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Finite Element Investigation of Load Transfer Efficiency in Jointed Plain Concrete Pavements

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Keywords

Concrete pavement,
Load transfer,
Finite element method,
Three-dimensional analysis,
Transverse joint.

Abstract

Due to the dynamic traffic loads, rigid pavements experience different types of damages such as the longitudinal and transverse cracks. It is important to understand the structural behavior of jointed plain concrete pavements (JPCP) under the traffic loads in order to design new or improve the existing pavements. Three-dimensional finite-element method (3D-FEM) was used to predict the exact behavior of rigid pavement under aforementioned loads. The 3D-FEM was validated using the numerical model and field measurement of the concrete slab loaded with a dump truck. The effects of different parameters such as slab geometry, material properties, load magnitude and friction coefficient between slab and the base layer on load transfer efficiency (LTE) of the transverse joints have been studied. In the 3D-FEM model, the load transfer efficiency has increased by increasing the elasticity modules of the concrete slab and base layer and It was increased by increasing the slab thickness. This can decrease the deflections of the joints, which will reduce the damages on the pavement joints.

1. Introduction

Most distress in the JPCP occures in the transverse joints. Indeed, with moving the base material or base erosion, slabs tend to deflect due to corner cracking and pumping effect. Consequently, we control the deflection and reduce the damage of pavement by using the load transfer device. When a concrete pavement is loaded near its transverse joints with dowel bars, some parts of the applied load transfer to the unloaded slab with dowel bars. Thus, both the load and unloaded slabs experience deflection. Dowel bars considerably decrease the deflections and stresses of the loaded slab compared to slabs without dowel bars. The magnitude of this reduction in stress and deflection of the joint depends on the amount of the load transfer efficiency. Different methods have been introduced by researchers to measure the load transfer efficiency. These methods are based on the deflection, stress and load transferred across the entire length of joint [1]. In this study, the deflection method has been used.

Three methods are used to determine the stresses and deflections of concrete pavements including the closed-form formulas, response charts and finite element computer programs. Formulas are mainly provided by Westergaard and used when the contact surface is applicable for the wheel load with circular, semi-circular, oval or semi- oval contact surface [2]. Picket and Ray presented response charts that were used to load a wheel with different combinations. These methods are applicable only on a large slab on the Winkler foundation. In the case of complex loading on jointed concrete slabs on the solid foundations, the first two modes cannot be used, and FEM should be used [3]. FEM is a common computer-based method used to design and investigate different types of pavements. Two-dimensional FEMs have been used for the last two decades to analyze behavior of road pavements. With increasing computer processing power and memory and necessity to determine pavement failure modes, 3D-FEM was presented by researchers [4].

Finite-element modeling work has been very rich in rigid pavements since its inception and led to progress in analysis and design of pavements. Study of previous works in this area shows that many computer models have been used to simulate the behavior of this type of pavement based on the finite-element method, although many of the underlying assumptions about modeling have been ignored.

Some of these assumptions are as follows

a) The proposed 3D FEMs for the rigid pavements has either ignored the dowel bars or modeled it with beam or spring elements.

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b) Embedded length of dowel bars hasn’t been modeled, therfore the interaction between bars and concrete had been ignored.

c) None of the previous studies modelled the dowel bars by an eight-node solid brick elements.

d) Load transfer by aggregate interlock in transverse joints were modeled using shear spring elements or classical frictional behavior. This approximation does not simulate actual behavior of aggregate interlock.

e) Previous 3D FEMs studied the dynamic effect of the moving loads on pavements using the superposition principle or considering the load as a group of impacts with a fixed distance and velocity with linear or non-linear shapes. This paper studies load transfer across doweled joints in jointed plain concrete pavements under dynamic traffic loads.

2. 3D-FEM

A jointed plain concrete pavement (JPCP) was modeled in this study. The purpose of this work is limited to investigate the response of dowel JPCP under moving axle loads. The effects of concrete shrinkage during curing, moisture and thermal gradient were not taken into consideration. The 3D-FE program used in this study is ABAQUS.This model includes a 4.57-meters slab length that was joined to two semi-slabs. The pavement system includes a base layer which placed on subgrade layer. In this model, symmetric boundary conditions were used to reduce the analysis time by reducing the running time of program and computer memory. Using symmetric boundary conditions and half-model save the required memory and time of analysis. Figure 1 show the studied pavement geometry.

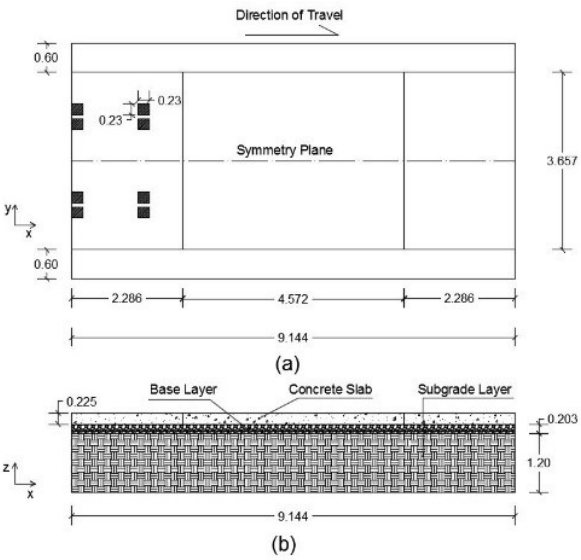

Figure 1. 3D finite element model geometry: (a) Plan, (b) Section (Dimensions in meters)

All layers were meshed with using hexahedron element shape with 8 node which is C3D8R type. The mesh sizes varied through the model to provide accurate results. Thus, a refined mesh was necessary in regions of high stress such as dowel bar at the transverse joints. A coarser mesh was used for the base and subgrade layer. Figures 2-4 show the studied pavement geometry and meshing.

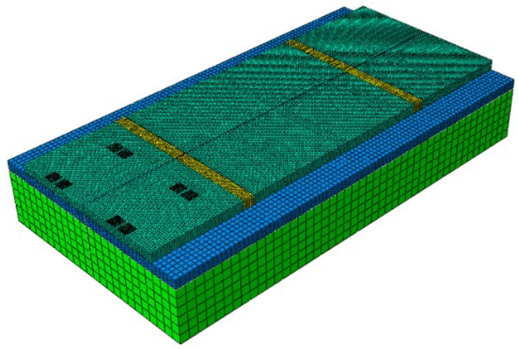

Figure 2. 3D FEM full model mesh

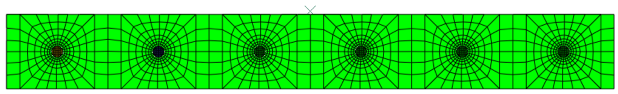

Figure 3. 3D FEM mesh adjustments for the adjacent joints

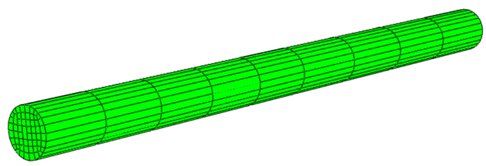

Figure 4. 3D FEM mesh adjustments for the dowel bars

One of the limitations of the finite element method is its dependence on the mesh size. Convergence has to take place to validate a finite element solving, this means that the smaller the elements will not change the answers.

To study the effect of finite element mesh size on the response of the rigid pavement, maximum longtidonal strain at 1.52 meters from joint for three models with different mesh sizes are compared as shown in Figures 5-7. This comparision is presented in Table 1.

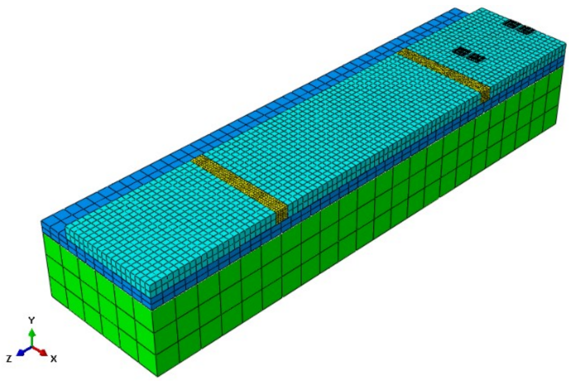

Figure 5. FEM meshing with 32116 Nodes & 22850 Elements

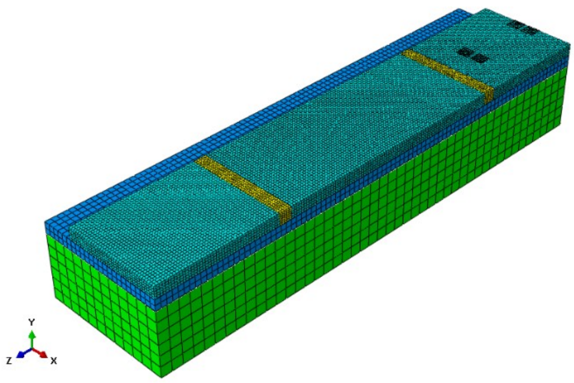

Figure 6. FEM meshing with 76014 Nodes & 58070 Elements

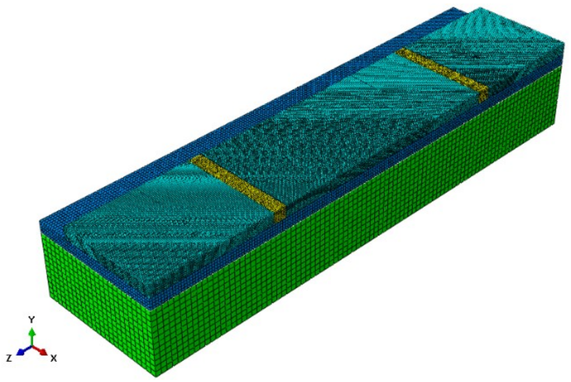

Figure 7. FEM meshing with 378207 Nodes & 322574 Elements

Table 1. Maximum strain comparision between three FEM with different mesh sizes

Model	Number of nodes	Number of elements	Response (Microstrain)
1	32116	22850	17.2
2	76014	58070	21.9
3	378207	322574	22.4

2. 1. General Description

The 3D-FEM model details are as follows

1) In order to simulate the slippery condition between dowel bars and concrete slab, fiction coefficient of the dowel bar-concrete interface with assuming a bar with an epoxy-oil coat was considered to be 0.05. The friction coefficient for the wheel-pavement interactions was set to 0.02.

2) Lateral sides of the concrete slab boundaries perpendicular to traffic direction are assumed to be free. Boundary condition was considered completely fixed beneath the subgrade layer. To maintain the continuity of subgrade and base layers on their lateral sides and simulate the semi-infinite of soil, the boundary conditions were used as shown in Figure 3.

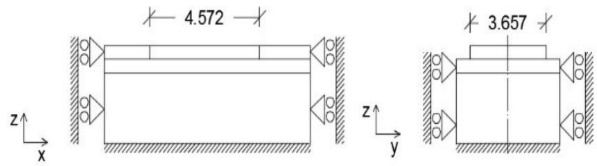

Figure 3. Boundary conditions (Dimentions in meters)

3) In order to simulate the effect of moving load as the load approaches the transverse joint, explicit FE integration is used. The tire loads are applied on a set of contact patches.The 3D finite-element model was supposed to be under a load of a dump truck that is driving with 77 km/hr. The applied load was assumed to be non-uniform tire-pavement interfaces (Figure 4).

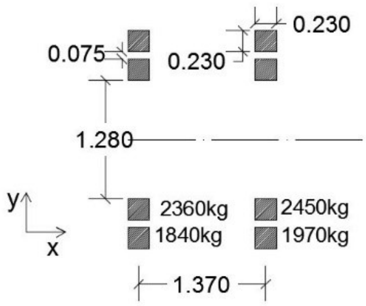

Figure 4. Wheel load configuration (Dimensions in meters)

4) Materials of pavement layers were assumed to have a linear elastic behavior. Table 2 summarizes the characteristics of the materials used in this study (Ohio road tests). These characteristics were reported from Ohio road test [5].

Table 2. Characteristics of the pavement materials used for the 3D FEM

Layer	Density(kg/m^3)	Poison Ratio	Module of Elasticity (Mpa)
Concrete Slab	2400	0.18	34450
Base	2240	0.4	176
Subgrade	2080	0.45	63
Steel	7780	0.3	203850

2. 2. 3D-FEM Verification

Dynamic behavior of the proposed model has been verified using the Ohio Road Tests and Shoukri's numerical analysis results in 2007 [5,6].Studied road section was tested by using cord wire-string strain gauge installed at 25.4 mm bottom and top of the concrete slabs in distances as seen in Figure 5. The results obtained from the pressure cells installed in 1.52 meters from the joint, and at the top of the base layer surface were also studied. Figures 6 and 7 summarize the obtained results.

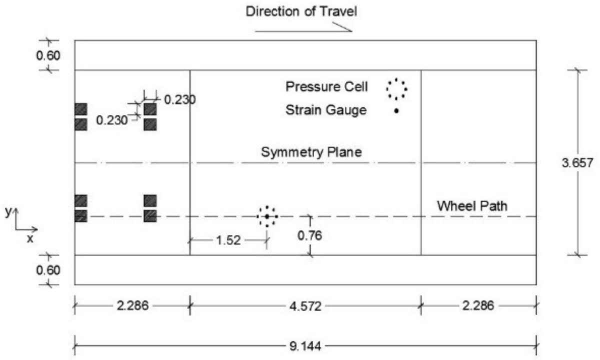

Figure 5. Measurement locations used in Ohio road test (Dimensions in meters)

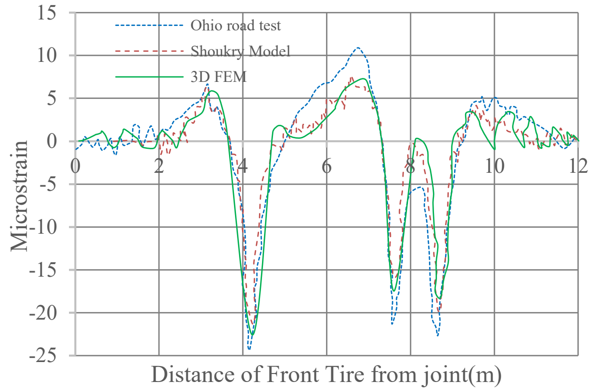

Figure 6. Strains at top of the slab

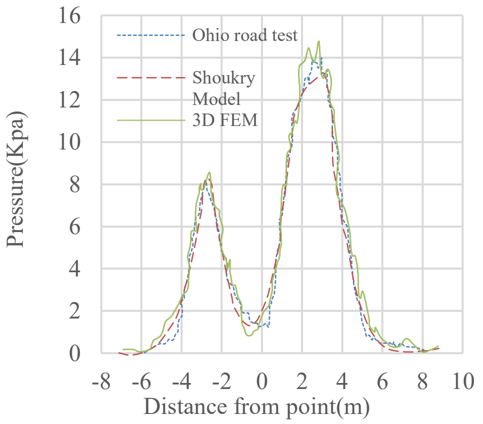

Figure 7. Pressures at top of the base layer surface (point @1.52 m from joint)

3. LTE

Load transfer efficiency expresses the pavement joint's ability to transfer some parts of the applied load from the loaded slab to the unloaded one [6].

Numerous researchers proposed various equation to determine the load transfer efficiency using different parameters. The most common equation to determine LTE is as given by

$$LTE_\delta = \frac{d_u}{d_l} \qquad (1)$$

where d_u and d_l are the joint's vertical displacement in the unloaded and loaded slabs, respectively and are measured at top of the joint's edge.

Teller proposed Eq. (2) to determine LTE, which is still used by researchers [8]:

$$LTE_\delta^* = \frac{2d_u}{d_u+d_l} \qquad (2)$$

In case of joints with low load transfer ability, displacement of unloaded slabs is much lower than displacement of loaded slabs, and the transferred loads in these joints are almost zero. For joints with high load transfer ability, displacements of the slabs in both sides of the joint are close and LTE is almost equal to 1. LTE of the two aforementioned cases can be correlated with using the following Eq. (3)

$$LTE_\delta^* = 2 \times \left(1 - \frac{1}{1 + LTE_\delta}\right) \qquad (3)$$

Since the load transfer efficiency in these cases are correlated, each of them can be found using the other one. In this study, LTE from the first case is used to find the LTE of the joints, as it is widely used by other researchers and is also accepted by AASHTO standard [9].

Effects of different parameters on LTE were studied by using the obtained vertical displacement curve for joint edge at 0.9 meters from slab center in the top of dowel bar. Figure 8 and Figure 9 show the samples of program output and curve for vertical displacement. Table 3 to Table 7 summarizes the obtained results from vertical displacement curves and the overall effects of these parameters were also illustrated in Figure 10 to Figure 14 and compared in Figure 15.

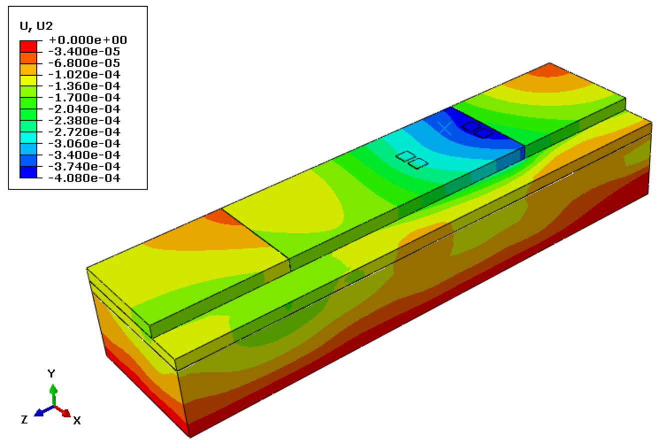

Figure 8. program output for vertical displacement when the wheel load arrive the joint

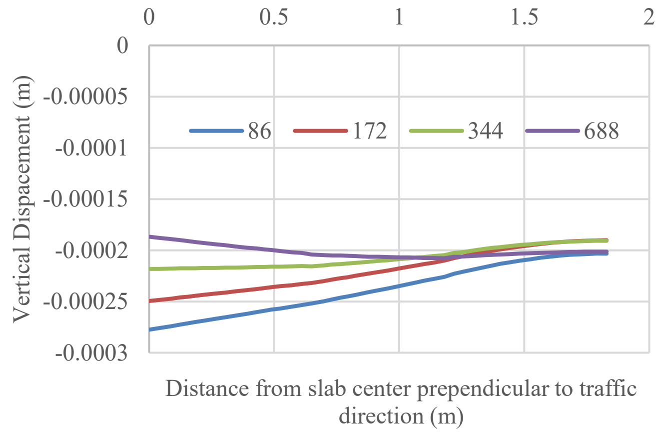

Figure 9. Variation of vertical displacement for different base module of elasticity (Mpa)

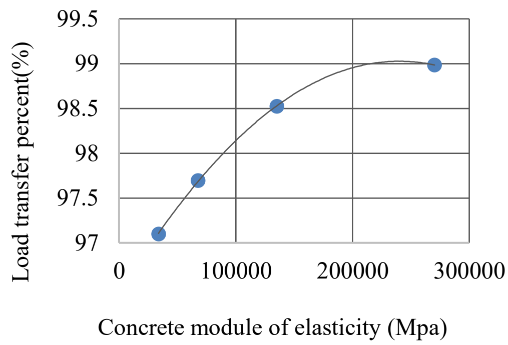

Figure 10. LTE for different concrete elasticity modulus

Table 3. Vertical displacement of the loaded and unloaded slab in transverse joint for different concrete elasticity modulus

Concrete module (Mpa)	Vertical Displacement (m)	
	Loaded slab	Unloaded slab
33784	-0.00022131	-0.000212862
67568	-0.000215575	-0.00021061
135136	-0.0002141	-0.000211161
270272	-0.000214188	-0.000212395

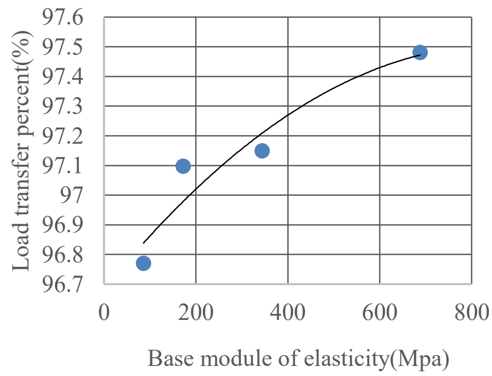

Figure 11. LTE for different base elasticity modulus

Table 4. Vertical displacement of the loaded and unloaded slab in transverse joint for different base elasticity modulus

Base module (Mpa)	Vertical Displacement (m)	
	Loaded slab	Unloaded slab
86	-0.000239116	-0.000228743
172	-0.00022131	-0.000212862
344	-0.000210407	-0.00020331
688	-0.000206317	-0.000201296

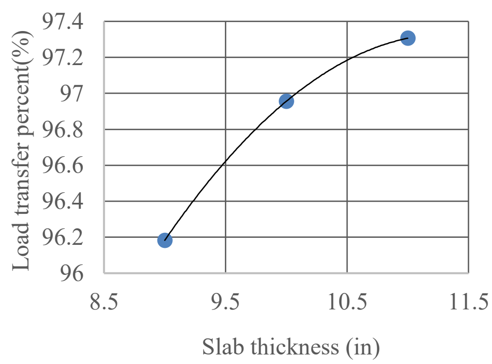

Figure 12. LTE vs concrete slab's thickness

Table 5. Vertical displacement of the loaded and unloaded slab in transverse joint for different slab thicknesses

Slab thickness (in)	Vertical Displacement (m)	
	Loaded slab	Unloaded slab
9	-0.00022131	-0.000212862
10	-0.000226614	-0.000219714
11	-0.000233133	-0.000225264

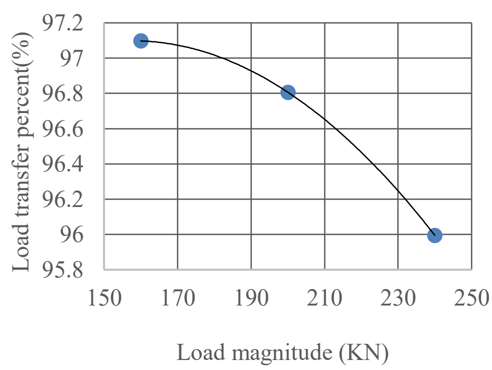

Figure 13. LTE for different load magnitudes

Table 6. Vertical displacement of the loaded and unloaded slab in transverse joint for different load magnitudes

Load magnitude (KN)	Vertical Displacement (m)	
	Loaded slab	Unloaded slab
160	-0.00022131	-0.000212862
200	-0.000227885	-0.000218468
240	-0.00023991	-0.000228235

Table 7. Vertical displacement of the loaded and unloaded slab in transverse joint for different friction coefficients

Friction coefficient	Vertical Displacement (m)	
	Loaded slab	Unloaded slab
0.9	-0.000222006	-0.00021249
1.5	-0.00022131	-0.00021286
1.8	-0.00022124	-0.00021269

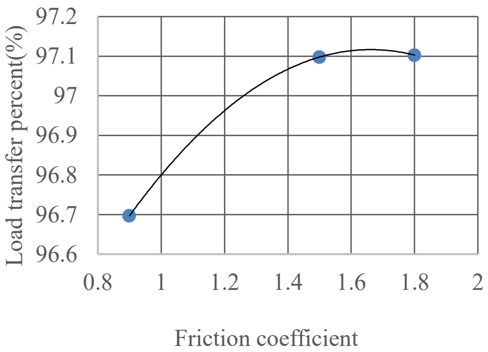

Figure 14. LTE for different friction coefficients between the base layer and slab

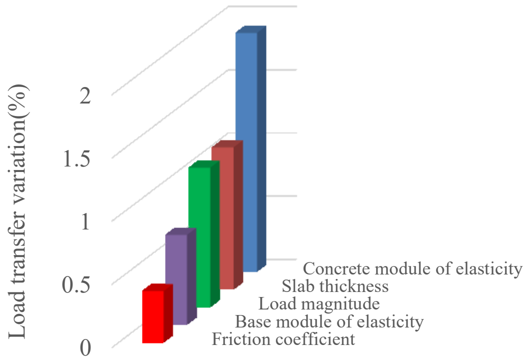

Figure 15. Effect of different parameters on LTE

It was observed that by increasing the elasticity modulus of the concrete and base layer, and also by increasing the thickness, the magnitude of the load transfers of the dowel bars increases. Coefficient of the friction increase has shown a small effect on the load transfer efficiency. It was also observed that increase in load magnitude has a negative effect in LTE. As it is seen in Figure 15, increase of elasticity modulus had the highest effect in increasing the LTE and can be considerably effective in reducing the joints' damages.

With increasing module of elasticity strain decrease, for a constant level of stress and this leads to reduced deflection, therfore LTE increase. Increasing the slab thickness reduces both stresses and strains induced in the concrete slab. Therefore, the thickness increase may reduce joint deflection and LTE decrease. Increasing load magnitude increase deflecttion, therfore LTE decrease. Increasing friction coefficient between slab and base layer have a small effect on LTE since changing the friction coefficient does not considerably affect the stresses or strains induced in the concrete slab.

4. Conclusion

This study presents the power of finite element modeling in perdicting and investigating the effective factors in performance for rigid pavements.

Material properties have a vital effect on the structural response of the slab and therefore its service life. To reduce the strains induced in concrete slabs, it is more effective to increase the concrete slab module of elasticity than to increasing the other parameters. Increasing the concrete slab and the base course module has a significant effect on pavement performance.

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