As shown in Figure 1c, after the first 2.3 years of service with 1,312,054 ESALs, UTW section on US90 had very little cracking and patch area (with distress density of 0.07%). The distress density was only 1.2% after 10.2 years of service with 6,052,101 ESALs. Among these distresses, there were 5.2% of patch, 83.0% of longitudinal cracking area, and 11.8% of transverse cracking area.

Figure 1d presents the field performance survey results of cracking and patch distress for three selected UTW sections versus ESAL. When the ESAL was less than 1.8 million, very little cracking or patch would be found in UTW sections. After that, the distress density generally increased as the ESAL increased. The distress density was less 4.0% after 6.0 million ESALs.

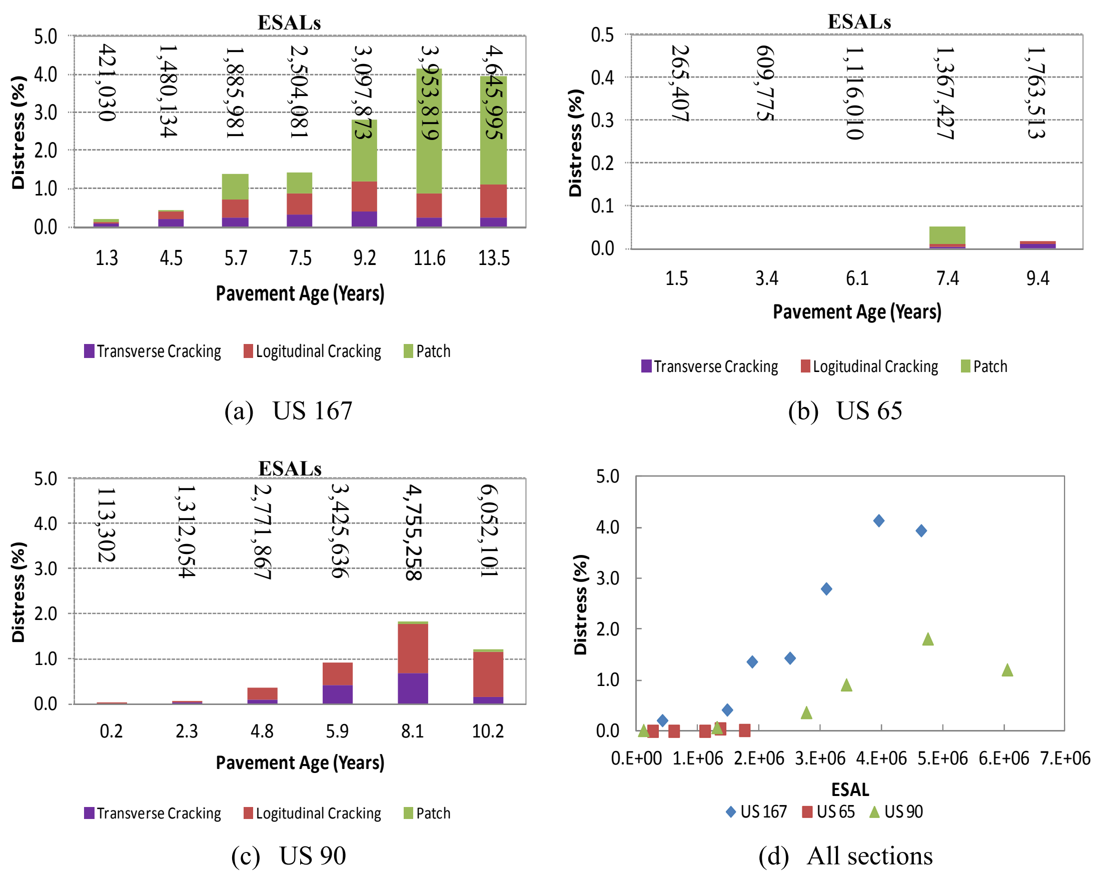
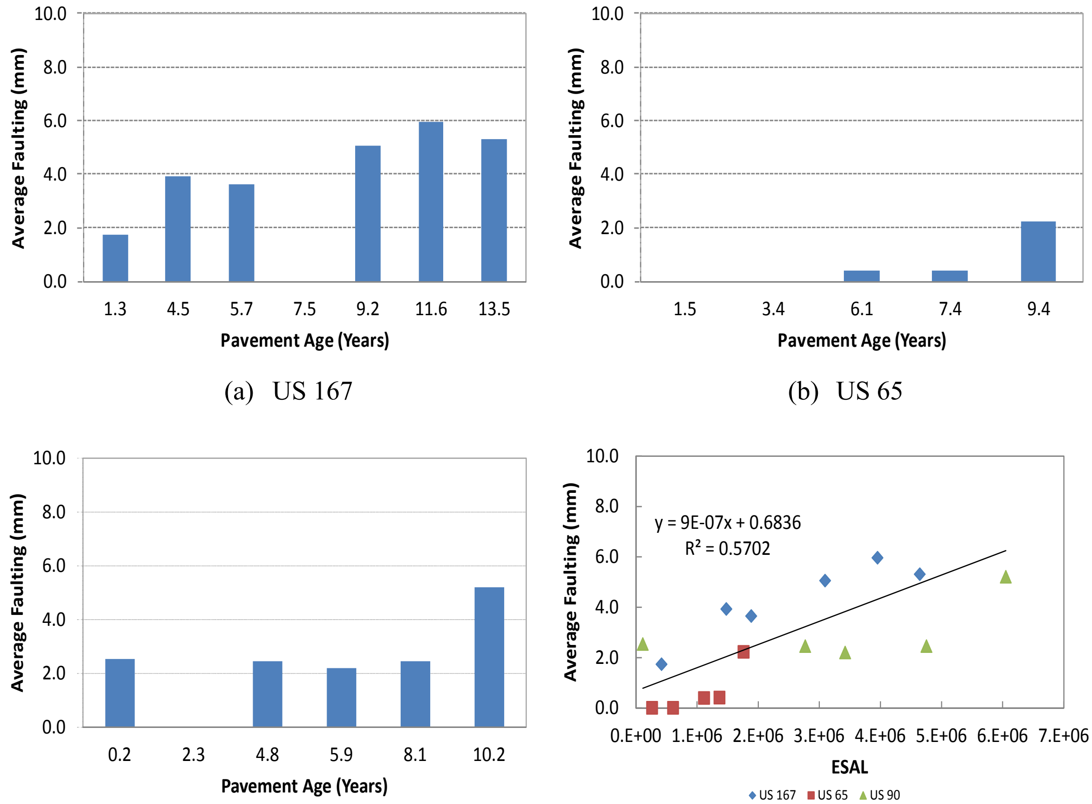


FIGURE 1 Field performance survey results for cracking and patch distress

Figure 2 presents the field performance survey results of faulting of UTW sections. As shown in Figure 2a, the average faulting value generally increased as the pavement age increased. After 13.5 years of service, the average faulting value was 5.3 mm for UTW section on US 167. As shown in Figure 2b, no faulting was detected by PMS survey after the first 3.4 years of service for UTW section on US 65. After 9.4 years of service, the average faulting value reached 2.3 mm. As shown in Figure 2c, the average faulting value was about 2.5 mm after the first 8.1 years of service for UTW section on US 90. The average faulting value increased to 5.2 mm after 10.2 years of service. Figure 2d presents the field performance survey results of faulting for three selected UTW sections versus ESAL. The average faulting value generally increased as the ESAL increased. The average faulting value reached about 5.2 mm after 6.0 million ESALs.



(a) US 167 (b) US 65

(c) US 90 (d) All sections

FIGURE 2 Field performance survey results for faulting

Figure 3 presents the field performance survey results of IRI of UTW sections. As shown in Figure 3a, the average IRI value was 2.56 m/km after 1.3 years of service for UTW section on US 167. The IRI value generally increased as the pavement age increased. After 13.5 years of service, the average IRI value reached 3.64 m/km. As shown in Figure 3b, the average IRI value was 1.3 m/km after 1.5 years of service for UTW section on US 65. After 9.4 years of service, the UTW section still had a relatively low average IRI value of 1.54 m/km. As shown in Figure 3c, the initial average IRI value was 1.80 m/km for UTW section on US 90. After 10.2 years of service, the average IRI value increased to 3.08 m/km. Figure 3d presents the field performance survey results of IRI for three selected UTW sections versus ESAL. The average IRI value generally increased as the ESAL increased. The average IRI value could reach around 3.18 m/km after 6.0 million ESALs.

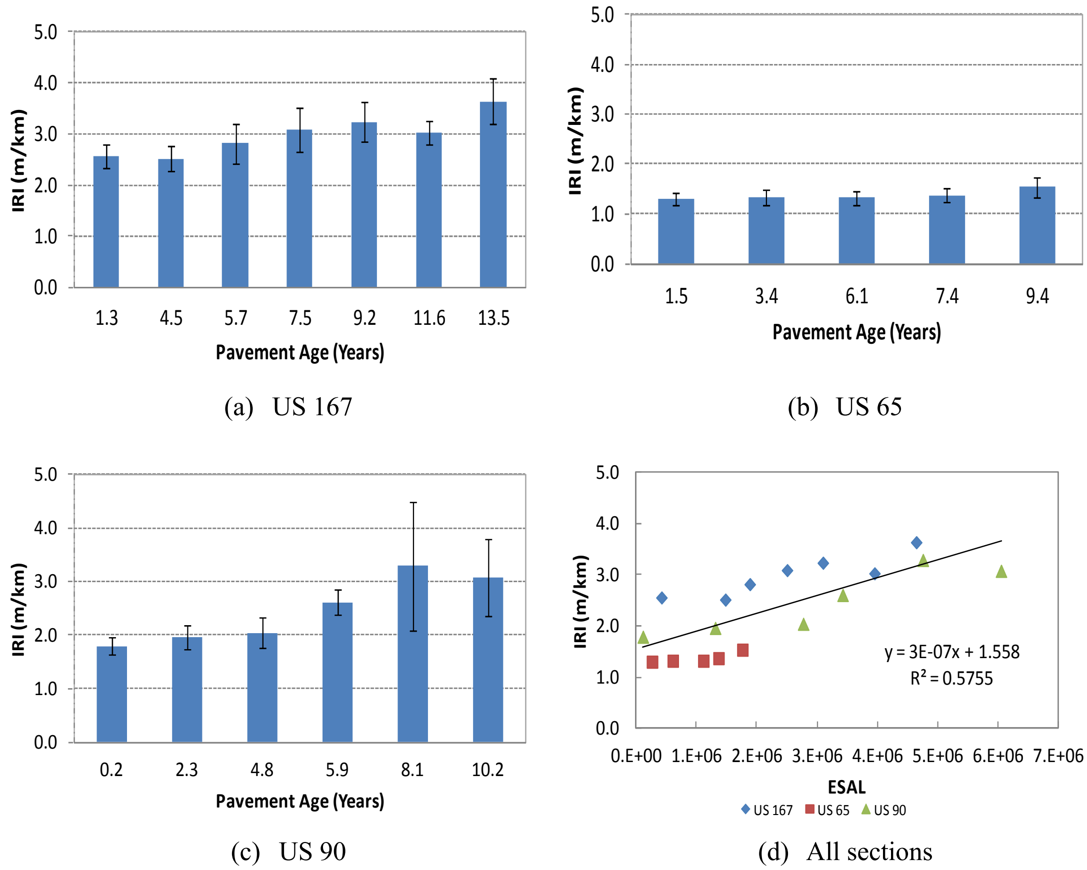
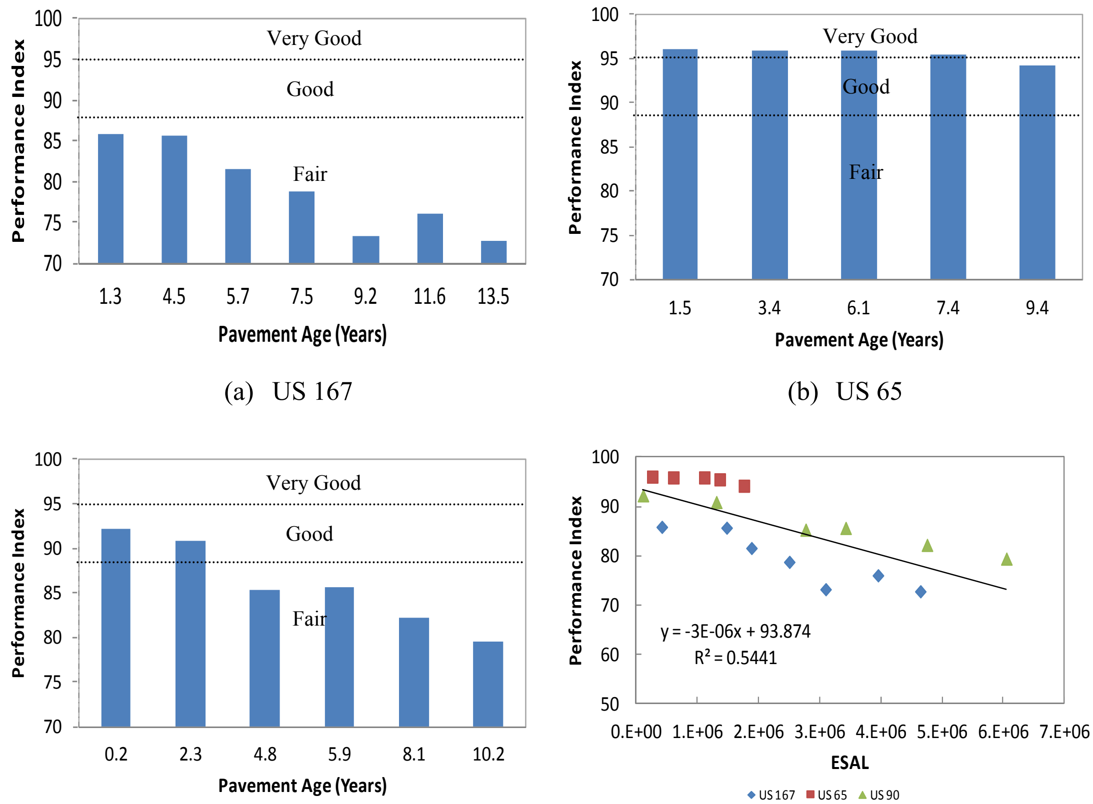


FIGURE 3 Field performance survey results for IRI

In LADOTD PMS, the pavement performance index (PPI) was used to represent the overall composite performance based upon longitudinal and transverse cracking, roughness, and patch data for a rigid pavement. A value of 100 represents a new pavement with no distress and value of 0 indicates pavement failure. More details on calculation and criteria of the PPI in LADOTD PMS can be referred to PMS manual (LADOTD, 2010).

Figure 4 presents the PPI values for three UTW sections. Figure 4a presents the PPI for UTW section on US 167 over 13.5 years. The PPI value was 85.9 after 1.3 years service, and generally decreased as the pavement age increased. After 13.5 years of service, the PPI value reached 72.8. The pavement condition was fair after 1.3 years service based on the LADOTD PMS criteria for national highway system ($70 \leq PPI < 88$) (LADOTD, 2010). The fair pavement condition was mainly due to the relatively high IRI and faulting values. Figure 4b presents the PPI for UTW section on US 65. The pavement condition was very good ($PPI \geq 95$) after the first 7.4 years of service. After 9.4 years of service, the pavement condition was still good ($88 \leq PPI < 95$) with PPI value of 94.2. As shown in Figure 4c, the pavement condition for UTW section on US 90 was good ($88 \leq PPI < 95$) after the first 2.3 years of service. After 10.2 years of service, the pavement condition was fair ($70 \leq PPI < 88$) with PPI value of 79.5. The fair pavement condition was mainly due to the relatively high IRI and faulting values.

Figure 4d presents the PPI for three selected UTW sections versus ESAL. The PPI generally decreased as the ESAL increased. The UTW pavement condition was fair after the 6.0 million ESALs based on LADOTD PMS criterion for the national highway system (LADOTD, 2010).



(a) US 167 (b) US 65

(c) US 90 (d) All sections

FIGURE 4 Field performance survey results for pavement performance index

SUMMARY AND CONCLUSIONS

In this study, field performance of three UTW sections in Louisiana was monitored up to 13.5 years of service. The cracking and patch distresses were few for these three UTW sections. The distress density was only 3.94, 0.02, and 1.2 percent for US167, US65, and US90 after 13.5, 9.4 and 10.2 years of service, respectively. When the ESAL was less than 1.8 million, very little cracking or patch would be found in UTW sections. The distress density was still less 4.0% after 6.0 million ESALs, which shows a good potential for UTW as an alternate rehabilitation technique for HMA pavement.

The average faulting and IRI values generally increased as the pavement age and ESAL increased. The average faulting value was 5.3, 2.3, and 5.2 mm. for US167, US65, and US90 after 13.5, 9.4 and 10.2 years of service, respectively. The IRI value was 3.64, 1.54, and 3.08 m/km for US167, US65, and US90 after 13.5, 9.4 and 10.2 years of service, respectively.

The PPI value generally decreased as the pavement age and ESAL increased. The pavement condition was fair, good, and fair for US167, US65, and US90 after 13.5, 9.4 and 10.2 years of service, respectively. The fair pavement condition for US167 and US90 was mainly due to the relatively high IRI and faulting values.

ACKNOWLEDGMENTS

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Evaluation of Doweled Joints in Concrete Pavements Using Three-Dimensional Finite Element Analysis

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Keywords: Finite element analysis, doweled joint, concrete pavement, load transfer, sublayer void

ABSTRACT: Transverse joints in rigid pavements are the locations where most pavement distress appears, leading to deteriorating the riding quality and feature high maintenance cost. The state of stresses in the concrete surrounding dowel bars, in dowel jointed concrete pavements, is a major factor that contributes to transverse joint distress. As such, a three-dimensional finite element model was developed for analysing a dowel-jointed concrete pavement. The effect of different pavement and joint related parameters on the load transfer characteristics of a joint has been evaluated using the FE model. Group action of the dowel bar system has also been examined. Five loading cases are applied to replicate realistic vehicular loadings approaching and leaving the joint. The structural behaviour of the pavement at the doweled joint is investigated for: (1) pavement with and without voids, (2) dowel spacing variation, (3) pavement with and without lean concrete base, (4) slab thickness (5) tire pressure and (6) single and dual wheel loads. The amount of load transfer was obtained from the shear force in the beam elements that simulate dowels. Results show that the voids underneath the joint causes an increase in the vertical displacement of the concrete slab and vertical stress at concrete/dowel bar interface which may result in crushing of the concrete and dowel loosening. Wider dowel spacings result in increased shear forces and the size of the region containing engaged dowels does not change significantly with dowel spacing, only effecting the distribution of shear forces. Maximum Principle Stress (MPS) is about 6.7 times greater and steeper variation in the distribution pattern in the concrete pavement without Lean Concrete Base (LCB). A thick concrete slab provides a significant benefit: higher load transfer and develops less curvature along the loaded side of the joint. The deformed shape explains why more dowels are engaged in the load transfer for the thicker concrete slab models. There were no significantly affects on load transfer ratio with the increase applied wheel load. This phenomenon is also evident in the dowel shear force distribution. However, it will increases the demand on a few inner dowels beneath the wheel load, which may cause more damage to the joints and eventually lead to pavement failure. The study shows that the dowel bars perform effectively as a load transfer device in the concrete pavement system even under severe conditions.

INTRODUCTION

Concrete pavement systems typically consist of jointed plain (unreinforced) concrete pavements (PCP); jointed reinforced concrete pavements (JRCP); continuously reinforced concrete pavements (CRCP); and steel fibre reinforced concrete pavements (SFCP). There are two main categories of PCP suitable for Australian conditions, (1) slabs 4.2m long, with undowelled skewed joints, and (2) slabs 4.5m long, with dowelled square joints [1]. A PCP is composed of numerous discrete concrete slabs, longitudinal and transverse joints, and dowels. Longitudinal joints are allow for the reduction of stresses induced due to temperature warping and transverse joints are provided to control cracks caused by thermal deformation and drying shrinkage of the concrete slab. Despite those benefits, the joint often reduces the load carrying capacity of the concrete slab near the edge and results in pavement damage under repeated wheel loads [2,3]. Several studies [4,5] have indicated that critical stresses within the concrete slab are more likely to occur close to the transverse joints than the longitudinal joints especially for negative temperature gradients and widened lane widths. Fig. 1 shows a typical concrete pavement system. When joints have no means to transfer the load across the two slab boundaries, each slab edge must bear the full applied load at a time. This case produces not only high dynamic tensile stresses in the concrete slab, but also large compressive stresses at the foundation layers in addition to increasing the pavement roughness and diminishing the riding quality. To overcome this condition, three means of load transfer mechanisms at the transverse joints have been widely used. These are dowel bars, aggregate interlock, and keyways.

The dowel bars transfer load without restricting the horizontal joint movement caused by thermal and moisture contraction and expansion. They also help in maintaining the horizontal and vertical alignments of slabs. Note that a Load Transfer Efficiency (LTE) of less than 60% would necessitate load transfer restoration of the pavement [6]. Note that the most severe loading occurs when the vehicle is on the edge of the concrete slab on both the approach and leave sides, as illustrated in Fig. 1. Previous studies [8,9] have evaluated pavement performance with dowel bars and showed that the normal stress in the vertical direction is an indicator of fatigue fracturing at concrete/dowel bar interface. A bound or lean mix concrete base course is recommended under a concrete pavement for the following reasons: (1) to resist erosion of the base course and limit "pumping" at joints and slab edges; (2) to provide uniform support under the pavement; (3) to reduce deflection at joints and enhance load transfer across joints; and (4) to assist in the control of shrinkage and swelling of high volume change subgrade soils.[1,10] The base course extends roughly 300mm beyond the edge of the concrete slab thus providing more support and preventing concrete failure [9]. Subsurface voids (see Fig. 1) form within the base course as a result of moisture ingress which loosens and subsequently weakens the base course. Moisture may enter the base course through cracks on the concrete slab and leaking drainage systems. Voids may also form close to cracks or joints due to water infiltration from the pavement surface. Once developed, voids can be detected through the use of a Ground Penetrating Radar (GPR) and Impact-Echo, or by core drilling. Subgrade forms the bottom layer of the pavement system and is generally compacted and can be stabilised through the addition of asphalt, cement or lime.

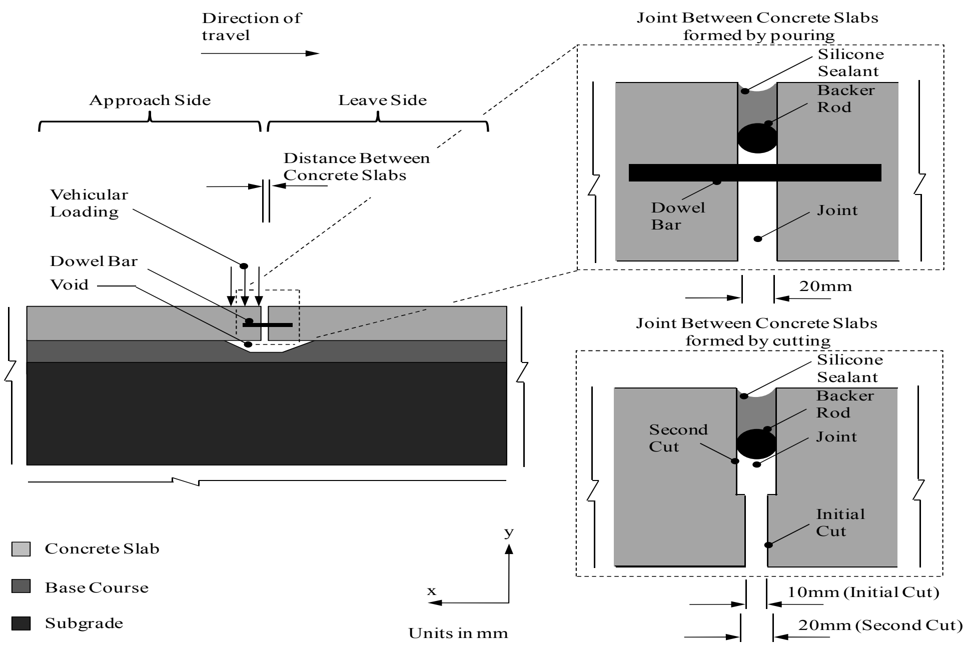

Figure 1: Concrete pavement system (Location of vehicular loading, dowel bar and joint).

Warping deformation of the concrete slab is a characteristic phenomenon under environmental and repeated vehicle loads [11] which may lead to void formation due to the accumulated plastic deformation and subsequent disengagement of the base course from the concrete. Distress of the pavement in the form of joint deterioration or cracking also attributes to void formation by allowing moisture infiltration. The combination of distress and layer voids will further reduce the pavement load carrying capacity. Friberg and Quintus [7,11] stated that distress is influenced mostly by compressive stress and that the first sign of deterioration is the formation of transverse or longitudinal cracking within the concrete slab. It has also been reported that transverse and longitudinal cracking are more common than D-cracks, corner cracks and meander cracks [12,13]. It is frequently understood that the aim of joint design for concrete pavement is to reduce transverse and longitudinal cracking [14]. Transverse cracks are typically due to shrinkage of the concrete layer from low temperatures, reflective crack caused by cracks beneath the surface layer and top-down cracking [8]. Longitudinal cracks may be due to incorrect joint orientation and subsequent reflective cracking of layers [6]. In fact, a deep understanding of the mechanical behavior of dowel bars and induced stresses at their interface with concrete is a high importance for the development of feasible and effective doweled joints. Contact stresses between dowel bars and concrete are major importance for improvement of the load transfer efficiency.

METHODOLOGY

The modelling and simulation herein are performed using Strand7 Finite Element Analysis (FEA) System. The Finite Element Method (FEM) is a numerical method of analysis for stresses and deformations in structures of any given geometry. The structure is discretised into 'finite elements' connected through nodes. The type, arrangement and total number of elements affect the accuracy of the results. FEM has become one of the most successful engineering computational methods and most useful analysis tools since the 1960. It is showing overwhelming capability and versatility in concrete pavement evaluation. Illustrated in Fig. 2 are the vehicular loading and restraint conditions applied to the pavement. These loading and restraint conditions are commonly assumed in previous literature [15,16]. Dowel bars are modelled using beam elements with a defined diameter of 32mm, see Fig. 2. The mesh size is reduced in the vicinity of the joint and dowel/concrete interface to aid the accuracy of displacement and stress measurements.

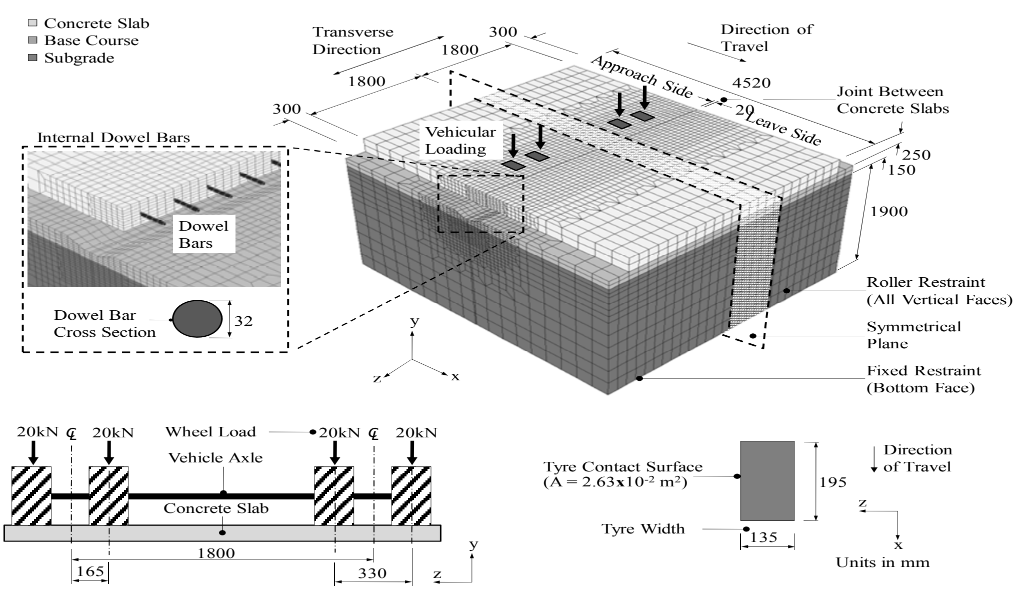

Figure 2: Finite element model of pavement system.

As indicated in Fig. 2, the symmetrical plane is restrained from rotating around the z-axis and translating along the x- and y-axes. The bottom surface of the pavement is restraint from deforming in all directions and roller restraints are applied to the sides of the pavement. The material properties are provided in Table 1 and are assumed to be linear, homogeneous and elastic in behaviour.

Table 1: Material properties and layer thicknesses.

Description	Concrete Slab	Lean Concrete Base	Base Course	Subgrade	Dowel Bar
Young's modulus [MPa]	28,000	15000	350	50	200,000
Layer thickness [mm]	250	150	150	1,900	-
Poisson's ratio	0.18	0.25	0.4	0.4	0.3
Density [kg/m^3]	2,400	2,100	2,000	1,800	7,830

Loading Conditions, Four wheel loads of 20kN each representing an equivalent 80kN (i.e. 707kPa) single axle load is assumed. The effect of the air pressure within the tyre is neglected, hence the contact pressure of the tyre is assumed to be uniformly distributed over a rectangular area of 2.66×10^{-2} m^2 (see Fig. 2). Five loading cases are applied to the model to replicate a vehicle approaching the joint as shown in Fig. 3. The first (*LC1*), second (*LC2*), third (*LC3*), and forth load case (*LC4*) are 370 mm, 270 mm, 165 mm and 55 mm to the centre of the joint, and the fifth load case (*LC5*) is at the centre of the joint.

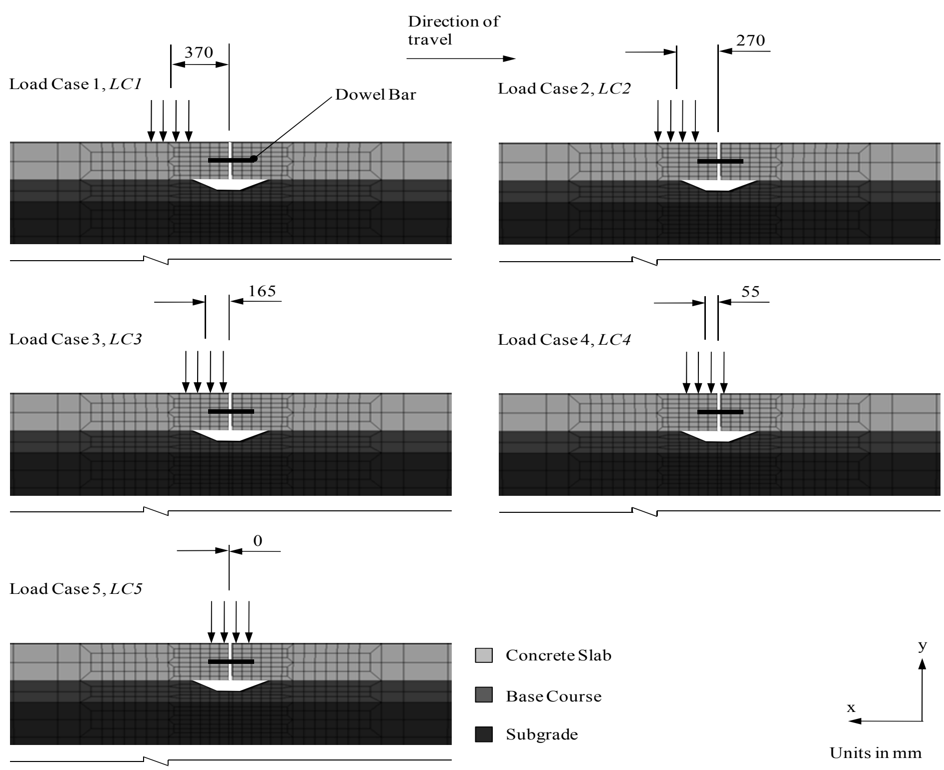

Figure 3: Loading scenarios.

RESULTS AND DISCUSSION

Doweled Joint with and without Voids

Vertical Displacement, Figure 4 shows vertical displacement distributions and contours along the line TT_{HH} for all loading cases for pavement with voids. Table 2 (a) and (b) summarises the maximum deflection and LTE of the five LC with and without voids.

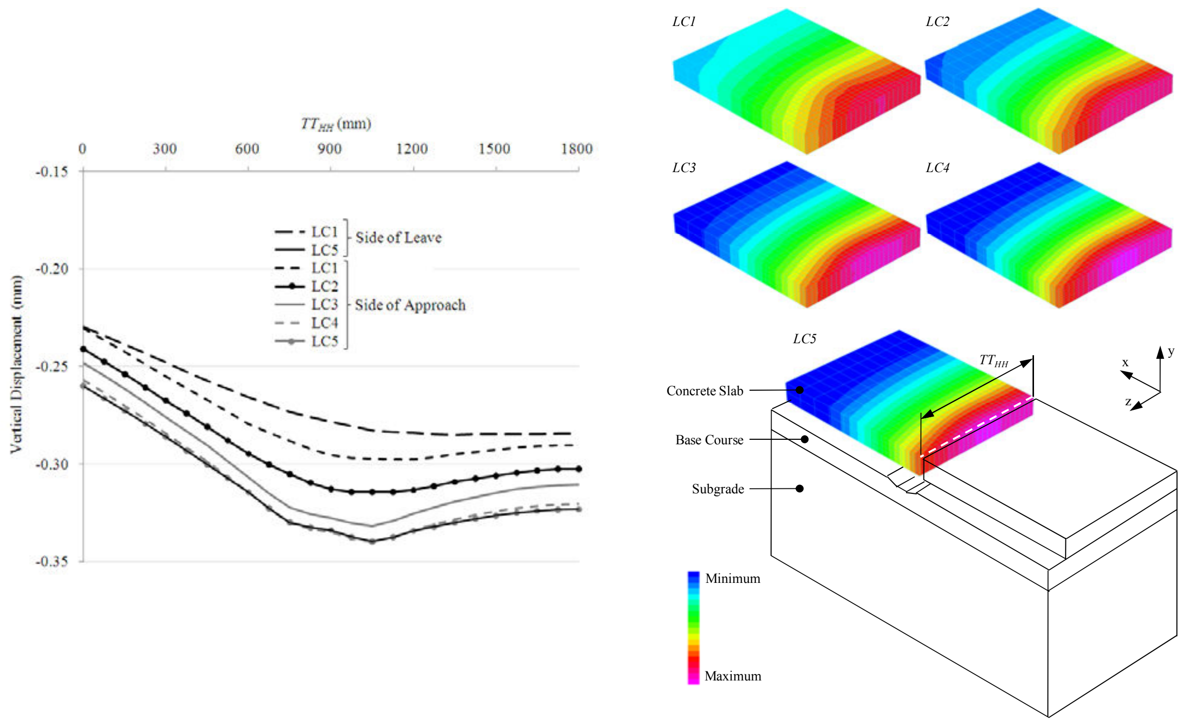

Figure 4: Vertical displacement at transverse joint along line TT_{HH} with void

From the observation of figure 4, the maximum displacement for the load case 1&2 were increased by 16.7%; 18.2% increased for load case 3&4 and 20.6% increased for load case 5 respectively in pavement with voids.

Load Transfer Efficiency (LTE) at Top of Concrete Layer. 'Load transfer' is a term used to describe the transfer of load across discontinuities such as joints [17]. When vehicular loading is applied near a pavement joint, both loaded and unloaded slabs deflect because a portion of the load applied to the loaded slab is transferred to the unloaded slab. The amount the unloaded slab deflects is directly related to joint performance. If a joint is performing perfectly, both the loaded and unloaded slabs deflect equally. During vehicular loading that is relatively close to joint of the concrete slab, dowel bars immediately under the applied load assume a major portion of the load with other dowel bars assuming progressively lesser amounts [10]. The LTE is defined as a parameter that measures the load transfer from the loaded side to the unloaded side of the joint, and it is given by [17] as:

$$LTE = \frac{\delta_U}{\delta_L} \times 100 \tag{1}$$

where δ_U and δ_L are respectively the unloaded and loaded vertical displacements.