NUMERICAL RESPONSE ANALYSIS OF STRUCTURAL STRENGTH CAPACITY OF FLY-ASH-INVERTED PAVEMENT

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Abstract

In accumulating the success rate towards implementing inverted pavement in the United States and South Africa, an improved mechanical response in the Asphalt layer is observed. The unbounded granular aggregate in inverted pavement sandwiched between the Asphalt layer and cement-treated layer played a crucial role in minimising excessive deflection due to the stiff cement-treated or bitumen-treated layer constraint-resisting excessive deformations. In inverted pavement, layer material properties and positioning are reversed in order to analyse rutting and fatigue resistance when compared with conventional flexible pavement. Nonetheless, bitumen or cement-treated layer in pavement are neither economically viable. This study proposes fly-ash -treated base as a substitute for the cement or bitumen-treated base layer while modelling the pavement using Finite Element Analysis compared with Multi-Layered Elastic Design Method. Results from the resilient Modulus (Mr) provides a response threshold for optimum stiffness requirements. This indicates the use of empirical design methods, results to over-designing the pavement structure when compared with results from 3D FEM and Multi-Layered Elastic Design. Furthermore, 3D-FEM material characterisation using non-linear models are efficient and reliable when compared with linear models, which enhances efficiency and reliability. An adaptive mesh was used to discretise the individual pavement layer in response to actual load and material characterisation values. The results indicate that the Horizontal Tensile strain in the Inverted layer with 300 mm thickness is more efficient than conventional 300mm flexible pavement under the same loading conditions. Critical failure load points, as well as deflection models, were generated to assess the life expectancy of the pavement layers.

Keywords: inverted pavement, flexible pavement, finite element modelling, fly-ash, distress prediction

1 Introduction

Conventional flexible pavements with asphalt as surface are prevalent worldwide. This pavement type contains various material layers in composition which have different strengths and deformation characteristics [1]. Furthermore, the use of flexible pavement has many advantages, such as: low tire-pavement noise generation, smooth surface and sustainable environmental roads [2]. Considering the uniqueness of each material in terms of strength, deformation and durability, it is of great importance to understand each before using them.

In the quest to provide a sustainable solution to the occurrence of failures in the flexible pavement, researchers came up with the idea of layer rearrangement/interchange which brought about the innovation of Inverted Pavement [3].
Unlike flexible pavement, the inverted pavement has a cement-treated layer as its sub-base and UGA as the base layer, with other materials similar to that of flexible pavement. The concept of the rearrangement results in a potential and economic benefit structure which has been successfully used in South Africa and also tested in the US [3-5]. Furthermore, according to Cortes et al., [6], the inverted pavement has less cracking density and severity (after ten years), and delivers superior rutting and fatigue resistance, when compared with a conventional flexible pavement structure. Additionally, in the conventional flexible pavement, the surface layer acts like a slab, but in inverted pavement performs like a membrane. Overall, the performance achieved by the inverted pavement takes advantage of the engineering properties of various material layers, which results in better performance, economic saving and sustainability [4]. Considering the disadvantages of using a cement-treated layer in pavement structures, Fly-Ash as a replacement seems to be the way out. The selection of Fly-Ash as an alternative stabiliser can be justified by its availability and cement-like property [7].

2 Simulation of inverted pavement

Simulation in engineering systems entails creating series of occurrences in the behaviour of a structural member when subjected to loading or environmental effects while in service. In this process, the failure, as well as the stress values, are determined and used to provide a threshold to mitigate failure. Numerical simulation in recent times sets the pace for sustainable design of pavement structures and transportation facilities (bridges, tunnels and riding surfaces). In numerical analysis, the pavement is treated as a layered structure whilst simulating with varying materials, properties of individual strength and stiffness [1]. This makes the design efficient with the ability to determine stress-strain values and deflections in any layer of the pavement structure [8]. Additionally, numerous studies have been conducted with positive results in the design of inverted pavement considering mechanistic-empirical design methods. Cortes and Santamarina [9], through Abaqus, modelled inverted pavement and results show that an inverted pavement can deliver superior rutting resistance when compared with conventional pavement layer design configuration.

3 Numerical response analysis

Numerical Response Analysis provides a sophisticated and explicit approach in determining the response rate of engineering structures when subjected to service loads. In this study, two scenarios are modelled. First, a four-layered conventional flexible pavement with an asphalt surface, Fly-Ash stabilised base layer, UGA as the sub-base and a sub-grade. While the second scenario is an inverted pavement, having an unbound granular base (UGA) as a base, a Fly-Ash-stabilised layer as sub-base and other materials remains without change. These scenarios are modelled in an three-dimensional finite element environment using Abaqus [10], and the results are compared with those obtained using mePADS and WinJulea [11]. Geometry shapes used in this study are similar to that used by Papadopoulos and Santamarina [5].
On element type, a solid continuum of 8-noded elements with reduction integration (C3D8R) and the 4-node, reduced-integration, first-order, axisymmetric solid element (CAX4R) are used in the 3D and axial symmetric Abaqus model respectively. A bias seed meshing is adopted in this study (Table 1 and 2). This defines a non-uniform distribution of elements

along each edge of the different pavement layers such that the mesh graduates from a fine mesh distribution at the loading plane to a coarse mesh distribution at the outer model section. The mesh density is seen to change from one end to the other end resulting in an adaptive mesh profile in FEM. Consequently, a double bias seed mesh was adopted in the Axial symmetric and 3D Abaqus model.

In this study, material characterisation for Asphalt, UGA and sub-grade is selected from TRH 4 [12], and Fly-Ash-stabilised material is adapted from a previous study by Adedeji [13]. These material characterisations are presented in Table 3 and Table 4. A Tie constraint interaction is assumed between each individual inverted pavement layer. The models are fixed at the bottom of the element (subgrade) and roller constraints on the vertical boundaries. The standard equivalent loading contact area is assumed to be rectangular (119355 mm^2) (i.e. 285 x 419 mm) with the wheel uniform contact pressure of 0.67 MPa [12]. Additionally, this analysis is run as a static linear perturbation analysis procedure type.

Table 1 Abaqus 3D Model Mesh Configuration

Pavement Structures		**Pavement @150 base & Subbase**	**Pavement @150 base & Subbase**	**Pavement @300 base & Subbase**	**Pavement @300 base & Subbase**
Meshing		**No. of Elements along the layer thickness**	**Total Elements in layers**	**No. of Elements along the layer thickness**	**Total Elements in layers**
No. of Elements	Asphalt	4	90424	4	90424
	Base	7	158242	14	316484
	Subbase	4	90424	8	180848
	Subgrade	5	113030	5	113030

Table 2 Abaqus Axial Symmetric 2D Model Mesh Configuration

Pavement structures		**Pavement @150 base & Subbase**	**Pavement @150 base & Subbase**	**Pavement @300 base & Subbase**	**Pavement @3000 base & Subbase**
Meshing		**No. of Elements along the layer thickness**	**Total Elements in layers**	**No. of Elements along the layer thickness**	**Total Elements in layers**
No. of Elements	Asphalt	39	4134	39	4134
	Base	26	2756	54	5724
	Subbase	24	2544	48	5088
	Subgrade	6	636	6	636

Table 3 Material Characterisation and input parameters for Flexible Pavement

Flexible pavement	**Layer thickness** [mm]	**Elastic modulus** [MPa]	**Poisson ratio**	**Density**
Asphalt	50	4274.24	0.44	2370
Fly-Ash	150/300	2560	0.35	2050
UGA	150/300	300	0.35	2000
Subgrade	2000	60	0.35	1680

Table 4 Material Characterisation and input parameters for Inverted Pavement

Inverted pavement	Layer thickness [mm]	Elastic modulus [MPa]	Poisson ratio	Density
Asphalt	50	4274.24	0.44	2370
UGA	150/300	450	0.35	2000
Fly-Ash	150/300	2560	0.35	2050
Subgrade	2000	60	0.35	1680

4 Results and conclusions

4.1 Comparative analysis

The comparative analysis in this study serves as a performance check for the models developed in Abaqus. The results obtained using Abaqus, mePADS and WinJulea are significantly similar (Fig. 1, Table 5 and 6). The mePADS results, however, show very close similarity to that of Abaqus Axial Symmetric numerical model in terms of the horizontal strains generated at the bottom of the asphalt layer and similarly the vertical compressive strains generated at the top of the subgrade. Although, if the lifecycle of the pavements is calculated using the Asphalt Institute damage model for both Abaqus and mePADS models, Abaqus CAE would have the higher design life for the pavement structures (either inverted and flexible pavement).

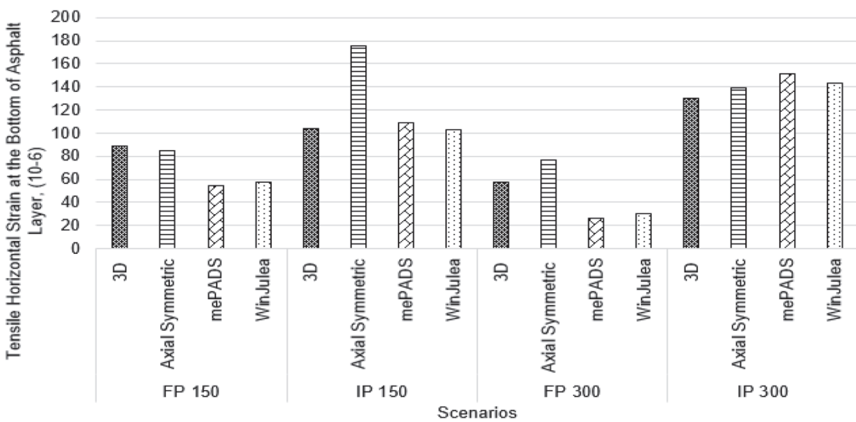

Figure 1 Effect of Fly-Ash stabilised layer thickness in the Anisotropy of Flexible Pavement and Inverted Pavement.

Table 5 Numerical Analysis results of Flexible Pavement Anisotropy using Abaqus, mePADS and WinJulea

		Pavement Responses					
		Tensile Strain Asphalt Bottom 10^6	Tensile Strain Stabilised Layer 10^6	Stress in UGA 10^3	Vertical Strain in Subgrade	Total Deflection in Pavement	Total Stress (Mises) 10^3
Scenarios	Platform						
Flexible Pavement @150 mm base & Subbase	3D	88.66	241.2	171.3	808.0	59.13	1291
	Axial S.	84.55	263.5	187.8	900.6	66.43	1526.0
	mePADS	54.83	276.86		935.0		
	WinJulea	57.46	275.5		937.9		
Flexible Pavement @300 mm base & Subbase	3D	57.23	105.3	77.10	285.9	36.05	539.3
	Axial S.	76.55	121.0	87.79	315.9	35.37	679.3
	mePADS	26.77	124.66		320.0		
	WinJulea	30.3	126.01		327.1		

Table 6 Numerical Analysis results of Inverted Pavement Anisotropy using Abaqus, mePADS and WinJulea

		Pavement Responses					
		Tensile Strain Asphalt Bottom 10^6	Tensile Strain Stabilised Layer 10^6	Stress in UGA 10^3	Vertical Strain in Subgrade	Total Deflection in Pavement	Total Stress (Mises) 10^3
Scenarios	Platform						
Inverted Pavement @150 mm base & Subbase	3D	104.3	181.7	399.2	710.2	62.22	1264.0
	Axial S.	175.2	226.6	404.0	764.8	66.55	1583.0
	mePADS	108.96	236.90		785.0		
	WinJulea	103.0	237.34		788.7		
Inverted Pavement @300 mm base & Subbase	3D	130.5	61.10	423.0	266.8	52.09	1067
	Axial S.	139.3	79.31	434.1	263.1	48.51	1405
	mePADS	150.88	81.01		267.0		
	WinJulea	142.9	89.72		270.2		

4.2 Effect of Fly-Ash-stabilised layer thickness

The effect of a Fly-Ash-stabilised layer can be seen in the increased pavement lifecycle resulting from reduced overall von-mises stress deformation as the thickness of the layer increases from 150 mm – 300 mm for both flexible and inverted pavement; Table 5 and 6. However, on a comparative note of the two models, the flexible pavement had a reduced deflection ratio as compared with the inverted pavement. However, in performance, the inverted pavement is more durable with minimal stress resultant deformations under service loads. This observation conforms to findings from previous studies [5, 6, 9], which state that inverted pavement is superior to the flexible pavement. Furthermore, the deformation diagrams in Fig. 2 provide a graphic description of the response of the Flexible Pavement (FP) and the Inverted Pavement (IP) under service loads. The contour distribution, as observed from the Multi-layered Elastic Design in mePADS, is as presented in Fig. 3 for the flexible pavement at 150 mm. The contour distribution diagram for both models indicates that the Inverted pavement is resistant to deformation at 300 mm when compared to the conventional Flexible pavement having an infinite value of deformation with a thickness of 300mm. Thus, this makes the Inverted pavement a more efficient and sustainable solution than the conventional pavement.

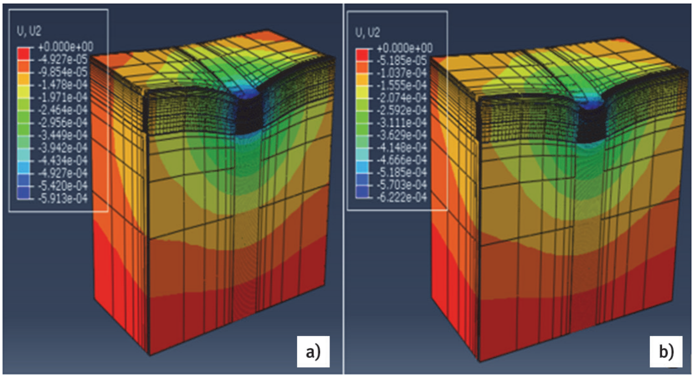

Figure 2 3D Deformation model for 150mm: a) FP; b) IP

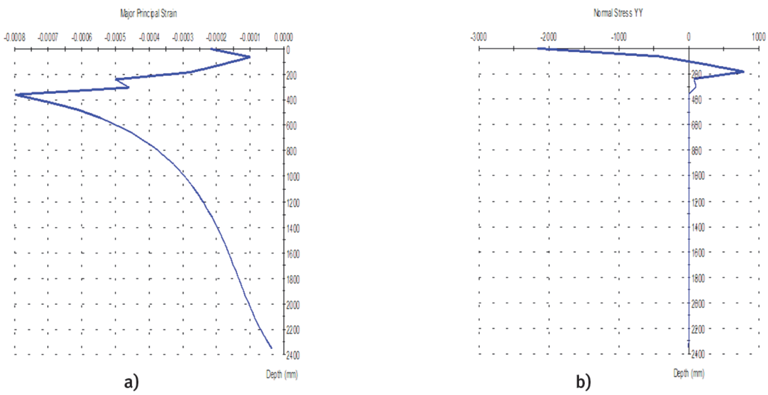

Figure 3 50 mm Flexible Pavement: a) Major Principal Strain YY; b) Normal stress YY.

5 Conclusions

Further justification of the results from this study indicates that: increase in the UGA thickness from 150 mm – 300 mm with a constant Fly-Ash-stabilised layer (150 mm) sustains the service loads. The results also indicate that with the increase in the thickness (300 mm UGA) layer with a corresponding stabilised layer, the inverted pavement tends to deliver better resistance to rutting when compared with the flexible pavement. This result is comparable to the findings, according to Cortes et al. [6]. Nevertheless, flexible pavement delivers better resistance to fatigue cracking, even with the increase in UGA layer thickness. Overall, the increase in the thickness of the stabilised layer gives a better result when compared to the increase in the UGA layer. According to a review from the literature, inverted pavements are more superior to flexible pavements [3-5]. Nevertheless, the use of conventional stabilisers (such as cement, lime, slag and bituminous treated bases, etc.) in pavement layer would further increase the construction cost of a pavement structure which is durable and efficient. Similar to the findings in previous studies, the results obtained in this study show that the increase in the Fly-Ash-stabilised layer thickness increased pavement life. However, on the contrary, increasing the thickness of the Fly-Ash-stabilised layer reduces the horizontal tensile strain at the bottom of the asphalt layer for flexible pavement, but otherwise in the inverted pavement.

Overall, it is worth noting that inverted pavements perform better in terms of vertical strain in the subgrade layer when compared with the flexible pavement. Thus, it can be recommended that when considering the use of Fly-Ash as a stabiliser in pavement structures, Inverted pavement bases should be considered over the conventional flexible pavement.

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