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Development of 3-D Finite Element Models for Geo-Jute Reinforced Flexible Pavement

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Abstract

In this study, three dimensional (3-D) finite element analysis are performed to evaluate the effect of geo-textile interlayer on the performance of flexible pavement. The main objective of this study is to evaluate the improvement in stress distribution of flexible pavement due to the application of geo-jute at three specific positions i.e., subgrade-base interface, base-asphalt layer interface, and within asphalt layers. Stress, strain and displacement values are investigated and compared for the application of geo-jute interlayer on various positions. Moreover, to better understand the mechanistic behavior of geo-jute on pavement subgrade, a separate 3-D finite element model is developed to simulate the California bearing ratio (CBR) test on geo-jute reinforced soil. Results showed that the inclusion of geo-jute on flexible pavement significantly improves the pavement performance by producing lower stress, strain, and displacement at top of the subgrade. Moreover, the bearing capacity of subgrade soil increased more than 20% due to the inclusion of geo-jute.

Keywords: Finite Element Model; Flexible Pavement; Geotextile; Stress Distribution; California Bearing Ratio.

1. Introduction

The flexible pavement under wheel loads is considered as a homogeneous and elastic half-space in Boussinesq's theory, which can be used to determine the stresses, strains, and deflections in the subgrade if the modulus ratio between the pavement and the subgrade is close to unity [1]. As Poisson's ratio has little influence on stresses and deflections, a half space can be assumed as incompressible with a Poisson's ratio of 0.5 [2]. However, pavements are layered systems with better materials on top, and it cannot be assumed as a homogeneous mass. To overcome this limitation, Burmister developed two- and three-layer system, where tangential and radial stresses are considered as identical on the axis of symmetry [3, 4]. The vertical stress on the top of the subgrade is a crucial factor in pavement design, which can decrease significantly with the increase in modulus ratio in layer system. As the Burmister's theory is only applicable for idealized conditions, numerical procedures are often adopted for complicated pavement systems. In 1968, Duncan et al. first introduced the finite element method for pavement analysis [5].

Both functional and structural performance are considered to design pavement sections [6, 7]. During the past three decades, the use of geosynthetics in pavement has increased dramatically to enhance the structural and functional

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condition of pavement [8–10]. Numerous studies have been performed to validate the performance of geosynthetics in flexible pavements [11–14]. Al-Qadi et al. performed a laboratory study to validate the performance of geogrids and geotextiles and observed that geosynthetics can substantially improve the performance of pavement [11]. Howard and Kimberly used full-scale instrumented testing and finite element analysis for thin pavements incorporating geosynthetics [13]. It was observed that geosynthetics incorporated in poor soils showed improvement in the flexible pavements. Application of geosynthetics in pavement engineering were also presented by Koerner [14].

Development of geotextile and geogrid reinforced pavement design methods were attempted in many other studies [15-17]. Kuo and Chou observed significant improvement of estimated service life of asphalt overlays on concrete slabs after placing geogrid between overlay and slabs [15]. It was observed on another study that geogrid reinforcement can be effectively used when placed at the base/subgrade interface for producing the lowest vertical strain on top of the subgrade [16]. Abu-Farsakh et al. concluded that the use of geogrid base reinforcement results in reducing the lateral strains within the base course and the subgrade layers, reducing the vertical strain, and shear strain at top of the subgrade, and reducing the surface permanent deformation [17]. Several field and laboratory studies were performed to improve pavement performance due to the application of geosynthetics. It was reported on many previous studies that geotextile can improve flexible pavement performance by providing reinforcement [11, 14, 16, 17, 18, 19]. Among other studies, Perkins et al. presented results of laboratory-scale model pavement experiments, and observed reinforcement benefit due to inclusion of geosynthetics [19].

Two-dimensional finite element models were developed to investigate geosynthetics reinforced flexible pavement in several studies [17, 20, 21]. Correia et al. conducted two-dimensional finite element simulations to identify the variables that govern the performance of geogrid-reinforced asphalt overlays and their effect on the response of flexible pavements. However, 2-D analysis cannot properly capture non-uniform wheel pressure and multiple wheel loads; and hence, 3-D finite element models are recommended [22]. Three-dimensional finite element model was developed to investigate pavement stress-strain responses in few studies [23, 24]. Taherkhani and Jalali studied the performance of geogrid-reinforced asphalt pavement under various axle loads using 3-D finite element analysis [25]. Several types of geogrid had been placed in various positions in a typical flexible pavement, and critical strains, i.e., the compressive vertical strain on top of subgrade had been evaluated under different axle loads. It was observed that the maximum tensile strain in asphalt layer and the maximum compressive strain on the subgrade decreases with geogrid, which can increase pavement service life by reducing the permanent deformation and fatigue cracking. A 3-D finite element approach for modeling biaxial geogrid with application to geogrid-reinforced soils were also presented by Hussain and Meguid [26]. It was concluded that modeling the 3-D geogrid geometry is important to accurately capture the true response of geogrid under both confined and unconfined condition. However, extensive research is still required on natural geosynthetic or geo-jute reinforced pavement, in order to grasp its effect on permanent deformation.

Geo-jute or jute geotextile can be very effectively used in pavement structure as it has the advantage of being sustainable and cost-effective [27, 28]. The application of jute materials in pavement engineering can both improve the performance of pavements as well as can flourish the jute industries. Singh and Sonthwal summarized the usefulness of jute as reinforcing materials for various projects [29]. It was observed that reinforcing of jute fiber into subgrade layer increases the California bearing Ratio (CBR) value of soil [30-34]. Hamid and Shafiq found jute fiber as a suitable material for improving the CBR of sub-base soil. It increases the CBR of sub-base soil up to 200% than the plain soil [35]. Another study showed CBR value of cohesive soil is increased by 130.74% due to the application of jute geotextile [36]. Saride and Kumar studied the influence of geo-jute interlayers on the performance of asphalt overlays on pre-cracked pavements [37]. It was observed that geo-jute interlayers proved effective in controlling the reflection cracking and increasing fatigue life of the overlays. Evaluation of cracking resistance potential of geo-jute reinforced asphalt overlays using direct tensile test was also conducted [38]. The tensile strains in geo-jute reinforced specimens found lower than the unreinforced specimens.

Considering the above literature review, this study focuses on the determination of stresses, strains and deflections of various layers of a flexible pavement under an instantaneous rectangular loading by 3-D finite element modeling due to geo-jute application. The objectives of this research are to determine the effects of geo-jute on stress-strain distribution and deformation characteristics of flexible pavement structure using finite element analysis. In order to assist in conventional design and construction process of flexible pavement, the study also investigates the effect of geo-jute on California Bearing Ratio (CBR) of subgrade soil.

2. Methodology

The function of the pavement is to reduce the stress and strain on the subgrade soil to avoid detrimental pavement deformations. Geotextile performs many functions which could be utilized for pavement construction, such as, filtration, separation, reinforcement, slope stabilization etc. In this study, improvement in subgrade soil stress distribution due to geo-jute was investigated using finite element analysis. Geo-jute was used as reinforcing material on three positions such as subgrade-base interface, base-asphalt layer interface, and within asphalt layers to evaluate stress, strain and deformation at top of the subgrade.

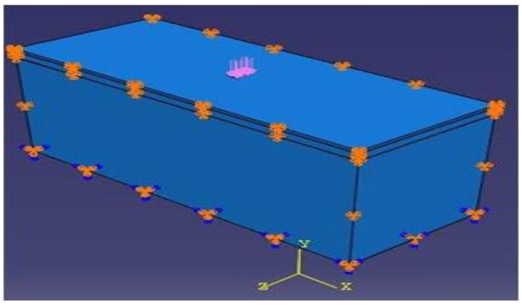
Recently, finite element method has become an essential tool in pavement industries. Numerical solutions of very complicated stress problems can now be obtained easily using finite element analysis. However, it is necessary to consider how the stresses in pavement layers are influenced by important variables such as material properties and geometric features. In this study, 3-D finite element models were developed using ABAQUS software to evaluate the performance of flexible pavement with or with geo-jute interlayer. Stress, strain and displacement were investigated and compared due to the inclusion of geo-jute interlayer in three positions. Additionally, to better understand the mechanistic behaviour of geo-jute on the pavement subgrade, another 3-D finite element model was developed for the California bearing ratio (CBR) test on geo-jute reinforced soil.

2.1. ABAQUS as Finite Element Tool

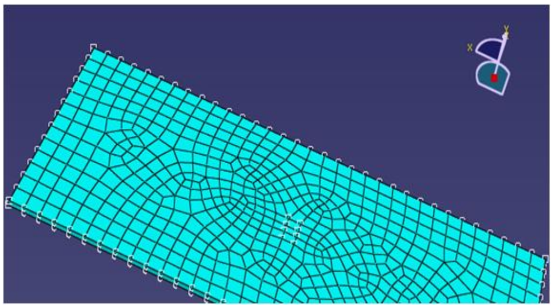
For this study, ABAQUS software was used which has versatile drawing and finite element analysis tools. In ABAQUS, the pavement can be modeled using many solid elements, and the number of elements used depends largely on the geometric parameter such as the length and the cross-sectional perimeter.

The following procedure was adopted to model the pavement layers in ABAQUS. Firstly, parts were created using drawing tool bars. In this study, 3-D deformable type, solid extrusion was used to model various parts. Then material properties were assigned to the desired part. A typical flexible pavement was modeled with asphalt surface, granular base, and subgrade. Additionally, geo-jute layer was incorporated into three positions. All pavement materials were assumed to respond linearly and elastically to the applied load. Next step was to assemble the created parts either independently or dependently, and translation of various parts. Assembles of the parts (i.e., asphalt, base, and subgrade), was completed in this step, and the wheel load area was also sketched in this step.

Then steps were created, and the selected procedure type was linear perturbation. Field output and history output was also created in this step. Next, interaction was created and interaction properties were assigned. Interaction property between two adjacent layers were assumed to be perfectly bonded; therefore, frictionless contact was given. Load and boundary condition were created in next step. Pressure load was applied at desired region. Boundary condition was given at bottom of the subgrade, and two sides of the pavement. Displacement or rotation type boundary condition was chosen. Figure 1a shows load and boundary condition used in this study. Then global seeds were created and part was seeded for meshing. Mesh is the necessary step to discretize or modeling the structure using suitable number, shape, and size of the element. For the study, the 300 mm mesh spacing was found to be adequate to obtain reasonably accurate results. Element type and meshing strategy of asphalt layer used in this study is shown in Figure 1b. Then the job was submitted for the analysis in job manager. Last step is called visualization. After the analysis was completed, stress, strain, deformation of the structure was visualized. Various colored strata could be provided to indicate different values. Both deformed and un-deformed shape visualization is possible. Animation of load and displacement could also be produced, and results at various sections could be achieved by cutting the model at various sections.



a) Load and Boundary Condition



b) Element Type and Meshing

Figure 1. Boundary Condition and Mesh Generation

2.2. Application of Geo-Jute at Pavement Layers

Geo-jute can be employed at three positions in flexible pavement: i) subgrade-base interface, ii) base-asphalt layer interface, and iii) within asphalt layers or at the bottom of asphalt overlay. Benefits of geo-jute inclusion in different layers are described below.

2.2.1. Subgrade-Base Interface

Geo-jute into subgrade-base interface prevents pavement base aggregate from infiltrating the subgrade soil. It also prevents fine particles from the subgrade soil penetrating the base aggregate. It advances placement of the base aggregate during construction, and reduces the need for excavation of soft subgrade soils. One of the principle advantages of placing geo-jute in base-subgrade interface is that it reduces rutting of the base aggregate over any pockets of weak materials that may have been overlooked.

2.2.2. Base-Asphalt Layer Interface

Geo-jute can also be placed into base-asphalt layer interface. As the tensile strength of an unreinforced pavement is low in comparison to its compressive strength, the presence of the geo-jute within pavement structure can improve the overall tensile strength of the pavement structure. It gives greater resistance to cracking, and prolongs fatigue life. However, geo-jute placed within the pavement will be in contact with hot mix asphalt, and therefore, requires high thermal stability.

2.2.3. Within Asphalt Layers

Geo-jute can be placed within asphalt layers, or the geo-jute can be laid on the surface of an existing pavement prior to the asphalt overlay. Application of geo-jute at the base of the overlay restricts reflective cracking; therefore, increases the life of the overlay. However, a high tensile strength of geo-jute is advantageous for applying within asphalt layers.

2.3. Finite Element Model of California Bearing Ratio (CBR) Test

The CBR represents the mechanical strength of subgrade soil, which was developed to quantify the load-bearing capacity of soils used for road pavements. The CBR test is performed by measuring the load required to penetrate a plunger to the soil sample, and CBR value is obtained by dividing the measured load with the load required to achieve an equal penetration on a standard crushed rock. The CBR test is described in AASHTO T193 [39].

To better understand the mechanistic behaviour of geo-jute on pavement subgrade, 3-D finite element model was developed to simulate the California bearing ratio (CBR) test on geo-jute reinforced soil. A numerical test method of CBR on geo-jute reinforced soil was developed using finite element technique. The CBR model was developed by using similar load, sample dimension, and boundary condition, which are mentioned in the standard laboratory procedure.

3. Finite Element Analysis

A 3-D finite element model was developed using ABAQUS. The flexible pavement model was produced by creating various parts such as subgrade, base, and asphalt layer. Load condition was applied for impact loading by duel wheel system. The stress, strain, and displacement at top of the subgrade layer was considered as output, while the impact loading at top of the asphalt layer was one input. The analysis was performed initially with no geo-jute interlayer. Then geo-jute was applied at various positions of pavement structure. All material properties were assumed to be linearly elastic, and the magnitude of loading, and the position of geo-jute layer was varied.

3.1. Finite Element Input Variables

In this study, static pressure load was applied to a rectangular contact area. Duel wheel system was considered, and each wheel had a contact area of 160 × 230 mm dimension. Five different wheel loads were applied on each wheel (i.e., 20.5, 41, 61.5, 82, and 102.5 KN) on five different wheel pressures (i.e., 0.56, 1.12, 1.68, 2.24 MPa, and 2.80 MPa respectively). The model dimension of roadway segment was chosen as 10 × 5 *m* to avoid the boundary effects. Material property used for this study are shown in Table 1, which is taken from a previous literature [40]. Material property of geo-jute are adopted from Gowda et al. [41] and AASHTO M288 [42].

Table 1. Thickness and Material Properties

Inputs	Asphalt Layer	Base Layer	Subgrade Layer	Geo-jute Layer
Layer Thickness (*mm*)	100	250	2000	1
Modulus of Elasticity, *E* (MPa)	2175	415	52	2100
Poisson's Ratio, υ	0.35	0.40	0.45	0.39

3.2. Convergence Analysis

The convergence investigation includes different meshing framework where the whole model is divided into three parts. To satisfy convergence criteria, analyses was performed for decreasing mesh sizes and increasing number of elements. The output of convergence study for 0.56 MPa wheel pressure and with no geo-jute inclusion is shown in Figure 2. For the parameters used in this study, the 300 mm mesh spacing (14,000 total number of elements) was found to be adequate to obtain reasonably accurate results. It can be noted that the increasing number of elements increases the degree of accuracy. The analytical results showed lower values of stress than the analysis results. The deviation from analytical solution may be due to following reasons.

- The assembly used in finite element model has finite length and finite depth.
- The analytical solution gives the exact value. However, finite element analysis gives an approximate value.
- The output of finite element analysis depends on the number of elements.
- The boundary condition used in finite element model may cause divergence.

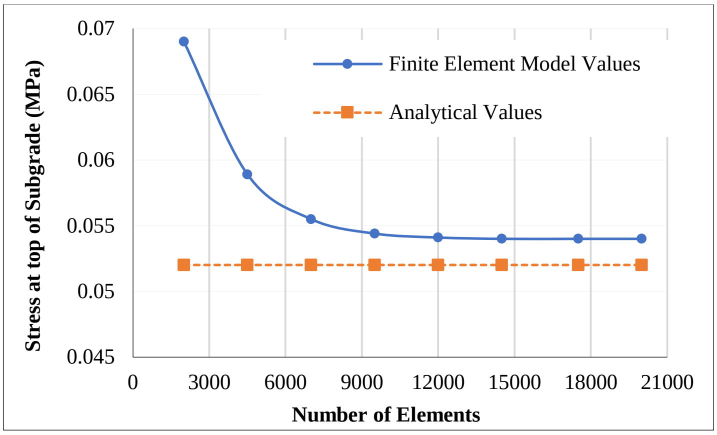


Figure 2. Convergence Analysis

3.3. Results and Discussions

For five different wheel pressure and wheel loads, stress, strain, and displacement were studied for four different scenarios shown in Figure 3.

- Scenario 1: With no geo-jute layer (Figure 3a).
- Scenario 2: Geo-jute at subgrade-base interface (Figure 3b).
- Scenario 3: Geo-jute at base-asphalt layer interface (Figure 3c).
- Scenario 4: Geo-jute within the asphalt layers (Figure 3d).

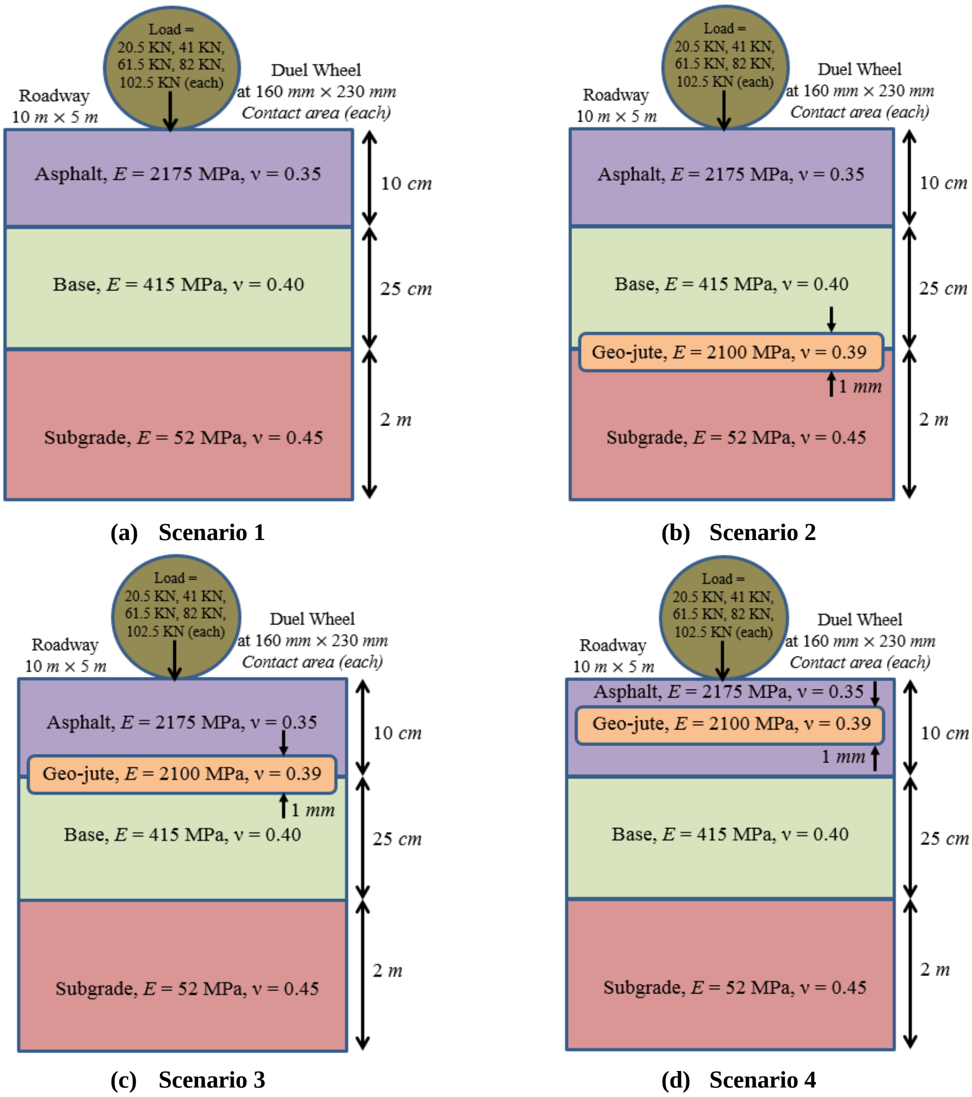
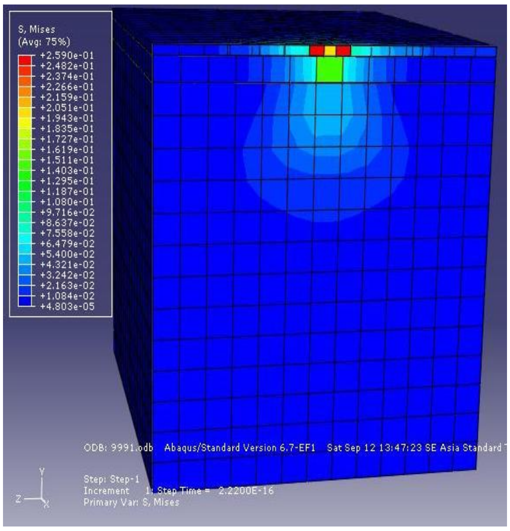
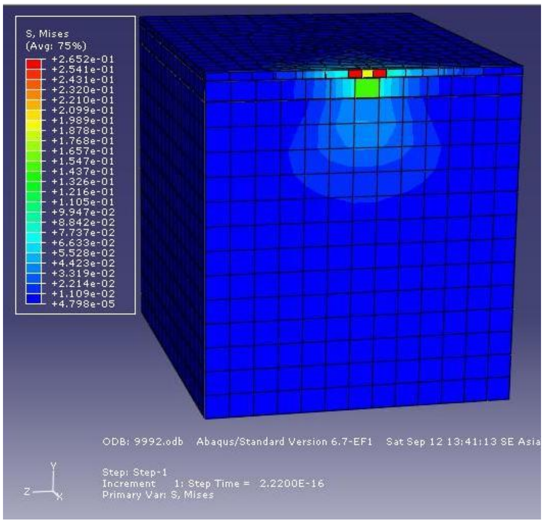


Figure 3. Cross Section of Pavement Structure (Not in scale)

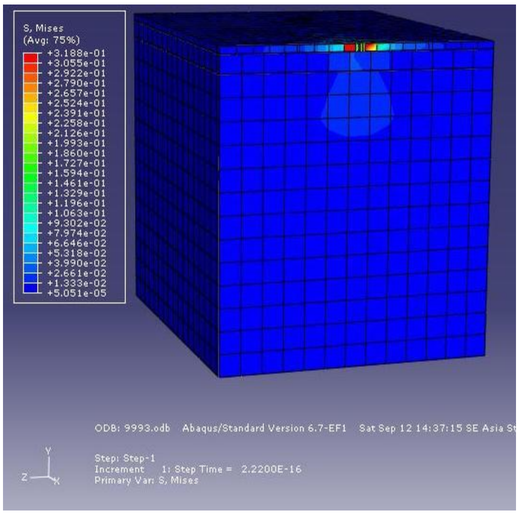
Stress distribution contour for 0.56 MPa wheel pressure for Scenario 1 is showing in Figure 4a. From the figure, the maximum stress is observed at the top layer just under the wheel load application point. The magnitude of stress at top of the subgrade is found 0.054 MPa. Stress distribution contour for 0.56 MPa wheel pressure for Scenario 2 after inclusion of geo-jute layer on subgrade-base interface is showing in Figure 4b. From the figure, the magnitude of stress at top of the subgrade is found 0.044 MPa. Figure 4c and 4d showed the stress diagram for geo-jute at base-asphalt layer interface, and geo-jute within the asphalt layers respectively. Stress at top of the subgrade is found 0.039 MPa for geo-jute at base-asphalt layer, and 0.026 MPa for geo-jute within asphalt layers. Therefore, the subgrade soil experienced lower stress due to the application of geo-jute at various pavement layers for 0.56 MPa wheel pressure. Similar results were observed for different wheel pressures.



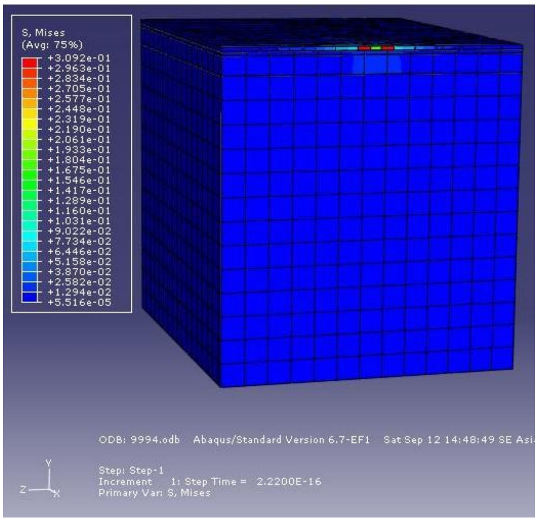
a) with no Geo-jute



b) with Geo-jute at Subgrade-Base Interface



c) With Geo-jute at Base-Asphalt Layer Interface

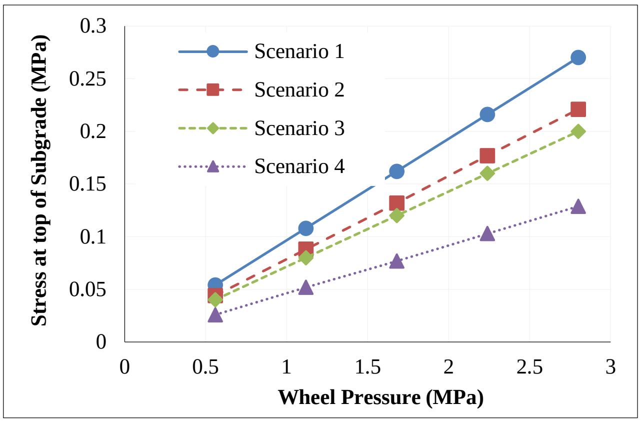


d) Geo-jute within the Asphalt Layers

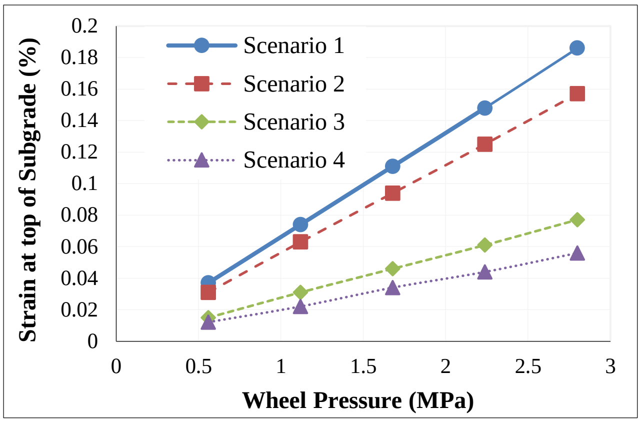
Figure 4. Stress Contour for 0.56 MPa Wheel Pressure

The stress, strain, and displacement at top of the subgrade for four different scenarios are shown in Figure 5a, 5b and 5c respectively. The figure shows that stress, strain, and displacement at top of the subgrade increases for increasing wheel pressure. It also indicates that after implementation of geo-jute, the stress, strain, and displacement at top of the subgrade decreased. For the applied wheel pressure of 2.80 MPa, subgrade soils experienced 0.27 MPa stress for no geo-jute, and 0.22 MPa stress for geo-jute application at subgrade-base interface. Therefore, application of geo-jute at subgrade-base interface reduced 20% of stresses at top of the subgrade. Similarly, the application of geo-jute at base-asphalt layer produced 25% less stresses at top of the subgrade, and geo-jute within asphalt layer showed even 50% less stresses at top of the subgrade. The maximum displacement at top of the subgrade was observed 7.1 mm for no geo-jute application, and the minimum displacement was observed 2.3 mm for geo-jute application within the asphalt layers. Therefore, 67% less displacement was observed due to geo-jute application. The maximum strain at top of the subgrade was found 0.19% for no geo-jute application, and the minimum displacement was observed 0.06% for geo-jute application within the asphalt layers. Therefore, 16% less strain was observed due to geo-jute application.

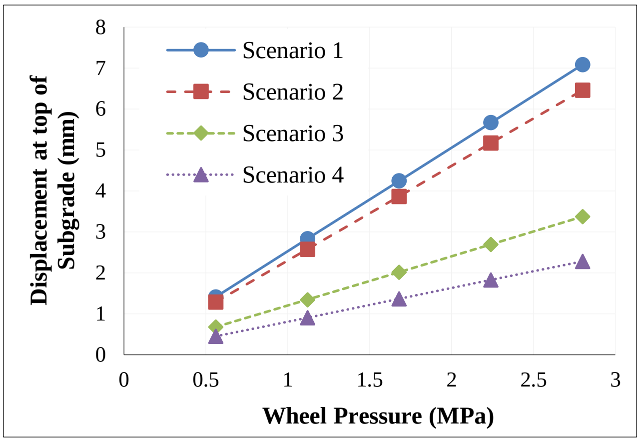
The subgrade soil had minimum stress, strain, and displacement when geo-jute is placed within asphalt layers. The improvement in reduction in stress, strain, and displacement due to geo-jute is more significant when higher wheel pressure is applied. Figure 5d shows stress strain diagram for four different scenarios for different axle loads. Slope indicates the resilience of subgrade soil due to placement of geo-jute at various positions. Steepest slope was found for application of geo-jute on base-asphalt layer interface. That means if geo-jute is placed at base-asphalt interface, subgrade soil will carry maximum stress for a specific strain.



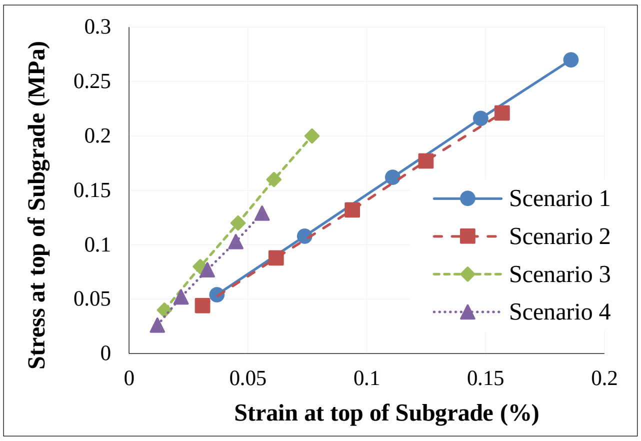
a) Stress



b) Strain



c) Displacement



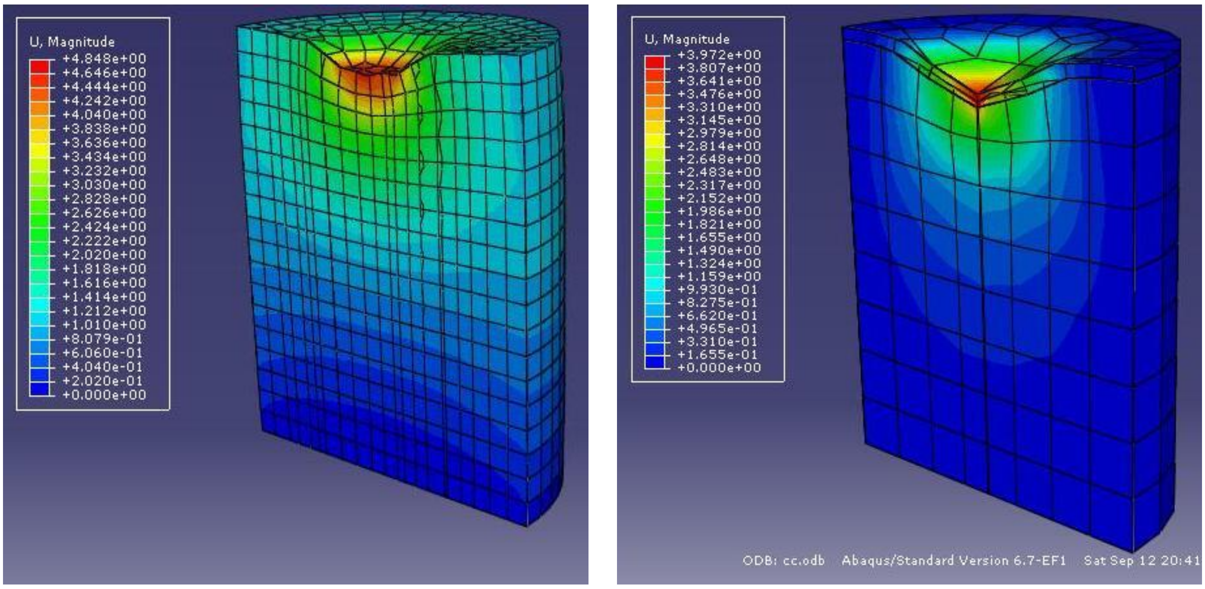
d) Stress-Strain

Note:
Scenario 1: With no geo-jute
Scenario 2: Geo-jute at subgrade-base interface
Scenario 3: Geo-jute at base-asphalt layer interface
Scenario 4: Geo-jute within asphalt layers

Figure 5. Stress Strain and Displacement

Three-dimensional FEM of California bearing ratio (CBR) test was also developed. Figure 6a, and 6b shows the displacement with no geo-jute, and with geo-jute at top of the subgrade respectively for 2.5 MPa pressure load and 4.54 kg surcharge load. The subgrade displacement was found 4.45 and 3.97 mm respectively for no geo-jute and for geo-jute inclusion respectively. Stress required for 2.54 mm penetration was estimated assuming linear relation for elastic subgrade materials, which was estimated 1.31 MPa for no geo-jute, and 1.60 MPa for geo-jute inclusion. The corresponding CBR values for 0.1 in. or 2.54 mm penetration was obtained by comparing with standard stress of 6.9 MPa. The CBR of subgrade material was improved from 19 to 23 for geo-jute inclusion. Therefore, CBR or bearing capacity of soil increases 20% due to geo-jute incorporation. CBR value was found relatively high because well graded granular material was assumed as subgrade material.

The stress, strain, and displacement showed linear relation with wheel pressure because the elastic behaviour of pavement elements. Due to incorporation of geo-jute into pavement structures, load is distributed into wider area of subgrade, and lower stress, strain, and displacement was observed at top of the subgrade layer. Lowest stress, strain, and displacement was observed for various wheel pressure when geo-jute was placed within the asphalt layer. However, highest resilience of subgrade soil was found when geo-jute is placed at base-asphalt interface.



a) With no Geo-jute **b) With Geo-jute at Top of Subgrade**

Figure 6. Displacement for CBR Test

4. Conclusions

This paper presented the preliminary research of geo-jute incorporation in flexible pavement using finite element analysis. The following conclusions can be made based on the current study.

- Higher traffic load produced higher stress, strain, and displacement at top of the subgrade with or with no geo-jute inclusion. Linear relation with wheel pressure was observed because of the elastic behavior of pavement elements.
- After application of geo-jute, the stress was distributed into wider region of subgrade soil. The subgrade soil experienced lower stress, strain, and displacement when geo-jute was incorporated. Lowest stress, strain, and displacement was observed when geo-jute is placed within the asphalt layer. Highest resilience of subgrade soil was found when geo-jute is placed at base-asphalt interface.
- The improvement in reduction in stress, strain, and displacement due to geo-jute is more significant if higher wheel pressure is applied. Overall, higher the geo-jute was placed, lower the stress, strain, and displacement was observed at top of the subgrade. Geo-jute provided higher overall resilience to the layers underneath it.
- For the applied wheel pressure of 2.80 MPa, subgrade soils experienced 0.27 MPa stress for no geo-jute, and 0.22 MPa stress for geo-jute application at subgrade-base interface. Therefore, application of geo-jute at subgrade-base interface reduced 20% of stresses at top of the subgrade.
- Improvement of California bearing ratio due to geo-jute incorporation indicates that the load bearing capacity increased more than 20% due to the application of geo-jute.

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6. Conflict of Interest

The authors declare no conflict of interest.

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