Analysis of Flexible Pavement Structural Behavior Considering Decreased Subgrade Resilient Modulus

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Abstract. This research focuses on the subgrade resilient modulus and its significance in investigating flexible pavements. The study compares results obtained from two distinct flexible pavement structures, utilizing numerical analysis using FLAC^{3D} softawere. Four decreasing levels of subgrade resilient modulus (PF50, PF25, PF10, and PF5) were examined. Our findings reveal that the decrease in subgrade resilient modulus has a more pronounced effect on the GB/GB structure compared to the GB/GNT structure, with the latter demonstrating superior performance. By assessing subgrade resilient modulus, this research contributes to a better understanding and improving road infrastructure investigation not only in Algeria but also in broader contexts.

Keywords: Flexible Pavement, Subgrade, Unsaturated Behavior, Von Mises stress.

1 Introduction

Flexible pavements are constructed of bituminous and granular materials [1], their performance is greatly influenced by environmental conditions including precipitation, temperature, freeze-thaw cycles, and depth to ground water table (GWT) that plays a crucial role in determining the extent of environmental impact on pavement performance [2]. The subgrade layer of a pavement serves as the foundational layer that sustains road infrastructures, with its stiffness playing a pivotal role as it carries the weight of traffic loads. El-Hamrawy and Abd El-Hakim [3] reported that the pavement's fatigue lifespan extends as subgrade stiffness increases.
Zhang et al. [4] observed that the resilient modulus (RM) showed a significant increase as matric suction increased. This increase was attributed to the effect an additional interparticle normal forces and consequently, the soil specimens exhibited a stiffer behavior [5]. Subgrades are usually granular unbound material of unsaturated nature to keep their strength, however they are usually subjected to rainfall infiltration or fluctuation of GWT which reduce the RM due to saturation process that follow such environmental events.
The performance of a pavement system is significantly influenced by the modulus of each layer, making it one of the key parameters to consider [6]. Specifically, the resilient modulus of aggregates plays a crucial role as an input parameter in characterizing Unbound Granular Materials and forecasting the structural performance of pavements [7].
This study presents a scientific contribution to assess through a numerical simulation the structural behavior of flexible pavements considering the effect of decreasing resilient modulus that may follow a saturation process using the powerful code FLAC^{3D}. Two different flexible pavement structures were chosen, from the Algerian Guide for Pavement Design, to conduct the analysis. The pavement structures are GB/GB and GB/GNT where the GB reflects Hot Mixed Asphalt (HMA) and GNT reflects Non-Treated Gravel used for Base and Subbase layers, respectively. Generally, the minimum allowed value of RM of subgrade layers is 50 MPa which corresponds to the S2 or PF50 platform class. To simplify the study, the decrease of subgrade RM is considered by the definition of three platform subclasses PF25, PF10 and PF5 with decreasing RMs as follow: 25 MPa, 10 MPa and 5 MPa, as the saturation process causes the decrease of RM by decreasing the matric suction that holds together the particles of granular material. The analysis is focused on comparing the calculated results from the two pavement structures which are: (1) vertical deformation (deflection) at the Top Surface of the Pavement (TSP) and at the Top Surface of the Subgrade (TSS) layer and (2) Von Mises Stresses (VMS) under the loading stress that comes from tires of heavy traffic vehicles.

The subgrade provides foundational support to the pavement layers above it. A decrease in the subgrade's resilient modulus reduces its ability to support the overlying pavement layers, leading to increased stress and strain within the pavement structure. This can compromises the structural integrity of the pavement system, leading to accelerated deterioration of the surface and underlying layers (Cracking, fatigue damage) (see Fig.1).

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Fig. 1. Pavement deterioration due decreases in the subgrade's resilient modulus.

2 Materials

The study employed the widely accepted linear elastic model for pavement analysis. This model operates under the assumption that stresses are directly proportional to strains. **Table 2** presents a concise overview of the distinctive attributes characterizing each layer. The essential parameters include the elastic modulus (E), Poisson's ratio (ν), and the thickness of each layer (h_i).

2.1 Subgrade soil

The subgrade foundational support for the pavement structures in this study is defined as a bottom layer with a thickness of 2000 mm. Numerous researchers have reported a non-linear increase in the modulus of elasticity of unsaturated soils relative to soil suction [5]. The Algerian Guide for Pavement Design categorizes platforms into five classes S0, S1, S2, S3, and S4 based on the minimum young’s modulus that presents the soil; the minimum accepted class of platform should demonstrate a RM of at least 50 MPa. The AGPD adopt the USCS classification system to classiy soils. To decide the youg’s modulus of a soil platfrom, the Califrnia Bearng Ratio (CBR) is used as the key parameters in the empirical formula (1):

$$E = 5 * CBR \tag{1}$$

Table 1 groups the soil bearing capacity classes in ascending order from S4 to S0.

Subgrade soils exist in an unsaturated state, where the presence of suction provides additional cohesive forces that bind soil particles together [5]. The process of saturation in unsaturated soils primarily results in a decrease in Young's modulus, corresponding to the loss of suction within the soil matrix. In this study, we delve into the unsaturated behavior of subgrade soils, delineating them into three subclasses defined by their young’s moduli as follows: PF50 = 50 MPa, PF25 = 25 MPa, PF10 = 10 MPa, and PF5 = 5 MPa. It's worth noting that the subgrade elastic modulus remains assumedly constant throughout the layer's depth.

Table 1. AGPD soil bearing capacity classes from S4 to S0 based on the CBR values [8].

Platform’s class	CBR	Young’s modulus (MPa)
S4	< 5	/
S3	5 to 10	25 to 50
S2	10 to 25	50 to 125
S1	25 to 40	25 to 200
S0	>40	> 200

2.2 Pavement layers

Flexible pavement consists of a multilayer system designed to distribute traffic loads and withstand deformation. Each layer in a flexible pavement system plays a specific role in distributing traffic loads, providing structural support, and preserving the overall integrity of the road. The composition and thickness of each layer are determined based on factors such as traffic volume, soil conditions, climate, and intended service life of the pavement. Typically, a flexible pavement structure includes the following layers from the top down: suface course layer, base layer, subbase layer and subgrade.

In the preset stud, both structures consist of a 60 mm thick surface course layer, composed of HMA with a particle size grading of 0/14. The underlying base layers comprise HMA with a particle size grading of 0/20. The thickness of the base layers is 110 mm and 200 mm for the GB/GB and GB/GNT structures, respectively. The GB/GNT configuration incorporates a subbase layer composed of 300 mm thick Non-Treated Gravel (GNT), whereas the GB/GB structure employs a 120 mm thick of HMA with a particle size grading of 0/20 for its subbase.

Table 2. Material mechanical characteristic

	Moduli of Elasticity E (MPa)	Poisson’s ratio ν	Density (kg/m3)
HMA (0/14)	3500	0.4	2400
HMA (0/20)	5500	0.4	2300
GNT	350	0.3	2300
Subgrade (Soil)	PF50 PF25 PF10 PF5	0.4	2200

3 Numerical model

The numerical model is shown in Fig. 2. The model's radius is set at 2000 mm to avoid boundary condition effects. Its height measures 2560 mm and 2290 mm for GB/GNT and GB/GB structures, respectively. The symmetry boundaries located at x = 0 and y = 0 are constrained in their displacement along the x- and y-directions, respectively. Similarly, both the circular boundary and the base of the cylinder have their displacement restricted in all directions. To simulate the wheel load, a vertical stress of 0.675 MPa is applied on the gridpoints that correspond to the contact area of the wheel in the downward z-direction.

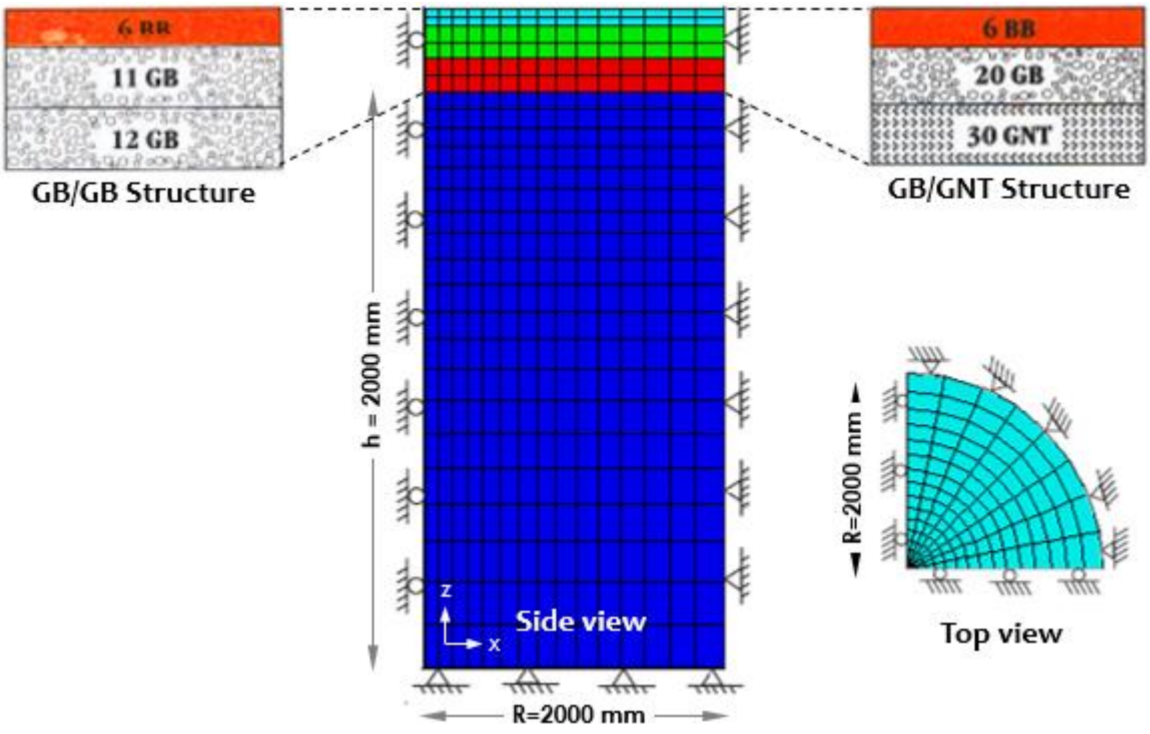

Fig. 2. Numerical model of the simulations and boundary conditions

4 Results and discussion

The present study investigates the influence of the surbgrade resilient modulus on the behavior of two flexible pavements chosen from the AGPD. The results are presnted as follow: (1) the vertical displacements calculated at the TSS and TSP of each pavement sructure (i.e., GB/GB and GB/GNT) and (2) von Mises stresses computed around the area where the traffic load is applied.

4.1 Vertical displacements

In pavement design, fatigue failure often occurs due to the repeated application of loads from passing vehicles. These loads induce stress and strain within the pavement structure. Over time, the accumulated strains can lead to the development of cracks and other forms of damage. Understanding the vertical displacement caused by cyclic loading of tires is crucial for assessing fatigue.

Fig. 3 displays the vertical displacements with respect to the platform young’s modulus computed at the TSS and TSP for both pavement sructures. A clear increasing in vertical displacements (deflection) is observed and which is directly correlated with the decrease in the elastic moduli of the platform. Considering the platform PF50, the TSP of the GB/GNT structure exhibited a displacement of 329 µm, while the TSS displayed a displacement of 250 µm. The displacements were augmented by the ratios: 55%, 192%, and 426% for the TSS, and 42%, 146%, and 324% for the TSP corresponding to PF25, PF10, and PF5 respectively. On the hand, the GB/GB structure showed a displacement of 391 µm and 366 µm for the TSP and TSS, respectively while the ratios of increasing are as follow 36%, 135% and 286% for the TSP and 38%, 144% and 307% for the TSS. Upon comparing the displacements obtained from the two distinct structures, it's evident that those from GB/GB are significantly higher than those from GB/GNT. This disparity can be attributed to the flexural rigidity of the two pavement structures.

Comparing the displacements calculated between the TSS and TSP of the two pavement structures, it is obvious that the gap of displacement between these two locations is more pronounced in the case of the GB/GNT structure when contrasted with the GB/GB structure. This disparity can be attributed to the lower Young’s modulus of the GNT that underlies the HMA layers in the case of the GB/GNT structure. Moreover, the difference analysis indicates that the lower the platform class, the smaller the gap of difference in vertical displacementS between the two locations (i.e., TSP and TSS).

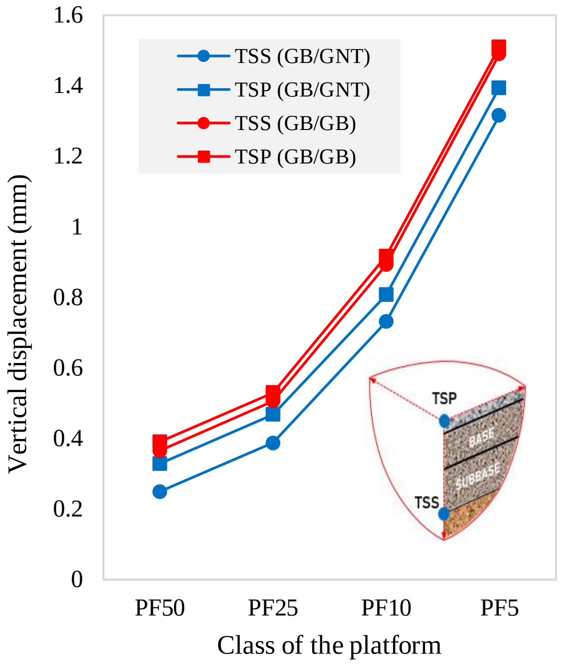

Fig. 3. Vertical displacement on the TSS and TSP : GB/GNT and GB/GB structures.

4.2 Von Mises stresses

Von Mises stresses are used in the field of solid mechanics to quantify the stress experienced by a material subjected to complex loading conditions. It is based on the concept of equivalent stress and accounts for multiaxial loading, including both tensile and compressive stresses. The calculation of von Mises stresses indicates that, in the case of GB/GNT structures, the maximum stress values occur at the bottom of the base layer. Conversely, for GB/GB structures, the maximum von Mises stresses are observed at the bottom of the foundation layer. This distinction underscores the differing stress distributions between the two types of structures (see 3).

Figure 4 illustrates the highest computed VMSs values within the numerical model. Considering the pavement structure GB/GNT, the maximum VMS value for the PF50 platform amounts to 6.47 x 10^5 Pa. However, these values are increased by 3%, 7%, and 8% for the PF25, PF10, and PF5 platforms, respectively. Similarly, for the same platforms, these increasing percentiles are equal to 8%, 16% and 18% in the case of the GB/GB structure, knowing that the maximum VMS computed is equal to 7.52 x 10^5 Pa for the PF50 platforms. The computed values of VMS are much higher in the case of GB/GB structure than those calculated in the case of GB/GNT structure due to the high rigidity that characterizes the GB/GB structure layers and consequently it could store higher energy than the GB/GNT structure.

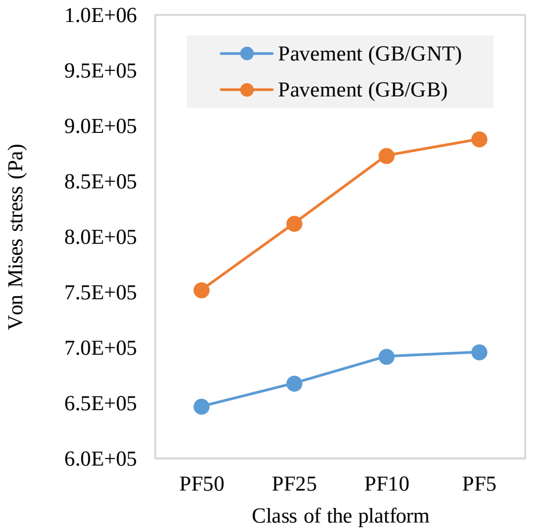

Fig. 4. Maximum von Mises stresses (Unity : Pa)

5 Conclusion

The present study highlights through a simplified 3D numerical finite element analysis the key role that the subgrade RM lays in the performances of flexible pavements. Based on the results of simulations, the following findings can be concluded:

- As flexible pavements are designed to withstand fatigue behavior, subgrade saturation process leads to a reduction in service life due to an increase in the magnitude of calculated deflections at the TSP structures.
- The GB/GB pavement structure exhibits greater deformation when compared to the GB/GNT configuration, which can be attributed to differences in flexural rigidity.
- The reduction in mechanical properties of the subgrade layer has a more pronounced effect on the GB/GB structure compared to the GB/GNT structure.
- Engineer investigators of pavement degradation must also incorporate the unsaturated behavior of subgrade materials and genuinely account for the saturation processes arising from fluctuations in GWT or the infiltration of rainfall.

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