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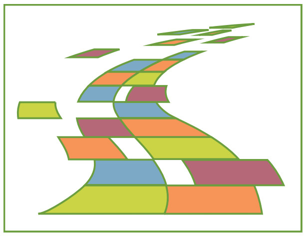

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ROAD MAP TRACK 7

PROJECT TITLE
Concrete Pavement Curling and Warping: Observations and Mitigation

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Moving Advancements into Practice (MAP) Briefs describe innovative research and promising technologies that can be used now to enhance concrete paving practices. The April 2015 MAP Brief provides information relevant to Track 7 of the CP Road Map: 7.Concrete Pavement Maintenance and Preservation.

This MAP Brief is available at www.cproadmap.org/publications/MAPbriefApril2015.pdf.

“Moving Advancements into Practice”

MAP Brief April 2015

Describing promising technologies that can be used now to enhance concrete paving practices

Concrete Pavement Curling and Warping: Observations and Mitigation

Introduction

With today’s modern concrete paving technologies, including use of optimized concrete mixtures, stringless paving and real-time smoothness measurements, the opportunity exists to construct the smoothest concrete pavements in history. Paving projects with International Roughness Index (IRI) measurements of less than 50 in/mile have become commonplace in some locations as contractors respond to the need for smooth pavements demanded by transportation agencies and the traveling public.

Yet, a trend has been observed on some projects where concrete pavement roughness increased within months of construction and continued to increase in the coming years even in the absence of distress (e.g. cracking, spalling, faulting, etc.). It is believed that this increase in roughness is largely related to differential volumetric changes in the concrete itself, resulting in individual concrete slabs developing upward curvature under the influence of climatic factors.

This MAP Brief describes research that has observed the occurrence of this curvature, the mechanisms thought to be responsible, and strategies that can be employed to mitigate it.

The problem

An evaluation of data collected on the Arizona LTPP SPS-2 site clearly shows the influence of concrete slab curvature (ascribed to curl and warp) on the development of roughness (Karamihas and Senn 2012). For concrete pavements, curling is defined as curvature induced in the concrete pavement slab as a result of a temperature gradient, in which the surface of the slab has a temperature that is different from that at the bottom. If the top of the slab is warmer (daytime conditions), a downward curvature will develop as the top expands relative to the bottom. The opposite occurs at night when the slab surface is cooler than the bottom and the slab develops upward curl. As the temperature gradient typically cycles once in the course of a day, the effects are often referred to as diurnal.

Warping, on the other hand, is curvature in the slab that is induced due to a moisture gradient. After the slab is cast, the surface begins to dry and eventually undergoes wetting and drying cycles depending on the local environment. The bottom of the slab often remains near or at saturation. As a result, the warping induced curvature is almost always upward, and will increase with time due to the mechanisms discussed later. Figure 1 illustrates these two similar, but separate phenomena.

Karamihas and Senn (2012) studied the development of slab curvature and its influence on ride quality as defined by the IRI. As summarized in a Tech Brief (FHWA 2013), they concluded that “long-term increases in IRI may be caused solely by changes in curl and warp and do not necessarily indicate structural failure or increased surface distress.” They also observed that temperature variations and sunlight explain relatively small daily changes in curvature, but that these daily changes did not impact the overall trend towards increasing upward curvature over the life to the experiment (approximately 17 years at the time of the analysis).

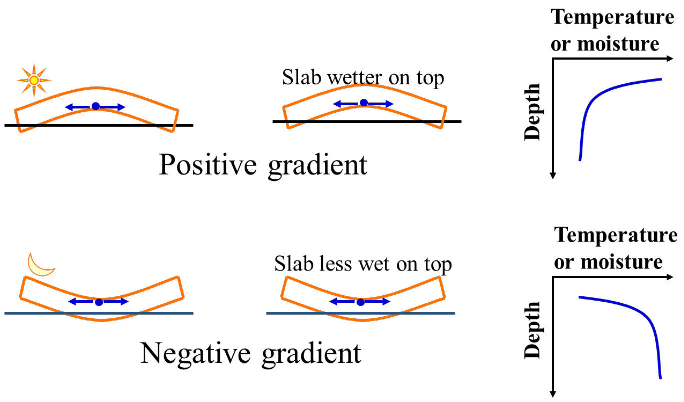

Figure 1. Illustration of curvature due to temperature curling and moisture warping (Mack 2009)

In the analysis presented by Karamihas and Senn (2012), section 040215 is quite revealing. This section is a typical jointed plain concrete pavement being 11 inches thick on 6 inches of dense-graded aggregate base with 15 ft joint spacing and a 12 ft width. Figure 2 is a plot of the change in IRI with age, showing a steady increase in the IRI until about Year 10 and then it stabilizes. Figure 2 also shows the high degree of variability in the data from wheel path to wheel path and even in the same wheel path on the same day. During the analysis period, no distress was observed and faulting was less than 0.05 inches. Yet the IRI increased from an average of 90 in/mile for both wheel paths at 4 months and 124 in/mile in just over 16 years.

Detailed analysis of the profile data allowed the researchers to separate out the changes in IRI due to curvature. An example from the left wheel path of section 040215 is plotted in Figure 3. It shows that ALL of the IRI increases over the 16 years of service were due to increasing curvature and that almost all of the daily and seasonal variability in the measured profile was also due to the curvature. Because section 040215 is in the LTPP seasonal monitoring program (SMP), considerable profiling data was collected including in the morning and afternoon of the same day. This allowed for Karamihas and Senn (2012) to separate out diurnal curvature due to temperature curling from long-term upward curvature which is most closely linked to moisture warping. This analysis found that long-term increases in curvature most closely associated with moisture warping resulted in an average net increase in IRI of 37 in/mile whereas the range in IRI differences due to diurnal temperature curling were on the order of 10 in/mile.

Although there is considerable variability in the data, other trends observed in the Arizona SPS 2 data included the following:

- Increases in IRI due to curvature were often less at the second inspection (approximately 18 months after construction) than the first inspection (approximately 4 months after construction) suggesting that the slab initially curled upward and then flattened out
- Curvature continued to increase, contributing to an increase in IRI for the next 4 to 10 years depending on the section.
- At some age, long-term curvature appears to stabilize and further increases in IRI were linked to the development of distress, particularly in the thinner concrete sections

The study by Karamihas and Senn (2012) only evaluated SPS-2 sites in Arizona (a very dry climate) and a broader study is currently underway examining whether the same trends are observed in other SPS sites. Yet evidence in practice suggests that concrete pavements increase in roughness at early ages absent the development of distress and IRI becomes a controlling factor in design. Based on this knowledge, if long-term slab curvature can be reduced, concrete pavement performance will be enhanced.

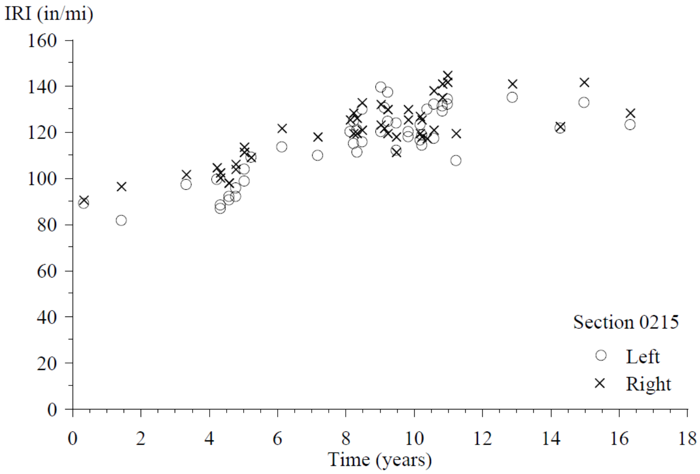

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Figure 2. IRI progression for section 040215 (Karamihas and Senn 2011)

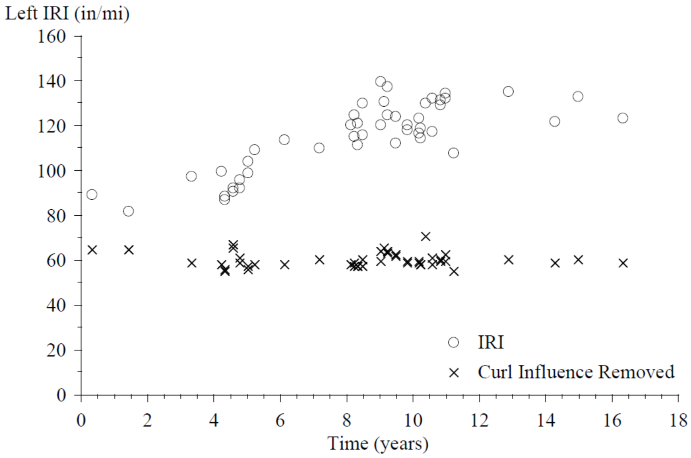

Figure 3. IRI progression in left wheel path for section 040215, with and without the influence of slab curvature (Karamihas and Senn 2011).

Drying shrinkage

The development of long-term slab curvature is largely controlled by the drying shrinkage characteristics of the concrete. As the top of the slab dries and undergoes cycles of wetting and drying, the bottom of the slab remains near or at saturation. As illustrated in Figure 4, concrete shrinks as it dries. Upon rewetting, it gains back some of this shrinkage (known as recoverable shrinkage), yet some of the shrinkage is permanently lost (irreversible shrinkage).

Equally important, as illustrated in Figure 5, as concrete undergoes cycles of wetting and drying, the irreversible shrinkage continues to accrue, with small increments of irreversible shrinkage added at each drying cycle. This behavior is critical to the development of long-term curvature as the surface of a concrete slab in-service undergoes multiply wetting and drying cycles throughout the year and year after year. Under these conditions, the surface continues to accrue increments of irreversible shrink until the ultimate shrinkage for the ambient conditions is reached.

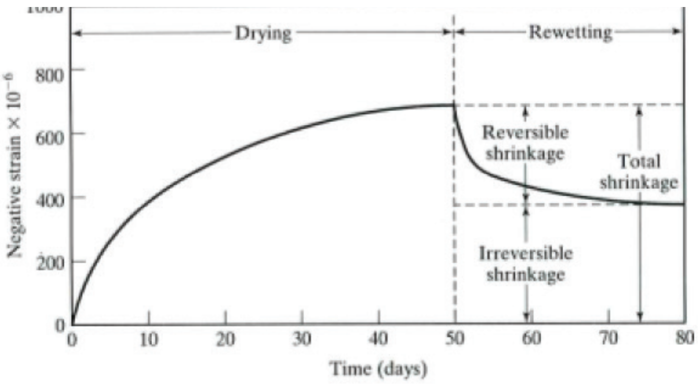

Figure 4. Components of drying shrinkage (Mindess, Young, and Darwin 2003)

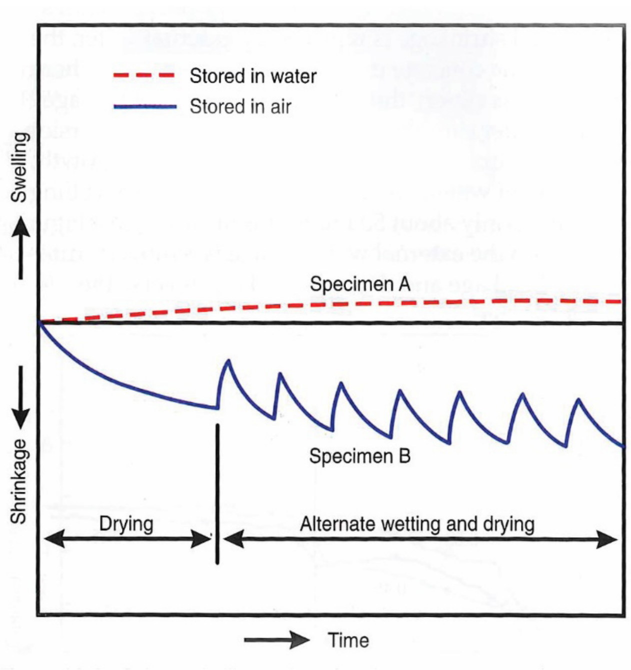

Figure 5. Long-term shrinkage under alternate wetting and drying (Kosmatka and Wilson 2011)

Mitigation Strategies

It is impossible to significantly affect the development of the moisture gradient or conditioning of a slab on ground as the bottom is often near or at saturation and the top will continually undergo wetting and drying cycles depending on ambient conditions. Thus, the only viable approaches to mitigate the negative impacts of long-term slab curvature on pavement IRI are:

- Alter the concrete constituents to reduce the ultimate drying shrinkage.
- Establish better curing practices that minimize moisture loss at early ages.
- Use concrete pavement design elements that minimize the impact of long-term curvature on ride quality.

Mixture Constituents

With regards to mixture constituents, the most important factor affecting drying shrinkage is the amount of water added per unit volume of concrete (Kosmatka and Wilson 2011). The volume of water is most closely related to the overall cementitious materials content (paste content) of the concrete and the water-to-cementitious ratio (w/cm). For a given w/cm, reducing the cementitious materials content through increasing aggregate volume will reduce the ultimate shrinkage of the concrete, not only because of the reduction in water but also because aggregates provide internal resistance to shrinkage.

Water is also reduced for a given cementitious materials content by reducing the w/cm; but there is a limit as the w/cm of paving concrete should not be reduced much below 0.42 as autogenous shrinkage (due to chemical shrinkage and self-drying of the paste as water is consumed in hydration) becomes prominent (Kosmatka and Wilson 2011). In recent years, shrinkage-reducing admixtures (SRAs) have been developed that can significantly reduce drying shrinkage in concrete. Yet SRAs have not seen widespread use in pavements due to their high cost and unproven long-term effectiveness in pavement applications.

Other properties of mixture constituents are also influential with regards to drying shrinkage including the fineness of the cement, the type and volume of supplementary cementitious materials, the nature of the aggregates, and some admixtures (Kosmatka and Wilson 2011). Saturated lightweight aggregates (SLWA), discussed next under curing, can also be effective in reducing early age shrinkage by providing an internal source of curing water. As awareness of the importance of drying shrinkage increases, shrinkage testing (e.g. ASTM C157) should be considered as part of the mixture design process to help assess the drying shrinkage characteristics of proposed concrete mixtures.

Curing

Curing practices can influence the rate and magnitude of ultimate drying shrinkage (Kosmatka and Wilson 2011). Proper use of effective membrane-forming curing compounds that hold free moisture in the concrete for long periods of time and wet curing methods delay the onset of shrinkage, although their impact on ultimate drying shrinkage is less clear. Recent research has suggested that wet curing can actually increase warping in concrete slabs and thus might not be the best approach for curing slabs in dry environments (Hajibabaee and Ley 2015).

Temperature also plays a role as cool initial curing temperatures can reduce ultimate shrinkage for a given mixture (Kosmatka and Wilson 2011). The use of SLWA has shown promise to improve curing and reduce ultimate drying shrinkage in concrete, but additional work is needed to determine the effectiveness of SLWA in reducing long-term upward curvature in concrete pavements.

Design elements

The use of shorter slabs, dowelled joints, and bonding of the concrete slab to an underlying stabilized base are design elements that can help mitigate the magnitude of long-term upward curvature in jointed concrete pavements, reducing its impact on IRI. Note that all design elements must be considered together to address the anticipated traffic and site-specific environmental conditions.

Alternatively, the elimination of transverse joints through the use of continuously reinforced concrete pavement (CRCP) is quite effective at minimizing upward curvature as the effective slab length is very short, being the distance between the naturally occurring transverse cracks (e.g., 3 to 8 feet). As more understanding is gained regarding the impact of long-term curvature on IRI, the calibration of the AASHTOWare Pavement ME Design models may need to be adjusted to more fully account for changes in concrete material properties and design elements.

Conclusions

A study of Arizona LTPP SPS 2 data has observed that long-term upward slab curvature is an important contributor to increasing IRI of jointed concrete pavements in this environment. Although diurnal temperature effects played a role, the predominant mechanism contributing to the long-term upward curvature and loss of IRI is likely moisture warping that occurs as the surface of the concrete slab dries and undergoes wetting and drying cycles whereas the bottom remains near or at saturation.

Ultimate drying shrinkage of concrete is most closely linked to the amount of water added per unit volume of concrete, although other factors can contribute including other mixture constituents and curing practices. It is recommended that highway agencies assess the drying shrinkage of their concrete paving mixtures as part of the mixture design process to better understand how long-term drying shrinkage can be reduced. Pavement design elements that reduce slab length and provide restraint to upward curl can help mitigate the negative impact of drying shrinkage on IRI.

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