Abstract
Dowel jointed concrete pavements exhibit premature top-down transverse cracking at mid-slab leading to dramatic decrease of pavement service life. In this study, nonlinear 3D Finite Element (3DFE) analysis that includes detailed consideration of slab constraints by dowel bars is used to analyze the problem of premature transverse cracking in jointed concrete pavements. The 3DFE model response to ambient temperature variations is validated versus field-measured data obtained from West Virginia Smart Road constructed along Route 33 in West Virginia, USA. The modeling results indicate that the combination of ambient temperature drop and slab curling induces slab constraints that lead to the development of mid-slab transverse cracks. The slab length is shown to be a critical parameter that governs the magnitude of the maximum thermal stress induced at maximum mid-slab. It is shown in this paper that 4.57 m long slabs are most resistant to mid-slab cracking, a conclusion that agrees with the recent observations obtained from the analysis of LTPP.

1. Introduction
Westergaard attributed cracking of continuous concrete slabs to the high tensile stresses developed in the slab due to the decrease in its mean temperature (1). Therefore, He recommended constructing concrete pavements with transverse joints that would alleviate the slab movements due to contraction and relieve such high stresses. Slab friction with the underlying base layer was considered the only restraint to slab contraction in jointed slabs (2). Tensile stresses due to friction were found to have minimal effect on the slab stresses and ignored in concrete pavement design. Dowel bars have been installed at transverse joints to enhance load transfer efficiency between adjacent slabs and minimize faulting (3). It was postulated that lubricating the dowel bars would break the bond between the dowels and concrete, hence dowels will not restrain the slab contraction. Recent field measurements from West Virginia Smart Road (4), constructed by the authors near Elkins, West Virginia USA in September 2001, showed that high magnitudes of tensile forces develop in each dowel bar at transverse joint as the slab contracts due to the decrease in its mean temperature as illustrated in Figure 1. The plots in Figure 1 indicate that both dowel bending moment and axial forces changes due to the daily temperature changes rather than seasonal temperature changes. The magnitudes of dowel axial dowel forces illustrated in Figure 1 (b) quantitatively agree with laboratory measurement of dowel-pulling force on
simulated dowel joint specimens (5) as well as the pulling force measured on transverse joints cut from I-80 three years of opening to traffic (6). Detailed 3D finite element analyses of thermoelastic response of the concrete slab under temperature variations indicated that dowel bars bend as the slab curl due to temperature differential and act as hooks resisting slab contraction (7,8,9). This is evident from field measurements of dowel bending moment as illustrated in Figure 1 (c).

Ignoring the restraining effect of dowel bars on the slab axial movement due to temperature changes, mid-slab cracking has been attributed to the combined effect of negative temperature gradient and heavy vehicle joint loading (6,10,11). The idea is that
built-in curling caused by differential shrinkage and/or temperature gradient can cause high tensile stresses on slab top. Under such condition, if the slab is loaded by axle loads acting at transverse joints, the resulting tensile stress at the slab top will be added to those due to negative temperature gradient resulting in higher stress magnitude that may lead to top-down cracking at mid slab. Assuming large negative temperature gradients that amount to 0.121 °C/mm which is very high compared with measured temperature gradients, such an approach has been used to justify the formation of premature transverse cracks that took place on:

1. 6.1 m long slabs on Interstate I-80 in Pennsylvania (6).
2. 4.6 m long slabs in Michigan (10).
3. 6.1 m long slabs in Palmdale, California (11).

However, such an approach failed to explain the documented field observation mid-slab cracks develop in long slabs faster than in the shorter ones (12). Results from detailed 3DFE analyses indicated that changing the slab length from 3.6 m to 9.1 m has insignificant effect on mid-slab curling stress (8), which agrees with the finding of Westergaard (1). Therefore, slab curling cannot be used to explain the correlation between slab length and mid-slab cracking. The effect of axle loading applied at transverse joints on mid-slab stress is small compared to the effect of temperature variations. It was also shown that axle loading cannot cause mid-slab cracking in absence of unrealistically large magnitude of negative temperature gradient (7).

In this paper, 3DFE analysis is used to identify the contribution of temperature changes on premature mid-slab that takes place in dowel jointed concrete pavements under the restraining action of the dowel bars installed at transverse joints. The thermoelastic response of the developed model is validated versus field measured data obtained from West Virginia Smart Road (4). The effects of slab-length, slab-thickness, dowel bar diameter, and concrete-dowel interface on mid-slab slab stresses are examined.

2. 3D Finite Element Pavement Model

The 3DFE model of the dowel jointed concrete pavement used in this study is illustrated in Figure 2. The model consists of two dowel jointed concrete slabs supported on base and subgrade. To examine the effect of the slab length on the state of thermal stress in

Fig. 2 – 3D finite element model of concrete pavement.
concrete slab, slabs of lengths 3.66, 4.57, 6.10, 7.24, and 9.15 were considered. Dowel bars are simulated in the model using eight nodes solid brick elements. Sliding interfaces with frictional contact were assumed between the concrete and the subgrade (coefficient of friction $\mu = 1.5$) and between each dowel and the surrounding concrete ($\mu = 0.05$). If the dowels do not suffer bending deformation due to temperature gradient, the concrete slabs can contract freely without interference with the dowels. However, if the slabs curl, the dowel-concrete interface would allow non-uniform and partial contact along the interface of each dowel at any angular position depending on the dowel position along the transverse joint. The slab weight is active as a body force that influences the magnitude of slab deflection and stress due to curling. Both the concrete and dowel bar materials were represented using thermo-elastic-plastic material models. The subgrade and base materials were represented using elastic material models. The material constants used for all layers are listed in Table 1. For the range of temperature variations, Figure 1 (a), the concrete does not display significant changes in its properties. Therefore, linear thermoelastic material model was assumed for concrete. The maximum stress on the subgrade material due to temperature gradient and traffic loading is about 0.07 MPa, which is well below the linearity limit experienced by cohesive soils (0.35 MPa). Thus, linear elastic material was assumed for the subgrade.

Table 1. Material properties

<table>
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<tr>
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<th>Concrete</th>
<th>Dowels</th>
<th>Base</th>
<th>Subgrade</th>
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<tbody>
<tr>
<td>Density (Kg/m³)</td>
<td>2400</td>
<td>7830</td>
<td>2100</td>
<td>2040</td>
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<tr>
<td>Compressive strength (MPa)</td>
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<td>Tensile strength (MPa)</td>
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<tr>
<td>Modulus of elasticity (MPa)</td>
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<td>Poisson's ratio</td>
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<td>0.30</td>
<td>0.30</td>
<td>0.40</td>
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<tr>
<td>Thermal expansion coefficient ($^\circ$C)</td>
<td>10.8x10⁻⁶</td>
<td>10.8x10⁻⁶</td>
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<td></td>
</tr>
</tbody>
</table>

3. Validation of 3DFE Model Response

The model response to temperature variations was validated versus experimentally measured field data collected from West Virginia Smart Road (4). The material parameters and layers' thicknesses of different pavement layers in the 3DFE model were adjusted to those obtained for West Virginia Smart Road. The interfaces, boundary conditions, element types, number of layers, and the finite element equation solver were not changed. At any instance of time, the strain measured at any point in a concrete slab results from the combined effect of shrinkage, moisture, curing, and temperature changes. The current constitutive equations of concrete adopted in 3DFE models can only account for the effect of temperature variations. Therefore, no direct comparison can be made between the 3DFE-computed strains due to a temperature gradient profile and the experimentally measured ones. In order to facilitate such a comparison, the effects of other nonlinear strain contributors should be minimized or eliminated. This is done by considering the change in the measured strain that takes place over a short duration and assuming that this change in the strain is entirely due to the change in temperature profile measured at the same period of time.
As an example for this technique, we will consider the change occurred in the measured strains along longitudinal and transverse slab centerline during the period starting at 8:20 PM on March 25, 2002 and ending at 8:20 AM on March 26, 2002 (200 days from pavement construction). During this period, the mean slab temperature decreased by 3.4 °C accompanied with a temperature differential of -1.6 °C between slab top and bottom. The partial openings of transverse joints of transverse joints are accounted for in the 3DFE model by applying the change in the measured joint opening as prescribed nodal displacements on the joint faces. The temperature change is applied to the nodal points of the concrete slab, and the model is processed using LS-DYNA equation solver. The 3DFE-computed strains are found for all points in the model that correspond to the location of strain gages in the instrumented slab. Both the measured and 3DFE-computed longitudinal and transverse strains are shown for day 200 in Figure 3. The comparison indicates an acceptable agreement between the measured and 3DFE-computed strains. A similar agreement was also obtained for different time intervals in the months of October 2001, December 2001, February 2002, and May 2002.

The bending moment of the dowel bars at transverse joint changes following the change in the slab curling. Since steel is an elastic material and expected to behave linearly elastic over the range of concrete slab deformation due to slab curling, dowel bars offer an excellent means to check the accuracy of the 3DFE model. Figure 4 illustrates a comparison between the change in the dowel bending moment measured in near-shoulder dowel and the 3DFE-computed ones. The close agreement seen in Figure 4 indicates that the 3DFE model closely predicts the slab curling profile.
4. Effect of Uniform Temperature Variations

Temperature differential through the slab thickness occurs simultaneously with a change in the mean slab temperature. The constraints from the bent dowel bars at transverse joint cause the magnitudes of thermal stresses induced in the concrete slab to change with every degree of uniform temperature decrease or increase. Figure 5 shows distribution of longitudinal stresses along the longitudinal centerline of a 4.57 m long slab due to a negative temperature gradient of -0.02 °C/mm accompanied with amounts of decrease in slab mean temperature: 0, -16.7, and -33.3 °C. Since the same magnitude of temperature differential is used in both cases in Figure 5, the large differences in longitudinal stress profiles and magnitudes can only be attributed to the introduction of the uniform temperature drops of –16.67 and -33.3 ºC. The 160 and 188 percent increase in mid-slab stress, observed in Figure 5, can only be attributed to the fact that bent dowels (due to slab curling) introduced significant slab constraining force that resist slab contraction due to uniform temperature drop. It can be seen from Figure 1 (c) that dowel bending develops as soon as the concrete is placed.

![Fig. 5– Longitudinal stresses due to -0.02 °C/mm gradient combined with temperature drops.](image)

The amounts of uniform temperature decrease, assumed in this study, seem reasonable considering the temperature difference that occurs between construction time in hot summer construction and winter (See Figure 1-a). The additional stress component due uniform temperature decrease is currently not accounted for in rigid pavement design procedures.

The amount of joint opening due to slab contraction depends on the slab length. Thus, it is plausible to postulate that mid-slab stress is dependent on slab length. To validate this observation, a constant gradient magnitude of –0.02 °C/mm was applied to slabs of different lengths range from 3.6 m to 9.1 m and the resulting stresses are plotted in Figure 6. It can be noticed that mid-slab longitudinal stress increases as the slab length increases, Figure 6 (a). However, decreasing the slab length results in an increase in transverse stress which makes shorter slab more susceptible to longitudinal cracking, which is evident from Figure 6 (b). Since cracks initiate in concrete as the maximum principal stress reaches the modulus of rupture, 4.57 m length seems to be the most optimized slab length that minimizes maximum principal stresses in concrete slab and so minimize the chance of developing cracks for different amounts of uniform temperature
drops. This finding explains the documented field-observation from the LTPP program (12) and is supported by the experience of pavement engineers in West Virginia Department of highways who after 30 years of trials reduced the slab length from 18 m to 4.57 m to avoid mid-slab cracking.

The stress due to uniform temperature decrease is uniform through the slab thickness.

Therefore, unlike with traffic loading, changing the slab thickness is not expected to have a significant effect on mid-slab stress. This can be observed from Figure 7 that illustrates that under the effect of a temperature gradient of -0.02 °C/mm combined with a uniform temperature drop of -33.3 °C, changing slab thickness from 0.2 m to 0.3 m does not have a significant effect on mid-slab stress.

Figure 8 illustrates the effect of the characteristics of the concrete-dowel interface on mid-slab longitudinal stress. If the dowel bars are free to slide along their sockets, an initial diametral clearance of 25 micron would slightly reduce mid-slab stress than that measured for sliding intact interface. A strong bond exists between the dowel and surrounding concrete results in a 220 percent increase in mid-slab longitudinal stress. Cases of sliding and bonded dowels represent the two extremes for the condition of the concrete-dowel interface in concrete pavements.
5. Conclusions

1. Dowel bars at transverse joints introduce significant restraints to the slab contraction due to uniform temperature decrease.

2. Dowel bending is the main cause of restraint so that mid-slab stress remains high even with the presence of an initial concrete-dowel clearance.

3. Under the restraining effect of dowel bars, 4.57 m seems is the most optimum slab length to avoid premature mid-slab cracking. Such finding agrees with the observation from LTPP program.

4. Increasing the slab thickness is not beneficial in reducing thermal stresses in concrete slabs and overcoming the problem of concrete pavement cracking.

6. References


