Cracking due to Curling Stresses in Concrete Slabs

1 Introduction

Very few writings on cracking systems and causes in concrete pavements have considered "curling stresses", as a possible major contributor to cracking. As part of the research for calculation of the required locations for longitudinal joints in full width paving, I have had to familiarize and evaluate the curling stress levels across the width of pavements.

2 Purpose

RTA Specifications prohibit any "unplanned" cracking in pavement slabs without regard to the likely reasons and the fact that the Specifications are 90% "method" and 10% "end product". The purpose of this PIN is to draw attention to the role of curling stresses in both short and long term cracking. It should be noted particularly that many of the causes are outside the control of the Contractor.

Please also refer to:

PIN 8 - Bleeding Notes
PIN 11 – Control of Thermal and Drying Shrinkage in LCSs
PIN 20 – The Importance of Factors Affecting Concrete Shrinkage, and
PIN 50 – Concrete Cracking and Heat of Hydration

Contractual Note
When some "unplanned" cracking has occurred and after diagnosing the reasons and type of the crack(s), this PIN may be made available to the IV/RTA Representative as an explanation for the disposition.

3 Curling Stresses

Differences in temperature between the top and bottom surfaces of the concrete slabs will cause the slabs to curl. Since the slab weight and contact with the subbase restrict its movement, stresses are created.

Substantial tensile stresses occur in the top of the slab from the edges curling up as gravity tries to pull them down. This, plus linear shrinkage can produce cracking. Often cracks that are attributed to shrinkage are actually due to a combination of curling and linear shrinkage stresses. Typically, the curling stresses are far greater than the linear shrinkage stresses.

Curling and linear shrinkage are intimately related and cannot be considered completely independent from each other. In fact, the linear shrinkage stresses could be of the order of 0.2 to 0.4 MPa compared to curling stresses of 1.4 to 2.8 MPa. Thus, the term "shrinkage crack" is not appropriate to pavement slabs and "curling crack" or "curling and shrinkage crack" would be a more accurate description.

Comparing these stresses with the typical range of concrete flexural stress capacity with the modulus of rupture of the order of 3.1 to 4.5 MPa, illustrates the significance of curling. Obviously, the slab load carrying capacity will be reduced also significantly by high curling stresses.

The reason that curling and shrinkage are more prominent today is that since the 1960s the design concrete compressive stresses have increased from 17 - 26 MPa to 34 - 43 MPa. The latter bracket is now common. Nowadays it is normal to get the 28 day strengths well in the 50 MPa range. (The Warringah Expressway pavement of 1968 had a concrete design strength of 17 MPa). Higher strength concrete generally shrinks more and always has a higher modulus of elasticity. The modulus 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.

4 Effect of "Poor" Practices

Anything that will increase or decrease shrinkage, will have the same effect on curl. This is illustrated by the following extracts from Ref 6:

Cumulative effect of adverse factors on shrinkage

Poor practices = Increased shrinkage	Equivalent shrinkage	Cumulative effect
Temp of concrete at placement 27°C instead of 16°C	8%	1.00 x 1.08 = 1.08
Excessive haul in transit mixer, too long waiting period at job site or too many revolutions at mixing speed	10%	1.08 x 1.10 = 1.19
Use of 19 mm max size aggregate instead of 38 mm	25%	1.19 x 1.25 = 1.49
Use of cement with high shrinkage characteristics	25%	1.49 x 1.25 = 1.86
Dirty aggregate due to insufficient washing or contamination during handling	25%	1.86 x 1.25 = 2.33
Use of aggregates with poor inherent quality with respect to shrinkage	50%	2.33 x 1.50 = 3.50
Use of admixture that produces high shrinkage	30%	3.50 x 1.30 = 4.55
TOTAL INCREASE (%)	**173%**	Cumulative = **355**

This table illustrates that in a worst case scenario there can be an increase of some 350% in the calculated curling stress. This means that it will become significantly greater than the design flexural strength and cracking will take place.

5 Points to Note

- The **water demand** of a mix at a given temperature is primarily a function of the ratio of the surface area per unit volume of the millions of particles that must be coated with the cement paste. 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 material required. Therefore the shrinkage is increased.

- As an example, a 45 kg sample of 38 to19 mm aggregate has a surface area of about 6.5 m^2, but an average grading sand will have a surface area of ~185 m^2. Obviously dirty aggregates make the problem much worse due to the increased fines plus the increased shrinkage potential of the dirt particles.

- Significant **bleeding** also exacerbates curl. It occurs because water is the lightest constituent in concrete and is displaced upwards as the heavier particles settle downward. This effect increases shrinkage in the top of the slab as compared to the bottom, thereby increasing the curl.

- Although **calcium chloride** is an inexpensive accelerator and can be used in appropriate situations, it will significantly increase shrinkage in both the short term and long term.

- 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 shrinkage and curling. Even though, the higher the strength the greater the surface durability, however, for road slabs the problem is to define what level of durability is required for unsurfaced and asphalt surfaced slabs.

- Literature suggests that for plain concrete slabs the joint spacing should not exceed **4.6 m**.
  When the joint spacing is kept below 4.6 m, the curling stress is reduced as the slab thickness increases.

- Both concrete and ambient **temperatures at placement** should be as low as feasible. In addition to minimizing shrinkage and surface drying, this will also reduce thermal contraction from cooling.

- It has been suggested that **0.5 mm** is the maximum differential vertical movement that can be tolerated.

- The **highest curling stresses** occur over a large central area of a slab panel. This explains why almost all cracks, typically called "shrinkage cracks" occur in the middle third of the slab width.

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

- The slab area that is **not in contact with the ground** (i.e. subbase) is approaching 50% of the total slab panel area...

- Curling **stresses are reduced** for low concrete strengths with the same shrinkage potential, because the modulus of elasticity is lower

- Specifying **a higher strength concrete** in conjunction longer joint spacings will reduce the flexural load capacity of the slab, rather than increasing it.

- Ref 6 has demonstrated that for concrete with reasonably high shrinkage potential and long joint spacings, the remaining flexural capacity for a slab with compressive strength of **39 MPa is only slightly higher than a slab with a compressive strength of 26 MPa.** This small increase in flexural capacity is unlikely to be cost effective

- Slab curling calculations seek to find the points of maximum tensile stress as the slab curls due to temperature gradients within. In 1935, measurements reported by Teller showed that the maximum temperature differential (hence, maximum curling and maximum tensile stress) is **much larger during the day** than during the night.

6 Summary

The following are curling stress issues in addition of to the cracking reasons given in the above PINs 8, 11, 20 and 50. To reduce the amount of curling (and curling stresses) the following factors, which are not all under the control of the Contractor, should be considered:

1. W/c kept as low as possible
2. Check design grading of fine aggregate whether the proportion can be reduced whilst it is still within the approved grading envelope
3. Note the effect of our small coarse aggregate vs the US 38 mm aggregate
4. Removal of proneness to bleed (exacerbates curling)
5. The effect of the ambient and placement temperatures
6. The serious detriment of having dirty aggregate (if it has to be washed twice, so be it)
7. The effect of admixtures (we need performance checks)
8. The very high compressive strengths nowadays required (RTA)
9. The need to keep heat of hydration down (maximum flyash)

References

1 FHWA **"Guidelines for Timing Construction Joint Sawing and Earliest Loading of Concrete Pavements"** Volume 1: Final Report (FHWA-RD-91-079) February 1994

2 Okamoto Paul A et al **"Guideline Recommendations for Timing Contraction Joint Sawing of PCC Highway Pavements",** Purdue Conference 1993

3 Pavement Interactive, **"Rigid Pavement Response"**

4 Tatsuo Nishizava et al **"Curling Stress Equation for Transverse Joint Edge of a Concrete Pavement Slab Based on Finite-Element Method Analysis",** Transportation Research Record 1525

5 Washington DoT, **"Curling Stress Calculation Example".**

6 Wayne W Walker and Jerry A Holland **"Though Shalt not Curl nor Crack ….. (hopefully)."** Concrete International, January 1999