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## MECHANISTIC RESPONSES OF ASPHALT CONCRETE OVERLAY OVER JOINTED PLAIN CONCRETE PAVEMENT USING FINITE ELEMENT METHOD

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**Abstract.** This study focused on the development of a three-dimensional Finite Element Model of an asphalt concrete overlaid on a jointed plain concrete pavement to assess the mechanical behaviour of the pavement under traffic load. The objective of this study was to determine the influence of different asphalt concrete thickness, asphalt concrete modulus, the interface bond between the asphalt concrete and the Portland cement concrete layer, Portland cement concrete modulus, and joint width on the tensile strain at the bottom of the asphalt overlay. The results showed that changes in the pavement parameters result in a large range of variations on the magnitude of pavement responses. The magnitude of the longitudinal tensile strain at the bottom of the overlay varied between 25  $\mu$ s and 460  $\mu$ s. Asphalt concrete thickness, interface contact condition, and asphalt concrete modulus parameters had the most influence on the pavement responses. The interface bonding condition was significant, regardless of the thickness of the surface layer.

**Keywords:** asphalt overlay, Finite Element Model (FEM), Portland cement concrete (PCC), reflective cracking.

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Mechanistic Responses of Asphalt Concrete Overlay Over Jointed Plain Concrete Pavement Using Finite Element Method

## Introduction

Portland cement concrete (PCC) pavement is known for its longlasting durability service life with regular maintenance. However, despite their good performance, PCC pavements overtime reach the end of their service life due to the combination of weather conditions and traffic loading. Thus, rehabilitation needs to be carried out before the pavement reach this level. There are several techniques for rehabilitating deteriorated PCC pavement. Depending on the traffic volume, placing an overlay is the most used method to restore the pavement structural capacity and also improving the ride quality (Huang, 1993). The placement of asphalt concrete (AC) overlay is considered to be the most common technique used for rigid pavement rehabilitation (Freeman & Board, 2002; Pavement Consultancy Services, 1991). The good performance of this method of rigid pavement rehabilitation is affected negatively by the apparition of cracks knows as "reflective cracking". These cracks are the results of high strain concentration in the asphalt overlay due to the bending and shearing movements of the underlying slabs at the joints or cracks present in the old structure, caused by temperature changes, moisture cycles, and traffic loads (Lytton, 1989; Lytton, Tsai, Lee, Luo, Hu, & Zhou, 2010; Nunn, 1989). Reflected crack leads to premature failure of the overlaid pavement, and it severely impacts the performance and the serviceability of the road (Francois, Larson, Pennsylvania, Borchert, Braun, Dustin, & Manheim, 1982).

The critical responses are the concentration of tensile strains at the bottom of the AC layer at the vicinity of cracks and joints. Several researchers have been effectuated to investigate the sensitivity of these critical responses to the changes in the pavement characteristic parameters (structure, material properties, layer interactions) by using accelerated pavement testing facilities, laboratory studies, and numerical analysis. Some studies, for instance, focused on the interface contact condition between the asphalt and the existing PCC layer (Al-Qadi, Carpenter, Leng, Ozer, & Trepanier, 2009; Ozer, Al-Qadi, Wang, & Leng, 2012). Some have studied the design of the Hot Mix Asphalt (HMA) and the thickness of the AC and also the use of reflective cracking countermeasures such as paving fabrics interlayer (Amini, 2005; Fallah & Khodaii, 2015; Shen, Zhang, Wang, & Huang, 2017; Sobhan & Tandon, 2008). All these parameters were found to be affecting the performance of the overlay on a different level.

This study compares pavement characteristics cited below on the performance of an asphalt overlay over jointed Portland cement concrete pavement.

AC overlay thickness;

- AC overlay modulus;
- bonding interface condition between the AC and the PCC layers;
- modulus of the existing PCC pavement;
- dimensions of the joints in the existing pavement.

## 1. Materials and methods

A 3D Finite Element model (3D FEM) able to simulate the responses of an AC overlaid on an existing jointed plain concrete pavement (JPCP) with various parameters under traffic axle loading was created to accomplish the study objectives. The ANSYS APDL 16.0 was used to simulate the pavement responses. The Finite Element modelling included the creation of the pavement geometric model, the attribution of the materials, the meshing, the creation of the contact between the layers, and the application of loads and boundary conditions.

#### 1.1. Geometry model

As this study focused on analysis rather than design, a typical fourlayer pavement structure consisting of an AC overlaid on an existing JPCP resting on an aggregate base, and a subgrade was adopted (Figure1). The typical slab length in a JPCP is around 6 m. However, since the critical responses are located near to the joint, only half of the slab from either side of a 1 cm width joint was modelled. This assumption allowed modelling a 3D pavement section of 6 m length in traffic



Figure 1. Pavement model geometry

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direction (longitudinal direction), and 4 m in the transverse direction. The total depth of the existing pavement was assumed to be 2.4 m consisting of 0.2 m of the PCC layer, 0.2 m of the base layer and 2.0 m of the subgrade layer. Different overlay thicknesses varying from 3 cm to 25 cm were modelled. The joint width also varied from 0 cm to 2 cm to determine the joint opening effect.

## 1.2. Element types and material properties

The model created for this study was an assembly of solid elements with different thicknesses and material properties. Both eight nodes solid element (also known as a brick element) and 20-node solid element are to model the layers of the composite pavement. Using the eight nodes solid element is less time-consuming (Cable, Fanous, Ceylan, Wood, Frentress, Tabbert, ..., & Gopalakrishnan, 2005; Williamson, 2015). However, the 20-node solid element provides more accurate results despite a higher requirement for the computational resource. Kumara, Tia, Wu, & Choubane (2003) used 20-node solid elements in his study of ultra-thin white topping pavement layers (Kumara, Tia, Wu, & Choubane, 2003). The 20-node solid 186 elements were used in this study for all the elements. All layer materials were assumed to be linear, elastic and isotropic (Lytton, Tsai, Lee, Luo, Hu, & Zhou, 2010; Sobhan & Tandon, 2008). Since the asphalt material stiffness depends on the temperature (low elastic modulus in hot weather and high elastic modulus in cold weather) and the design mixture of the HMA, four different asphalt moduli were considered to determine its effect on the responses in the AC layer. Three different PCC modulus were also considered when analysing its effect on the pavement responses. Table 1 gives the material properties of the different layers.

Layer	Elastic modulus, MPa	Poisson's ratio	
Asphalt concrete	2000, 3500*, 5000, 10 000	0.35	
Portland cement concrete	34 000, 28 000*, 20 000	0.20	
Granular base	250	0.40	
Subgrade	150	0.45	

Table 1.	Properties	of the	materials
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Note: \* unless otherwise stated, the value used.

## 1.3. Boundaries conditions and loading

The size and quality of the model mesh affect the rightness of the result. Studies have shown that fine mesh gives more accurate results even though it requires much time to analyse. The fine mesh was used for the surface and a relatively coarse mesh for the subgrade (Williamson, 2015) (Figure 2).

In ANSYS the contacts are generated by pair. For the node-surface contact, the node is "contact" and the surface a "target". For the surface to surface contact both "contact" and "target" are surfaces and the user has to specify which surface is contact or target. In this study "surface to surface" contact was used. There are several types of interaction behaviour for the "surface to surface" contact in ANSYS: standard, rough, bonded. The "bonded always" was used to simulate fully bonding interfaces, and the "standard" contact with a coefficient of friction equal to zero was used for unbonded interfaces. In this study, all the layers in the existing pavement were assumed to be fully bonded. Whereas fully bonded and unbonded interaction between the AC overlay and the PCC was considered (Thompson & Thompson, 2017).

All nodes at the bottom of the subgrade were restrained in all directions. The nodes on the sides were restrained in *X*-direction for traffic direction sides and *Z*-direction for pavement width sides (Williamson, 2015). The standard axle load of 80 kN with a tire pressure of 689 kPa was adopted (Lytton, Tsai, Lee, Luo, Hu, & Zhou, 2010). This study used uniform pressure applied to rectangular areas with dimensions approximating those of a single tire contact area. This loading concept of considering uniform pressure over the entire length of the wheel has been used successfully in previews studies (Lytton, Tsai, Lee, Luo, Hu, & Zhou, 2010). A static axle-load single tire was selected for this study (Figure 3).



Figure 2. Model mesh



**Figure 3.** Axle load and tires contact dimensions

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Figure 4. Axle load positions in respect of the joint

Axle load was placed at three different positions on the surface to find the critical axle load position on the pavement responses (Figure 4). The axle load was centered for the transverse direction of the pavement.

## 2. Results and discussions

## 2.1. Critical axle load position and critical response

The results showed that the critical position of the axle load was when the load was applied to one side of the joint. The longitudinal strains were found to be the most critical compared to the transverse ones, 113  $\mu\epsilon$  and 69  $\mu\epsilon$  for longitudinal and transverse strain, respectively (Figure 5). The longitudinal tensile strains at the different positions were 73  $\mu\epsilon$  (for the first two positions) and 113  $\mu\epsilon$ .



**Figure 5.** Tensile strain at the bottom of the asphalt concrete overlay versus axle load position

#### 2.2. Effect of the asphalt overlay thickness

Figure 6 shows the variation of the tensile strain at the bottom of the overlay with the AC thickness at different asphalt modulus. For the AC elastic modulus 2000 MPa, 3500 MPa, 5000 MPa and 10 000 MPa and thickness of 3 cm, 6 cm, 10 cm, 15 cm, 20 cm, and 25 cm, the magnitude of the tensile strain varied from 25  $\mu\epsilon$  to 318  $\mu\epsilon$ . The range of the pavement response variation due to the changes in the overlay thickness and modulus is large. It confirms that the performance of the overlaid pavement depends a lot on the design of the asphalt concrete overlay.

In terms of tensile strain, regardless of the modulus of the asphalt material when increasing the thickness of the overlay the magnitude of the tensile strain decreases; the reverse is also true, i.e. when the asphalt material modulus increases the tensile strain decreases. For example, for an AC thickness of 10 cm when increasing the AC modulus of 2000 MPa to 10 000 MPa, the tensile strain decreases by about 64%. Moreover, for an AC modulus of 3500 MPa by increasing the AC thickness from 3 cm to 25 cm, the magnitude of the tensile strain decreases about 84%. Tensile strain due to the change in the AC modulus decreases when the thickness of the overlay is higher than 10 cm. For example, for an AC thickness of 6 cm by changing the AC modulus of 2000 MPa to 10 000 MPa, the magnitude of the strain decreases by 71%, and the strains for 20 cm decreases 60%.



**Figure 6.** Longitudinal tensile strain at the bottom of the asphalt concrete versus overlay thickness

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## 2.3. Bonding effect

One of the objectives of this study was to investigate the bonding effect between the AC and the PCC under traffic loading. The AC and PCC interface bonding condition is one of the most important factors affecting the performance of the overlay pavement. With a bonded interface, the AC and the existing PCC behave as a unit and the PCC layer carries a significant part of the load. Whereas when unbonded, the PCC only provides a base for the AC overlay. The effect of the AC and PCC bonding condition on the longitudinal tensile strain at the bottom of the AC overlay is shown in Figure 7 and Figure 8.



Figure 7. Effect of interfaces contact condition for different overlay thicknesses



**Figure 8.** Effect of interface contact condition for different asphalt concrete modulus

The study results showed that the load-induced tensile strain at the bottom of the overlay was significantly influenced by the AC and PCC bonding condition regardless of the AC thickness or modulus. The magnitude of the tensile strain at the bottom of the overlay increased by 113% and up to 198% by changing the interface contact from bonded to unbonded depending on the AC thickness and modulus. For example, for an AC thickness of 6 cm and 3500 MPa, the values of the strains were 113  $\mu\epsilon$  and 277  $\mu\epsilon$  for bonded and unbonded AC and PCC interfaces respectively.

# 2.4. Effect of the existing Portland cement concrete modulus

The effect of the rigidity of the existing Portland cement concrete (PCC) layer was evaluated by considering three PCC modulus 20 000 MPa, 28 000 MPa, and 34 000 MPa. In the analysis, three AC thicknesses (6 cm, 10 cm, and 15 cm) with 3500 MPa AC modulus at different AC and PCC bonding conditions were considered. The effect of the PCC modulus on the tensile strain is shown in Figure 9 and Figure 10. The results showed that by decreasing the PCC modulus, the tensile strain in the AC increase for both bonded and unbonded interfaces. However, the PCC modulus has a small effect on strain in unbonded interfaces on the PCC. The tensile strain increased by 8%, 11%, and



Figure 9. Longitudinal tensile strain variation for bonded condition



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Figure 10. Longitudinal tensile strain for unbonded condition

13% for 6 cm, 10 cm, and 15 cm AC thickness respectively for bonded AC and PCC, and increased by 6 % for 6cm AC and 7% for 10 cm, and 15 cm AC for unbonded AC and PCC interfaces.

## 2.5. Effect of the dimension of the joint

The width of the joint or crack is another factor representing the condition of the existing PCC pavement. Figure 11 shows the AC tensile strain at the bottom of the overlay versus the joint width for different



Figure 11. Longitudinal tensile strain at the bottom of the asphalt concrete versus joint width

overlay thickness. As shown in Figure 11, when increasing the joint width from 0 cm to 1 cm, the magnitude of the tensile strain remains the same for the same overlay thickness. The value of the tensile strain was 113  $\mu\epsilon$ , 64  $\mu\epsilon$ , and 48  $\mu\epsilon$  for 6 cm, 10 cm, and 15 cm overlay thickness, respectively. However, by widening the joint to 1.5 cm and 2 cm the magnitude of the tensile strain increased by 24%, 33%, and 25% for 6 cm, 10 cm, and 15 cm overlay thickness respectively. Therefore, to lessen the magnitude of the strain in the AC overlay due to traffic loading, 1cm or smaller joint width is reasonable.

## 2.6. Comparison of the variations of the tensile strain

The effect of variations in different parameters was compared to assess their influence on longitudinal tensile strain at the bottom of the AC overlay. The following procedure was adopted: the pavement reference characteristics and range of variation of each parameter are shown in Table 2.

When determining the influence of a given parameter, the other parameters remain constant and have their reference value. Table 3 shows the variation of the longitudinal tensile strain at the bottom of the AC overlay caused by each investigated parameter.

All the investigated parameters influenced the performance of the pavement at a different level (Table 3). Strain at the bottom of the overlay responded differently to the changes of the pavement characteristics. The level of influence of all the parameters was related to the AC thickness. The variations induced by the changes in AC thickness and

Parameter	Reference	Range
Asphalt concrete thickness	6 cm, 10 cm, 15 cm	3 cm – 25 cm
Asphalt concrete modulus	3500 MPa	2000 MPa – 10 000 MPa
Asphalt concrete and Portland cement concrete interface	Fully bonded	Fully bonded – fully unbonded
Portland cement concrete modulus	28 000 MPa	20 000 MPa - 34 000 MPa
Joint width	1 cm	0 cm – 2 cm

Table 2. Pavement parameters reference characteristics and range of variation

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Parameters	Asphalt concrete thickness, cm	Micro	ostrain, με	Difference,
		max	min	~ %
Asphalt concrete thickness		216	35	84
Asphalt concrete	6	198	51	74
modulus	10	98	35	64
	15	76	48	37
Asphalt concrete and Portland cement concrete bond	6	277	133	52
	10	174	64	63
	15	143	48	66
Portland cement concrete modulus	6	119	110	8
	10	69	62	10
	15	53	47	11
Joint width	6	148	113	24
	10	85	64	25
	15	60	48	20

Table 3. Longitudinal tensile strain variation versus pavement parameters

AC modulus were 84% and 75%, respectively. Portland cement concrete modulus induced a maximum variation of 11% The variation induced by the joint width was up to 25%

## Conclusions

The objective of this study was to evaluate the performance of an asphalt concrete overlay on an existing jointed plain concrete pavement under axle loading for different asphalt concrete thickness, asphalt concrete modulus, asphalt concrete, and Portland cement concrete interface condition, Portland cement concrete modulus, and joints width. From the study, the following conclusions are drawn.

1. In bonded asphalt concrete and Portland cement concrete by changing the asphalt concrete thickness between 3 cm and 25 cm and the asphalt concrete modulus between 2000 MPa to 10 000 MPa the longitudinal tensile strain at the bottom of the overlay varied from 25  $\mu\epsilon$  to 318  $\mu\epsilon$ . In general, increasing asphalt

concrete thickness decreased strain values and increasing asphalt concrete modulus decreased stain values.

- 2. The bond between the asphalt concrete and the existing Portland cement concrete pavement was found to be one of the most important factors in terms of the strain of the pavement. The magnitude of the tensile strain was at least 113% and increased up to 198% by changing the interface contact from bonded to unbonded depending on the asphalt concrete thickness and modulus.
- 3. By decreasing the Portland cement concrete modulus, the tensile strain in the asphalt concrete increased for both bonded and unbonded interfaces. However, the Portland cement concrete modulus had less effect on both strain in the unbonded asphalt concrete and Portland cement concrete interface. The tensile strain increased by 8% to 13% for bonded asphalt concrete and Portland cement concrete and Portland cement concrete interface by 7% asphalt concrete for unbonded asphalt concrete and Portland cement concrete interfaces depending on the thickness of the asphalt concrete.
- 4. Increasing joint width from 1 cm to 2 cm, tensile strain increased about 24% up to 33% depending on the asphalt concrete thickness.
- 5. Interface bonding condition was found to be a significant influencer regardless of surface layer thickness.

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