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Finite Element Analysis of Subgrade Rutting Behaviour of Flexible Pavements with Terrasil and Zycobond Stabilized Black-Cotton Soil

Sharat S Chouka[1], Dr. N Venkata Ramana[2]

[1)] *Visveswaraya Technological University, Civil Engineering Department/Assistant Professor/Unit, PDA College of Engineering, Kalaburagi City, 585103, Karnataka, India*

[2)] *Visveswaraya Technological University, Civil Engineering Department/Associate Professor/Unit, University BDT College of Engineering, Davangere City, 577004, Karnataka, India*

Abstract:

This study mainly focused on evaluating the maximum vertical compressive strains and permanent strains at the top of the subgrade with black-cotton soil stabilized with terrasil and zycobond in flexible pavements using finite element analysis. Firstly, a 2-dimensional finite-element model was developed for 4 layered flexible pavements with the bonded interfaces. All the four layers were modelled as elastic materials for evaluating the maximum subgrade strains for a contact pressure of 0.56 MPa and 0.8 MPa. Later, the subgrade was modelled as Mohr-Coulomb plasticity model for evaluating the initiation of permanent strains and thus failure load. The change in cohesion of terrasil, zycobond stabilized back-cotton soils showed significant change in failure loads whereas the friction angle showed minimal influence on failure loads. The results showed significantly increased failure loads with the increase in thickness of bituminous concrete layer.

Keywords: 2-dimensional finite element model; Mohr-Coulomb Plasticity model; black-cotton soil; failure load

Background:

Flexible pavements are constructed on natural soil foundations or compacted subgrades, which must possess sufficient strength and stability to support the overlying pavement structure. While the primary causes of flexible pavement failure are rutting or cracking in the bituminous concrete (BC) layer due to repetitive traffic loads and environmental factors, the performance of the subgrade plays a critical role in the overall structural integrity and lifespan of the pavement, particularly in the case of thin or low-traffic pavements. Soils with high fine content can experience significant permanent deformation when exposed to moisture. Under repeated traffic loading, this deformation can lead to surface rutting along the wheel paths, which compromises the pavement's surface. This not only reduces driving comfort but can also be dangerous by impacting vehicle control and increasing the risk of hydroplaning. The extent of rutting is a key factor in the decision-making process for pavement rehabilitation projects, making it essential to reduce excessive subgrade deformation and minimize surface rutting.

Soils with a high fine content are especially vulnerable to moisture fluctuations and the resulting decrease in load-bearing capacity, which is particularly problematic during wet seasons. In Pennsylvania, fine-grained soils such as clays and silts are commonly found in subgrade construction, presenting a state-wide challenge (Col & Cepko, 2006; Pennsylvania Department of Transportation [PennDOT], 2010). According to PennDOT specifications, any subgrade soil with a California Bearing Ratio (CBR) lower than '5' must be improved. Problematic soils may be removed and replaced with higher-quality materials, or stabilized chemically using lime or cement. While the excavation and backfilling method generally ensures a stable subgrade, it can be expensive due to the costs associated with excavation and material transport. Chemical stabilization has proven effective in reducing soil permeability, stabilizing volume changes, and increasing strength and stiffness, provided the correct additive is chosen and the mix is properly designed (Little, 1995; Little & Nair, 2009).

Alternatively, geogrids offer a potentially more cost-effective solution for reinforcing and stabilizing pavements constructed over soft subgrades. Numerous studies have demonstrated the advantages of incorporating geogrids into flexible pavements, including extended pavement service life or comparable performance with a reduced structural thickness (Al-Qadi et al., 2008; Barksdale et al., 1989; Henry et al., 2009; Perkins, 1999; Tang et al., 2008; Webster, 1993). Geogrids are typically installed at the interface between the base layer and subgrade, and sometimes in the upper third of the base layer. It is widely recognized that geogrids enhance pavement systems through three key mechanisms: (1) providing separation between the base and subgrade materials, (2) limiting lateral spreading of the base material through interlocking with surrounding granular materials, and (3) acting as a reinforcing membrane under sufficient deformation (Abu-Farsakh et al., 2012; Al-Qadi et al., 2008; Qian et al., 2013).

Several studies have employed cyclic plate load tests on laboratory-scale pavement models, which raise concerns regarding scale effects and unrealistic loading conditions (Abu-Farsakh & Chen, 2011; Carroll et al., 1987; Leng et al., 2002; Montanelli et al., 1997; Tingle & Jersey, 2005). Some researchers have conducted full-scale accelerated pavement testing (APT) to assess geogrid reinforcement in flexible pavements, providing more realistic insights. However, full-scale testing is resource-intensive and time-consuming (Al-Qadi et al., 2008; Henry et al., 2009; Perkins, 2002; Tang et al., 2015). This study

Mohr-Coulomb Plasticity model:

The Mohr-Coulomb (MC) plasticity model is employed to represent materials using the traditional Mohr-Coulomb yield criterion. It accounts for both isotropic hardening and softening behaviour of materials. The model incorporates a smooth flow potential with a hyperbolic shape in the meridional stress plane and a piecewise elliptical shape in the deviatoric stress plane. It works alongside a linear elastic material model, assuming linear elastic behaviour. Additionally, the model can be combined with the Rankine failure surface, which introduces a tension cutoff to limit the material's load-carrying capacity in the tensile region. This model is widely applied in geotechnical engineering for simulating the behaviour of materials under primarily monotonic loading conditions. In the current article, this plasticity model was used for evaluating failure load causing the permanent-strains using a finite element software ABAQUS. The yield surface (F) for the MC-plasticity model can be represented in terms of hydrostatic pressure (p), mises equivalent stress (q) and cohesion (c) and is given by

$$F = Z_{mc}q - ptan\emptyset - c = 0$$

Where $Z_{mc} = \frac{1}{\sqrt{3}cos\emptyset} sin\left(\theta + \frac{\pi}{3}\right) + \frac{1}{3}cos\left(\theta + \frac{\pi}{3}\right)tan\emptyset;\ cos3\theta = \left(\frac{r}{q}\right)^3;$

$$p = \frac{I_1}{3};\ q = \sqrt{3J_2},\ r = J_3$$

In the above expressions, '$\emptyset$' represents the friction angle and 'θ' represents deviatoric plane angle whereas I_1, J_2 and J_3 represent first Cauchy stress invariant, second and third deviatoric stress invariants respectively. The failure plane of MC-model with shear tress (τ) on vertical axis and normal stress (σ) on horizontal axis is depicted in figure 1.

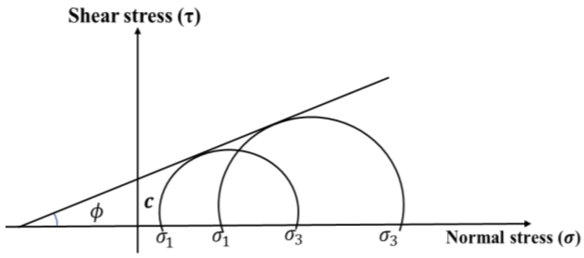

Figure 1. Failure plane of Mohr-Coulomb yield criteria

Study Methodology:

The present study involved in the numerical evaluation of vertical compressive strains at the top of subgrade made of different bio-enzyme based stabilizers such as terrasil and zycobond and recycled concrete dust using 2-dimesnional finite element analysis. Further, the study evaluated the failure load of flexible pavements based on permanent deformation initiation in subgrade as elasto-plastic material using non-linear 2-dimensional finite element analysis. In case of evaluation of vertical compressive strains at the top of the subgrade, a 2-dimensional FE-model of a flexible pavement with 4 linear elastic layers was developed. The interfaces between the layers were assumed to bonded and modelled by a tie-constraint in the ABAQUS. In the present study, 1m wide surface (bituminous concrete) and base layers were supported by 1.5 m wide subbase and subgrade layer.

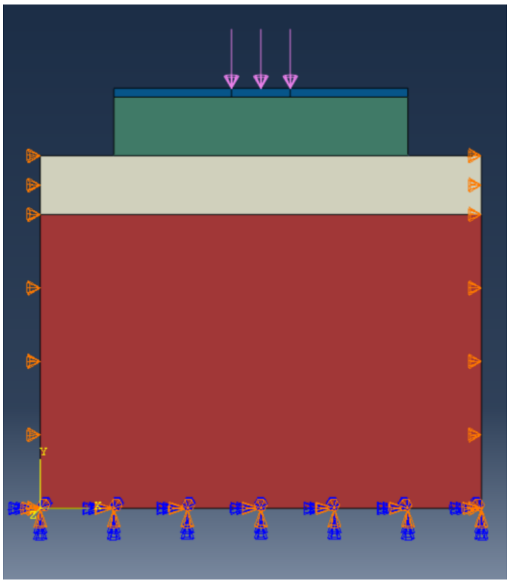

Figure 2. Two-dimensional FE-model and boundary conditions for a 4-layerd flexible pavement

As the main focus of the study was on vertical compressive strains in elastic models and failure loads causing the permanent strain initiation, the mesh convergence was performed based on the compressive strain at the top of the subgrade. Further, the subgrade-depth was taken as 2.0 m to avoid the influence of fixed boundary conditions at the bottom of the subgrade. The sides of subbase and subgrade layers were restrained in lateral directions to allow only vertical displacements at the edge of each layer as depicted in the above figure 2. A pressure of 0.56 MPa and 0.8 MPa was applied at a contact area with a radius of 100 mm and corresponding vertical subgrade compressive strains were validated with the vertical subgrade strains obtained from IIT-PAVE analysis which is based on multi-layered linear elastic theory. Finally, the influence of shear properties of black cotton coils stabilized with zycobond, terrasil and recycled concrete dust such as friction-angle, cohesion, and thickness of bituminous concrete layer on failure load of 4 layered flexible pavements were evaluated.

Results and Discussions:

Maximum vertical subgrade compressive strain:

A series of 2-dimesional FE-models were developed with an elastic modulus of subgrade ranging from 25 MPa to 100 MPa. A parametric study was conducted to evaluate the effect of thickness (30 mm to 120 mm) of bituminous concrete, the maximum vertical compressive strain at the top of the subgrade ($\varepsilon_{c,max}$). A vertical pressure of 560 kPa and 800 kPa was applied at the top of the surface layer. In the following figure 3, the vertical stress and strain distribution in subgrade are illustrated. The influence of thickness of BC layer is presented in table 1. The results showed a reduction of 8.0%, 14.5% and 19.7% in maximum compressive strain with increase in BC-thickness to 60, 90 and 120 mm respectively from 30 mm for a contact pressure of 560 kPa. Similar trend was observed for the contact pressure of 800 kPa. Further, the number standard axle load repetitions (N_R) causing

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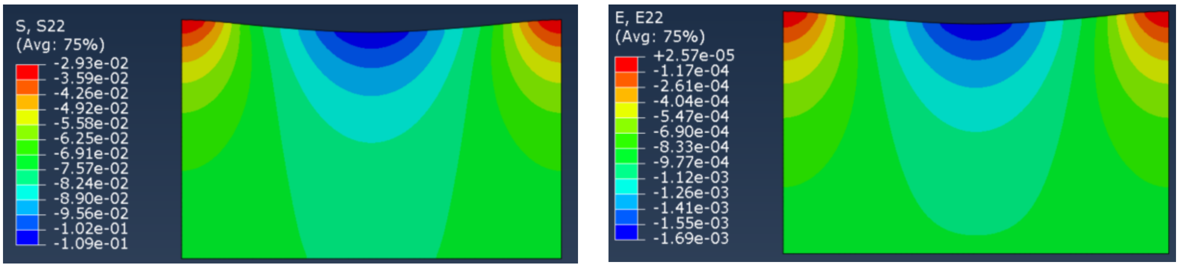
the subgrade-rutting failure was calculated using the following performance equation given IRC:37-2018 guidelines.

$$N_R = k_1 \times 10^{-8} \times \varepsilon_{c,max}^{-k_2}$$

Where k_1 = 4.1656 for 80% reliability and 1.41 for 90% reliability; k_2=4.5337. The results showed a rutting life in the range of 0.1-0.5 msa for subgrade modulus of 50 MPa with a BC-thickness in the range of 30-120 mm,



(a) Vertical stress distribution (b) Vertical strain distribution

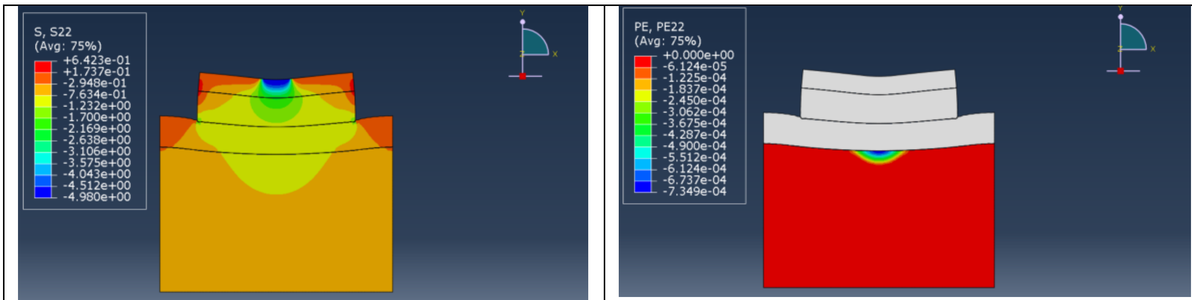
Figure 3. Vertical stress and strain distribution in subgrade with an elastic modulus of 50 MPa, 60 mm thick BC

Table 1. Influence of thickness of BC layer on maximum subgrade compressive strains

BC-thickness (mm)	**Maximum vertical subgrade compressive strain (με) at a contact pressure of**	
	560 kPa	**800 kPa**
30	1840	2629
60	1693	2418
90	1574	2249
120	1478	2112

Failure load of flexible pavements:

In the previous study, the triaxial test results showed a friction angle in the range of 20-25° and a cohesion in the range of 100 kPa to 2000 kPa for bio-enzyme stabilized expansive subgrade soils. Hence, a parametric study was performed to evaluate the influence of friction angle (20-30°) and cohesion (100-1000 kPa) on failure load of 4 layered flexible pavements. Based on the initiation of permanent strain at the top of subgrade, the failure loads were evaluated by modelling the subgrade with M-C plasticity model. The vertical stress and permanent strain at the top of the subgrade for a flexible pavement with 120 mm thick BC (3000 MPa), 200 mm thick base layer (300 MPa), 200 mm thick subbase (100 MPa) are presented in the following figure 4. The corresponding subgrade modulus is 50 MPa, friction angle 20°, and cohesion of 100 kPa.



(a) Vertical stress (b) Permanent strain

Figure 4. Compressive stress and permanent strain distribution in flexible pavement

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The influence of shear parameters and BC-thickness on failure load are presented in table 2 and 3 respectively. The results showed a significant increase in failure with increase in cohesion from 100 to 1000 kPa. However, the influence of friction angle on failure was found to be insignificant. Similarly, the increase in BC-thickness significantly increased the failure load but the increments were found to be lower than those obtained with change in cohesion values.

Table 2. Effect of shear parameters on failure load of flexible pavements with bituminous concrete thickness of 60 mm and subgrade modulus of 50 MPa

Friction Angle (º)	**Cohesion (kPa)**	**Failure Load (kN)**
20	100	467.1
20	200	100.7
20	400	1869
20	500	2216
20	1000	4703
25	100	652
25	200	1073
25	400	2143
25	500	2921
25	1000	5813
30	100	748.9
30	200	1369
30	400	2586
30	500	3806
30	1000	6791

Table 2. Effect of thickness of bituminous concrete layer

Cohesion (kPa)	**Friction Angle (º)**	**BC-thickness (mm)**	**Failure Load (kN)**
100	25	30	623.3
		60	652
		90	699
		120	789
200		30	1029
		60	1073
		90	1172
		120	1473
400		30	2089
		60	2143
		90	2188
		120	2239
500		30	2879
		60	2921
		90	3082
		120	3198

Conclusions:

The present study developed 2-dimesnional finite element model for evaluating the vertical subgrade compressive strains, permanent strains and thus failure loads of 4 layered flexible pavements with subgrade as an elastic material and elasto-plastic material respectively. The study mainly evaluated the influence of shear parameters such as friction angle and cohesion of terrasil and zycobond stabilized black-cotton subgrade soils on failure loads. The following conclusions were withdrawn.

- The change in cohesion of terrasil, zycobond stabilized back-cotton soils showed significant change in failure loads whereas the friction angle showed minimal influence on failure loads.
- The increase in thickness of BC increased the failure loads significantly.

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