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INFLUENCE OF VEHICULAR POSITIONS AND THERMAL EFFECTS ON STRUCTURAL BEHAVIOUR OF CONCRETE PAVEMENT

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Structural response of concrete pavements is influenced by the position of the axle loads and if critical load positions are not considered in concrete pavement analysis, the design may be inadequate and lead to early failure of the pavement. Whilst there has been a great deal of research conducted on concrete pavement performance and deterioration under vehicular loads and environmental forces, there is a lack of adequate information on effects of vehicular load positions on pavement responses.

Critical positions of different axle groups in uncurled and curled jointed concrete pavement with different configurations were determined in the current study. Results indicate that structural performance of concrete pavements is significantly affected by boundary conditions between concrete slab and base. Corner loading was found to be critical in bonded concrete pavement. Corner loading is also critical when a separation occurs between unbonded concrete slab and base. Furthermore, the benefits offered by unbonded boundary condition cease at a certain differential temperature. Hence, a particular care needs to be considered in projects constructed in extremes of heat or cold. In presence of high differential temperature together with axle loading, joint faulting in unreinforced concrete pavements is affected by concrete slab thickness.

1. Introduction

Although there has been a great deal of research conducted on concrete pavement performance and deterioration under vehicular loads and environmental forces, there is a lack of adequate information on effects of vehicular load positions on pavement responses. If the load positions which give the maximum response parameters are not considered in the analysis, the design may be inadequate and lead to early failure of concrete pavements. Structural response of concrete pavements is affected by vehicular load configurations, magnitude of applied loads and position of axle groups on the pavement as well as environmental effects. This paper treats the influence of vehicular load positions on pavement responses in terms of induced tensile stresses. Effects of configuration and magnitude of vehicular loads on concrete pavement responses have also been investigated and the findings will appear in another paper.

In concrete pavements, applied loads are generally transferred to base and subgrade layers by the bending action of concrete slab which results in a tensile stress at the top or the bottom surface layers of the concrete slab. The applied loads can be vehicular and/or environmentally related. Research conducted in the past for determination of the critical position of vehicular loads upon the concrete pavements can

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be divided into two categories, with and without consideration of differential temperature effects. The most significant one in the absence of differential temperature is the work of Packard and Tayabji [1985].

A single traffic lane confined at one longitudinal edge by shoulder, subjected to single axle, tandem axle and triple axle loads was considered in Packard and Tayabji's research [Packard and Tayabji 1985] to determine the critical position of the above mentioned axle groups on uncurled concrete pavements. Although many jointed concrete pavements suffered from corner and longitudinal cracking Packard and Tayabji [1985], and Heath et al. [2003], found that the maximum vehicular induced tensile stress occurs when axle group loads are applied at the middle of the longitudinal joints between transverse joints. This leads to bottom-up mid-edge transverse cracking. Vehicular induced tensile stress in the absence of differential temperature gradients occurs at the deepest surface layer of the concrete slab, particularly when the load is applied at longitudinal joints [Ongel and Harvey 2004]. Recommendation of American Association of States and Highway Officials [AASHTO 2003] for analysis of jointed concrete pavements is the use of a single lane with at least three concrete slab panels in the longitudinal direction. This is compatible with what Packard and Tayabji [1985] considered.

In addition to the traditional bottom-up mid-edge transverse fatigue cracking, environmental effects together with built-in temperature curling result in other failure modes [Hiller and Roesler 2005]. Temperature fluctuation has different effects on concrete pavements. Nonuniform temperature distribution within concrete slab depth results in upward (nighttime) or downward (daytime) curling. Curling induced tensile stress occurs at the top surface layer of the concrete slab during nighttime and at the bottom surface layer of the concrete slab during daytime [Ongel and Harvey 2004].

Traditional methods of thermal analysis were based on a linear temperature distribution in pavement depth [Westergaard 1926; Bradbury 1938]. However, Choubane and Tia [1995] showed that temperature distribution in pavement depth is nonlinear. Mohamed and Hansen [1997] developed an analytical method to estimate the induced tensile stress in concrete pavements subjected to a nonlinear temperature gradients. The concept of equivalent temperature distributions was then employed in concrete pavement analysis based on the plate theory [Ioannides and Khazanovich 1998]. In their study, a plate consisting one or more layers (plate layers with no separation and compressible layers with possible separation using Totsky model [Totsky 1981] resting on an elastic foundation was investigated. Consequently, mathematical formulations for analysis of a typical concrete pavement subjected to a linear function, a quadratic function or multilinear function of differential temperature together with arbitrary wheel load were developed.

Results of Mohamed and Hansen [1997] and also Heath and Roesler [1999] indicated that nonlinear temperature distribution through the depth of concrete slab results in tensile stress that is lower than that of linear temperature distribution when concrete pavement is subjected to a positive temperature gradient (daytime) and produces tensile stress that is greater than that of linear temperature distribution when concrete pavements are subjected to negative temperature gradients (nighttime). Liang and Niu [1998] showed that concrete pavement responses are significantly affected by environmental forces. Kuo [1998] indicated curling induced stress is affected by temperature differential, self-weight of concrete pavement and support under concrete slab. Furthermore, Kuo [1998] recommended that (i) mid-slab loading in daytime curling and (ii) joint loading in nighttime curling should be considered in pavement analysis.

Byrum and Hansen [1994] contributed the influence function lines in analysis of jointed concrete pavement under environmental effects and wheel load. The wheel load was applied in a distance of

838 mm away from longitudinal joint. Their results indicated that (i) maximum stress occurs at some distance away from the joint when the load passes across the joint (ii) thermal, moisture and shrinkage gradients have a significant effect on the residual stresses of the concrete slab (iii) highway slabs are predominantly in the upward curled condition.

Several field tests were carried out in the past to determine the range of temperature gradient in depth of concrete slab. Richardson and Armaghani [1990] and Shoukry et al. [2002] reported that the differential temperature is about 10° C in a concrete slab with 225 mm thickness. Byrum and Hansen [1994] based on other research in this field used a temperature gradient between 0.087 and 0.109° C/mm during daytime and between 0.044 and 0.065° C/mm during nighttime. Darter et al. [1995] provided a range between 0.0219 and 0.656° C/mm whereas Ongel and Harvey [2004] reported monthly values of temperature gradient in concrete pavement for a period of 5 years with an average of 0.125° C/mm. As temperature gradient is strongly affected by air temperature, ratio of the top surface area of the concrete slab to its depth, duration and density of solar radiation, rain fall, thermal conductivity of concrete and wind speed, it is obvious that differential temperature changes from one location to other locations.

Since the top surface layer of concrete slab is exposed to solar radiation and wind, it dries and cures faster than other layers within the concrete slab depth and consequently results in nonuniform shrinkage which is the reason for concrete slab warping and top-down cracking [Ongel and Harvey 2004]. The effect of drying shrinkage on concrete pavement is similar to nighttime differential temperature effects. Hence, Reddy et al. [1963] recommended the use of equivalent nighttime temperature gradients between 0.065 and 0.13° C/mm in concrete pavement analysis to represent the effects of drying shrinkage in concrete pavement responses.

Results of Yu et al. [1998] on concrete pavement response to temperature and wheel loads suggested that corner loading may results in greater stress than mid-edge loading. Effect of single axle dual tyre (SADT), tandem axle dual tyre (TADT) and triple axle dual tyre (TRDT) on pavement response were then taken into account by Hiller and Roesler [2002] to develop a method for predicting concrete pavement deterioration. Since the assumptions considered by Hiller and Roesler [2002] are not compatible with concrete pavement construction in Australia, results of the current research may or may not agree with what they found. Reasons behind this can be absence of base layer, consideration of shoulder with 3000 mm width, concrete slab interaction, the use of 200 mm thickness for concrete slab and long distance between transverse joints (5800 mm) in their study.

In 2005, Hiller and Roesler [2005] used the influence stress lines to determine the critical location of fatigue damage under certain truck loads in a typical California concrete pavement having permanent built-in curling. They found that the critical damage location in the absence of environmental effects was at the bottom surface layer of the mid-slab edge for a load transfer efficiency of 70%. However, top-down transverse cracking near the mid-slab edge was the critical failure mode in the presence of a nighttime differential temperature of −16.5° C.

Buch et al. [2004] parametrically investigated the structural response of jointed concrete pavement under single axle (SA), tandem axle (TA), triple axle (TR), quad axle (QA), multi axles, together with differential temperature using influence stress line approaches. In addition, diverse truck loads (combination of different axle group loads) were also studied. Their results indicated that mid-edge loading results in bottom-up cracking and corner loading results in top-down cracking for SA, TA, TR and QA.

They also found that an increase in the subgrade reaction and thickness of the concrete slab increases and decreases the induced tensile stresses respectively.

Structural behaviour of curled concrete pavements depends on provision of debonding layer between concrete slab and base. If a full bonded condition between concrete slab and base is considered, a tensile stress will be produced at the interface of concrete slab and base during the first 28 days of concrete placement due to plastic and drying shrinkage. This subsequently results in early age cracking. Because of this, a debonding layer is placed between concrete slab and base to eliminate the early age cracking. The concept of frictional stress in concrete pavement analysis was introduced by Wimsatt et al. [1987] and Wesevich et al. [1987]. It was also adopted in most finite element softwares developed for analysing concrete pavements. The frictional stress is a shear stress induced at each square metre of concrete slab and base interface. This parameter is highly independent of concrete slab thickness and bearing stress.

Different boundary conditions including bonded, unbonded and partially bonded may be created between concrete slab and base depending on types of debonding layer. While bonded boundary condition keeps concrete slab and subbase together with no vertical separation, fully unbonded boundary condition lets them to be separated under tensile force without inducing any shear force between these layers. Partially bonded boundary condition, on the other hand, keeps concrete slab and base together for a certain shear force. Beyond this shear force, a vertical separation will occur between these layers. Note that information on effects of debonding layer on concrete pavement behaviour does not lead to a specific conclusion as Tarr et al. [1999] indicated that unbonded condition could only be achieved by using a double layer of polyethylene sheets and Yu et al. [1998] stated that friction between concrete slab and base is sufficient to produce bonded behaviour even if polyethylene sheets are placed between them.

Whilst most research on concrete pavements is based on either fully bonded or fully unbonded boundary condition between concrete slab and base [Heath and Roesler 1999], effects of different boundary conditions on concrete pavement responses are not clearly understood. Since configuration and magnitude of vehicular loads have a significant effect on induced tensile stress in concrete pavements [Yu et al. 1998; Hiller and Roesler 2002] and a variety of axle group configurations is employed in heavy vehicle industries, further study shall be carried out for other axle group types. Moreover, there is no inclusive information on critical positions of each individual axle group on curled and uncurled concrete pavement.

This study seeks to establish the critical positions of axle groups on jointed concrete pavement based on Austroads [2004] recommendations. Loads from different axle groups are separately applied at various locations on a number of pavement configurations — unconfined and confined by adjacent lanes and shoulders — to evaluate the critical design parameters of maximum tensile stress. Fully bonded and unbonded boundary conditions between concrete slab and base are considered. Different axle groups based on Austroads [2004] consisting of (i) Single Axle Single Tyre (SAST), (ii) Single Axle Dual Tyre (SADT), (iii) Tandem Axle Single Tyre (TAST), (iv) Tandem Axle Dual Tyre (TADT), (v) Triple Axle Dual tyre (TRDT) and (vi) Quad Axle Dual Tyre (QADT) are positioned at different locations of the pavement.

Curling and warping of concrete pavement were also taken into account. Effects of axle group loadings and differential temperature gradients on both bonded and unbonded concrete pavement will be separately studied. A sensitivity analysis on structural behaviour of unbonded and bonded concrete pavements subjected to diverse differential temperatures will be done to estimate the accuracy of superposition

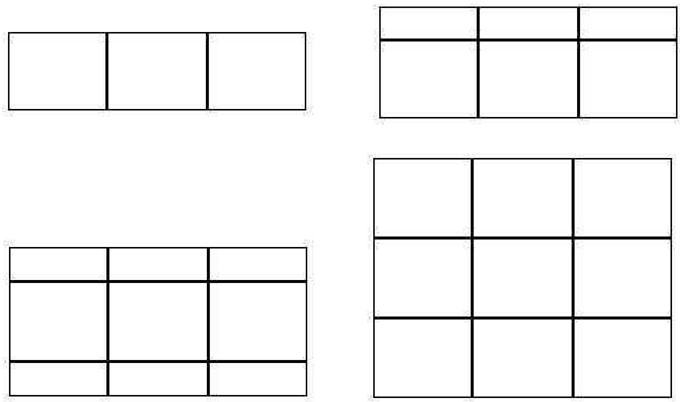

Figure 1. PCP configurations considered in this research. Top left: single lane; top right: a lane confined at one longitudinal edge by shoulder (confined lane); bottom left: a lane confined at both longitudinal edges by shoulders (double confined lane); and bottom right: a lane confined by adjacent traffic lanes (full pavement).

of load and curling stresses. A full configuration of concrete pavement subjected to a combination of SADT and differential temperatures will then be studied. Effects of modulus of subgrade reaction and thickness of concrete slab on induced stress will subsequently be discussed. Results for different pavement configuration, namely, a single lane, a lane confined at one longitudinal edge by shoulder, a single lane confined at both longitudinal edges by shoulders and a single lane confined by adjacent traffic lanes called respectively in this paper a single lane, a confined lane, a double confined lane and full pavement (Figure 1) are evaluated and compared with those from existing research.

Results from the current study are also able to examine whether the findings of Packard and Tayabji [1985] and AASHTO [2003] can be extended when other axle groups, pavement configurations, curling and warping of concrete pavement and bonded or unbonded boundary conditions between concrete slab and base are considered.

2. Methodology

Diverse jointed plain concrete pavement (JPCP) configurations consisting of a single lane (top left in Figure 1), confined lane (top right), double confined lane (bottom left) and full pavement (bottom right) were analysed to determine the critical positions of the applied vehicular axle group loads on the pavement together with temperature curling effects. EverFE2.23 [Davids and Mahoney 1999] finite element program was employed in this study.

EverFE2.23 is a three dimensional finite element analysis software jointly developed by the universities of Maine and Washington to simulate the behaviour of jointed plain concrete pavements under axle group loads and environmental effects. This programme employs 20-noded quadratic solid elements, beam elements, shear spring and 8-noded dense liquid shell elements to simulate behaviour of concrete slab and base, dowels and tie bars, aggregate interlock and subgrade layers under applied loads respectively. This program is also able to simulate a tensionless property in the subgrade. This lets a separation occur between base and subgrade if the base curls.

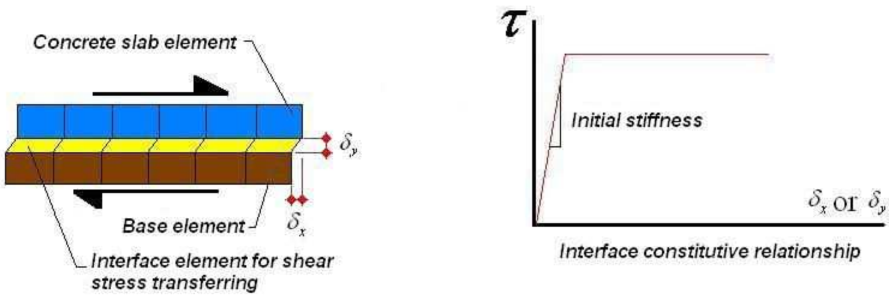

Figure 2. Schematic interface element behaviour and interface constitutive relationship [Davids and Wang 2003].

EverFE employs 16-noded zero thickness quadratic interface element for simulating the debonding layer between concrete slab and base. The element is capable to transfer the shear force between the concrete slab and the base. It is meshed in accordance with size of the mesh used in the concrete slab and the base. A bilinear constitutive relationship [Wimsatt et al. 1987; Wesevich et al. 1987] was considered to define the characteristics of the element under the applied load. Hence, the debonding layer can be defined by introducing initial distributed stiffness and slip displacement. Note that a free separation under tension occurs between the concrete slab and the base when unbonded boundary condition is selected. Figure 2 shows a schematic behaviour of the interface element used in the EverFE finite element program as well as the required information for its definition. Further information on this matter can be found elsewhere [Davids and Wang 2003].

In this study, distance between transverse joints and distance between longitudinal joints were considered to be 4600 mm and 3600 mm respectively. Tied shoulders with 1500 mm width [Austroads 2004] were considered. The slab thickness was considered to be 250 mm with modulus of elasticity and Poisson's ratio of 28000 MPa and 0.2 respectively. A cement stabilized base of 150 mm thickness, 5000 MPa modulus of elasticity, and 0.2 Poisson's ratio was considered beneath the slab and upon a subgrade with modulus of subgrade reaction of 0.03 MPa/mm (CBR $\approx$ 3.5). Transverse joints were doweled by eleven evenly spaced cylindrical bars having 32 mm diameter, 450 mm length and 1000 MPa dowel-slab support modulus. Tie bars with 13 mm diameter and 1000 mm length spaced at 1000 mm centre to centre were considered at longitudinal joints. The above mentioned values of the parameters are within the range recommended by [Austroads 2004]. These secure load transfer efficiency (LTE) of 95% in both transverse and longitudinal joints for bonded boundary condition and LTE of not less than 85% in

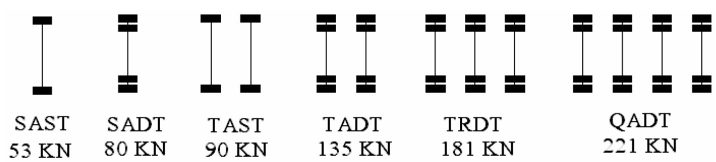

Figure 3. Axle groups type considered in this study based on [Austroads 2004].

transverse joint and 70% in longitudinal joints for unbonded boundary condition. Since information on behaviour of debonding layer provided in the literature did not lead to a specific conclusion, fully bonded and unbonded boundary conditions between concrete slab and base are taken into consideration in the current study to determine how provision of this layer as either bonded or unbonded affects concrete pavement responses.

In regards with effects of modulus of subgrade reaction and thickness of concrete slab on induced tensile stress of a curled pavement [Kuo 1998], different base thicknesses of 200, 250 and 300 mm and different modulus of subgrade reactions of 0.03, 0.05 and 0.07 MPa/mm were considered in a full pavement configuration.

SAST, SADT, TAST, TADT, TRDT, and QADT with average gross loads of 53 kN, 80 kN, 90 kN, 135 kN, 181 kN, and 221 kN (Figure 3) based on [Austroads 2004] were respectively applied as the vehicular loads at the centre, middle of the longitudinal edge and corner of the centre slab as shown in Figure 4. These load locations are respectively called a centre, mid-edge and corner loadings in this paper. A rectangular shaped tyre-pavement contact area based on the findings of Gillespie et al. [1992] was considered in the current study. Other assumptions for load configuration were as follows:

- Tyre inflation pressure: 750 kPa,
- Width-to-length ratio of tyre contact area: 0.7,
- Space between centre of dual tyres: 300 mm,
- Axle width: 1800 mm,
- Distance between axles in a given axle group 1250 mm.

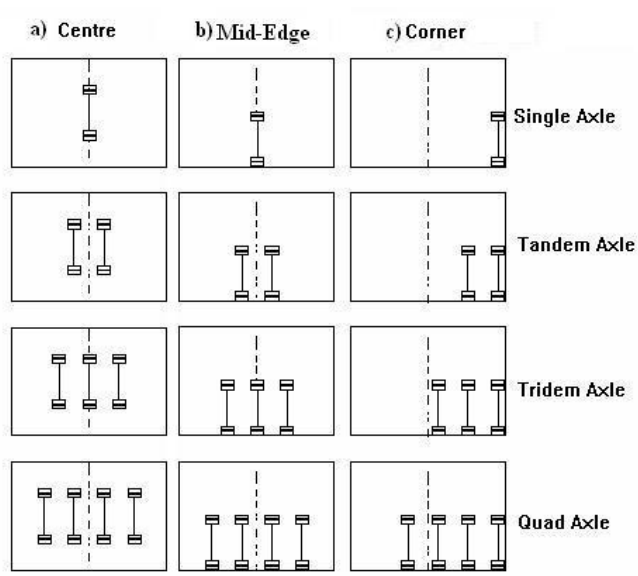

Figure 4. The position of applied loads for different axle groups on the centre concrete slab.

It should be noted that for those projects where valid statistical information on axle configuration are not available, research on critical axle group configurations Darestani et al. [2005] showed that the critical width-to-length ratio of tyre contact area is between 0.6 and 0.8 with average of 0.7, the critical distance between axles in a given axle group is between 1050 mm and 1150 mm with average of 1100 mm for all axle groups. In addition for TAST and TADT groups this value can also be between 1350 mm to 1450 mm with an average of 1400 mm. However, a value of 0.7 for width to length ratio of tyre contact area and 1250 mm distance between axles in a given axle group, as assumed by Packard and Tayabji [1985], have been chosen in the present study in order to compare present results with their results.

As high differential temperature (more than 25° C) would result in severe damage of unreinforced concrete slab of a normal thickness, linear differential temperature of −25° C (nighttime temperature) to 25° C (daytime temperature) were therefore considered between the top and the bottom surface layers of concrete slab. The concrete coefficient of thermal expansion was considered to be 1×10^{-5} mm/mm/° C.

3. Results and discussion

3.1. ***Axle group loadings.*** In the absence of differential temperature gradients, results of current study indicate that vehicular induced tensile stresses in unbonded concrete pavement due to mid-edge loading are greater than those from centre and corner loading for all pavement configurations when SAST, SADT, TAST and TADT are studied (Figure 5). In contrast, corner loading of QADT results in greater tensile stress than mid-edge loading for all pavement configurations. Corner loading of TRDT shows similar results for double confined lane. Furthermore, centre loading of QADT in double confined lane and full pavement configurations result in higher tensile stress than mid-edge loading.

Consideration of bonded boundary condition between concrete slab and base always results in lower tensile stress due to centre loading than other loading types (Figure 6). But, corner loading results in greater induced tensile stress than mid-edge loading for all axle groups except for SADT and SAST. This becomes predominant when traffic lane is confined by shoulders or adjacent traffic lanes.

Results of the current study reveal that the AASHTO recommendation [AASHTO 2003] is valid for fully unbonded boundary condition between concrete slab and base though this was not true for corner

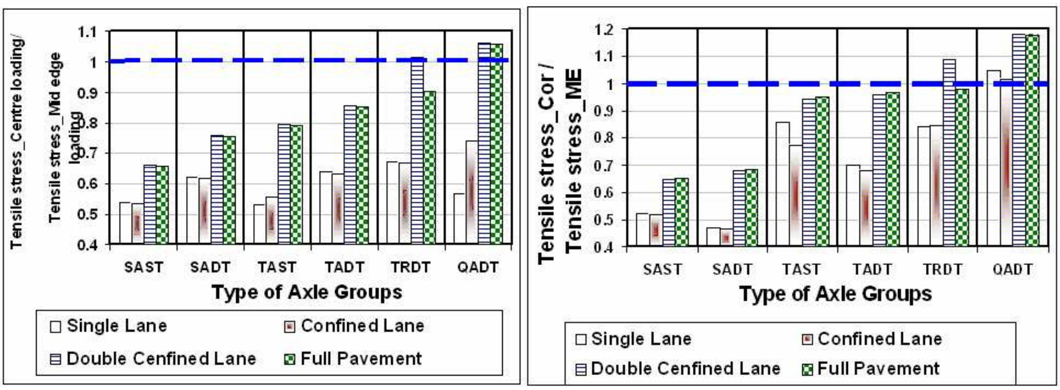

Figure 5. Vehicular induced stress in different pavement configurations for unbonded boundary condition.

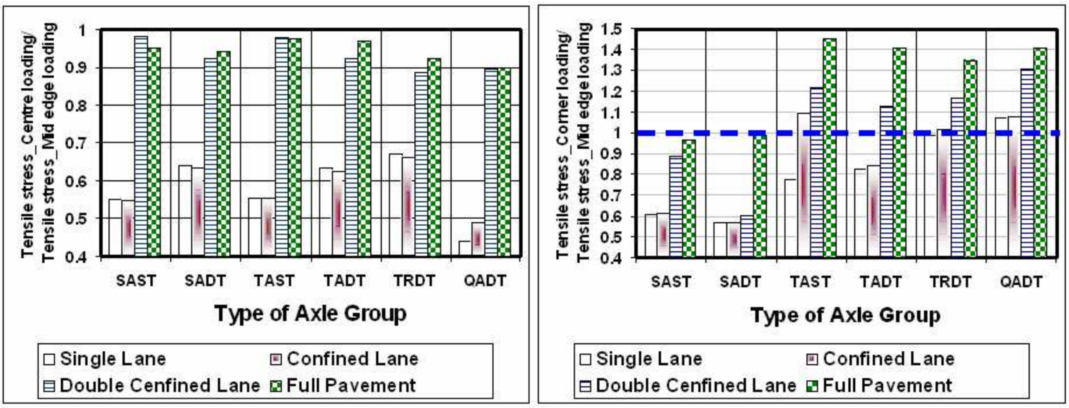

Figure 6. Vehicular induced stress in different pavement configurations for bonded boundary condition.

loading of SADT. While the bonded boundary condition is considered in the analysis, the AASHTO recommendation [AASHTO 2003] is not able to capture maximum vehicular induced tensile stress as induced tensile stresses in full pavement are greater than those tensile stresses produced in confined lane when vehicular loads are applied at the corner of the pavement (Figure 6).

As mentioned earlier, mid-edge loading was the critical loading case in research conducted by Packard and Tayabji [1985]. Results of the current study show that mid-edge loading, in the absence of differential temperature is the key factor for fatigue cracking of unbonded concrete pavements though this is not true for QADT. Corner loading results in greater vehicular induced tensile stress when fully bonded boundary condition is considered and TAST, TADT, TRDT and QADT are studied.

A comparison between vehicular induced stresses in bonded and unbonded boundary conditions between concrete slab and base shows that an unbonded boundary condition produces greater vehicular induced tensile stress in concrete pavement. This is due to loss of support in those locations of the concrete slab that were lifted-off. The minimum increase in the value of tensile stress is 30 per cent for corner loading of TRDT and the maximum increase is about 133 per cent for mid-edge loading of TAST. These results show that vehicular induced tensile stress is highly affected by the boundary condition between concrete slab and base.

3.2. ***Thermal induced stress.*** As mentioned earlier in this paper, the main reason for placing a friction reducer layer between concrete slab and base is to reduce the early age cracking in concrete slabs. Nevertheless, it plays a significant role in structural behaviour of concrete pavements during pavement life. As differential temperature and drying shrinkage tend to curl and warp concrete pavement, the location of neutral axis changes from its original location toward the top or the bottom surface layer of the concrete slab depending on the concrete slab curvature. Hence, the critical position of axle groups may be affected by consideration of environmental forces. For that purpose, daytime and nighttime differential temperature of 10° C and 25° C were considered in the current study.

Ongel and Harvey [2004] found that nighttime curling and warping are two reasons behind longitudinal cracking. Results of the current study show that the thermal tensile stress is at maximum along

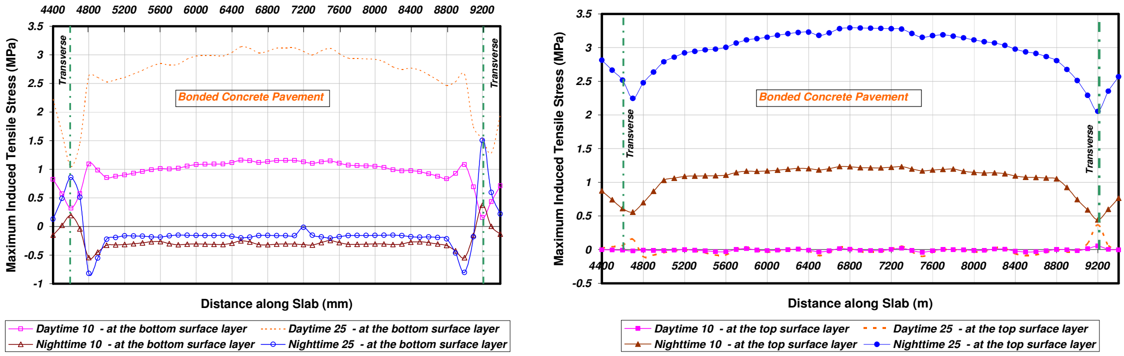

Figure 7. Curling induced stress in bonded concrete slab with full pavement configuration.

the longitudinal centreline of each traffic lane and decreases toward the edges of the traffic lane as expected. Furthermore, high daytime differential temperature results in bottom-up longitudinal cracking and consequently shall also be considered a reason for longitudinal cracking.

Figure 7 shows induced thermal stress at longitudinal joint along the wheel path for the centre panel of a full pavement configuration with the fully bonded boundary conditions between concrete slab and base. Figure 8 presents similar results for fully unbonded condition. In these Figures, Daytime and Nighttime represent daytime differential temperature and nighttime differential temperature, respectively. The number after Daytime or Nighttime indicates the absolute temperature difference between the top and the bottom surface layers of the concrete slab. For instance, Daytime 10 indicates a differential temperature between the top and the bottom surface layer of 10° C.

Results of the current study indicate nighttime temperature gradients produce greater tensile stress at the top surface layer of the concrete slab whereas daytime temperature gradients result in greater tensile stress at the bottom surface layer of the concrete slab as expected. When the top or the bottom surface layer of the pavement are individually studied, results indicate that daytime differential temperature may result in top-down cracking in the corner of the concrete slabs and bottom-up cracking at mid-edge of

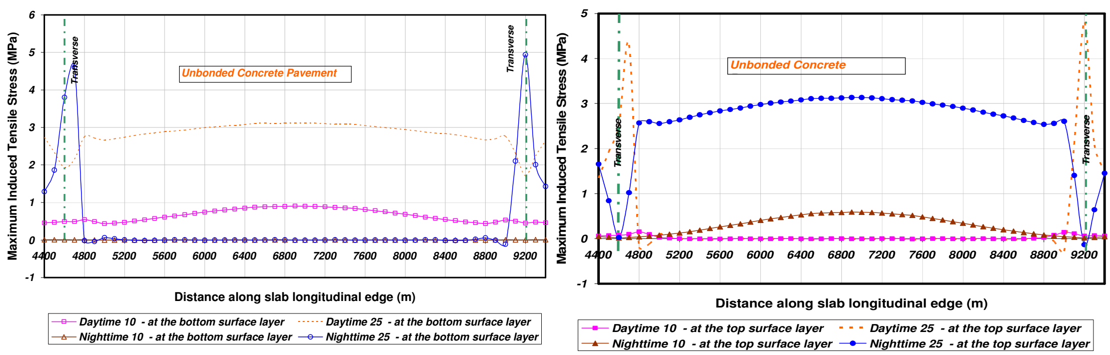

Figure 8. Curling induced stress in unbonded concrete slab with full pavement configuration.

the slab. Nighttime differential temperature, on the other hand, may produce bottom-up cracking in the corner of the slab and top-down cracking at the mid-edge of the slab.

In terms of absolute induced tensile stress, the critical location is mid-edge of the longitudinal joints for fully bonded boundary condition between concrete slab and base (Figure 7). In unbonded concrete pavement, however, the critical location depends on the magnitude of differential temperature. While concrete pavement is subjected to a low differential temperature, that is, 10° C, the middle of longitudinal joint is the critical location where the maximum thermal stress is produced. On the other hand, corner of the slab experiences greater tensile stress than mid-edge location when a higher differential temperature, i.e. 25° C, is considered (Figure 8).

When a single concrete slab is freely curled due to a differential temperature gradient and in the absence of the restraining factors such as subgrade and base resistant, vehicular loads and friction force at the interface of the concrete slab and base, a bending stress (flexural stress) is induced at the top or bottom surface layer of it due to its residual stiffness [Mohamed and Hansen 1997]. In this case, maximum induced tensile stress occurs at the centre of the slab and at the top surface layer during the day and at the bottom surface layer during the night. On the other hand, in the presence of the restraining factors another tensile stress will occur in the opposite sides of the residual tensile stress. In this condition, curling induced tensile stress occurs at the top surface layer of the concrete slab during nighttime and at the bottom surface layer of the concrete slab during daytime [Ongel and Harvey 2004].

Combination of these stresses together with the location of neutral axis in the concrete slab and provision of load transfer devices (dowels and tie bars) dictate a specific stress distribution in the slab depth. As it can be observed in Figure 8, the top surface layer of the concrete slab is subjected to tensile stress during nighttime and its bottom surface layer experiences greater tensile stress during daytime as expected. However, these statements are not valid in the area close to the transverse joints for unbonded concrete pavement subjected to high differential temperature. Provision of dowels in transverse joints tends to reverse concrete slab curvature in the area close to transverse joints. This consequently changes stress distribution regime in this area. For instance, the top surface layer of concrete slab is subjected to tensile stress if pavement is subjected to a nighttime differential temperature of 25° C. However, pavement curvature has to change in the area close to transverse joints due to availability of dowels. Hence, the top surface layer is subjected to compression stress. As a result, the magnitude of tensile stress at the top surface layer starts to decrease while the magnitude of tensile stress at the bottom layer increases. Consequently, the top and the bottom surface layers of the concrete slab are subjected to tensile stress at this area and finally form a transverse crack close to the transverse joints.

For the base dimensions selected, the critical location of thermal stress is at distance of about 400 mm from the transverse joints. Since this distance is a function of pavement length, varying the length by ±2 metres may shift the location by ±50 mm. This finding explains the reason behind the formation of transverse cracks commonly found near transverse joints. In addition to the finding by Ongel and Harvey [2004] (corner loading associated with nighttime curling and warping results in corner cracking), high daytime and nighttime differential temperature can also crack the concrete slab in the area close to transverse joints.

A comparison between thermal stresses in bonded pavement with those from unbonded pavement shows that unbonded boundary condition decreases the induced tensile stress when lower differential temperature is considered. In other words, the benefits offered by a consideration of the unbonded

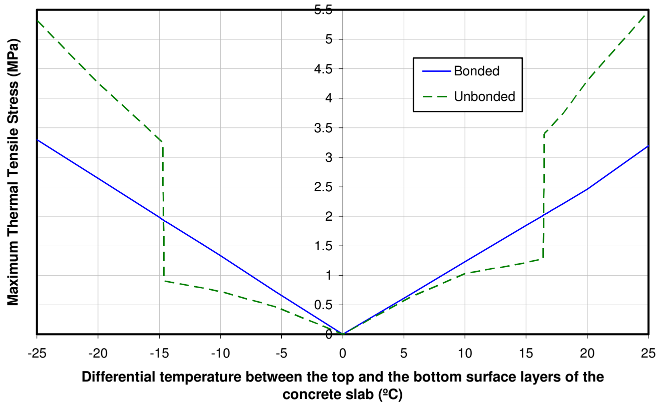

Figure 9. Comparison between thermal induced stresses for bonded and unbonded boundary conditions in single lane configuration.

boundary condition ceases at a certain value of differential temperature. Figure 9 shows an example of this finding in a single lane configuration. In this figure, negative values of differential temperature gradients represent nighttime differential temperatures and positive values represent daytime differential temperatures.

This finding suggests that with an increase in differential temperature, shear stress between slab and base increases until a full separation between concrete slab and base occurs. In this condition, the contact area between concrete slab and base rapidly decreases and consequently a significant bending stress is produced at the edge of the contact area. As a result, top-down corner cracking in upward curling or warping and bottom-up mid-slab transverse cracking in downward curling can be addressed by consideration of thermal induced stresses.

With regards to the significant effect of the boundary condition between concrete slab and base on induced thermal stress, Kuo's findings [Kuo 1998] will be modified as curling induced stress is affected by temperature differential, self-weight of concrete pavement, supported under concrete slab and boundary condition between concrete slab and base.

3.3. ***Combination of vehicular and thermal induced stresses.*** Information provided in Figure 9 indicates that the stress distribution in the concrete slab linearly changes with variations in differential temperatures in the presence of a fully bonded boundary condition between the concrete slab and the base. Similar results can be obtained in fully unbonded pavements subjected to a differential temperature greater than 16.5° C during daytime or lower than −14.5° C during nighttime. This suggests that accurate results can be expected when thermal induced stress at a certain location superimposed to vehicular induced stress at the same location. In the presence of fully unbonded boundary condition between the concrete slab and the base, however, the above mentioned consideration leads to inaccurate results when differential temperature during daytime and nighttime is lower than 16.5° C and greater than −14.5° C respectively, as the stress distribution in the above mentioned ranges seems to be nonlinear.

Figure 10 presents results of the current study for the bonded boundary condition between the concrete slab and the base when a full pavement configuration is subjected to temperature gradients of 10° C and

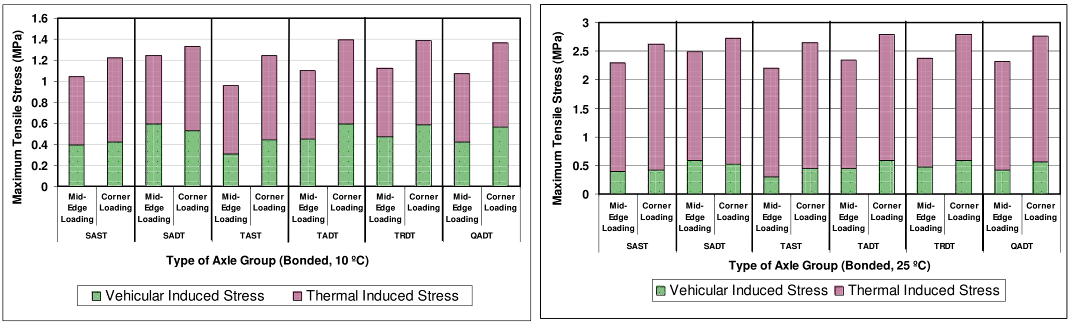

Figure 10. Vehicular and thermal induced tensile stresses in bonded concrete slab with full pavement configuration.

25° C. Vehicular induced tensile stresses for mid-edge and corner loadings have also been represented in this figure.

Results indicate that corner loading in the presence of thermal curling produces greater induced tensile stress than mid-edge loading if the bonded boundary condition is considered. In the unbonded boundary condition, higher differential temperatures change the critical location of axle groups toward an area close to the corner of the pavement (Figure 11). However, mid-edge loading results in greater induced tensile stress if pavement experiences lower differential temperatures.

Hiller and Roesler [2002] captured similar results when pavement was subjected to a nighttime differential temperature of 8.3° C which is very much lower than the differential temperature considered in the current study and moved the critical axle position from mid-edge toward corner of the concrete slab. This difference may be explained by taking into account the length of the pavement as 4.6 m in the current study and 5.8 m in the work of Hiller and Roesler [2002]. An increase in the pavement length increases the magnitude of shear stress between concrete slab and base or subgrade (in the absence of base) and consequently increases thermal induced stress. Consequently, the possibility of separation between layers in lower differential temperature increases. Hence, the aforementioned finding can be revised as corner loading will result in greater tensile stress than mid-edge loading if a separation due to environmental force occurs between concrete slab and base.

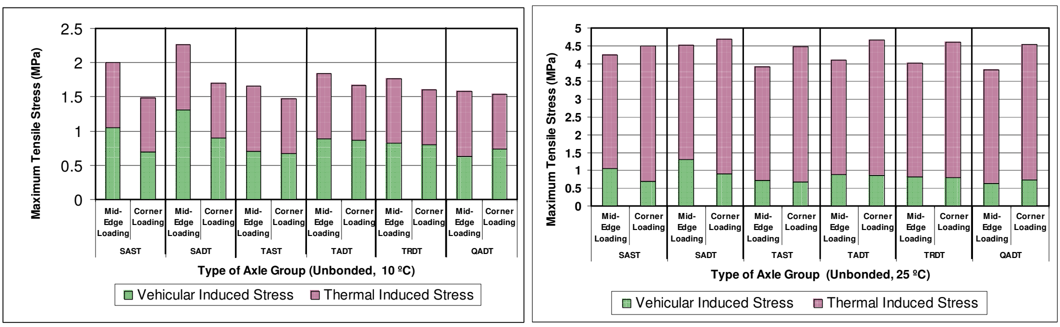

Figure 11. Vehicular and thermal induced tensile stresses in unbonded concrete slab with full pavement configuration.

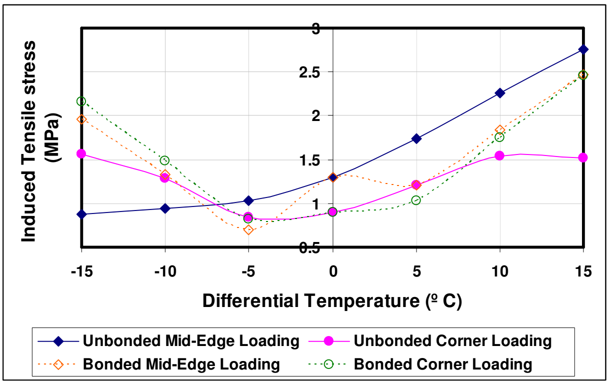

Figure 12. Combination of vehicular and thermal induced tensile stresses in a full pavement configuration subjected to SADT.

Since superposition law is not accurate enough when an unbonded pavement is subjected to small variation of temperature gradients, a full pavement configuration was examined for corner and mid-edge loadings together with differential temperature for better understanding of pavement behaviour under vehicular load and low or moderate differential temperature. SADT was considered in the analysis. Figure 12 compares thermal and vehicular induced tensile stresses due to mid-edge loading with the corresponding stresses of corner loading for bonded and unbonded pavements.

Results indicate that corner loading during nighttime produces greater tensile stresses than mid-edge loading in bonded concrete slab. By contrast, mid-edge loading during daytime results in greater tensile stress than corner loading. Nevertheless, corner loading is the critical loading condition when differential temperature exceeds 15° C. In fully unbonded pavement, on the other hand, mid-edge loading result in greater tensile stress than corner loading when a differential temperature greater than $-5°$ C is considered. Further decrease in differential temperature results in greater tensile stresses in corner loading than mid-edge loading.

These can be explained by taking the pavement curvature into consideration. During daytime, thermal induced tensile stress similar to vehicular induced stress occurs at bottom surface layer of the slab with a maximum at mid-edge. As a result, mid-edge loading produces greater tensile stresses than corner loading regardless of boundary condition between concrete slab and base. However, further increase in differential temperature tends to lift-off the centre of the slab. As a result, a greater tensile stress at the bottom surface layer of the slab occurs due to corner loading than mid-edge loading. Note that provision

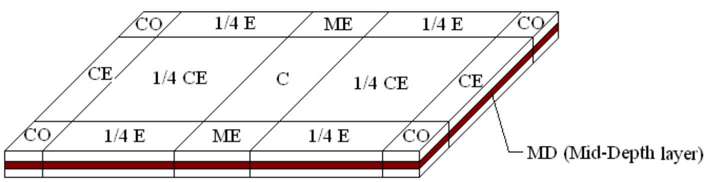

Figure 13. Information on location of fatigue cracking (see also Table 1).

of dowels at transverse joints together with slab weight results in a bending stress in the same direction of induced stress due to corner loading in daytime curling.

While nighttime differential temperature tend to lift-off transverse edges of the concrete slab, corner loading presses down the slab edge to return it to its original location. Consequently, tensile stress occurs at a location close to transverse joint and at the top surface layer of the slab due to cantilever action of the slab.

Crack location within the concrete slab is affected by vehicular loading conditions (corner, centre and mid-edge) and differential temperatures. To efficiently determine crack locations in concrete slab, the centre slab was divided into six areas (Figure 13). Table 1 presents the critical locations of concrete slab for fatigue cracking in a full pavement configuration subjected to combination of SADT and differential temperatures.

Interestingly, high differential temperatures result in joint faulting irrespective of the vehicular loading conditions and boundary conditions between the concrete slab and the base. This indicates that the finding of Ongel and Harvey [2004] – daytime and nighttime differential temperatures result in bottom-up and top-down cracking, respectively – is correct for a differential temperature lower than 15° C during daytime and greater than −15° C during nighttime. Furthermore, corner, centre and mid-edge loadings can result in different types of fatigue failure of the concrete slab depending on differential temperature.

These can be summarised as follows:

- While an unbonded pavement experiences a daytime differential temperature lower than 15° C, the maximum stress always occurs at the bottom surface layer of the slab where the vehicular load is applied.
- While an unbonded pavement experiences a nighttime differential temperature greater than −15° C,
  - centre loading results in top-down cracking at the corner or an area between corner and mid-edge areas,
  - mid-edge loading results in top-down cracking at the location between corner and mid-edge areas,
  - corner loading results in top-down longitudinal cracking passing along the centre area of the slab.
- While a bonded pavement experiences daytime differential temperature lower than 10° C, the maximum stress always occurs at the bottom surface layer of the slab where the vehicular load is applied.
- While a bonded pavement experiences nighttime differential temperature greater than −15° C,
  - centre loading results in longitudinal top-down cracking of the slab,
  - mid-edge loading results in mid-edge bottom-up transverse cracking,
  - corner loading results in top-down transverse cracking at a location between corner and mid-edge areas.

As mentioned earlier, Hiller and Roesler [2005] indicated that the nighttime differential temperature results in mid-edge top-down cracking. Results of the current study, however, indicate that this is not true when pavement experiences nighttime differential temperature lower than −20° C as joint faulting becomes the critical damage of concrete pavements in this case. Buch et al. [2004] mentioned that mid-edge and corner loadings result in bottom-up and top-down cracking respectively. Nevertheless, results

Slab thickness = 250 mm Modulus of subgrade reaction = 0.03 MPa/mm Axle group load = SADT		Temperature (°C)	Centre Loading	Mid-edge Loading	Corner Loading
	Daytime	25	CE at MD	CE at MD	CO at MD
		20	CE at MD	CE at MD	CO at MD
		15	UW at B	ME at B	CO at B
		10	UW at B	ME at B	CO at B
		5	UW at B	ME at B	CO at B
Unbonded		0	UW at B	ME at B	CO at B
	Nighttime	−5	CO at T	$1/4E$ at T	C at T
		−10	$1/4E$ at T	$1/4E$ at T	C at T
		−15	$1/4E$ at T	$1/4E$ at T	C at T
		−20	CO at MD	CO at MD	CO at MD
		−25	CO at MD	CO at MD	CO at MD
	Daytime	25	CO at MD	CO at MD	CE at MD
		20	CE at MD	CO at MD	CO at MD
		15	CE at MD	ME at B	CE at B
		10	UW at B	ME at B	CO at B
		5	UW at B	ME at B	CO at B
Bonded		0	UW at B	ME at B	CE at B
	Nighttime	−5	UW at B	ME at B	$1/4E$ at T
		−10	C at T	ME at B	$1/4E$ at T
		−15	C at T	ME at B	$1/4E$ at T
		−20	CO at MD	CO at MD	CO at MD
		−25	CO at MD	CO at MD	CO at MD

Table 1. Critical location of fatigue cracking in full pavement model due to different differential temperatures and SADT. Here, UW: under wheel; B: bottom surface layer; T: top surface layer; CE: centre area of transverse edge; MD: mid-depth Layer; CO: corner; C: centre area of the slab; ME: middle of the longitudinal edge; and $1/4E$: area at longitudinal edge between mid-edge and corner. See also Figure 13.

of the current study show that mid-edge loading results in bottom-up cracking in the absence of nighttime differential temperatures or in the presence of daytime differential temperature lower than 15° C. In the presence of nighttime differential temperature, mid-edge loading can results in top-down cracking at the slab edge or joint faulting (Table 1). Furthermore, corner loading results in top-down cracking in the absence of daytime differential temperature or in the presence of nighttime differential temperature

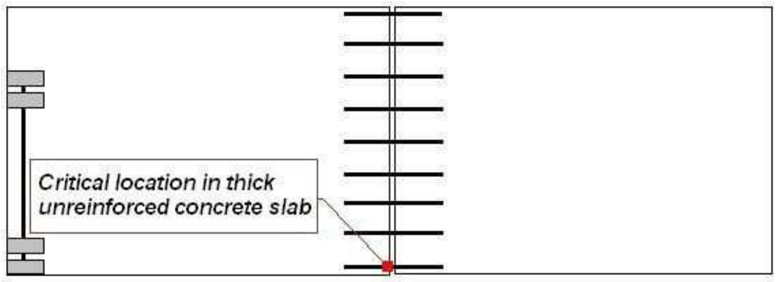

Figure 14. Position of the critical location in thick unreinforced concrete pavement.

lower than −20° C. In the presence of daytime differential temperature, corner loading results in bottom-up cracking at the corner. It should be noted that reasons behind joint faulting are presented later in this paper when effect of concrete slab thickness on pavement response is discussed.

Since [Austroads 2004] restricts the maximum distance between transverse joints in unreinforced concrete slab to 4600 mm, a separation between concrete slab and base in the absence of vehicular loads occurs when a differential temperature close to what presented in Figure 8 is considered. Vehicular loads can increase or decrease the critical value of differential temperature depending on position of vehicular loads and nature of differential temperature (daytime or nighttime).

Results of Hiller and Roesler [2002] were developed for unbonded boundary condition between concrete slab and base. Kuo's recommendation [Kuo 1998] is also valid for a certain range of differential temperatures and only unbonded boundary condition as mid-edge loading results in greater tensile stress than corner loading when lower nighttime differential temperature is considered or no separation occurs between concrete slab and base.

A comparison between induced tensile stresses in bonded and unbonded boundary conditions reveals that the unbonded boundary condition between concrete slab and base requires careful consideration when pavement is constructed in hot or cold weather where high differential temperature gradients may be produced in the concrete depth.

3.4. ***Effects of slab thickness on induced tensile stress.*** To find how slab thickness affects the results of the current study, a full pavement configuration subjected to different daytime and nighttime differential temperature gradients together with corner and mid-edge loadings was considered. Both bonded and unbonded boundary conditions were taken into account. Table 2 shows results of the current study for maximum induced tensile stress when modulus of subgrade reaction was held constant and SADT was applied on the centre concrete slab panel as either corner loading or mid-edge loading.

Results indicate that an increase in thickness of concrete slab decreases the magnitude of induced tensile stress regardless of boundary condition between concrete slab and base as mentioned by Buch et al. [2004]. However, the use of thicker concrete slab (300 mm thickness) associated with higher differential temperature (15° C) rapidly increases the value of induced tensile stress at mid-depth of the concrete slab for a node in unloaded transverse joint and close to the corner of the concrete slab (Figure 14). This can be explained by taking into account the concrete slab curvature together with location of axle group upon pavement.

Modulus of Subgrade Reaction = 0.03 MPa/mm Axle group load = SADT			Temperature (°C)	Slab Thickness (mm)		
				200	250	300
Unbonded	Corner loading	Daytime	5	1.627	1.213	0.876
			10	1.944	1.544	1.32
			15	2.172	1.52	4.52
		Nighttime	5	1.02	0.846	0.685
			10	1.6	1.282	1.009
			15	2.038	1.56	3.623
	Mid-edge loading	Daytime	5	2.296	1.744	1.333
			10	2.938	2.257	1.724
			15	3.514	2.758	2.044
		Nighttime	5	1.351	1.028	0.803
			10	1.328	0.945	0.704
			15	1.351	0.881	3.381
Bonded	Corner loading	Daytime	5	1.206	1.028	0.897
			10	2.025	1.745	1.524
			15	2.845	2.46	2.14
		Nighttime	5	0.922	0.825	0.722
			10	1.659	1.489	1.305
			15	2.404	2.16	1.9
	Mid-edge loading	Daytime	5	1.4	1.211	1.027
			10	2.12	1.837	1.557
			15	2.841	2.465	2.086
		Nighttime	5	0.839	0.703	0.623
			10	1.566	1.332	1.13
			15	2.298	1.965	1.674

Table 2. Effect of concrete slab thickness on maximum induced stress (MPa) due to different differential temperatures and SADT. Highlighted values occur very close to the corner of loaded concrete slab and at the middle of the concrete slab depth.

A downward curvature is produced during daytime temperature gradients. Corner loading associated with thermal curvature results in an increase in the area of separation between concrete slab and base toward the unloaded corners of the base. It ultimately induces a lifting-off at unloaded corners of the concrete slab. While thinner concrete slab is considered, the unloaded transverse edge of the concrete slab lifts off. In this case, induced bending stresses for transferring the weight of adjacent concrete panel are divided equally between all dowels located in unloaded transverse joint. Consequently, induced stress at interface of dowel and concrete remains in the normal range. On the other hand, thicker concrete slab results in nonuniform lift-off of unloaded corners which ultimately induce higher bending stress in that dowel located close to lifted-off corner. Mid-edge loading, on the other hand, alleviates the severity of the problem.

Nighttime temperature results in upward curvature. Both corner and mid-edge loadings together with nighttime temperature enhanced the magnitude of induced stress in thick concrete pavement as describes above. This finding suggests a particular dowel arrangement at corner of the concrete slab or a maximum slab thickness that shall be considered in the design of unreinforced concrete pavement.

Hiller and Roesler [2002] showed that a change in the thickness of the concrete slab changes the magnitude of induced stresses due to corner and mid-edge loadings uniformly. However, results of the current study indicate a nonuniform change between corner loading and mid-edge loading induced stresses. For instance, the proportion of induced tensile stress due to corner loading to induced tensile stress due to mid-edge loading, when unbonded pavement is subjected to a nighttime differential temperature of 10° C, is 1.205, 1.357 and 1.433 for slab thickness of 200 mm, 250 mm and 300 mm respectively.

3.5. ***Effects of modulus of subgrade reaction on induced tensile stress.*** To determine effects of modulus of subgrade reaction on the results of the current study, a full pavement configuration was subjected to different daytime and nighttime differential temperature gradients together with corner and mid-edge loadings. Both bonded and unbonded boundary conditions were taken into account. Table 3 shows results of the current study for maximum induced tensile stress when concrete slab thickness was held constant and SADT was applied on the centre concrete slab panel as either corner loading or mid-edge loading.

Results shows that modulus of subgrade reaction has different effects on the pavement response when daytime or nighttime differential temperature, corner or mid-edge loading, and unbonded or bonded boundary condition between concrete slab and base are considered.

An increase in modulus of subgrade reaction in the presence of nighttime temperature increases the magnitude of induced tensile stresses in most case studies. This is compatible with the statement of Buch et al. [2004]. In contrast, induced tensile stresses in the bonded pavement and in the presence of daytime differential temperatures decrease when modulus of subgrade reaction is increased and SADT is applied at the corner of the concrete slab. An increase in modulus of subgrade reaction associate with higher daytime differential temperatures and mid-edge loading increases the magnitude of induced tensile stress regardless of boundary condition between concrete slab and base. In some cases such as when the unbonded pavement is subjected to daytime differential temperature and mid-edge loading, modulus of subgrade reaction has no effect on maximum induced tensile stress as axle load induced stress is in negative direction of thermal induced tensile stress.

Hiller and Roesler [2002] showed that an increase in modulus of subgrade reaction in the presence of nighttime differential temperature of 8.3°C increases the proportion of corner loading induced stress to mid-edge loading induced stress. Results of the current study for unbonded pavement subjected to nighttime differential temperature of 10° C shows similar result.

Slab thickness = 250 mm Axle group load = SADT			Temperature (°C)	Modulus of Subgrade Reaction (MPa/mm)		
				0.03	0.05	0.07
Unbonded	Corner loading	Daytime	5 10 15	1.213 1.544 1.52	1.18 1.413 1.58	1.2 1.458 1.649
		Nighttime	5 10 15	0.846 1.282 1.56	1.18 1.377 1.58	0.924 1.434 1.757
	Mid-edge loading	Daytime	5 10 15	1.744 2.257 2.758	1.686 2.31 2.781	1.632 2.329 2.853
		Nighttime	5 10 15	1.028 0.945 0.881	0.847 0.791 0.895	0.751 0.826 1.007
Bonded	Corner loading	Daytime	5 10 15	1.028 1.745 2.46	0.967 1.651 2.234	0.946 1.581 2.248
		Nighttime	5 10 15	0.825 1.489 2.16	0.848 1.543 2.248	0.864 1.586 2.315
	Mid-edge loading	Daytime	5 10 15	1.211 1.837 2.465	1.198 1.859 2.519	1.197 1.885 2.573
		Nighttime	5 10 15	0.703 1.332 1.965	0.705 1.345 2.015	0.709 1.372 2.075

Table 3. Effect of modulus of subgrade reaction on maximum induced stress (MPa) due to different differential temperatures and SADT.

4. Conclusions

Critical positions of different axle groups in uncurled and curled jointed concrete pavement with different configurations were studied. Results of the current study indicate that AASHTO recommendation [AASHTO 2003] -except for SADT-and results of Packard and Tayabji [1985] –except for QADT- are valid for the fully unbonded boundary condition between concrete slab and base and uncurled pavement. Results of the current study also show that pavement performance under combinations of vehicular loads and differential temperatures is significantly affected by boundary condition between concrete slab and base.

The reasons behind longitudinal, transverse and corner cracking were addressed. The significant findings in this area were (i) corner loading is critical when there is a bonded boundary condition between concrete slab and base (ii) corner loading is also critical when a separation due to environmental forces occurs between the unbonded concrete slab and base. Furthermore, the benefits offered by consideration of the unbonded boundary condition cease at a certain value of differential temperature. Hence, a particular care needs to be given to those pavement projects constructed in hot or cold weather where high differential temperature gradients may be produced in concrete depth. Moreover, corner, centre and mid-edge loadings can result in different types of fatigue failure of the concrete slab depending on differential temperature.

There is an inverse relationship between induced tensile stress and thickness of concrete slab so that an increase in thickness of concrete slab decreases the magnitude of induced tensile stress. However, a maximum slab thickness or dowel arrangement at corners of the slab shall be considered in unreinforced concrete pavement as thicker slabs are sensitive to high differential temperature together with axle loading. An increase in modulus of subgrade reaction can increase or decrease the magnitude of tensile stress depending on boundary condition between concrete slab and base, corner or mid-edge loading and daytime or nighttime differential temperature.

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