Effect of Pavement Foundation Materials on Rigid Pavement Response

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Abstract. Rigid pavements are increasingly becoming a primary pavement type for highways under heavy traffic loading due to their long service life and less frequent requirements for maintenance compared to flexible pavements. The behaviour of a rigid pavement during service life is affected by several parameters such as applied loading features, pavement properties, environmental effects, and pavement foundation properties, which must be taken into account in the analysis and design of rigid pavements. The pavement foundation consists of base, subbase, and subgrade layers, all of which play substantial roles in the long-term performance of the rigid pavement. With the development of computer capacity, the three-dimensional finite element method (3D-FEM) has become a widely utilized tool for analysis of concrete structures such as pavements as it overcomes the limitations of analytical solutions. The main objective of this research is to evaluate the effects of pavement foundation characteristics on rigid pavement response using EverFE software. The parameters examined in this study included the thickness and properties of each layer of the pavement foundation. The analysis results revealed that, generally, stresses and settlements within rigid pavement are considerably reduced when a stiff or thick foundation is used. The analysis of results also showed that the tension bending stresses in the base layer decreased significantly with increases in the thickness of the base layer. It was also found that the addition of a subbase layer within the pavement foundation produced a significant reduction in the tension bending stresses in pavement and base layers with no in compression stresses in both layers noted.

Keywords: Rigid Pavement, FEM, Bending Stress, Stiffness, Foundation Materials.

1. Introduction:
The purpose of highways is to provide a public way for people and vehicles under an acceptable level of comfort. Although rigid pavement has a high initial cost when used for such purposes, its structural capacity to carry higher traffic and environmental loads makes it a promising choice in heavy use situations [1]. Rigid pavements are composed of several discrete Portland cement concrete slabs, connected by longitudinal and transverse joints, resting on multi-layered sub-structures. These transverse and longitudinal joints are perpendicular and parallel to the traffic direction, respectively. Jointed plain (unreinforced) concrete pavement (JPCP) is the most common type, and this is constructed with short joints spaces. Dowels and ties bars are usually used for transferring the wheel loads across the joints of the pavement, as using dowels bars instead of aggregate interlocks reduces the required pavement thickness. The JPCP’s dimensions are a function of slab thickness [2-5]. Based on UK practice [6], maximum joint spacing is recommended to be lower than 6.0 m for dowelled joints, and the ratio of longitudinal to transverse joint spacing should be less than 1.25. JPCP may be placed either on subgrade or multiple layers of stabilised material (base and subbase layers). Early
JPCP was constructed directly on the treated subgrade, but in recent decades, increasing traffic loads have prompted the utilisation of either low strength unbound materials as a subbase layer or higher-quality concrete material as a base layer beneath the JPCP, as the use of a base layer reduces the stresses in JPCP and subgrade caused by water pumping, frost action, shrinkage, and swell of subgrade. A subbase more specifically refers to an engineered layer placed between the prepared subgrade and a rigid pavement or base layer. This provides many functions, such as minimising frost action, preventing pumping, providing drainage way, and distributing applied loads. A subbase layer consists of a granular material, or a stabilized material such as treated cement or asphalt [7-9]. The objective of the paper is to evaluate the effect of the pavement foundation materials on rigid pavement response using three-dimensional finite element analysis software (EverFE). Several relevant parameters were thus examined, including the thickness and properties of each layer of the pavement foundation.

2. Three-Dimensional Finite Element Method
With the evolution of high-performance computers, the utilisation of 3D-FEM: three-dimensional finite element software to analyse pavements has grown rapidly, as researchers seek to better understand pavement responses under traffic and environmental loadings. The finite element approach is a numerical approach to analysis of displacements and stresses in structures in which a simulated structure is divided into elements connected by nodes. The number, type, and arrangement of elements affects the accuracy of the results [10-18], and thus, finite element analysis software is divided into two categories, general finite element software such as ANSYS [19] and ABAQUS [20], which analyse any structure, and specific finite element software for pavement analysis. Pavement software may be based on the three-dimensional solid elements or classical thin plate theory: KENSLAB [7], FEACONS [21], WESLAYER [22], LLISLAB [23], and JSLAB [24] are examples of finite element programs using classical thin plate theory, while EverFE [13] is a three-dimensional finite element analysis program initially developed by the universities of Washington and Maine to emulate the responses of jointed plain rigid pavement subjected to various traffic loads and temperature gradient effects. LLISLAB [23] and EVERFE [13] are the two most common FE software types utilised to model rigid pavements, but EverFE was selected in this study to simulate the performance of rigid pavement under wheel loadings due to its advantages over other software. EverFE is one of the few three-dimensional finite element software specifically designed to analyse jointed concrete pavements, and several studies show a good agreement in terms of analysis results between field data and EverFE’s numerical output [25-29].

There are many other significant features of EverFE including 1) the ability to model up to nine adjacent slabs in a 3×3 matrix connected together by longitudinal and transverse joints; 2) aggregate interlocking of transvers joints can be modelled to simulate shear transfer with linear or nonlinear options; 3) nonlinear or linear thermal gradients within the pavement system can be applied to simulate slab shrinkage; 4) various axle load configurations can be applied to the pavement system; 5) transverse and longitudinal joints can be dowelled and tied, respectively; 6) multi-base layers can be specified with unbonded or bonded conditions; and 7) visualisation of analysis results (moments, stresses and displacements) and pavement response from any point in the model can be easily retrieved.

3. Finite Element Discretisation
Five different element discretisations were used to model the pavement system within the EverFE program. Rigid pavement, base layer, and subbase layers were discretised using 20-noded quadratic brick elements with rectilinear meshes. These layers were then divided with the same number of element divisions in the x-y plane to achieve compatibility at the slab-base interface. The subgrade foundation was discretized using eight-noded planar quadratic elements, while the shear transfer between pavement and base layers and the aggregate interlocks of the transverse joint were implemented using 16-noded quadratic interface elements. The dowels and ties bars of the joints were
modelled using three-noded embedded flexural elements and two-noded shear beam elements, respectively. Figure (1) shows all five types of finite element discretisation. The boundary conditions of the pavement system have to prevent any motion within the pavement body, and the pavement layer is restrained in the horizontal x-y plane by the shear stiffness of the slab-base interface, while, the body motion of the base and sub-base layers is restricted by restricting the x- and y- displacements of one node on the –x face, and restricting the x-displacement of a second node on the –x face. Vertical support for the pavement body is provided by the subgrade foundation, which is incorporated below the pavement system [30].

Figure 1: Five Types of Finite Element Discretisation Using EverFE

4. Description of Finite Element Model
A six rigid concrete slab system was modelled to take account the effect of the load transfer provided by dowels and ties bars. All properties, dimensions, and features of pavements were determined according to UK recommendations [6], and the material properties were assumed to be linear, homogeneous, and elastic in behaviour. The rigid pavements were 3.0 m wide and 4.0 m long, with an elastic modulus of 30,000 MPa, a thermal expansion coefficient of 1.1 × 10^-5 per °C, a Poisson’s ratio of 0.20, and a density of 2,400 kg/m^3. The slabs were placed on three separate types of surfaces: (1) subgrade, (2) base and subgrade, and (3) base, subbase, and subgrade with variable thicknesses and modulus of elasticity. As shown in Figure (1.a), each transverse joint had seven dowels of 500 mm long and 30 mm in diameter spaced at 300 mm from the centre. The dowel-slab support modulus and dowel-slab restraint modulus were 1,000 and zero MPa, respectively. The tie bars of the longitudinal joint were 12 mm in diameter and 600 mm long, and these were spaced at 600 mm from the centre. Both dowels and ties bars had 200,000 MPa modulus of elasticity and a 0.3 Poisson’s ratio. The tie-slab support modulus and tie-slab restraint modulus were 1,000 and 10,000 MPa, respectively. The initial stiffness of the base/ slab interface was 0.0001 MPa/mm, and the slip displacement was zero, which is the minimum value used by EverFE2. Single wheel load of 22 KN representing an equivalent 88 KN single axle load was assumed, and the contact pressure of the tire was presumed to be uniformly applied over a rectangular area of 200 mm × 150 mm. The single wheel load was applied on the mid-edge slab, representing the critical wheel position, as in Figure (2.b). The input parameters used in the analysis of the rigid pavement are listed in Table (1), and these are reflective of the values utilised in the UK.
Table 1. Ranges of Inputs Parameters for the Analysis of Rigid Pavements

| Finite Element Input Variables                  | Range of Input Values                                      | Number of Studied Cases |
|------------------------------------------------|------------------------------------------------------------|-------------------------|
| Thickness of Rigid Pavement (mm)               | (150 - 400) with 50 intervals                              | 6                       |
| Thickness of Base Course Layer (mm)            | (150 - 500) with 50 intervals                              | 8                       |
| Thickness of Subbase Layer (mm)                | (150 - 300) with 50 intervals                              | 8                       |
|                                                 | (300 - 500) with 100 intervals                             |                         |
|                                                 | (500 - 1000) with 250 intervals                            |                         |
| Elastic Modulus of Base Layer ($10^3$ MPa)     | (30 - 160) with 10 intervals                               | 30                      |
|                                                 | (160 - 320) with 20 intervals                              |                         |
|                                                 | (325 - 500) with 25 intervals                              |                         |
| Elastic Modulus of Subbase ($10^3$ MPa)        | 30, 50, 100, & 200                                        | 4                       |
| Elastic Modulus of Subgrade (MPa)              | (5 – 12.5) with 2.5 interval                               | 17                      |
|                                                 | (20 – 150) with 10 intervals                               |                         |

5. Results and Discussion
5.1: Effect of Thickness of Concrete Slab
Figure (3.a) shows the relationship between the thickness of the concrete slab and the maximum principal bending stress. For a rigid pavement system with a 150 mm base layer, the results revealed that the increase of the slab thickness significantly reduced tension stresses at the bottom of concrete pavement layer; however, the magnitude of tension stresses at the top layer showed a slight reduction with the increase of the slab thickness. The results also showed no noticeable change in compression stresses at the top and bottom of the pavement layer with increases in slab thickness. The relationship between bending stresses in the base layer and the thickness of the concrete pavement slab is displayed in Figure (3.b). As the thickness of rigid pavement increased, the tension stress at the top of the base layer gradually increased also up to a thickness of 300 mm, while the compression stresses at top and bottom layers did not change with increasing pavement thickness. Additionally, no change in tensile stresses was identified at the bottom of the base layer with increasing thickness of the concrete slab. The general trend of these results agreed with the results of the numerical analysis study performed by Abdalla [31].
Figure 3: Effect of Thickness of Pavement Layer on Stress in: a) Pavement Layer b) Base Layer
5.2: Effect of Base Course Layer

Figure (4.a) shows the effect of changes to the thickness of the base layer on the maximum principal bending stress in the concrete slab. The results indicated no change for all maximum principal stresses (tension or compression) in the pavement layer with any increase of the base thickness, whereas in the base course layer, a slight increase in tension stresses occurred with increases in the thickness of the base layer, as shown in Figure (4.b). Moreover, all the compression stresses in the base layer were slightly affected at base thicknesses of more than 200 mm. The results of the effect of the thickness of the base layer matched the results obtained from the numerical analyses conducted by Abdalla [30].

![Fig. 4a](image_url)

![Fig.4b](image_url)

**Figure 4:** Effect of Thickness of Pavement Layer on Stress in: a) Pavement Layer b) Base Layer
The typical relationship between the bending stresses and modulus of elasticity of the base layer is shown in Figure (5). As illustrated in Figure (5.a), the elastic modulus of the base layer did not affect the values of any bending stresses (tension and compression) in the rigid pavement. However, the results did show that a significant increase in the modulus of elasticity of the base layer led to increased tension stress in the base layer for both surfaces (top and bottom), while compression stresses remained unchanged, as shown in Figure (5.b).

**Figure 5:** Effect of Modulus of Elasticity of Base Layer on: a) Pavement Layer and b) Base Layer
5.3: Effect of Subbase Layer

The relationship between tension bending stress in pavement and the modulus of elasticity of the subbase layer for various values of subbase thickness is illustrated in Figure (6.a). The use of a stiff subbase layer, of less than 500 mm thickness within pavement substructures causes only a slight decrease in the tension stress in the pavement; however, the elastic modulus of the subbase has a significant effect on tension stress when a subbase layer with a thickness of more than 500 mm is used. The effect of modulus of elasticity of the subbase materials on tension stress at the bottom of subbase layer is shown in Figure (6.b). The results showed that increasing modulus of elasticity of the subbase reduces tension stresses for all values of subbase thickness.

Figure 6: Effect of Modulus of Elasticity of Subbase on: a) Pavement Layer and b) Subbase Layer
5.4: Effect of Subgrade Layer

Figure (7) shows the effect of modulus of subgrade reaction on the bending stresses in the pavement layer. No compression and tension stresses on the top layer change with increases in the modulus of subgrade reaction; however, the tension stresses at the bottom of the pavement layer do reduce significantly with any increase of the modulus of subgrade reaction.

![Figure 7a](image1.png)

![Figure 7b](image2.png)

**Figure 7**: Effect of Modulus of Subgrade Reaction on stress in: a) Pavement Layer and b) Base Layer
6. Conclusions
A 3D finite element model was developed to analyse jointed plain concrete pavements. The effects of pavement foundation materials on bending stresses were thus examined and evaluated using EverFE software. The following conclusions were drawn from the results of this work:

- Correct pavement thickness can significantly reduce the maximum tension stresses at the bottom layer of the concrete pavement slab, though the compression stresses do not change.
- Increasing the concrete pavement thickness gradually increases the tension stress at the top layer in the base course layer to a thickness of 300 mm, while compression stresses at the top and bottom layers do not change.
- The bending stresses in the concrete layer do not show any change with increases in the thickness of the base layer, though the base layer itself did show a slight increase in tension stresses with increases in its thickness.
- Increasing the value of modulus of elasticity of the base course materials increased the tensile stresses in the base layer for both surfaces.
- The addition of a subbase layer within unbound pavement foundation layers produced a significant reduction in the tension bending stresses in the pavement and base layers, with no change in compression stresses in both layers.
- The analysis showed that increasing the modulus of subgrade reaction decreased the tension stress at the bottom layer of pavement, while all compression stresses and tension stress at top layer remained unchanged with increases in the modulus of subgrade reaction.

7. Reference
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