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EVALUATING PAVEMENT SUPPORT ALTERNATIVES FOR PRECAST CONCRETE INLAY PANELS

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Abstract: Precast concrete pavement can achieve excellent long-term performance when constructed with stable, uniform support underneath the panels. Precast concrete inlay panels (PCIP) are a unique type of precast pavement, developed to rehabilitate rutted high-volume asphalt highways. A trial section of PCIP was installed on Highway 400 in Ontario, Canada in 2016 using three different types of panel support conditions called asphalt-supported, grade-supported, and grout-supported that are prepared at the asphalt-panel interface. The purpose of this research is to evaluate the performance of PCIP with different support conditions under a combination of axle loading and linear temperature gradients. Three-dimensional models of the PCIP were created using Abaqus software. One model was developed to represent the asphalt-supported condition (AS) and a second model represents the grade- and grout-supported conditions (GR). Parametric studies were performed to evaluate the critical stresses in the loaded panel for the AS and GR models. The study considered different values of the elastic modulus for the asphalt and support and varied degrees of bonding between the panels, support, and asphalt layers. The GR models had lower or comparable stresses than the AS model, and higher degrees of bonding reduced the critical stresses. Overall, a grout-supported condition with a stiff support and a higher degree of bonding between the panel-to-support and support-to-asphalt layers is recommended to minimize the critical panel stresses under combined axle loading and a temperature gradient, based on the scope of this study.

1 INTRODUCTION

1.1 Precast Concrete Inlay Panels

Precast concrete pavement (PCP) is constructed by installing concrete panels along the length of the roadway. The panels are prefabricated, which eliminates curing time from the field activities. Therefore, PCP installations are rapid, making them ideal for constructions or rehabilitations that have short allowable construction windows. PCP repairs are long-lasting, with an expected service life of 20 or more years.

Near the City of Toronto, in the province of Ontario, Canada, highways sustain high-traffic volumes and heavy truck traffic. Heavy truck loading accelerates the rate of pavement deterioration, and pavement rehabilitations requiring lane closures are highly disruptive for the roadway users. To minimize the user impact of construction on high-traffic volume highways, transportation agencies often restrict construction-related lane closures to an overnight period from 10 p.m. to 6 a.m. On some of the 400-series highways in Ontario, structural rutting of the asphalt pavement has been observed. This type of rutting is a result of issues in the lower layers of the pavement structure that cause deformations which are then reflected at the surface layer. A full-depth reconstruction would address the issues; however, this option is not feasible in the short construction period allowed. The rutted pavement has been rehabilitated in the past by milling and replacing the affected area with a new layer of hot mix asphalt. However, this rehabilitation strategy was observed to last for only 5 – 7 years before the rutting reoccurred, which is half the service life that was expected. Therefore, the use of precast concrete pavement was considered as a rehabilitation strategy that could offer a long-lasting solution and that could be feasibly performed in a short timeframe. The panels can be installed overnight, and the rehabilitated lanes can be reopened to traffic for peak daytime travel.

In 2016, a 100-metre long trial section of PCIP was installed in the province of Ontario, Canada on Highway 400 near kilometre 88 (Figure 1). This portion of Highway 400 has an AADT of approximately 93,000 and an estimated 12% truck traffic (“Ontario Provincial Highways Traffic Volumes On Demand” 2016).

Figure 1: Precast concrete inlay panels installation in third lane on Highway 400 during construction (left) and in service (right)

The rehabilitation using PCIP is performed by partial-depth milling of the existing asphalt, preparation of a support condition for the panels, inlaying the panels into the milled-out lane, and grouting. The final layers of the pavement structure, from bottom to top, are the untouched subgrade, subbase and base layers, the existing asphalt remaining after milling, the support condition, and the precast panel.

Three alternatives for the panel support conditions were developed and constructed for the PCIP trial installation. The support conditions are called asphalt-supported, grade-supported, and grout-supported. For the asphalt-support condition, the panels were placed directly on top of the milled asphalt. Bedding grout was then pumped underneath to fill any remaining voids between the asphalt and panel. For the grade-supported panels, the existing asphalt was milled, then a cement-treated base material (CTBM) was placed, levelled, and compacted. The panels were placed on the CTBM, and any voids were again filled with bedding grout. For the grout-supported panels, the panels were placed directly on the milled asphalt, then raised to the proper position using levelling inserts cast into the panels. A rapid-setting grout (RSG) was pumped underneath the panels for support (Figure 2). (Pickel et al. 2018)

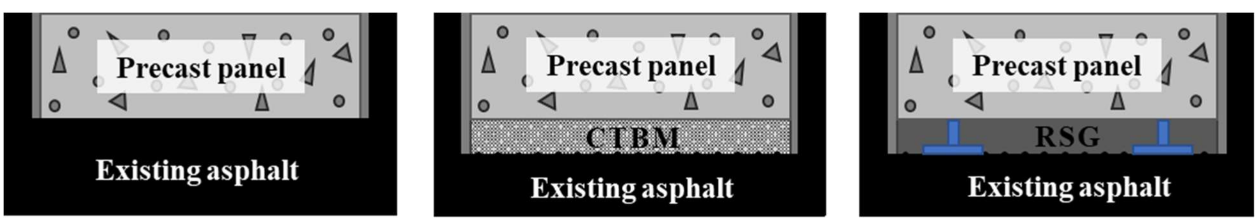

Figure 2: Support condition alternatives (L to R: asphalt-supported, grade-supported, and grout-supported)

The degree of bonding between the panels, asphalt, and support likely varies between each of these types of support conditions and will vary over time. It is hypothesized that the grout-supported condition would have the highest degree of bonding of the three support conditions since the leveling inserts would provide high friction between the panel and grout and the RSG is a stronger material than the bedding grout used in the asphalt-supported condition.

1.2 Precast Concrete Panel Support

The provision of a strong, stable support is a key consideration for precast concrete pavement. Typically, the base layer provides this support and a flowable bedding material is used to fill voids that exist between the base and panel because the precast panels do not precisely match the underlying surface. Inadequate support for the panel can result in gaps or loss of support underneath the panels that produce distresses in the pavement. Without proper support early stress development and uneven settlement can occur, which can lead to cracking, joint faulting, and early failure of the pavement (Tayabji, Ye, and Buch 2013). A strong support layer contributes to joint load transfer and reduces joint deflections, and a stable support is essential to reduce erosion of the subbase and prevent pumping, to improve drainage, insulate subgrade soils, and control shrinkage or swelling of the subgrade soils (Tutumluer, Xiao, and Wilde 2015; Bing Sii 2014).

1.3 Effects of Thermal Gradients on Pavement

Temperature gradients across the thickness of a precast concrete panel cause warping and curling of the panel. Under a temperature gradient, the concrete expands on the warmer face of the panel and contracts on the cooler face of the panel. During the daytime, the top of the panel is warmer than the bottom, causing the panel to curl upwards such that the centre of the panel is unsupported. During the nighttime, the top of the panel is cooler than the bottom side, causing the panel to curl downwards such that the panel edges are unsupported. Similarly, moisture differentials will cause panel curling since the concrete expands on the face that is exposed to more moisture. (Merritt et al. 2000)

Panel curling is counteracted by the self-weight of the slabs. The support provided by the underlying pavement layers is reduced when the panel curls upwards, and the panel self-weight induces tensile stresses at the bottom or top of the panel under a daytime or nighttime gradient, respectively. Sufficiently large tensile stresses cause transverse cracking in the concrete panels. Traffic loads also add to this effect. Repeated, heavy axle loads cause fatigue damage to the panels and cracking eventually occurs in the locations of high tensile stress. In jointed plain concrete pavements, the panel distresses are exacerbated when there is a temperature gradient present that reduces the support under the axle-loaded area. (Merritt et al. 2000; ARA Inc. 2004). Therefore, temperature effects can have a significant effect on the performance of precast concrete panels.

2 FINITE ELEMENT MODEL

2.1 Model Description

Three-dimensional finite element models of the precast concrete inlay panels were created using the software Abaqus. The model comprises six components: concrete panels, dowel bars, support condition, asphalt, granular base, and subgrade. Three panels were modelled, and to reduce computation time only a quarter of the geometry was explicitly modelled and symmetry boundary conditions and symmetrical loading were applied. There are two versions of the finite element model: the AS model represents the asphalt-supported PCIP and the GR model represents the grade- and grout-supported PCIP.

Each panel is 3.66 m wide and 4.57 m long, and has a thickness of 205 mm. The assumed joint width between panels was 15 mm. The asphalt and base layers were extended by 2 m in length and width beyond the panel boundaries. The asphalt and base layer thicknesses are the average thicknesses measured in the location of the PCIP trial section, identified by ground penetrating radar and boreholes performed during a site investigation in 2012. The subgrade was modelled as a dense-liquid foundation with a modulus of subgrade reaction (k-value) of 29.7 MPa/m, based on the site investigation. The foundation was modelled using the ‘elastic foundation’ option in the Abaqus. The model dimensions are summarized in Table 1.

Load transfer in the PCIP is provided by 11 dowel bars located asymmetrically. There is a set of 6 dowels in the inner wheel path and 5 dowels in the outer wheel path. For simplicity, five dowels were modelled symmetrically, spaced at 0.3 m centre-to-centre with the last dowel located at 0.3 m from the edge of the panel. The dowel bars are 0.355 m long with a 38 mm diameter, and the steel was assigned an Elastic Modulus of 200,000 MPa and Poisson’s ratio of 0.27.

All material properties were assumed to be isotropic, homogenous, and linear elastic. This is a common idealization used for static pavement analyses (Davids 2001; Kuo 1994; Maitra, Reddy, and Ramachandra

2009; Northmore and Tighe 2016). It was assumed that the pavement is not distressed, that the soils can be approximated by idealized linear behaviour, and that the static loads applied generally do not induce stresses that exceed the elastic range of the materials. In the case that the actual pavement behaviour does pass into the nonlinear region, a linear elastic approximation may overestimate the pavement strength. The dimensions and properties of each of the pavement components are summarized in Table 1.

Table 1: Model dimensions and material properties

Component	Width (m)	Length (m)	Thickness (m)	Elastic Modulus (MPa)	Poisson's Ratio (-)	Density (kg/m^3)
Concrete	3.66	4.57	0.205	34,109	0.15	2,396
Support	3.66	6.87	0.012	*Varies*	0.35	2,300
Asphalt	5.66	8.87	0.175*	*Varies*	0.35	2,300
Granular Base	5.66	8.87	0.600	80	0.35	2,100

*For the AS model. Asphalt thickness was reduced by 0.012 m for the GR models to account for the support layer thickness

Each component was meshed using three-dimensional 20-noded continuum elements (C3D20R) from the Abaqus element library. The dowel bars were located within the panels using the 'embedded region' option. This method allows a set of solid elements, such as the dowel bars, to be embedded in another set of solid host elements, such as the panels. Using this method, the host elements are used to constrain the translational degrees of freedom of the nodes of the embedded elements ("Abaqus Analysis User's Guide (6.14)" 2014).

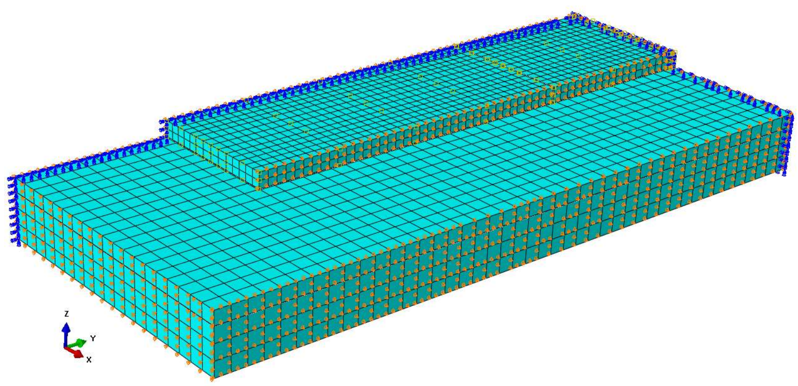

Figure 3: Finite element model of precast concrete inlay panels

2.2 Pavement Layer Interfaces

The behaviour of the interfaces between different pavement layers was modelled as the classical, isotropic Coulomb friction model using the 'surface-to-surface' contact option in Abaqus. The two surfaces in contact were defined and assigned a friction interaction property that consists of tangential and normal behaviour.

For the tangential friction formulation, either the 'penalty' or 'rough' option was implemented. For the 'penalty' option, a friction coefficient that affects the degree of bonding can be specified. This method allows varying degrees of bonding to be applied at the interface between two layers. To represent fully bonded layers, the tangential friction component can be defined as 'rough' rather than assigning a coefficient; this acts as an infinite friction coefficient that prevents any relative slip between the two surfaces in contact. The friction property has a normal component, in which the pressure-overclosure relationship was specified as 'hard' contact and the constraint enforcement method was set as 'default' which is the 'Penalty method'. The 'hard' contact relationship transmits any contact pressure when the surfaces are in contact (when there is no gap between them) and if the surfaces separate then the contact pressure is set to zero. The normal behaviour also includes an option to 'allow separation after contact; this was enabled for the 'penalty' formulation and disabled for the 'rough' formulation. ("Abaqus Analysis User's Guide (6.14)" 2014)

For the grade-supported and grout-supported conditions, the support is provided by cement-treated bedding material and rapid-setting grout, respectively. These support conditions were modelled by defining a part with a specified thickness and material properties, and by assigning a friction property at the panel-support and support-asphalt interfaces. A generic support material was included in the GR model which represents either the CTBM or the RSG. For the asphalt-supported case, a support layer was not explicitly included in the AS model because the panels are placed directly on top of the prepared asphalt, with a small amount of bedding grout used to fill any voids at the panel-asphalt interface. The support condition was accounted for in the model simply by defining a friction property at the panel-asphalt interface to represent a degree of bonding established by the bedding grout.

A friction property using the ‘penalty’ option and a friction coefficient of 0.5 was defined at the asphalt-base interface for both the AS and GR models. At the panel-asphalt interface for the AS model and at the panel-support and support-asphalt interfaces for the GR models, two different friction properties were compared; these interfaces were assigned either the ‘penalty’ option with a friction coefficient of 0.5 to represent a low degree of bonding or the ‘rough’ option to represent a high degree of bonding.

2.3 Boundary Conditions

Vertical rollers were applied to the asphalt and base layers (the sublayers) to prevent lateral translation of the longitudinal edges (U1 = 0) and to prevent longitudinal translation of the transverse edges (U2 = 0). The boundaries of the sublayers were extended beyond the panel dimensions such that the roller boundary conditions had a negligible effect on the responses of the loaded panel and the sublayers underneath the loaded area. To determine the optimal lateral extents of the sublayers varying extents were modelled, and it was found that an extension of 2m in length and width beyond the edges of the panels was sufficient.

The adjacent lane of asphalt pavement borders the longitudinal edge of the panels, and the longitudinal concrete-asphalt joint is filled with grout. Therefore, the longitudinal edges of the panels and the support layer were assigned boundary conditions that prevent lateral movement (U1 = 0).

Dowel bars connect adjacent panels and transfer load from the loaded panel to the adjacent unloaded panel causing both panels to deflect. A bond breaker was applied to one side of the dowels before grouting to allow the dowels and panel to move longitudinally. The modelled boundary condition for the panel edge should approximate the behaviour that would result from modelling additional panels. To establish an appropriate end condition, a five-panel model was developed and compared to a three-panel model with free end panels and a three-panel model with rollers on the end panels that prevented longitudinal movement. Both of these three-panel models closely approximated the five-panel model for the pavement responses of interest in this study (the loaded panel and underlying asphalt). The model with roller ends required significantly less computation time and was chosen over the free-end model for this reason. Therefore, boundary conditions were applied to the transverse edge of the end panel to restrict its longitudinal movement.

2.4 Loads

The pavement responses were investigated under a combination of temperature gradients, self-weight, and axle loading, since this load combination produces more critical responses than any of these loads alone. The applied daytime and nighttime gradients were 10°C and -10°C, respectively, and were assumed to be linear through the slab thickness.

Under a nighttime temperature gradient when the slab ends curl upwards, a 140 kN axle loading was applied at both ends of the panel near the transverse joint where there is reduced support. Under a daytime temperature gradient when the middle of the slab curls upwards, a 175 kN axle loading was applied at the centre of the panel where the support is reduced by the panel curling. The axle was centred transversely on the panel, and each wheel load was applied over an area of 0.6 m wide by 0.25 m long. This traffic loading is based on the CL-625-ONT design truck used in Ontario. (Canadian Standards Association 2006)

Self-weight was applied to the panels, support, asphalt, and base layers using the material densities summarized in Table 1.

2.5 Model Validation

To validate the 3-D finite element model, a single panel on a Winkler foundation was modelled and compared to theoretical solutions. Under interior and edge loading the results were compared with Westergaard theory. The panel was modelled as described previously and a k-value of 135 Pa/m was used to represent a stiff support with an asphalt layer (Delatte 2014). The finite-element and theoretical stresses and deflections matched reasonably well, within 2% and 11%, respectively (Table 2). Under a linear thermal gradient the finite-element results were compared with Westergaard-Bradbury theory and the responses matched very well, within 5% of each other. This demonstrates that the 3-D panel was behaving as expected under wheel loads and temperature gradients.

Table 2: Comparison of 3D FEM and Westergaard responses

Model	Max Stress (MPa)	Difference from Westergaard (%)	Max deflection (mm)	Difference from Westergaard (%)
Interior Loading				
Westergaard Theory	1.23	-	0.094	
3D FEM	1.26	2%	0.104	10%
Edge Loading				
Westergaard Theory	2.14		0.263	
3D FEM	2.17	1%	0.291	11%

Due to lack of field investigation and testing of the PCIP site, there is limited information available regarding the material properties of the existing pavement layers. Future research will involve trying to calibrate the unknown model inputs, such as the asphalt Elastic Modulus and friction properties, using Falling Weight Deflectometer test results. This study considers a range of possible values for the asphalt and support elastic Modulus and the friction properties since these parameters are unknown.

3 FINITE ELEMENT ANALYSIS

3.1 Methodology

The finite element analysis was performed to evaluate and compare the performance of the panel support conditions under a combination of self-weight, axle loading, and temperature gradients. Parametric studies were performed to evaluate the effect of changes in properties of the asphalt and support and varied degrees of bonding between the panel, support, and asphalt interfaces. The Elastic Modulus of the asphalt and support layers were varied, as well as the friction applied to the panel-to-asphalt interface (AS model) and panel-to-support/support-to-asphalt interfaces (GR model). Two levels of bonding were applied at the layer interfaces in the parametric study. A lower degree of bonding was applied to the interfaces by assigning a friction coefficient of 0.5, and higher degree of bonding was applied by assigning the tangential component as 'Rough' which prevents slip between the two surfaces. The rough interface approximates the behaviour of fully bonded layers. The parametric study values are summarized in Table 3.

Table 3: Parametric study values

Property	Values
Asphalt Elastic Modulus (MPa)	1000, 3000, 5000
Support Elastic Modulus (MPa)	4000, 12000, 20000
Friction (panel-to-asphalt, panel-to-support, support-to-asphalt) (-)	0.5, Rough

The critical stresses in the loaded panel were compared over the range of values considered in the parametric studies, for the AS and GR models. The stresses were normalized with respect to the maximum absolute stress, for direct comparison of the alternatives. The critical stresses are the maximum principal stresses and the minimum principal stresses.

3.2 Daytime Loading Results

The critical stresses in the loaded panel for the daytime loading combination are summarized in Figure 4 and Figure 5.

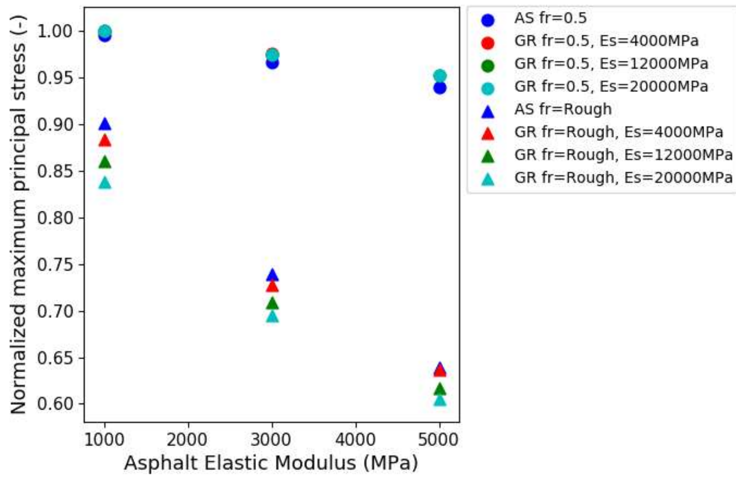

Figure 4: Maximum stresses in loaded panel for daytime temperature gradient

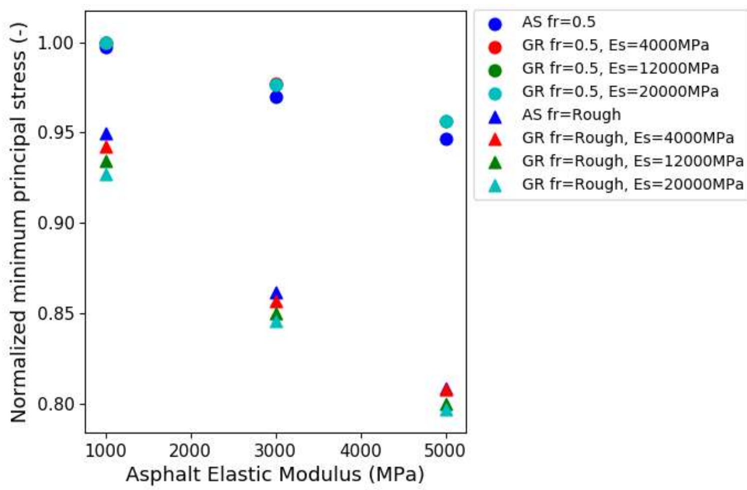

Figure 5: Minimum stresses in loaded panel for daytime temperature gradient

For the AS and GR models under daytime loading, the maximum and minimum stresses in the loaded panel occurred directly below the centres of the wheel loads at the bottom and top of the panel, respectively.

Under daytime loading, the critical stresses in the loaded panel decreased with an increase in the asphalt modulus. Due to increased in the asphalt stiffness, the stresses decreased by up to 5% with low interface friction and up to 35% with high friction. For low interface friction, the difference in critical stresses between the AS model and the GR models was negligible and changes in the support stiffness had a negligible effect. However, for higher friction, the GR models produced lower stresses than the AS model, and as the support stiffness increased the critical panel stresses decreased by up to 5%. Increases in the support stiffness were less significant when the asphalt stiffness was high. This behaviour occurs because a stiffer asphalt or support layer underneath the loaded panels reduced the panel deflections and stresses. It is generally expected that a stiffer base will increase temperature-induced curling stresses in concrete panels (Delatte 2014). However, a stiffer base has been shown to be beneficial in reducing stresses for axle loading and may result in an overall beneficial effect under combined temperature and axle loading (Davids 2000).

The critical stresses were up to 25% lower with higher friction than with lower friction. With higher friction, there is a greater degree of bonding between the panel and asphalt or support, which produces more monolithic behaviour and reduces the stresses in the panels.

3.3 Nighttime Loading Results

The critical stresses in the loaded panel for the nighttime loading combination are summarized in Figure 6 and Figure 7.

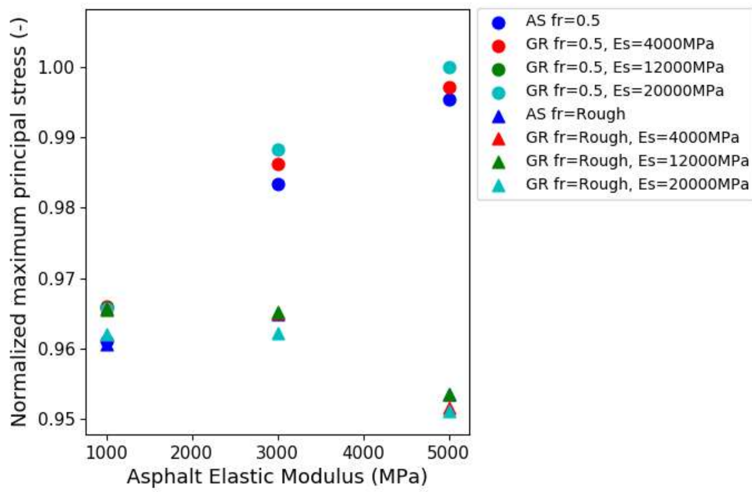

Figure 6: Maximum stresses in loaded panel for nighttime temperature gradient

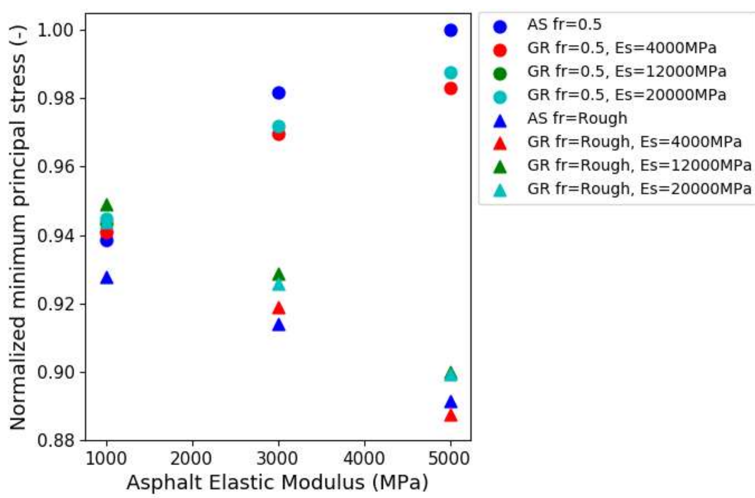

Figure 7: Minimum stresses in loaded panel for nighttime temperature gradient

Under nighttime loading, the maximum and minimum stresses in the loaded panel occurred in the corner at the top and bottom of the panel, respectively.

The range of critical stresses under nighttime loading was substantially smaller than the range of responses under daytime loading. This indicates that changes in the material properties and degree of bonding had a much smaller impact on the nighttime loading stresses than daytime.

As the asphalt elastic modulus increased, the critical stresses increased if the interface friction was low and the stresses decreased if the interface friction was high. Under nighttime loading, the panel edges curl upwards away from the underlying layers. For lower friction, the stresses increased with a stiffer support because the panels curl more than with a less stiff support. The beneficial effect of a stiffer support for axle loading was not significant enough to reduce the stresses in the nighttime loading combination. For higher friction, the panels have a stronger bond with the asphalt, which reduced the panel curling and stresses as the asphalt stiffness increased. When the asphalt stiffness was low at 1,000 MPa, the critical responses for low friction and high friction converged because both the unfavorable effect of increased panel curling with a low asphalt-concrete bond and the beneficial effect of decreased stresses with a strong asphalt-concrete bond were reduced.

The difference in critical responses between the AS and GR models was not significant, and changes in the support elastic modulus had a minor effect on the critical responses of the GR models.

The critical stresses were generally lower for models with high interface friction than for those with lower interface friction; this behaviour was more pronounced as the asphalt elastic modulus increased. A greater degree of bonding between the panels and asphalt reduces the panel curling and panel stresses, and the stiffer the asphalt the more this effect occurs.

3 CONCLUSIONS

Precast concrete inlay panels (PCIP) are used to rehabilitate rutted asphalt highways by milling a layer of asphalt and inlaying precast concrete panels into the roadway. Before placing the panels, a support condition is prepared to provide a uniform, stable support layer. There are three-types of possible support conditions which are called asphalt-supported, grade-supported, and grout-supported. Two different finite element models were developed using Abaqus; one model represents the asphalt-supported condition (AS) and the other represents both the grade- and grout-supported condition (GR). The applied loading included self-weight, axle loads, and either a 10°C daytime temperature gradient or a -10°C nighttime temperature gradient. Parametric studies were performed to evaluate the effect of the asphalt Elastic Modulus, support Elastic Modulus, and the degree of bonding between the panel, asphalt, and support interfaces on the critical stresses in the loaded panel. The asphalt Elastic Modulus was varied from 1,000 MPa to 5,000 MPa and the support Elastic Modulus was varied from 4,000 MPa to 20,000 MPa. Two levels of interface bonding were considered: lower friction assigned using a friction coefficient of 0.5 and higher bonding assigned using a ‘rough’ interface that approximates the behaviour of fully-bonded layers.

The following conclusions are provided specifically for the daytime and nighttime loading combinations studied. Based on the results, some practical recommendations can be made regarding the construction of the PCIP support conditions:

1. The grade- and grout-supported conditions generally have lower or comparable stresses to the asphalt-supported condition. Furthermore, in construction, it is likely that the grout-supported condition will achieve a better bond than the asphalt- or grade- supported condition. Comparing the GR model with higher friction to the AS model with lower friction, the critical stresses in the loaded panel are consistently lower with the GR high friction model. Therefore, based on construction knowledge and the results of the FEA the grout-supported condition is recommended.
2. A higher degree of bonding between the panels and the underlying layers reduces the critical stresses in the panels.
3. Increases in the support elastic modulus either had a negligible effect or, under some conditions, resulted in decreases in the critical panel stresses. Therefore, to minimize panel stresses it is recommended to increase the support stiffness within the range of values evaluated in this study.

The PCIP are installed over the existing asphalt so the asphalt stiffness could not be modified during design or construction. However, the study considers changes in the asphalt stiffness to establish the expected behaviour of the PCIP for the existing asphalt condition. In most cases, a stiffer asphalt would be beneficial in reducing the critical stresses in the loaded panel. However, in the case of nighttime loading with lower panel-to-asphalt friction the stresses would increase.

Overall, a grout-supported condition with a stiffer support and a high degree of bonding between the panel-to-support and support-to-asphalt layers is recommended to minimize the critical panel stresses for combined axle loading and temperature gradients, based on the scope of this study.

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