Much ado about Shrinkage

Strategies for reducing shrinkage cracking in flatwork

By Ken Hover

An inescapable fact of life is that concrete shrinks, but shrinkage alone is not much of a problem. The problem comes when the shrinking concrete is connected to fixed objects like walls, columns, adjacent slabs, concrete substrates, or the subgrade.

When that happens—when the shrinkage is restrained—tension stress develops in the concrete and as soon as the tension stress becomes greater than the tension strength of the concrete, the concrete cracks. So the problem is the "shrinkage cracks" not the shrinkage itself.

Solutions to the cracking problem include: reducing the shrinkage, reducing the restraint to shrinkage, increasing the tensile strength of concrete at the time the shrinkage occurs, delaying the shrinkage until the concrete is stronger, encouraging the cracks to form in acceptable locations, or accepting the inevitable and covering the slab with tile or carpet. We will revisit these strategies after exploring a few basics.

PHOTOS: KEN HOVER

Concrete does not like to stretch

Shrinkage is a volume change or "deformation" of the concrete. Although we commonly refer to the strength or load capacity of concrete, we less frequently refer to concrete's capacity to accept deformation without cracking, until we see unhappy evidence in the field that concrete's "strain capacity" has been exceeded. A crack is the proof that the concrete was stretched to its breaking point.

Let's take a 6x12-inch concrete cylinder and test it to compression failure at, say, 4000 psi. If we measure the cylinder during testing, we will observe that by the time the 12-inch-high cylinder was crushed it shortened by about $\frac{30}{1000}$ to $\frac{40}{1000}$ of an inch (30 to 40 mils, or the thickness of three to four sheets of 10-mil polyethylene).

Now, let's take that same 12-inch cylinder and pull on it until it cracks in tension. For most concrete, the tension strength is only about $\frac{1}{10}$ of the compression strength, or, in this example, about 400 psi. But we will discover through careful measurements that the 12-inch-long concrete specimen stretched only about $\frac{2}{1000}$ inch (2 mils) before cracking.

For most concrete, a crack (tension failure) is likely any time it is stretched in the range of $\frac{1}{1000}$ to $\frac{2}{1000}$ inch (1 to

Facing page: Fog spraying increases the humidity of the air above the concrete and slows the rate of evaporation at the concrete surface. Above: Application of a full wet cure with burlap and soaker hoses prevents drying until the concrete is strong enough to be able to resist shrinkage stresses.

2 mils) per foot of length. For all its general versatility, cost-effectiveness, and strength, concrete is a lot like a middle-aged person who just can't stretch like he used to!

But here's the kicker: Even though concrete cracks when it is stretched more than 1 to 2 mils per foot, shrinkage can shorten concrete by as much as 5 to 10 mils per foot. If that shrinkage is restrained, it's the same thing as letting the concrete shrink freely and then stretching it back out to reattach it to whatever is resisting the shortening, and we know it can't stretch that much. When restrained concrete shrinks, something's got to give!

What causes shrinkage?

A concrete mix is a lot like a T-shirt. A T-shirt is often made of a blend of cotton and polyester, and concrete is a blend of paste and aggregate. Polyester is cheaper than cotton and it doesn't shrink very much. Cotton, on the other hand, is soft, porous, absorbent, expensive, and it shrinks like mad. In concrete the aggregates don't cost as much as the cement paste, while the paste is soft, porous, absorbent, expensive, and it shrinks as much as 1% of its initial volume in the first day after casting. When you buy a 100% cotton T-shirt you know that you need to buy it one or two sizes too large. When you buy concrete with a high cement paste content, you should know that is it likely to shrink—and probably crack.

Why does the paste shrink? First, a soft, moist paste drying in the sun will shrink and crack just like mud, and for the same reason: as water evaporates from a saturated clay or cement paste the remaining water develops a suction that draws the grains of solid material together. You can observe this with wet sand that shrinks and becomes "packable" like a snowball as it dries. As it continues to dry, the internal films of water that drew the sand grains together evaporate, and the drying sand expands and loses its cohesion. That is the reason surface drying cracks in concrete look just like mud cracks. Shrinkage caused by the loss of water is called "drying shrinkage," and any resulting cracks are called "drying shrinkage cracks."

Right: Use of an early entry saw to cut the concrete before early shrinkage stresses lead to cracking.
Below: A successful saw cut— early enough and deep enough to cause the concrete to crack in the desired location.

When drying shrinkage and the resulting cracking occur shortly after placement (while the concrete is still soft, or "plastic"), we use the terms *plastic shrinkage* and *plastic shrinkage cracking*. The difference between plastic and drying shrinkage is therefore only the condition of the concrete when the drying, shrinkage, and cracking occur. And the key to controlling them both is to find ways to reduce the rate of drying of the concrete.

But controlling or even eliminating drying will not, unfortunately, eliminate shrinkage. The hydration of portland cement, even in a fully sealed or saturated environment, leads to a volume reduction of the cement paste in a series of mechanisms often referred to as *chemical* or *autogenous shrinkage*. The volume of the final products of hydration is less than the initial volume of the cement and water that reacted. Further, the hydrating cement consumes water, drying or self-desiccating the concrete from the inside. The overall shrinkage experienced by the concrete is the combined effect of drying shrinkage, plastic shrinkage, and the chemical shrinkage that accompanies hydration. The type of shrinkage that predominates depends on the mix, materials, and drying conditions.

Chemical shrinkage begins as soon as the cement comes in contact with the water. Pure cement-and-water pastes have been shown to shrink by as much as 1% of their initial volume within the first 24 hours. During the first few hours after mixing, chemical shrinkage of the paste can be the predominant cause of the shrinkage of the concrete, especially when the contractor is taking care to minimize drying. The potential for chemical shrinkage varies with the cement used, but for any given cement, the influence of chemical shrinkage on the overall shrinkage of the concrete will increase with higher paste contents.

Can we predict shrinkage?

Without mix-specific test data and reliable information about the jobsite environment, about all we can predict with confidence is that the concrete will shrink, and that it will crack when shrinkage stress becomes greater than tensile strength. The complicating factors that limit the precision we can bring to predicting shrinkage include:

- mixture variables like actual water content, paste content, cement composition and fineness
- cleanliness of the aggregates
- surface-to-volume ratio of the shrinking concrete
- restraint to shrinkage
- in-place temperature history of the concrete
- ambient weather conditions

ACI Committee 209 suggests that the long-term total shrinkage might vary from ½ to 1¼ inches per 100 feet, and that the factors affecting the rate of shrinkage are so variable that it could take from two weeks to more than six months to experience the first half of the total shrinkage. When it comes to a hands-on prediction of shrinkage, "floormeister" Alan Face's dictum No. 1 is that "every 20 feet of concrete is looking for ⅛ to ¼ inch of shrinkage." Considering the combination of hydration, chemical shrinkage, plastic shrinkage, and drying shrinkage that occurs in concrete, Face's dictum No. 2 is that "wild things are happening in the concrete in the hours immediately following placement."

The mix matters

In general, high-quality, clean aggregates exhibit negligible volume change with wetting and drying. Aggregates that pick up a clay, silt, or dust layer, however, can significantly increase shrinkage. ACI 209 says aggregate size is the most important factor, because the smaller the aggregate, the greater the paste volume—and the paste is the high-shrinkage component.

When contractors opt for ¾-inch stone when 1-inch would work, or 1-inch stone instead of 1½-inch, the payoff is higher workability, but at a cost of higher paste content and more shrinkage. Or, when a target water/cement (w-c) ratio is reached by increasing cement content instead of re-engineering the mix to reduce water content while still preserving workability, the cost is higher paste content and more shrinkage.

Thin, low-permeability overlays have a high shrinkage potential due to the double effect of small coarse aggregates and low w/c. Fortunately, mix design techniques are available to lower water content for these types of placements to minimize shrinkage. Shrinkage also generally increases with water content (all else being equal). When higher slumps are achieved with water at the plant or onsite, the net result is often higher shrinkage.

How and when to limit drying

Chemical shrinkage starts as soon as the water hits the cement. The surface drying that initiates plastic and drying shrinkage starts as soon as the concrete surface begins to dry, which is as soon as the rate of evaporation exceeds the rate of bleeding (to estimate the rate of bleeding, get a copy of Figure 1 in ACI 308). This is why many high-performance concrete mixtures are particularly vulnerable to plastic shrinkage cracking. The same mix characteristics that make it hard for water to penetrate into the hardened concrete make it tough for the bleed water to get out. A low or zero bleeding rate means a low or zero tolerance for evaporation before the surface starts to dry.

Controlling the early shrinkage and cracking caused by drying may require the use of wind breaks, sunshades, evaporation reducers, and fog spraying, followed by application of a membrane-forming curing compound immediately behind the last pass of the finishing tool. Once final set has been reached, a serious water cure can be applied. Depending on the weather, it may be necessary to shift the start time of concrete placement to find less hostile conditions.

Beat the crack

Preventing or delaying drying can be effective at controlling drying shrinkage cracking. As the concrete sets and hardens, three competing mechanisms are set in motion:

- Hydration of cement in combination with loss of water due to drying causes the concrete to start shrinking. If it is restrained it starts to be stretched.
- At the same time the concrete is getting stiffer. The stiffer it is, the more tension stress that is produced for any given amount of shrinkage (stretching).
- Meanwhile, the concrete's resistance to cracking is growing in the form of slowly developing tension strength.

Ultimately, the race comes down to two horses: If shrinkage stress gets out ahead of tension strength, the concrete cracks. If tension strength gain outpaces shrinkage stress, the concrete still shrinks but it does not crack.

While this sounds pretty straightforward, the race gets more complicated. The factors that dictate how fast shrinkage, stress, and strength develop include mix ingredients and proportions, air temperature, concrete temperature, humidity, wind speed, sunshine, finishing technique, and slab surface texture. Reliably predicting the effect of these factors is tough, and piecing them together afterward to try to explain why one slab cracked and another did not is even tougher.

Two strategies are generally effective for dealing with the race between shrinkage stress and tension strength. The first is to delay drying and shrinkage while you encourage strength gain of the concrete. This is accomplished by conscientious curing and temperature control. The other strategy is to assume that the cracks will win the race and to encourage the cracks to form where you can live with them.

Sawcutting the slab

Sawcuts intentionally weaken the concrete in pre-selected locations in an attempt to force shrinkage cracks to occur at those locations. The neat line of the sawcut across the slab is more visually acceptable than a zigzagging random crack, and the sawcut crack is more readily treated with joint filler material if required. The keys to a successful sawcut are cutting deeply enough to significantly weaken the concrete, and cutting soon enough to weaken the slab before the shrinkage stresses build to the breaking point.

As for depth, we all know that for a brittle material like glass or fired clay brick, we need only a shallow scratch on the surface to initiate a full-depth crack. Concrete is not as brittle as glass or brick, especially in its early stages of development, nor is the tension strength of concrete as uniform. As a result, the depth of the sawcut has to be in the range of ¼ of the depth of the slab to make sure that the weakest zone in the neighborhood is at the sawcut joint. When the slab goes into tension because of shrinkage, the concrete will effectively seek out the weakest spots, and connect them together with a crack.

The other key to sawcutting success is to saw as soon as the concrete can bear the weight of the saw and permit a good, clean cut. The early-entry saws have met this need and helped many contractors to "beat the crack." The best advice for sawcutting is just like for voting: "early and often." ■

— Kenneth C. Hover, Ph.D., P.E. is a structural/materials engineer and professor of structural engineering at Cornell University, Ithaca, N.Y. An active member of numerous ACI committees, he is also a popular speaker at Hanley Wood's World of Concrete.

Shrinkage cracking control strategies

To reduce shrinkage potential of the mixture, use
- Larger aggregate
- More aggregate
- Shrinkage-compensating cement
- Lower chemical shrinkage cement
- Lower water content
- Lower slump
- Cleaner aggregate
- Low-shrinkage aggregate
- Shrinkage-reducing admixture (SRA)

To reduce drying potential of the environment,
- Use sun shades
- Use wind screens
- Wait until dark
- Wait for more humid air
- Fog spray
- Use evaporation reducer (not finishing aid)
- Use intermediate cure
- Use initial cure
- Use final cure

To delay shrinkage to give strength a head start,
- Start curing and protection early

To augment the tension strength of the concrete, use
- Reinforcing mesh properly chaired
- Reinforcing bars
- Reinforcing details at corners
- Steel or synthetic fibers

To beat the crack, weaken the slab by
- Sawcutting
- Using early-entry saws
- Closely spacing the joints

To reduce restraint
- Carefully detail reinforcing and joints to accommodate movement
- Place concrete on a flat subbase
- Use a slick vapor barrier under the concrete

To prepare for the inevitable
- Don't expect and don't promise crack-free concrete without careful planning and cost considerations