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Top-Down Cracking of Jointed Plain Concrete Pavements

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Abstract: The principal mode of structural failure for jointed plain concrete pavements (JPCP) is fatigue cracking. The fatigue cracks initiating at the slab bottom under the edge loading condition were thought to be the only mode of failure. However, under certain combinations of exposure conditions and loading, the critical tensile stress can develop at the slab surface, causing the fatigue cracking to initiate from the top. A detailed evaluation of JPCP response showed that top-down cracking may indeed be the critical failure mode in many cases, but the magnitude of fatigue damage accumulating at the slab surface is very similar to that at the bottom of the slab. Therefore, the past practice of considering only bottom-up cracking is not likely to have resulted in significant prediction errors, especially since mechanistic performance models are typically calibrated with field performance data. Nevertheless, for improved design, consideration of both modes of failure is desirable.

Key Words: *top-down cracking, curling stress, temperature gradient, fatigue cracking*

1. INTRODUCTION

The principal mode of structural failure for JPCP is fatigue cracking. On highway pavements, the combination of pavement design and load configuration makes transverse cracking the critical failure mechanism. Although transverse cracking had long been recognized as the principal mode of fatigue failure on JPCP, the cracks initiating at the slab bottom under the edge loading condition (figure 1) were thought to be the only mode of failure. However, under certain combinations of exposure conditions and loading, the critical tensile stress can develop at the slab surface, causing the fatigue cracking to initiate from the top.

A detailed evaluation of structural response of JPCP showed that top-down cracking may indeed be the critical failure mode in many cases. However, the magnitude of fatigue damage accumulating at the slab surface is very similar to that at the bottom of the slab. Therefore, the past practice of considering only bottom-up cracking is not likely to have resulted in significant prediction errors, especially since mechanistic performance models are typically calibrated with field performance data. Nevertheless, for improved design reliability, consideration of both bottom-up and top-down modes of failure is desirable.

2. BACKGROUND

There are several reasons why the top-down mode of cracking had been overlooked in the past. The most common, perhaps, is that the stress under edge loading is much greater than that under any other loading conditions when a single slab is analyzed with a single load. The stress under edge loading is about twice that of the stresses under either corner or interior loading (figure 1). However, the simplified structural model shown in figure 1 ignores several factors that can significantly influence the maximum stress under the corner loading condition. A single slab under corner loading can rotate to relieve a significant portion of the applied load through rigid body motion. Under field conditions, a pavement slab is considerably restrained from this type of rotation by adjacent slabs. In addition, certain combinations of axles in heavy trucks place a load close to all corners of pavement slabs (figures 2 and 3), preventing slab rotation. The result is a substantially increased stress under the corner loading condition.

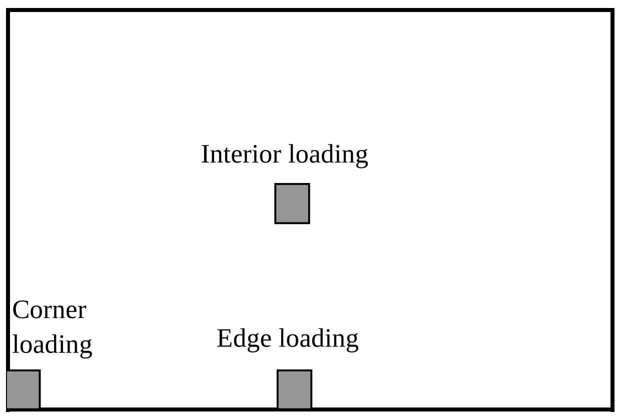

Figure 1 Critical loading conditions for JPCP

Another reason that top-down cracking had been neglected in the past is that corner loading was expected to cause corner breaks, not transverse cracks. For the most part, corner breaks on highway pavements occur only on nondoweled JPCP with skewed joints. Both pavement design factors and loading configuration contribute to the rare occurrence of corner breaks on inservice pavements. A single load placed at a corner of a single slab will produce stresses that would lead to corner breaks. However, corner loading as shown in figure 1 does not occur on real pavements because wheel loads on real pavements come in pairs as axle loads. The only exception is on JPCP with severely skewed joints. If transverse joints had no load transfer capacity, an axle load placed on a transverse edge with one of the wheels on the slab corner would cause the maximum tensile stress to develop between the wheels on the transverse joint. This would lead to longitudinal cracking. However, sufficient load transfer capacity is usually present across transverse joints on inservice pavements to minimize stresses along transverse joints, even on nondoweled pavements. The critical tensile stress, therefore, typically occurs along the longitudinal edge (lane–shoulder joint), and the resulting distress is transverse cracking.

Load transfer efficiency (LTE) across transverse joints also plays a role in making the top-down stress critical. Good LTE across transverse joints is important to reduce load stresses along the transverse joints; however, it can significantly increase top-down stresses along the longitudinal edge. High load transfer capacity enables the load placed on adjacent slabs to restrain rotation of the critical slab, greatly limiting the critical slab's ability to relieve stress through rigid body motion. For example, in figure 2, if LTE across transverse joint were zero, the single axle placed on the adjacent slab would have no effect on stresses in the middle slab. However, with good load transfer, the single axle on the adjacent slab can effectively restrain the rotation of the middle slab, resulting in higher stresses in the middle slab.

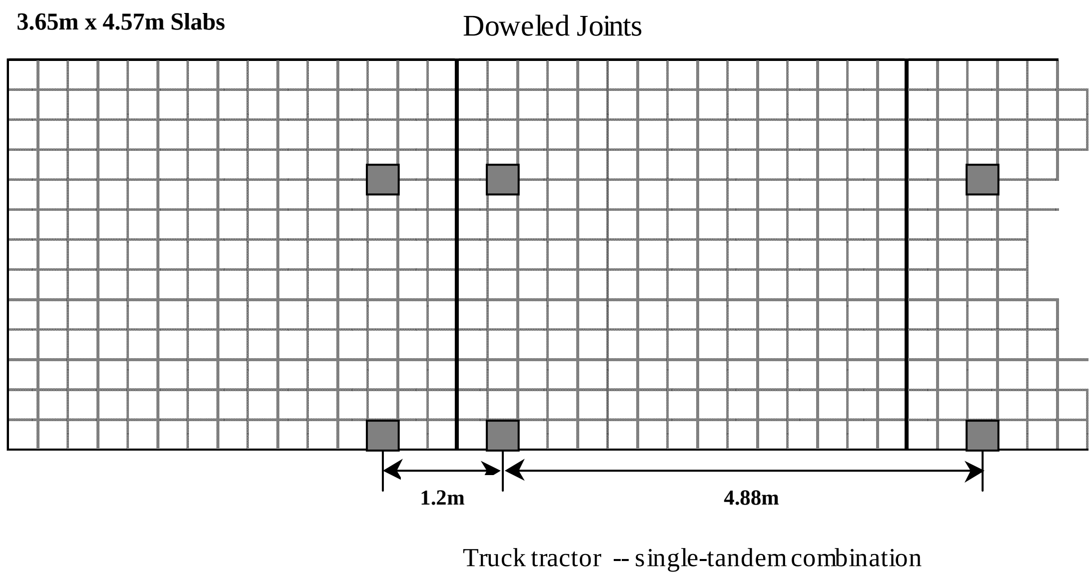

Figure 2 Critical loading condition for top-down cracking caused by a truck tractor, a single-tandem axle combination

Good LTE is usually beneficial in reducing stresses in the loaded slab because of the support provided by the adjacent slab. However, the effectiveness of good LTE is greatly diminished when slabs are loaded with tandem axles, because a tandem axle can be positioned to have an axle load on either side of a transverse joint. In some cases, it is possible for good LTE to cause a direct increase in stresses in the critical slab rather than a reduction, because the load from adjacent slabs could be transferred to the critical slab. In figure 3, for example, the critical top-down stress occurs in the middle slab; however, the two adjacent slabs have an axle load placed even closer to the corner than the middle slab. The result is a transfer of load from the adjacent slabs to the middle slab. The higher the LTE, the higher the amount of load transferred to the critical slab.

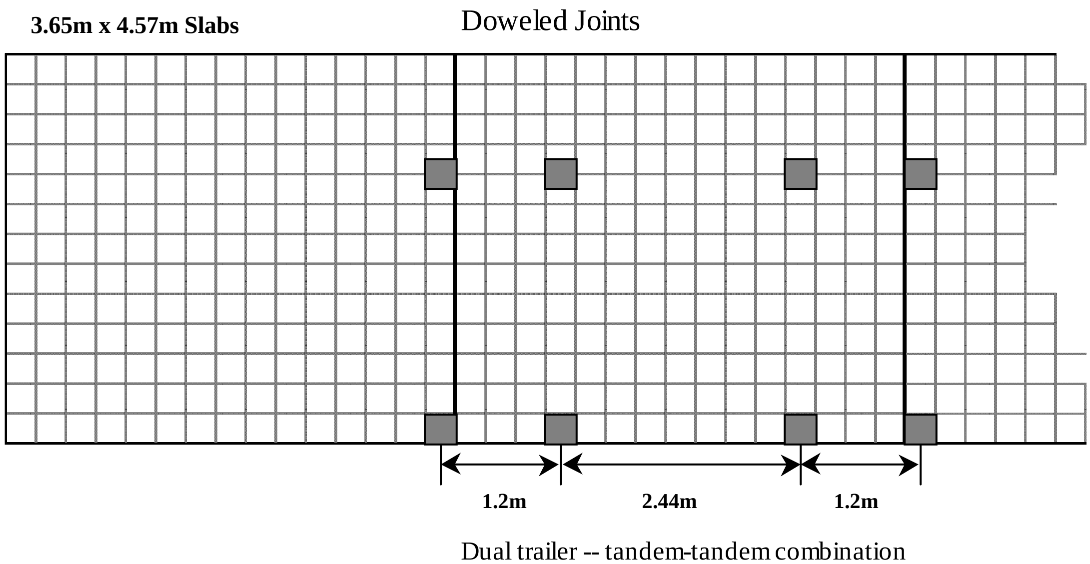

Figure 3 Critical loading condition for top-down cracking caused by dual trailer load, a tandem-tandem axle combination

Another major factor that can cause the corner-load stress to become critical is residual curling. Although the importance of curling stresses on concrete pavement performance is widely accepted, the fact that pavement slabs may not be flat under zero temperature gradient had not been given much consideration in the past. This is not to say that the presence of residual curling had been unknown. In 1987, Armaghani et al. reported that a positive temperature gradient of approximately 5 °C (9 °F) was required to flatten JPCP slabs in Florida. Performance studies of JPCP in Chile also showed the presence of high built-in upward curling in JPCP. Eisenmann and Leykauf (1990a; 1990b) studied the effects of construction temperatures and differential shrinkage on slab curling. They showed that residual curling caused by differential shrinkage can be represented in terms of an equivalent effective temperature gradient, and they developed a simple procedure for estimating the magnitude of curling caused by differential shrinkage.

Numerous factors can cause the pavement slabs to have a negative effective residual temperature gradient (i.e., pavement slabs are curled up under neutral temperature condition). One major source of the negative effective residual temperature gradient is the temperature gradient that is built into the pavement slabs. Whatever temperature gradient the slabs were exposed to while the concrete was plastic will show up in hardened slabs as an effective, built-in temperature gradient of the opposite sign. For example, if a pavement slab is exposed to +12 °C (22 °F) when the concrete hardened, the slab will curl up upon removal of this temperature gradient. The magnitude of curling will be the same as if the slab were exposed to a -12 °C (-22 °F) gradient. The slab will become flat again only when it is exposed to a +12 °C (22 °F) gradient. Effectively, the slab has a built-in negative temperature gradient of 12 °C (22 °F). Since pavements are typically constructed during the daytime, the chances are very high that pavement slabs will have a significant built-in negative temperature gradient. Differential shrinkage and moisture gradients also add to the residual negative temperature gradients in pavement slabs.

The FHWA study (Yu et al. 1998) showed that the average residual curling on concrete pavements ranges from 4.7 °C to 6.4 °C (8.5 °F to 11.5 °F), depending on climatic conditions. The pavements in both dry-freeze and dry-nonfreeze regions have higher residual curling than those in wet climates. These findings are consistent with the field measurements reported by Armaghani et al. (1987). Because pavement slabs are exposed to daily temperature cycles, much of the residual curling cannot be relieved through creep effects. An on-going FHWA study of curling in JPCP showed, however, that the long-term residual curling is about half that of the initial amount.

The built-in curling is directly additive to the actual temperature gradients. For example, if a pavement slab with -5 °C (-9 °F) built-in curling were exposed to +5 °C (+9 °F) actual temperature gradient, the net effect would be a 0 °C (0 °F) gradient. Thus, the built-in negative curling has the effect of reducing daytime temperature gradients while increasing the nighttime temperature gradients. This temperature "shift" is a very significant factor determining whether top-down or bottom-up stress will be more critical. If the top-down stress is more critical, the failure mode will be top-down cracking.

In general, the only possible means of determining whether a transverse crack was initiated at the top or bottom of the slab may be through analytical calculations. Depending on slab size and load configuration, the critical damage location may be the same for both top-down and bottom-up cracking. For example, the critical damage location under the dual trailer load shown in figure 3 is the longitudinal edge, halfway between the two transverse joints that bounds the slab. This is exactly the same location where the maximum tensile stress at the bottom of the slab would occur when an axle load is placed at that location.

For design purposes, both modes of failure need to be evaluated. The critical failure mode would be the one predicting the higher amount of cracking, and design should be based on the critical case. It is important to note that the cracking predicted based on different modes of failure are directly not additive. The slabs may crack from either top-down or bottom-up, but not from both directions on a same slab. If the predicted amount of slab cracking based on top-down model is more than that based on bottom-up, the fatigue damage for top-down cracking is greater, meaning that top-down cracking is more critical. On pavements with variable joint spacing, it is possible for the critical mode of failure to be different for different size slabs. For such designs, each slab size included in the design must be evaluated separately.

3. DISTRESS MECHANISM

Top-down cracking refers to fatigue cracking initiating at the slab surface caused by the axle loads placed close to slab corners. On highway JPCP, the predominant distress resulting from the critical tensile stresses occurring at the slab surface is transverse cracking.

Critical Pavement Response

The critical pavement response for top-down cracking is the tensile stress at the slab surface caused by the axle loads placed near slab corners under nighttime temperature conditions (large negative temperature gradients). At least two axle loads are needed to make top-down cracking critical, because the part of the slab opposite the loaded corner (in the longitudinal direction) needs to be held down to prevent rotation of the pavement slab under load. The critical load combinations are single-tandem, tandem-tandem, and single-single axles produced by different trucks and combinations of truck-trailer or trailer-trailer. The closer the axle loads are to the opposite ends of the slab, the higher the stress will be.

The critical loading conditions are shown in figures 2 and 3 for single-tandem and tandem-tandem axle combinations. The single-single axle combination is shown in figure 4. The axle combination shown in figure 2 is that of a typical highway truck tractor, and therefore is a very common load. The spacing between the drive axle and the steering axle of a typical truck tractor is 4.88 or 5.49m. The axle combination shown in figure 3 is most damaging to 4.57m slabs. Numerous combinations of truck-trailer, trailer-trailer, and multiple axles on a trailer produce the single-single axle combination shown in figure 4. The axle spacing for single-single combination can be highly variable, depending on the source. For the single-single axle combination, nondoweled joints present a more critical loading condition than doweled joints because no other axles are close enough to the two single axles to influence the behavior of the loaded slab. Under such conditions, the load transfer capacity across transverse joints does serve to reduce the stresses in the loaded slab.

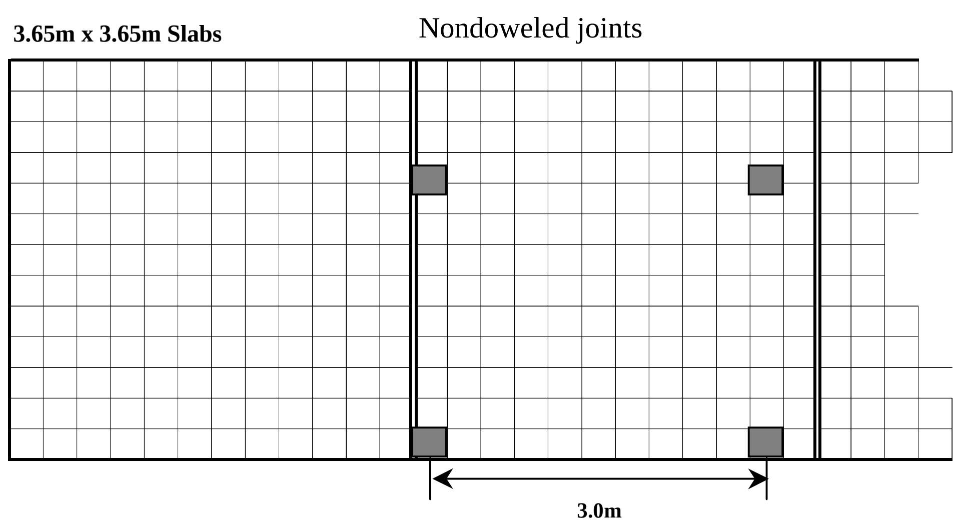

Figure 4 Critical loading condition for top-down cracking caused by dual trailer, a single-single axle combination

Factors Affecting Top-Down Cracking in JPCP

The factors that affect top-down cracking are similar to those that affect bottom-up cracking. In general, top-down stresses are somewhat more sensitive to the factors that affect pavement response than bottom-up stresses. By far, the single most dominant factor that affects top-down cracking is the built-in curling. The effect of built-in, residual curling on stresses in JPCP is shown in figure 5. Depending on load configuration and built-in curling, top-down stresses can become more critical than bottom-up stresses. The top-down stress can become critical when built-in curling in the slab is 5.5 °C (10 °F) or more. When the built-in curling is 9.2 °C (17 °F) or more, top-down stresses are more critical in all cases.

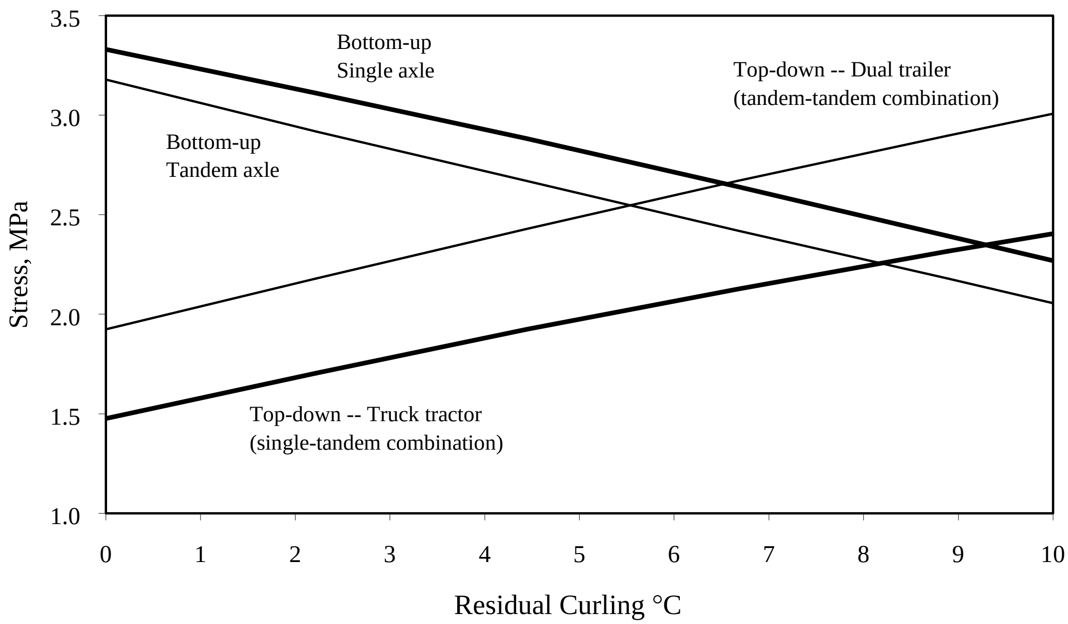

Figure 5 Effects of residual curling on critical stresses in JPCP with the thickness of 30cm

The FHWA study (Yu et al. 1998) showed that the average residual curling in in-service pavements ranges from 4.7 °C to 6.4 °C (8.5 °F to 11.5 °F), depending on climate. The standard deviation of the estimated built-in curling among the sections used in the study was 1.2 °C (2.2 °F). These figures by themselves do not show that top-down cracking would be a common mode of failure for JPCP. However, stress level is only a part of the factors that affect fatigue damage. Fatigue damage accumulation is a function of *n/N*, where *n* is the applied number of load applications and *N* is the allowable number of load applications. The stress level only affects *N*. Because of the differences in sensitivity of the top-down and bottom-up stresses to load position and the differences in the distribution of temperature gradients, the *n* (the effective applied number of load applications) for top-down cracking is substantially different than that for bottom-up cracking.

The sensitivity of the critical stress to load position is important because it determines what portion of the applied traffic will cause significant fatigue damage. The effects of load position on the critical stresses in JPCP are illustrated in figure 6. For both top-down and bottom-up cracking, the critical damage location is the longitudinal edge, and the critical stress is at a maximum when the load is placed at the pavement edge. As the load is moved away from the pavement edge, the critical stress for both top-down and bottom-up cracking reduces. However, the rate at which the stress drops off is much faster for the bottom-up case than for the top-down case.

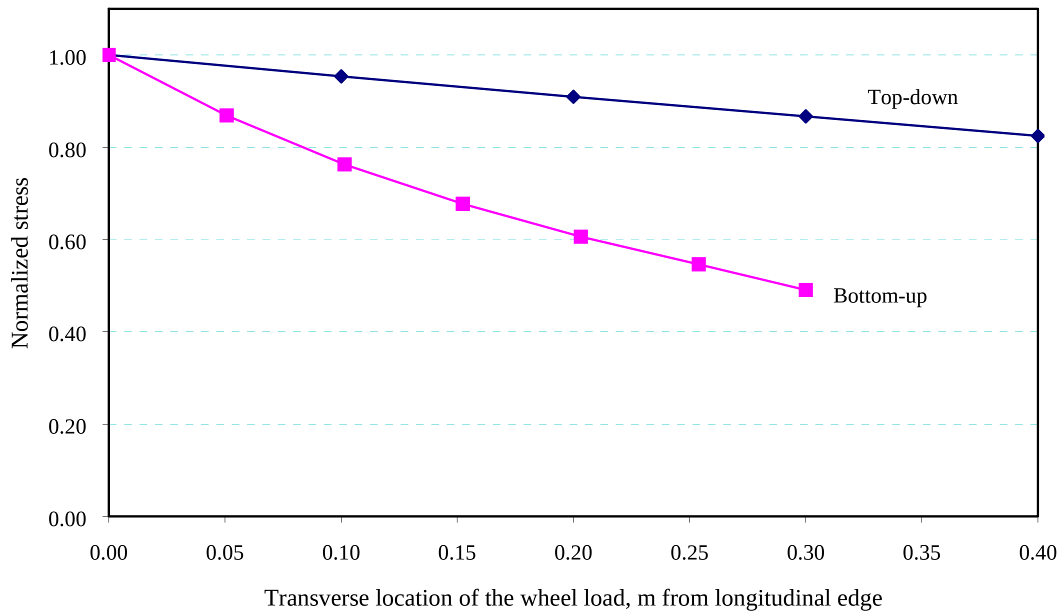

Figure 6 Effects of transverse wheel location on critical stresses in JPCP with the thickness of 30cm

Fatigue damage is extremely sensitive to stress level. The fatigue damage caused by one load application at the maximum stress level is more than 50 times that caused by one load application at 80 percent stress level. Compared to the fatigue damage caused by one load application at 75 percent stress level, the damage caused by one load application at the maximum stress level is more than 150 times greater. Therefore, the loads producing stresses that are less than about 80 percent of the maximum stress are insignificant, in terms of fatigue damage. Figure 6 shows that for bottom-up cracking, moving the load only 0.08 m (3 in) away from the pavement edge reduces the critical stress to the 80-percent level. However, for top-down cracking, the load placed 0.4 m (16 in) away from the edge still produces about 82 percent of the maximum stress. This means that for bottom-up cracking, only the traffic passing within 0.08 m (3 in) of the pavement edge is significant, whereas the traffic passing within 0.4 m (16 in) of the pavement edge must be considered for top-down cracking.

Studies have shown that the lateral placement of traffic wheels may be assumed normally distributed about the mean wheel path (Benekohal et al. 1990). For standard-width pavements (3.7-m [12-ft]), the mean wheel location ranges from about 0.46 to 0.56 m (18 to 22 in) from the pavement edge. The standard deviation of the traffic wander ranges from about 0.22 to 0.25 m (8.5 to 10 in). The probability of traffic coverage within each 0.05-m (2-in) strip of pavement is shown in figure 7 for a typical highway. Based on this figure, the number of load applications that must be considered for top-down cracking is about 15 times greater than must be considered for bottom-up cracking.

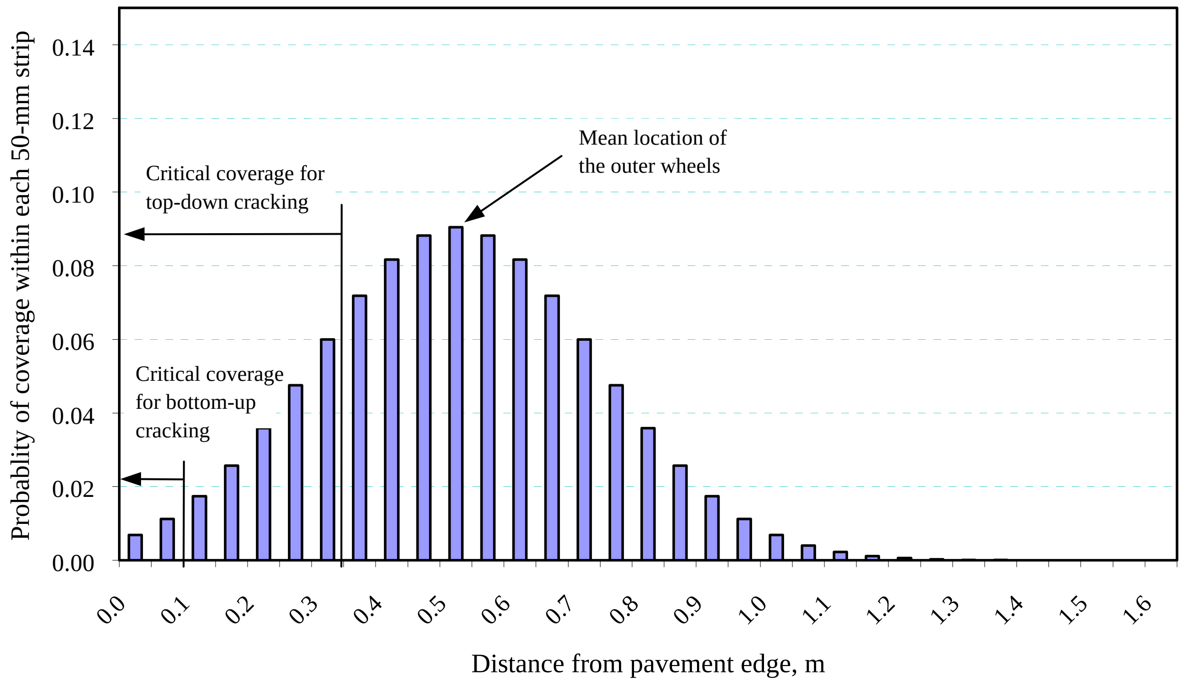

Figure 7 Probability of traffic coverage at different distances away from the pavement edge

Another factor that affects the *n* (the number of applied load applications) in fatigue damage calculations is the distribution of hourly temperature gradients. Because curling stress is an important component of the critical stresses in concrete pavement, an accurate account of temperature exposure conditions is extremely important to fatigue analysis. The *Integrated Climatic Model* (ICM) (Lytton et al. 1993) includes a temperature model developed at the University of Illinois (Dempsey et al. 1986) that can calculate the frequency of hourly temperature gradients based on weather station data and material properties. Figure 8 shows an example of the frequency of hourly temperature gradients at a project site over a typical year period. The frequencies shown in the figure can be used as the distribution factor for different exposure conditions.

The FHWA study showed that about 40 percent of total fatigue damage is caused during the top two temperature categories, and the damage incurred during the top seven temperature categories accounts for 99 percent of the damage for bottom-up cracking. Figure 8 shows much greater frequency of negative temperature gradients than positive temperature gradients. The sum of the frequencies of the top two negative temperature gradients is about 2.7 times that of the top two positive temperature gradients. In other words, the *n* for top-down cracking is about 2.7 times greater than that for bottom-up cracking, based on frequency of critical temperature gradients. The ratio is similar for the sum of the top seven temperature categories.

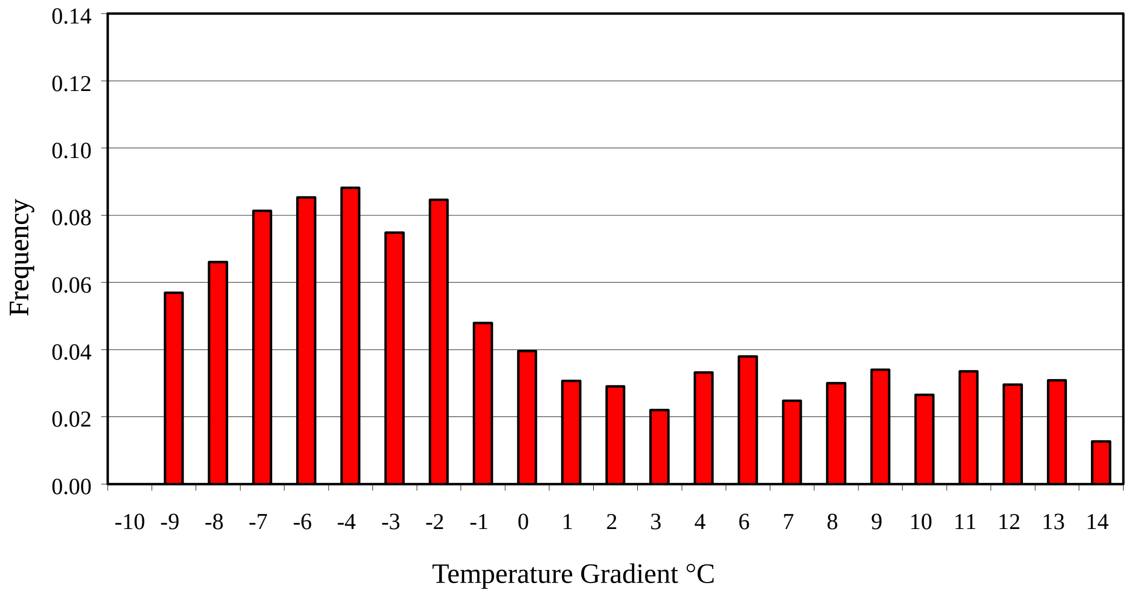

Figure 8 Example annual distribution of hourly temperature gradients obtained using the ICM model

The combined effects of the load position and the frequency of the critical temperature gradients result in much greater number of applied load applications (*n*) for top-down cracking than for bottom-up under the same design conditions. The *n* for top-down cracking is about 40 times that for bottom-up cracking. This means that top-down cracking will become more critical than bottom-up cracking even when the top-down stress is lower than the bottom-up stress. A fatigue damage ratio of 40 corresponds to about 15 percent difference in critical stress, meaning that top-down cracking will become more critical when the top-down stress reaches about 85 percent of the bottom-up stress.

The relationship between critical top-down and bottom-up stresses is shown in figure 9. If the differences in traffic coverage were considered, the top-down cracking would become more critical than bottom-up cracking at relatively low levels of residual curling. Top-down cracking becomes more critical than bottom-up cracking under the truck tractor load if the built-in curling is 6.5 to 7.2 °C (11.7 to 13 °F). These values are slightly greater than the average amount of built-in curling in inservice pavements reported in the FHWA study (Yu et al. 1998). However, the values are within 1 to 2 standard deviations of the average value, and studies have reported that initial levels of built-in curling can be as much as twice the long-term value. Therefore, top-down cracking could very well be the critical mode of failure in many design situations.

Comparisons of the sensitivity of top-down and bottom-up stresses to slab length and subgrade *k* are shown in figures 10 and 11, respectively. In this sensitivity analysis, the thickness of the concrete slab is specified as 30cm. Figure 10 shows that slab length is a very sensitive factor for both top-down and bottom-up stresses. The figure also shows that top-down stresses are more sensitive to slab length than bottom-up stresses. A 0.5-m (1.6-ft) increase in slab length results in an increase in top-down stress by more than 10 percent, which corresponds to an increase in fatigue damage by a factor of 10 or more. Figure 11 shows that *k* value is not a very sensitive factor affecting critical stresses in JPCP. Doubling of *k* changes the top-down stress by only about 5 percent. The bottom-up stresses are even less sensitive to *k*.

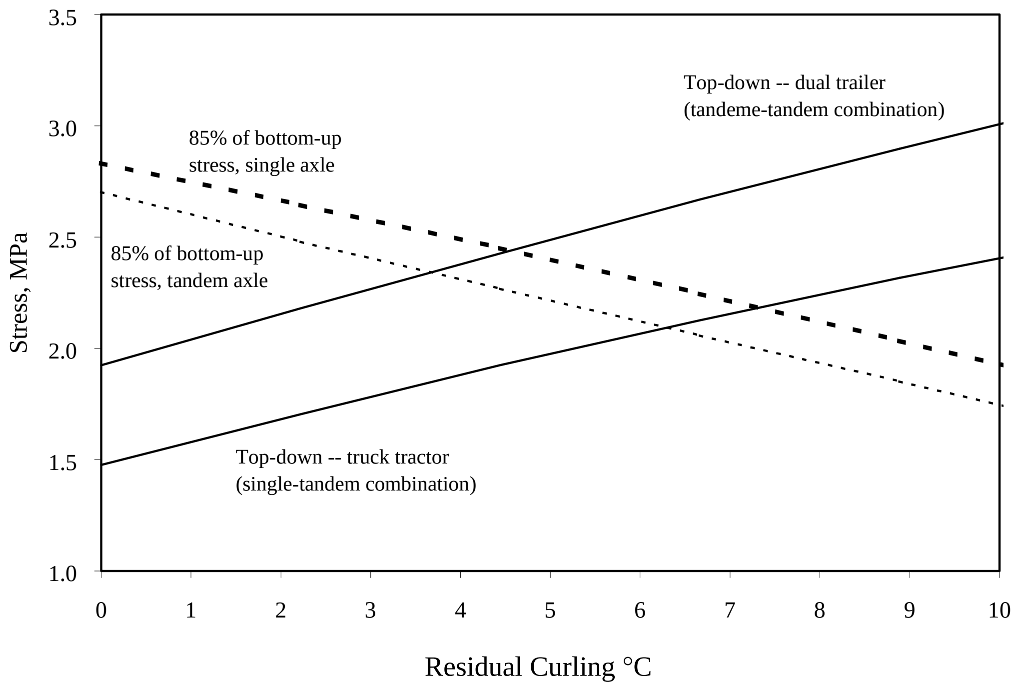

Figure 9 Relationship between critical top-down and bottom-up stresses

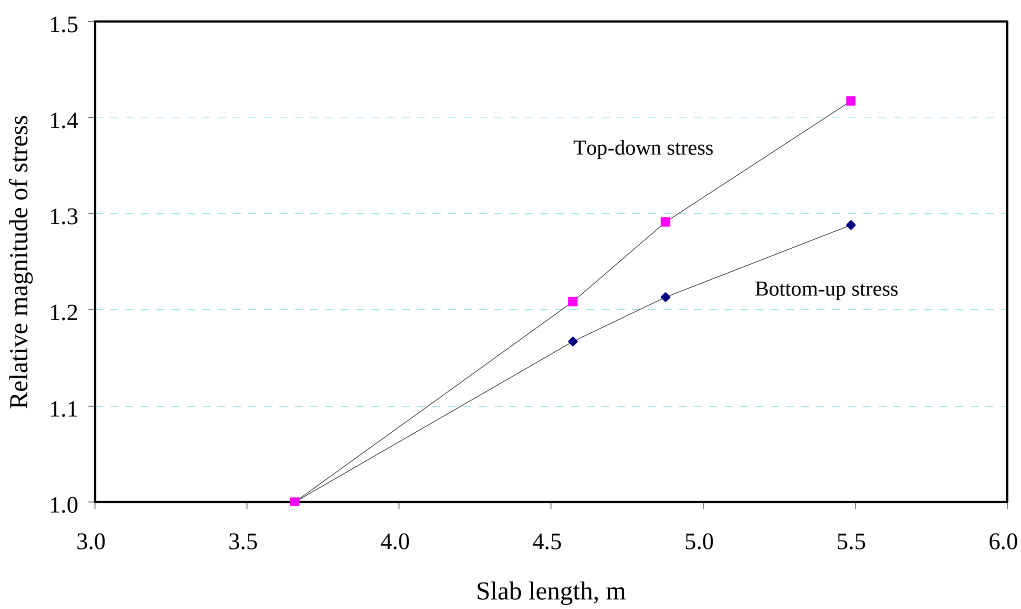

Figure 10 Comparison of the sensitivity of top-down and bottom-up stresses to changes in slab length

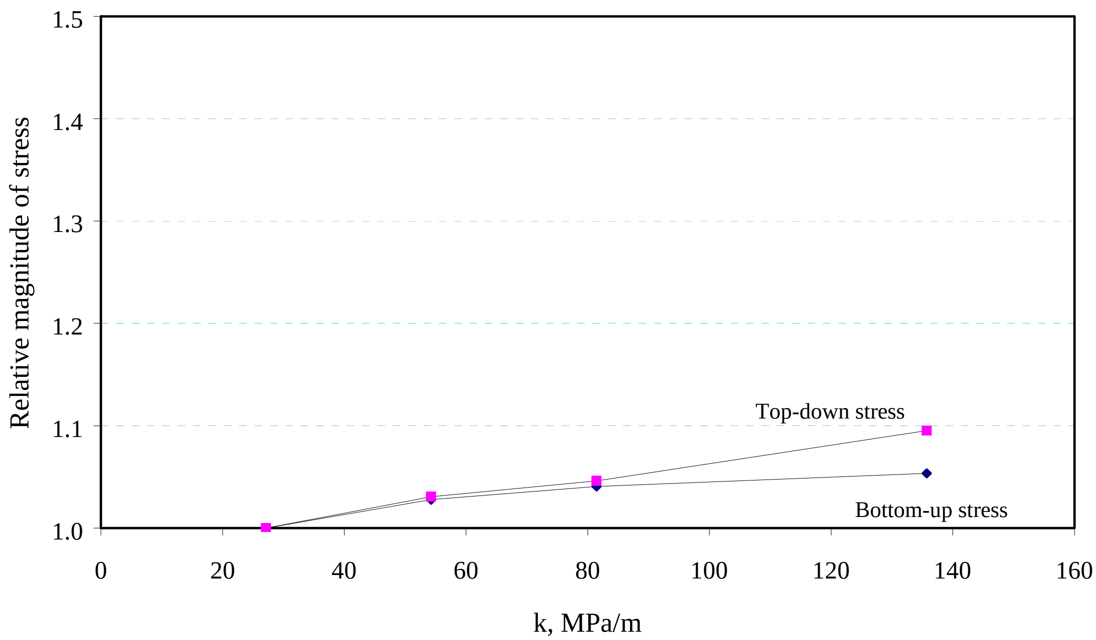

Figure 11 Comparison of the sensitivity of top-down and bottom-up stresses to changes in subgrade *k*

5. CONCLUSION

The results presented in this paper suggest that top-down cracking may be the dominant mode of fatigue failure for JPCP. Accurate analysis of the top-down mode of cracking requires a careful consideration of numerous factors, including the following:

- Effects of the adjacent slabs and LTE.
- Load configuration.
- Built-in curling.
- Traffic wander.
- Sensitivity of critical stresses to load placement.

Proper consideration of each of the above factors is essential to show the true significance of the top-down stresses. Top-down stresses are very sensitive to load configuration. Built-in curling plays a significant role in determining which mode (top-down or bottom-up) of cracking will be the critical mode of failure. For typical highway pavements, built-in curling of about 5 ^{o}C (9 ^{o}F) or more will cause top-down stresses to be more critical. Studies have shown that this level of built-in curling is common among inservice pavements.

The effects of nonlinear temperature distribution on stresses in pavement slabs were not considered in this paper. Nonlinear temperature distribution tends to increase the stresses under nighttime temperature conditions (negative temperature gradients), while reducing the stresses under daytime temperature conditions. Depending on the degree of nonlinearity of the through-thickness temperature distribution, the increase in stresses due to nonlinear temperature distribution can be substantial (20 percent or more). When the effects of nonlinear temperature gradients are considered, it is very likely that top-down cracking will turn out to be the dominant mode of fatigue cracking for JPCP.

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