# Why Slabs Curl

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

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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.

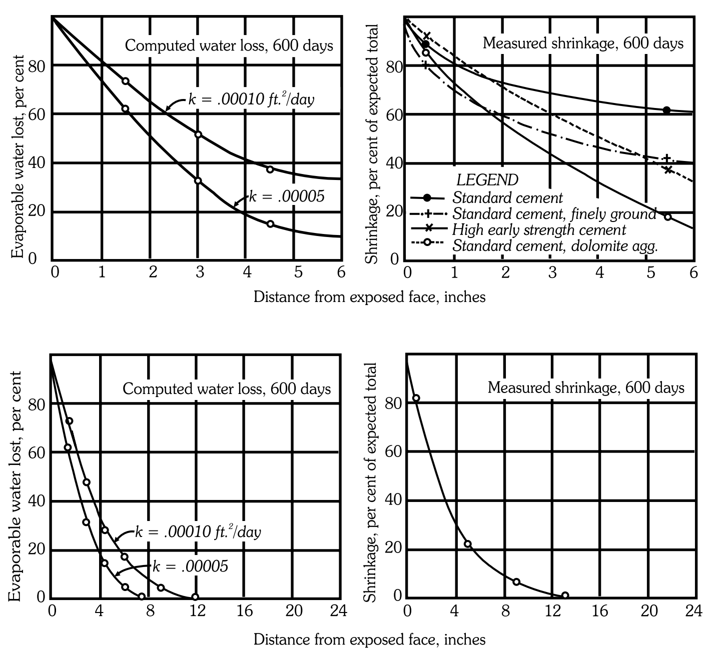


Fig. 1: Comparison between computed distribution of drying and measured distribution of shrinkage in 6-in. (152 mm) cubes of concrete drying from one face only (From Reference 2)

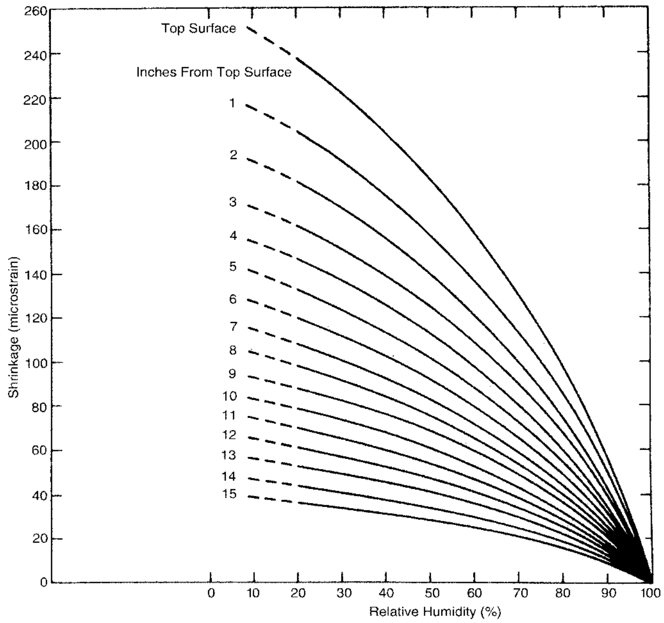


Fig. 2: One year of shrinkage data for a 15-in.-thick (380 mm) slab as a function of relative humidity with only the top surface exposed to drying (From Reference 3)

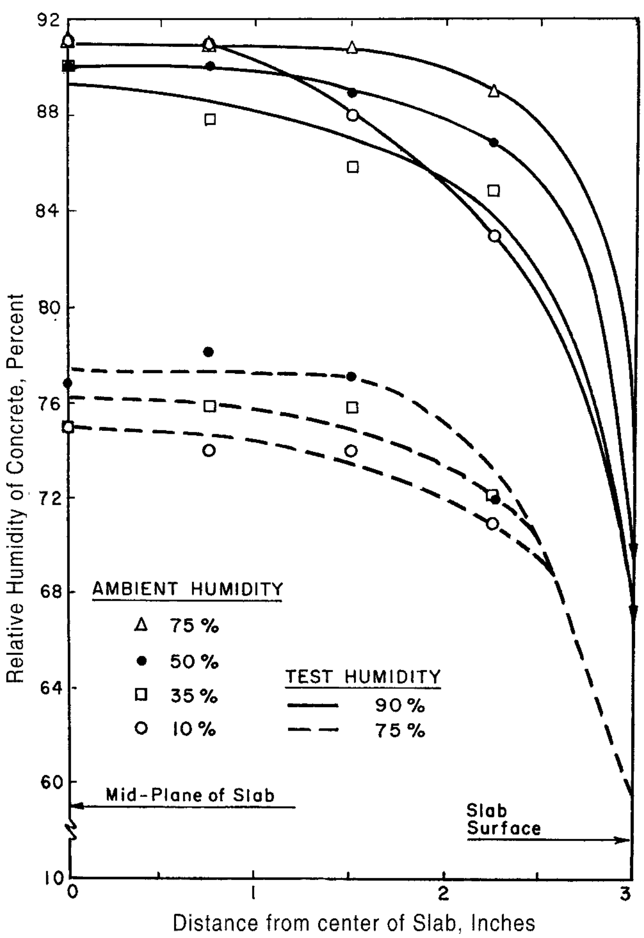


Fig. 3: Effect of ambient humidity on humidity gradient through slab sections (From Reference 4)

## 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.

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.

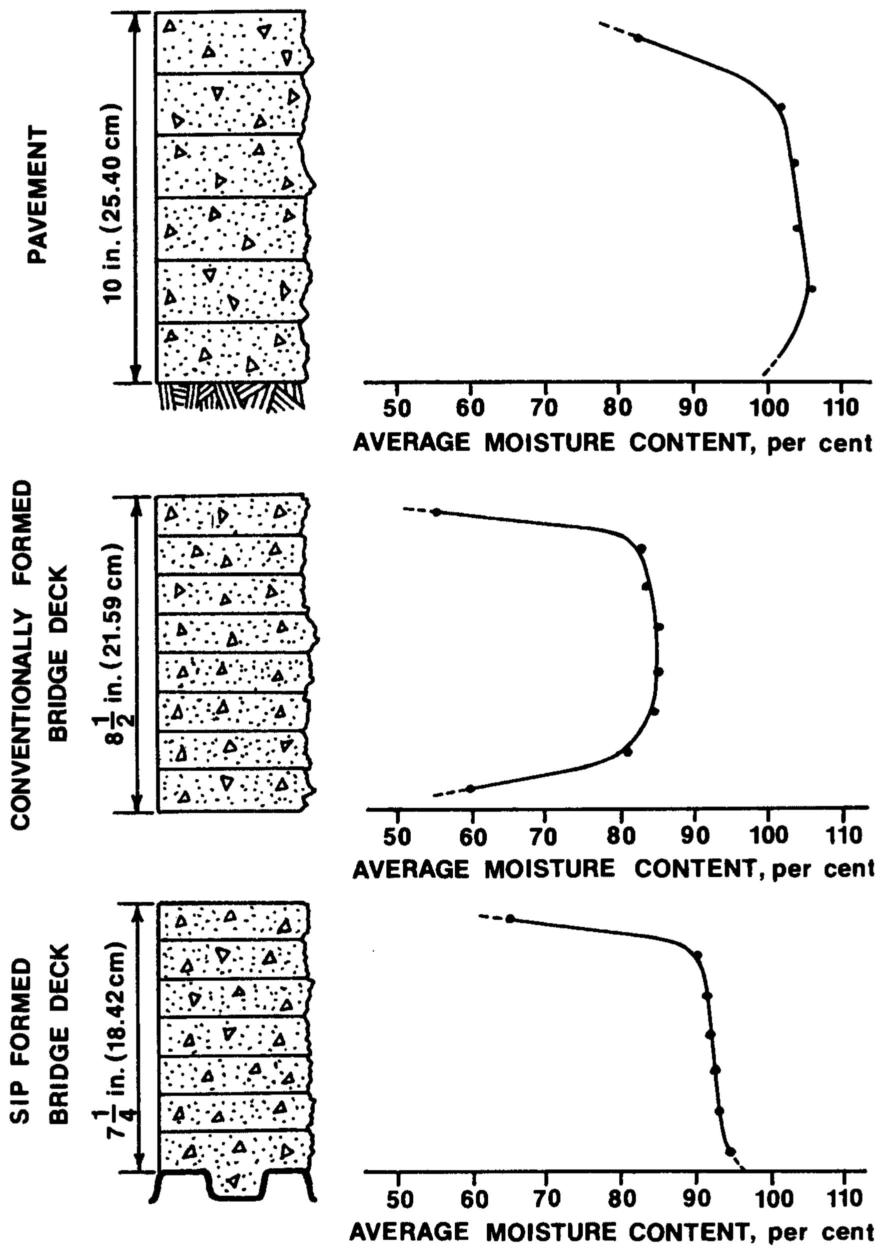

Fig. 4: Moisture distribution in a pavement and in bridge decks (From Reference 6)

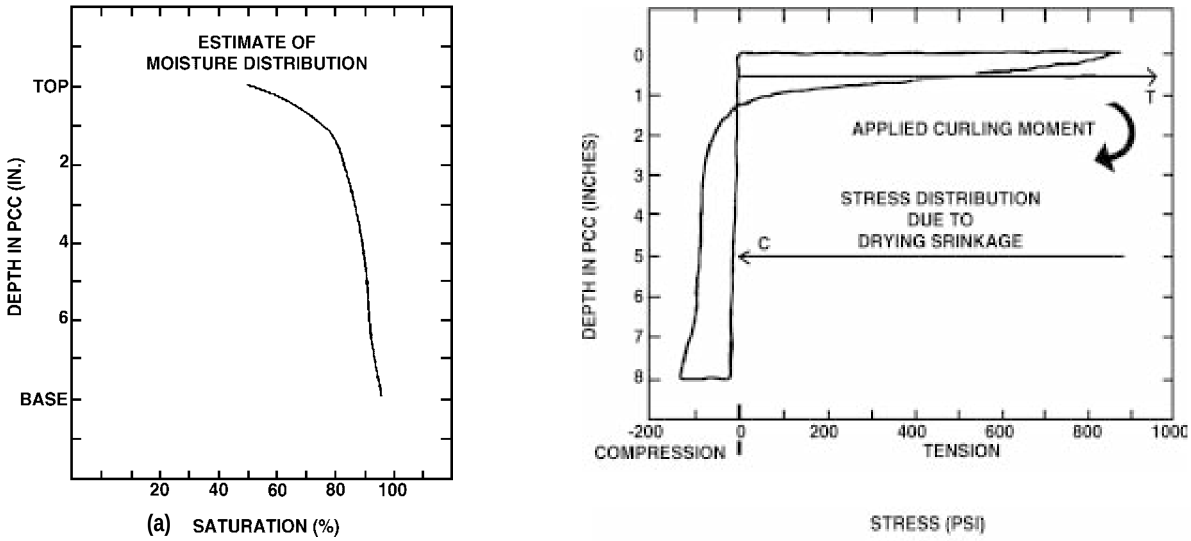


Fig. 5: (a) Estimate of moisture distribution for an 8-in.-thick (200 mm) pavement; (b) The stress distribution due to the moisture gradient. Arrows show the resulting applied curling moment (Modified from Reference 7)

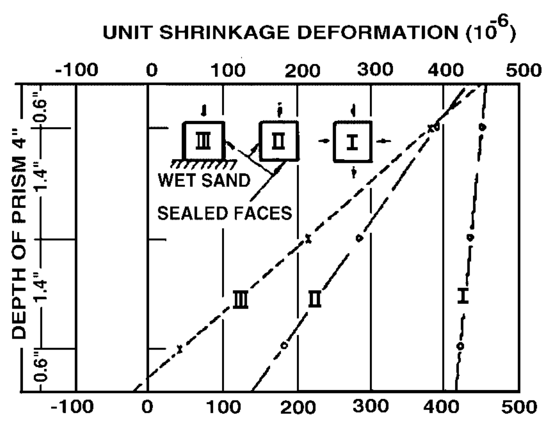


Fig. 6: Distribution of unit shrinkage deformation in prisms under different drying conditions (From Reference 9)

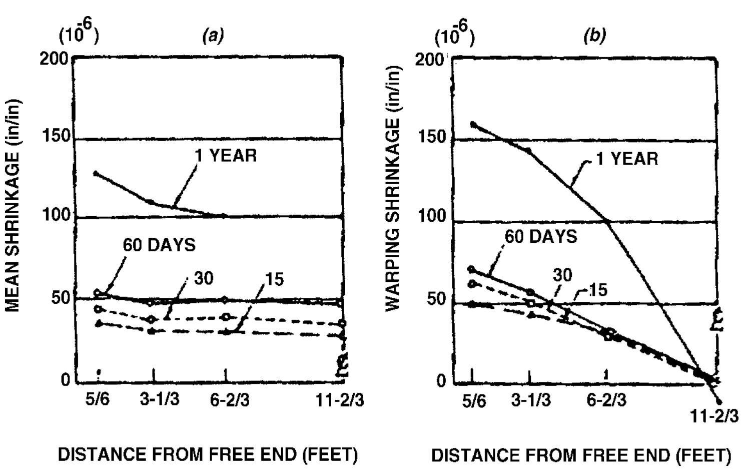


Fig. 7: (a) Mean shrinkage through the depth of pavement sections; and (b) warping shrinkage at the surface of each section (From Reference 9)

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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