make the problem much worse, due to the additional fines plus the increased shrinkage potential of the dirt particles. Thus, the coarse and fine aggregate particles should be as well graded and as large as feasible, with the fine aggregate content minimized, consistent with the required workability. Aggregate should also be generally cubical or rounded in shape and have low shrinkage potential.

Significant bleeding exacerbates curl. Bleeding is the migration of water to the top of the freshly-placed concrete. It occurs because water is the lightest constituent in concrete and is displaced upward as the heavier particles settle downward. This effect increases shrinkage in the top of the slab as compared to the bottom, thereby increasing curl. Bleeding can be decreased by the following: minimizing water content and gap-grading; optimizing fine aggregate retained on the No. 50 and 100 (300 and 0.15 μm) sieves (no more than necessary to prevent significant bleeding, finishing, or pumping problems); not placing concrete directly on a vapor barrier/retarder if appropriate (see comments elsewhere); using proper synthetic fiber enhancement; and placing concrete on a permeable, dry (or almost dry, if necessary for finishability) base that acts as a blotter. One of the rationales concerning the blotter base is to lose some water out of the bottom of the slab (in addition to what is normally lost from the top) in the critical first few hours after concrete placement, which will make the slab properties more uniform from top to bottom.

Chlorides

Although calcium chloride is an inexpensive accelerator and can be used in appropriate situations, it will significantly increase shrinkage in the short term and long term. Chlorides can get into fresh concrete from many sources, including some water-reducers and other admixtures, water, aggregates, or cement.

Strength

Concrete compressive strengths should be no higher than necessary to produce the required structural capacity and durability. Any more strength than that required is generally detrimental with respect to curling and shrinkage; with regards to slabs, more is not necessarily better. It is true that (other things being equal), the higher the strength, the greater the surface durability; however, other factors affect durability as well, such as materials, finishing practices, and curing. For a floor with heavy traffic and high abrasion, consider using a good 3000 psi (26 MPa cube strength) concrete mix with a mineral or metallic aggregate (as appropriate) hardener for surface durability.

Joint spacing and reinforcement

Minimizing slab joint spacing can greatly decrease curl and the resultant cracking as well as other problems. For unreinforced or lightly reinforced slabs, the commonly used joint spacing criteria of 36 times the slab thickness can be unconservative for many of today's concretes, especially as slab thickness increases. It is true that the thicker the slab, the longer the joint spacing can be; however, it is not a linear relationship, as can be seen by our analysis (and also our observation of hundreds of slabs). We believe that, unless a people really know what they are doing, a spacing of about 15 ft (4.6 m) should not be exceeded for unreinforced or lightly-reinforced slabs (even this can be unconservative for certain concretes and conditions).

If using mild reinforcing steel, it should be as close to the top of the slab as possible without causing plastic settlement cracks over the steel. Generally, this would be a concrete cover of 1 to 1-1/2 in. (25 to 38 mm). For slabs on ground, unless significant care is taken with steel placement, 1-1/2 in. is a safer cover. The more reinforcing used, the more curl will be reduced.

Other concerns

Other ways to minimize curl are to use properly designed and constructed slabs with continuous reinforcement (mild steel or steel fibers) and no contraction joints, shrinkage-compensating concrete, or post-tensioning. Post-tensioning can offset curl by gradually dropping the ends of the tendons down to about the bottom of the middle third of the slab depth. Mild reinforcement could also be increased perpendicular to the slab edge or construction joint and for 6 to 10 ft (2 to 3 m) from the edge or joint.

Both concrete and ambient temperatures at placement should be as low as feasible. In addition to minimizing shrinkage and surface drying, this can reduce thermal contraction from cooling (both in the short term and the long term).

Proper curing is always important, but it is especially critical in the first few hours after concrete placement. The surface should be kept from drying excessively between finishing operations. The principal curing operations should be started as soon as possible after slab finishing is complete and when the surface will not be damaged by the curing operations. After proper curing, the moisture content differential between the top and the bottom of the slab can be minimized by using coatings, sealers, waxes, etc. This will also minimize carbonation, which adds to surface shrinkage. Often, the greatest moisture loss is located near slab edges and construction joints, both during the curing period and afterwards, due to improper materials and/or practices. Unfortunately, this increases curl in the worst possible locations. Minimizing moisture content differential from top to bottom is critical because the slab bottom almost always has a higher moisture content, resulting in a larger volume than the top thereby increasing the curl.

In what applications is curling of more concern?

Curling is of even more concern than usual with certain applications. Minimizing curling is critical when there is significant vehicular traffic. Heavily loaded slabs are much more likely to crack when curled portions are not supported by the subgrade. Floors with toppings and/or coverings, such as wood flooring, are critical as well because these materials can be damaged by curling or will not function properly with curled portions.

How can existing problems be evaluated?

Existing curled slabs can be evaluated by establishing the elevation profile of the top surface. This can be done with a very accurate optical level, Dipstick™, or other appropriate device. Potential joint vertical movement can be checked by rolling a loaded vehicle over it. For the vehicles and loads expected, differential vertical movement should be no more than about 0.020 in. (0.5 mm), which can be easily felt by placing a hand across a joint. The amount of gap between the curled slab bottom and the subgrade can be determined by taking a small core and seeing how far it drops. One potential condition to be aware of is that edges and construction joints can have the appearance of excessive curl but are in reality a combination of normal curl and improper slab finishing; such finishing can result in dishing out of the surface in these locations. This can be determined by checking for vertical movement under load and/or taking a small core.

How can curled slabs be remediated?

For slabs with significant vehicular traffic and joint vertical movement, the void under the slabs should be pressure-grouted. Large voids can be grouted with cement, water, and perhaps a pozzolan or fine sand. Grout for medium voids would definitely not have fine sand. Voids that are small, but still allow excessive joint or crack movement, can be grouted with an appropriate chemical grout. When there are voids and a soft cohesive soil (such as clay or silt), pressure grouting may have to be supplemented with retrofitted dowels. Care must be taken during pressure-grouting so that the slabs are not lifted significantly, thereby making the problem worse. After grouting is complete, if the curl is too great for the intended use of the slab, the curl must be milled down. For slabs without vehicles, but with objectionable curl, milling and perhaps one or more other remedies may be needed.

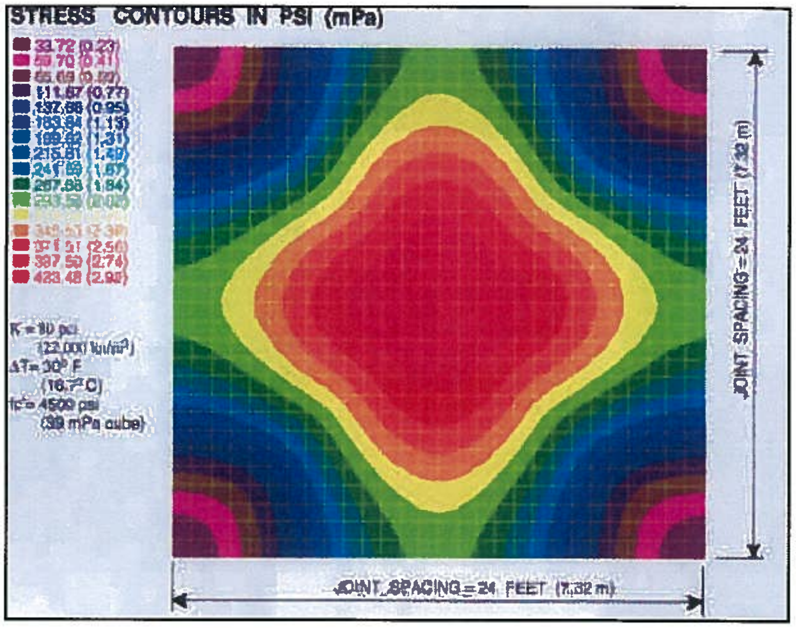

Fig. 2 — Curling stresses for a 6 in. (150 mm) thick slab)

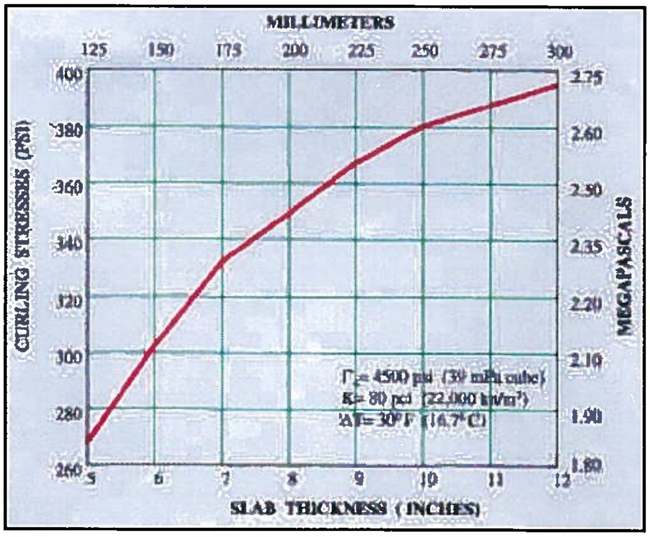

Fig. 3 — Curling stresses for slabs with joint spacing equal to 36

Other remedies for excessive curl generally have not been as satisfactory as those noted. Sawcutting full depth parallel to and back 2 to 8 ft (0.6 to 2.4 m) on both sides of the curled joint can lessen the curl somewhat, but it introduces two more joints that could spall or cause other problems. Furthermore, this remedy sometimes has resulted in two long, narrow strips that rocked excessively. Some have tried to reduce curl by keeping the slab wet for a period of time. This was partially successful while it was wet, but when it dried out again, the curl was the same as before. Application of an impervious surface material (such as a coating or rubber flooring) has been more successful, but if the vapor transmission rate is too high, the surface material may fail or have other problems.

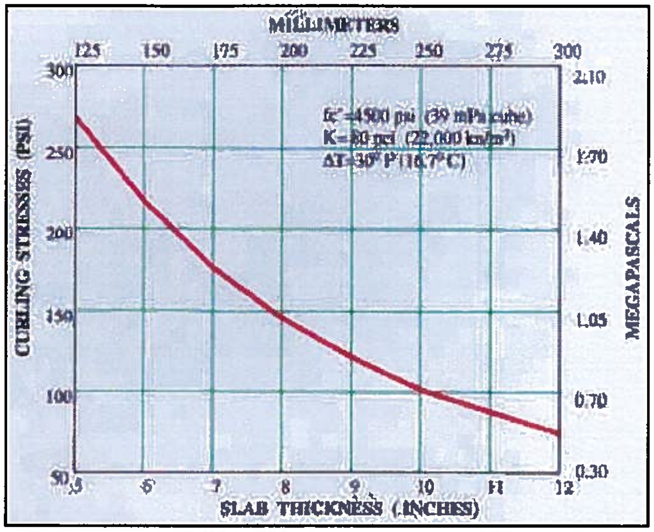

Fig. 4 — Curling stress for slabs with a joint spacing of 15 ft (4.6m)

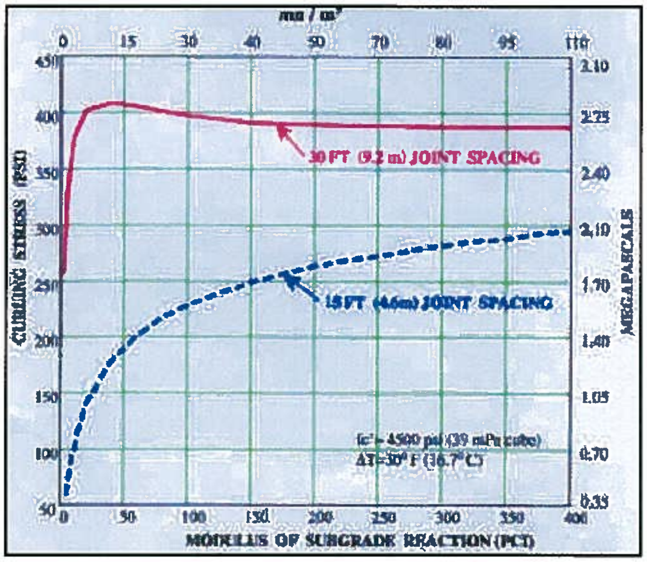

Fig. 5 — Curling stresses for a 6 in. (150 mm) thick slab on an increasing modulus of subgrade reaction

Analysis results

Some of the causes, effects, interaction of different factors, and implications of slab curling, can be best understood by reviewing the following figures and commentary developed from our analysis.

Figure 1: The slab's bottom presses into the ground due to its own weight. The maximum slab deflection into the ground occurs near the cantilever's edge. The deflection into the ground lessens towards the center of the slab, as the middle portion actually rises up somewhat. As curl increases, the cantilever distance increases, and the slab sinks further into the ground.

If a load is applied at the end of the cantilever, the flexural stress is increased dramatically as compared to a slab that has full contact with the ground. The applied load will cause the cantilever distance to decrease as slab deflects downward into the ground.

Note the obvious increased importance of proper dowel load transfer between the curled slab panels loaded at the edge (See article by authors on plate dowels in *Concrete International*, July 1998, pp 32 - 38).

The diagonal corner slab distance that is not in contact with the ground is approximately twice that of the centerline edge slab distance that is not in contact with the ground.

The gap under the slab's centerline edge is approximately 30 percent the gap under the slab's corner.

Figure 2: The highest curling stresses are over a large center area of the slab panel. This explains why almost all cracks typically called "shrinkage cracks" occur in the middle third of the slab width.

Approximately 36 percent of the slab area has a curling stress greater than 50 percent of the slab's flexural capacity.

The slab area that is not in contact with the ground is approaching 50 percent of the total slab panel area.

Figure 3: For slabs with a joint spacing of 36 times the thickness, the curling stress becomes increasingly more significant as slabs get thicker. For example, an 8 in. (200 mm) thick slab would have a curling stress of 350 psi (2.4 MPa), which is 58 percent of the flexural capacity of the slab (based on 9 $\sqrt{f_c}$). Thus, the joint spacing recommendation should not be a linear function proportional to the slab's thickness.

Figure 4: When the joint spacing is maintained at 15 ft (4.6 m), the curling stress is reduced as the slab thickness is increased (though not at a linear rate).

Figure 5: For all but very long joint spacings, as the modulus of subgrade reaction *K* increases (the soil provides stiffer support), the curling stresses go up. This is due to the slab not pressing into the supporting soil as much, thus increasing the length of the slab edge that is cantilevered.

When the slab joint spacing is 15 ft (4.6 m), the slab curling stress is not as sensitive to the value of the modulus of subgrade reaction as compared to a slab with a joint spacing of 30 ft (9.2 m).

The curling stresses for a slab with a joint spacing of 30 ft (9.2 m) are approximately double the curling stress for a slab with a joint spacing of 15 ft (4.6 m) for the common range of modulus of subgrade reaction values of 50 pci to 100 pci (15,000 to 30,000 kN/m^3).

For any commonly encountered modulus of subgrade reaction values, a joint spacing of 30 feet (9.2 m) will cause curling stresses of approximately 400 psi (2.8 MPa).

Figure 6: Shows that curling stress can be quite high for a 6-in. (150 mm) slab when the joint spacing reaches 24 ft (7.3 m). For example, a 6 in. (150 mm) thick slab with a compressive strength of 4500 psi (39 MPa cube strength) — as recommended by ACI 302 for a Class 6 floor, such as might be used in a warehouse or industrial facility — a reasonably high shrinkage potential and a joint spacing of 24 feet (7.3 m) has a curling stress of approximately 400 psi (2.8 MPa). The curling stress is approximately 66 percent of the uncracked flexural strength of the slab (based on 9 $\sqrt{f_c}$). This curling stress will not leave much flexural capacity to resist the applied loads. This capacity is further reduced due to the cantilever effect when a load is applied in areas at the slab's edges where the slab has lost contact with the ground.

The curling stresses are reduced for low concrete strengths with the same shrinkage potential because the modulus of elasticity is lower. Curling stresses for all concrete strengths and shrinkage potentials do not differ nearly so much as when the joint spacing is 15 ft (4.6 m). These curling stresses will be in the range of 175 to 225 psi (1.2 to 1.6 MPa).

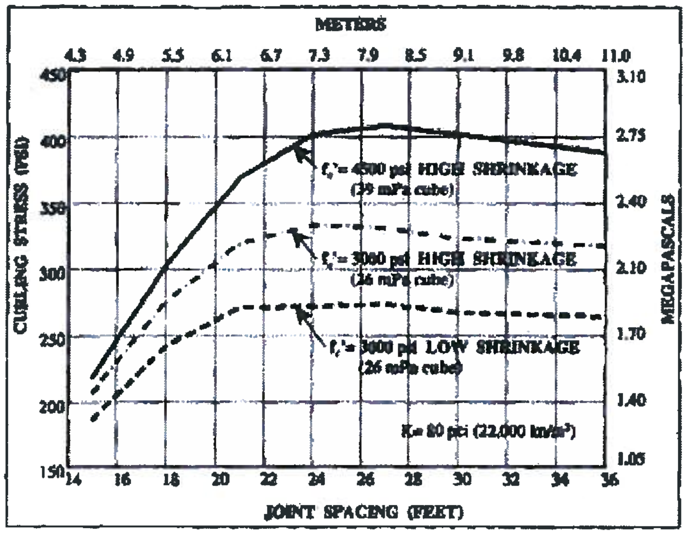

Fig. 6 — Curling stress for 6 in. (150 mm) thick slab with different shrinkage potential and joint spacing

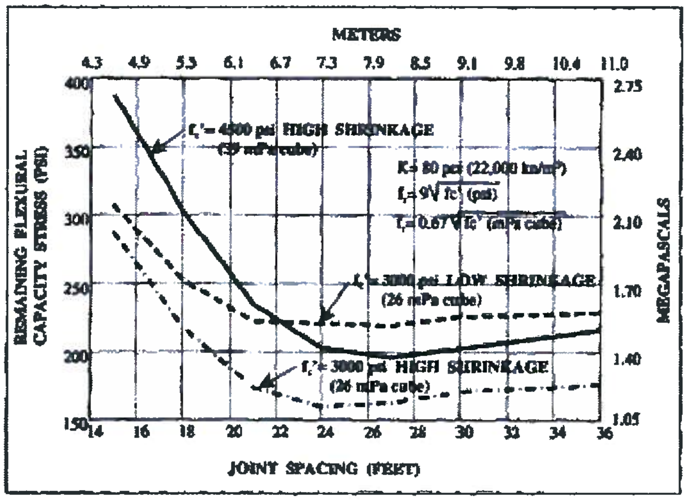

Fig. 7 — Remaining flexural capacity stress for a 6 in. (150 mm) thick slab with different shrinkage potential and joint spacing

Figure 7: For long joint spacings, a slab with a compressive strength of 3000 psi (26 MPa cube strength) and a low shrinkage potential will have a higher remaining flexural capacity than a slab with a compressive strength of 4500 psi (39 MPa cube strength) and higher shrinkage potential. This is because a higher strength concrete will have a higher modulus of elasticity and generally more shrinkage, both of which will increase the curling stresses, especially when the joint spacing is over 22 ft (6.7 m). Therefore, specifying a higher strength concrete in conjunction with long joint spacing can reduce the flexural load capacity of the slab, rather than increasing it.

For concrete with a reasonably high shrinkage potential and long joint spacings, the remaining flexural capacity for a slab with a compressive strength of 4500 psi (39 MPa cube strength) is only slightly higher than a slab with a compressive strength of 3000 psi (26 MPa cube strength). Furthermore, this small increase in the flexural capacity may not be cost effective.

Analysis procedure

A non-linear analysis was performed using a finite plate element supported on a compression-only spring foundation. To date, little experimental information on an enclosed building floor slab's shrinkage gradient is available. We typically used an equivalent shrinkage gradient of 30 F (17 C) between the top and bottom surfaces of the slab. The values obtained from the analysis using a shrinkage gradient of 30F (17 C) are representative of the field observations that the authors, the Portland Cement Association, and others,[3] have experienced. The initial shrinkage gradient may be somewhat higher than 30 F (17C) but is reduced due to concrete creep. We chose a typical value of 80 pci (22,000 kN/m³) for the modulus of subgrade reaction to calculate the curling stresses. This value is representative of many soils that are lightly loaded.

Future

The authors plan to publish a follow-up article in *Concrete International* giving other considerations concerning slab curl. It will include proposed joint spacing criteria, the effects of reinforcing amount and location, and other factors. One area of future research we hope others will consider is that of determining equivalent shrinkage gradients and related concerns.

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Selected for reader interest by the editors.

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