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NUMERICAL SIMULATION ON MECHANICAL BEHAVIOR OF DOWEL AS A LOAD TRANSFER DEVICE TO DISTRIBUTE THE CRITICAL STRESS IN RIGID PAVEMENT SLABS OVER EXPANSIVE SOIL SUBGRADE

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Abstract
The determination of the magnitude and location of critical stress in rigid pavement structures is very important. Critical stress occurs in an area that must be anticipated to prevent failure when subjected to service loads. Several previous researchers have studied this using various empirical, analytical, and numerical methods, yielding varying results from these studies. The stress distribution analysis on a single plate provides critical stress results according to variations in traffic load arrangements. Different results are obtained when the analysis is performed on more than one plate connected with dowels. This study examines the performance of dowels as load transfer devices from one plate to another and their effect on the magnitude and location of critical stress. The method used is a numerical study of the behavior of rigid pavement plates on expansive soil with axle loads. The implications of this further study are to improve the understanding of the flexural behavior of rigid pavement plates, thereby making it easier to determine the performance load of a rigid pavement construction.
Keywords: Rigid pavement; dowel; load transfer; slab; dowel

INTRODUCTION

Rigid pavement is a widely relied upon choice of pavement construction for highway structures. This preference for rigid pavement is due to its believed durability and endurance in field applications. Under normal conditions, rigid pavement will undergo minimal deformation and is capable of withstanding traffic loads (axle road) better than flexible pavement types. Although its production cost is high, it is worth it because its service life is significantly longer compared to flexible pavement systems.[1]

The properties of concrete as a material in rigid pavement construction are generally very brittle and absorb little energy, making it very susceptible to cracking during its service life.[2] Based on data from previous researchers, ordinary axle loads can be sufficiently supported by the pavement structure. However, its strength will slightly decrease if frequently subjected to exceed or superloads (heavy loads)[3], [4], [5] One significant cause of potential damage (cracking) to rigid pavement plates is the deformation of the subgrade, particularly with expansive subgrade soils. Expansive soils undergo swelling and shrinkage due to the presence of water in their structure. Swelling and shrinkage beyond certain limits can damage the concrete.[6], [7], [8]

Road pavement construction has infinite dimensions (kilometers), making it impossible to create slabs as large and long as the road being repaired. Thus, rigid pavement is poured segmentally to minimize cracking due to the overly large surface area of rigid pavement. Consequently, rigid pavement sections are constructed alternately and connected from one slab to another. This introduces the issue of load transfer between the segments of the rigid pavement slabs. Inaccurate planning of the slab connecting device (dowel) for load transfer can result in damage to the edges between the slabs and trigger more significant damage to the rigid pavement slabs.[9], [10], [11]

The purpose of studying dowel installation is to understand the load transfer mechanism from one slab segment to another due to light to heavy traffic loads (axle load). By understanding the working mechanism and determining the magnitude of the acting forces, this knowledge can be used as a basis for accurately planning the load transfer device (dowel).[12], [13], [14]

Previous studies have generally focused on the installation of dowels in rigid pavement slabs to address cracks caused by concrete shrinkage between slabs. However, an investigation into the role of dowels as mechanical load transfer elements, as discussed in this article, is essential to understand their effectiveness in distributing stress from mechanical loads. This distribution helps reduce critical stress, which in turn enhances the reliability and durability of rigid pavements.

METHODOLOGY

Speciment Testing

The research method used is numerical analysis of several test specimens representing various field application conditions. The numerical method employed is the finite element method. The output of the numerical method includes stress, deflection, and vertical shear force at the slab intersections. To determine the magnitude of the force vectors acting at the slab edges, several variations of test specimens are used, allowing for the identification of trends and patterns in the magnitude of these forces.[15]

The test specimens used are three segments of rigid pavement plates with dowels installed at the slab edges in the direction of traffic. A single plate without dowels is used as a control. Figure 1 shows the configuration of the rigid pavement slab test specimen

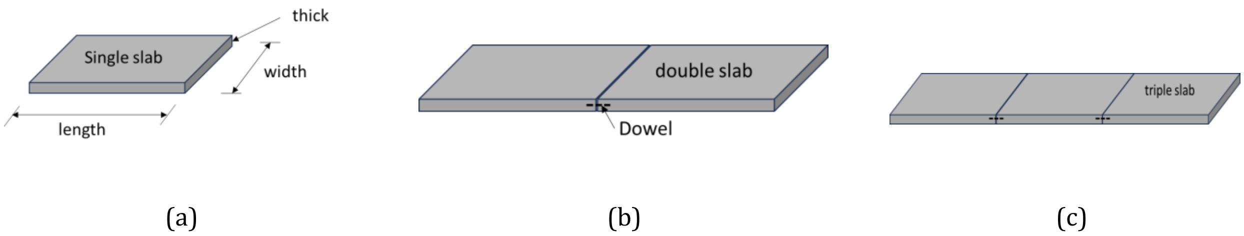

Fig. 1. Configuration of specimen model: (a) single slab, (b) double slab, (c) triple slab

The detailed configuration of the test object is described in Table 1 in centimeters. The size of the test object is actual size, such as a segment of rigid pavement slab commonly installed on highways.

Tabel 1 Dimension of specimen model

part	dimension (cm)
length	600
width	350
thick	25

The results of the numerical analysis on the test specimens are then used to determine the force vectors, which can serve as the basis for demand capacity in the planning of load transfer reinforcement (dowels). Critical stress and maximum deflection can also be compared

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from the results of structural analysis with various possible load combinations acting simultaneously at calculated moments. The position of the axle load also affects the magnitude of the force that must be transferred between adjacent slabs. In this study, the loads used are single axle loads positioned as end loading. Figure 2. Present schema triple slab specimen.

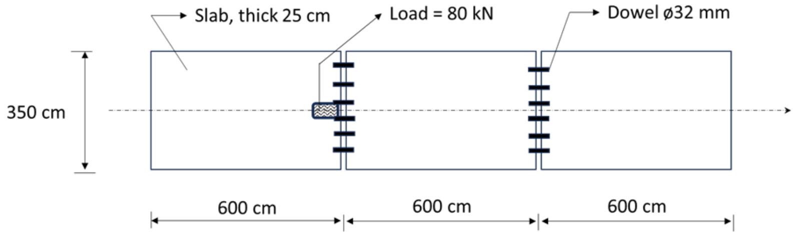


Fig 2. Speciment and load position: Tripel slab

Mathematic and Numerical Modelling

Rigid pavement models on dense liquid foundations are used to simulate and analyze the behavior of pavements (such as concrete roadways) when supported by a viscoelastic or elastic foundation, akin to how slabs interact with a dense liquid in geophysical models[16].

This refers to pavement structures that have high stiffness, such as concrete pavements. Unlike flexible pavements (asphalt), rigid pavements distribute loads over a wider area due to their rigidity. The dense liquid foundation is analogous to a viscoelastic or elastic layer that supports the rigid pavement. This foundation can represent subgrade soil, base layers, or any underlying materials that provide support to the pavement.[17]

The dense liquid foundation can be modeled using several approaches, such as the Winkler foundation model, the Pasternak foundation model, or more complex viscoelastic models. These models capture the interaction between the rigid pavement and the supporting medium[18].

This is the simplest model where the foundation is represented as a series of independent, discrete springs. Each spring's stiffness represents the subgrade reaction modulus. The pavement deflection is proportional to the applied load. Pasternak Foundation Model model adds shear interaction between adjacent springs, providing a more realistic representation of the subgrade. It accounts for both vertical support (spring stiffness) and horizontal shear (shear layer)[19].

The behavior of rigid pavements on a dense liquid foundation is described by differential equations that balance applied loads, pavement stiffness, and foundation reactions. For a Winkler foundation, the basic equation is:

$$\mathrm{D}\frac{d^4w(x)}{dx^4} + k(x) = q(x) \qquad (1)$$

where D is the flexural rigidity of the pavement, w(x) is the deflection, k is the foundation stiffness, and q(x) is the applied load.

These equations are solved with appropriate boundary conditions, such as continuity of deflection and slope at joints or edges of the pavement.[20], [21]

For complex pavement geometries and loading conditions, FEA (Finite element method) is often used. It discretizes the pavement and foundation into elements and solves the governing equations numerically. Engineers use these models to design pavement thickness, joint placement, and reinforcement to ensure adequate performance and longevity under traffic loads. These models predict pavement performance under various conditions, including traffic loads, temperature variations, and long-term settlement or creep of the foundation.

In this research, the study focuses on dowels as load transfer elements between slabs in rigid pavement based on numerical analysis using the finite element method. The structural models used are single slab and double slab, adjusted to the slab sizes commonly used in actual rigid pavement construction. The finite element method accommodates the theory of slab on dense liquid. The numerical analysis in this study using the finite element method employs the free software EverFE as a tool.[22], [23]

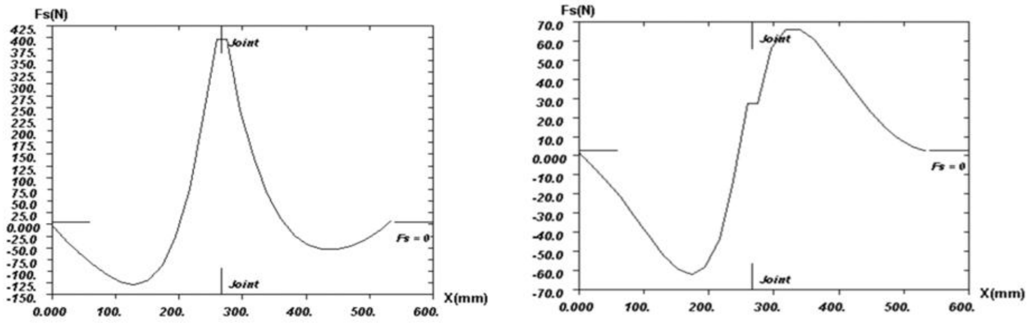
Expansive soil subgrade is represented by the soil reaction modulus. In this study, the expansive soil's bearing capacity properties do not vary; instead, a constant value of 0.03 MPa/mm is used. The influence of expansive soil is limited to the ease of vertical deformation due to the low bearing capacity of the soil.

Results

Loading Transfer Capacity

The maximum load transfer on rigid pavement slabs provides protection to the joint sections between slabs to prevent damage and maintain the smoothness between the rigid pavement slabs. In this study, the dowel capacity in transmitting shear and bending loads due to traffic loads was evaluated. The numerical analysis results provide a curve pattern of the shear force capacity received by each installed dowel. Figure 3 shows the numerical analysis results for dowels installed at the edge and center.

(a)



(a) (b)

Fig. 3. Shear Force Load Transfer capacity. (a) dowel installed at the edge and (b) dowel installed at the center of slab pavement

The load transfer capacity changes when considering 2 or 3 slabs connected by dowels. Triple slabs with dowels installed have a slightly higher capacity in transferring loads compared to triple slabs. The shear load transfer capacity increases as more dowels are installed. The joints between the slabs will become stronger and more unified, eliminating any gaps between the slabs. Table 2 shows the changes in load transfer capacity of the slabs influenced by the installation of dowels at the slab joints. The traffic load is a single axle load of 80 kN, and 10 dowels with a diameter of 32 mm are installed.

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Tabel. 2. Load transfer capacity

Configuration	Dowel Location	Shear Force, Fs (N)	Moment, Mr (N-mm)
Double Slab	Edge	392.9	14727.1
	Center	99.6	7681.9
Triple Slab	Edge	400.75	14902.5
	Center	113.2	7798.5

Table 2 presents data on the load transfer capacity for Double Slab and Triple Slab configurations, measured at the edge and center of the slabs. The force and moment are significantly higher at the edge compared to the center dowel location. The force and moment for the Triple Slab are slightly higher than those for the Double Slab. There is an increase, though not very significant, in the load transfer capacity of the dowels installed in the test specimens when comparing the 2-slab model (double slab) with the 3-slab model (triple slab).

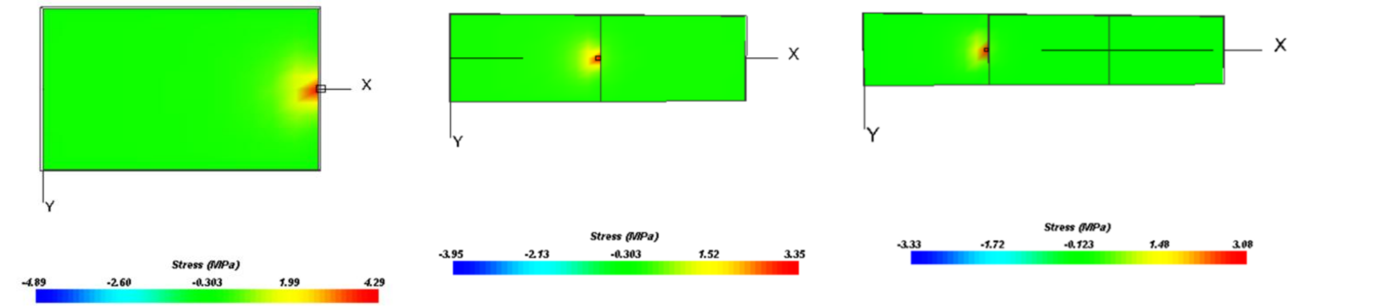
Critical Stress Distribution

The distribution of critical stress is very important, especially in the design of rigid pavements. The pattern of critical stress distribution is fundamental in mitigating and preventing structural failure of rigid pavements. This distribution pattern is also necessary in reinforcement design to ensure that the reinforcement installation is effective and efficient.The results of the numerical analysis show that the pattern of critical stress distribution changes as a result of dowel installation between slabs. The figure below shows the analysis results of the critical stress distribution in single slabs, double slabs, and triple slabs.

Table 3. Critical Stress in different configuration of slab pavement

Rigid pavement Slab Configuration	Critical Stress	
	Compression Stress (MPa)	Tension Stress (MPa)
Single Slab	-4.89	4.29
Double Slab	-3.95	3.35
Triple Slab	-3.33	3.08

Table 3 explains that a single slab will experience the highest stress due to the lack of a load transfer mechanism. After installing dowels, which facilitate load transfer, the stress within the rigid pavement slab is significantly reduced. This is very beneficial as it can help prevent structural failure of the rigid pavement and extend the service life of the pavement slab.



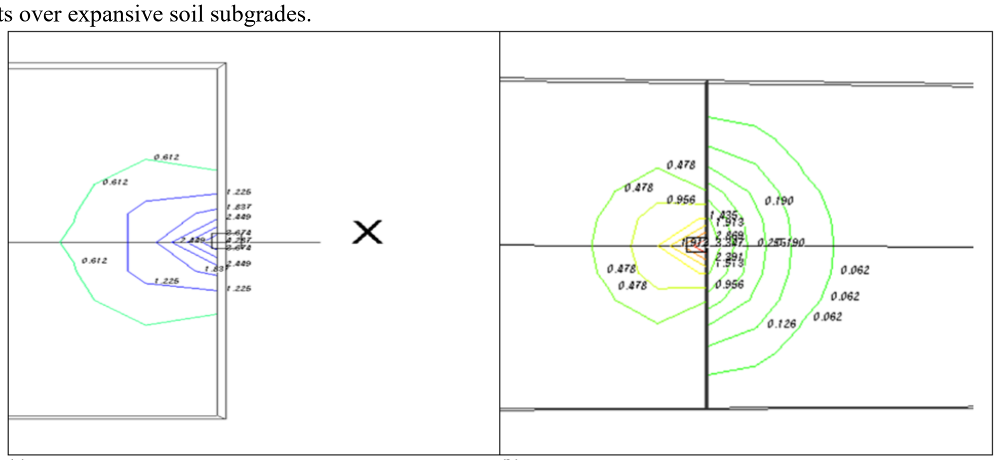
(a) (b) (c)

Fig. 4. Critical stress distribution. (a) single slab, (b) double slab and (c) triple slab

The installation of dowels as load transfer devices appears to be quite effective in reducing the tensile stress experienced by the slab. The stress decreased from 4.29 MPa to 3.08 MPa, or by approximately 28.2%. The graphical results are shown in Figure 3. The reduction in tensile stress increases the stress ratio, thereby enhancing the slab's strength capacity to withstand repeated loads, ultimately extending the service life of the rigid pavement.

DISSCUSION

Both configurations show higher forces and moments at the edges compared to the centers. The Triple Slab configuration tends to exhibit slightly higher forces and moments than the Double Slab configuration at both the edge and center locations. The data suggests that the Triple Slab configuration might provide better load transfer capacity, especially at the edges. This analysis helps in understanding the load distribution and the effectiveness of the dowel installation in different slab configurations, providing insights for designing more robust rigid pavements over expansive soil subgrades.



(a) (b)

Fig. 5. Different countur of stress in single and double slab

The stress contour shown in Figure 4 explains that dowels can bridge the load transfer from one slab to the next, distributing the stress from one slab to the next. This mechanism is highly effective in rigid pavement that withstands traffic loads. As a result, high stress is distributed, preventing pavement damage.

The role of the expansive soil subgrade is critical during the loss of bearing capacity, which occurs after swelling when the soil dries and shrinks. As a result of this shrinkage, the bearing capacity decreases to its lowest point. This will cause the dowels to potentially receive more load due to the uneven reduction in bearing capacity around the joint. The cyclic swelling and shrinking of expansive soil is also one of the reasons for installing dowels. The impact of subgrade swelling and shrinking is the emergence of slab deformation, which, if not addressed, will damage the slab itself.

In the scenario where traffic loads coincidentally reach or exceed the allowable limit and the expansive subgrade is at its lowest bearing capacity, the slab potentially face failure condition (cracking and structural failure). The installation of appropriate reinforcement will greatly help to address such conditions. Reinforcement in concrete structural elements can be implemented using various methods, such as adding steel fibers, installing flexural and shear reinforcements, including the installation of dowels and tie bars.

CONCLUSIONS

Considering the results of the study on the installation of dowels as a load transfer method in rigid pavement, the following conclusions can be drawn:

Load transfer in a joint slab system for rigid pavement is essential because it can reduce the very high tensile stress experienced when supported only by a single slab. This stress becomes much smaller with the load transfer mechanism that considers more than one slab.

A very important aspect is that load transfer allows the slab surface to remain level, preventing traffic loads from causing damage or cracking at the edges of the rigid pavement slab due to rapid load transfer. Sudden loads generate impact forces that can cause the slab edges to crack and break.According to the theory of the ability of rigid pavement to withstand repetitive loads, a reduction in stress increases the ratio of maximum stress to occurring stress, which enhances the resistance and increases the number of load repetitions. This ultimately extends the service life of the pavement.The dowels installed evenly from the center to the edge of the cross-section of the rigid pavement slab receive varying load transfers. Therefore, this should be considered during design, and the selection of the number and geometry of the dowels needs to be carefully reconsidered.Finally, load transfer consists of shear forces, bending moments, and deformation. These factors should be accommodated in the planning process to help enhance the comfort and safety levels of the road pavement construction.

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