FINITE ELEMENT ANALYSIS OF COIR GEOTEXTILES MODIFIED FLEXIBLE PAVEMENTS BASED ON FATIGUE FAILURE CRITERION

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ABSTRACT

Finite element analysis software, ABAQUS was used effectively in analyzing stress – strain behaviour under the application of static wheel load in the modeled flexible pavement structure. The parametric study for unreinforced and reinforced section showed that coir geotextile placed at the interface of asphalt layer and base course layer showed significant reduction in lateral strain. Also the inclusion of geotextile reinforcement helped in reducing the horizontal tensile strain developed in the pavement layers. Structural benefits of coir geotextile reinforcement over fatigue strain criteria had been quantified and fatigue life of unreinforced and coir geotextile reinforced pavement sections was predicted

Key words: FEM, Coir Geotextiles, Fatigue Failure, Elastic Strain, Damage Ratio.

1. INTRODUCTION

Pavements are life line of nations progress. Each year huge amount of money is expended by each nation, especially developing countries, for construction and maintenance of pavements. A large variety of detrimental factors affect the service life of roads and pavements such as environmental factors, subgrade conditions, traffic loading, utility cuts, road widenings, and aging. These factors contribute to an equally wide variety of pavement conditions and problems which must be addressed in the maintenance or rehabilitation of the pavements, if not dealt with during initial construction. Pavement maintenance treatments are often ineffective and short lived due to their inability to both treat the cause of the problems and renew the existing pavement condition.
Therefore, the preferred strategy for long-term road and pavement performance is to provide safeguards during initial construction. These safeguards include stabilizing the subgrade against moisture intrusion and associated weakening, strengthening road base aggregate without preventing efficient drainage of infiltrated water and enhancing the stress absorption and moisture proofing capabilities of selected maintenance treatments. Geosynthetics are the most cost effective tools for safeguarding roads and pavements in these ways. The four main applications for geosynthetics in roads are subgrade separation and stabilization, base reinforcement, overlay stress absorption, and overlay reinforcement. Geosynthetics are of different types such as geogrids, geotextiles, geofoams, geocomposites etc. The synthetic materials are costly and its production is power consuming. The natural geosynthetics abundantly available in Kerala is coir geotextiles. Studies on coir geotextiles provided in bituminous layers are limited though it is effectively used in subgrade stabilization.

2. NEED FOR THE STUDY

Accurate traffic loading estimates and analysis of the impact of heavy traffic on pavement performance are important issues for pavement designers. Hence a computational model that can be used to perform a pavement service life prediction based on a mechanistic analysis using a finite element method has to be developed. Finite element analysis is well suited in analyzing pavement systems subjected to various conditions due to its versatility. Various researchers [1-8,10-13] conducted several experimental and numerical studies to analyze pavement sections to study the benefits of geosynthetic materials using Finite element modelling under varying test conditions, different material property, loading and boundary conditions. But the study on coir geotextile analysis is limited. Hence coir geotextile reinforced flexible pavement was selected to investigate the benefits provided by coir geotextile reinforcement to the fatigue resistance of a flexible pavement system in conjunction with pavement design life and to identify the optimum thickness of bituminous layer required for the design traffic.

3. OBJECTIVES OF PRESENT STUDY

- To perform linear elastic finite element analysis of coir geotextile reinforced flexible pavements on the basis of stress – strain characteristics
- To evaluate reinforcing effect of coir geotextiles based on fatigue distress criteria
- To predict pavement fatigue life for unreinforced and coir geotextile reinforced pavement sections

4. COIR GEOTEXTILES

Coir geotextile is made from coconut fibre extracted from the husk of the coconut fruit. It is available in different mesh mattings and different trade names such as CCM 400, CCM 700, CCM 900. Coir fibres are of different types and are classified according to varying degree of colour, length and thickness. Length of coir fibre varies from 50mm to 150mm and diameters vary from 0.20mm to 0.60 mm. It is a lignocelluloses polymeric fibre with 45% lignin and 43% cellulose (Ayyar et al., 2002). Coir has the highest tensile strength than any natural fiber and retains much of its tensile strength when wet. It is also very long lasting, with infield service life varying from 4 to 10 years. The reason for the greater strength of coir is its high lignin content. The physical and engineering properties of various coir geotextiles are tabulated below in Table 1

Based on the literature review, it is clearly demonstrated that geosynthetic base reinforcement benefits depend on a number of factors. These factors include the location of geosynthetic layer...
within the pavement layer, base course thickness, strength/stiffness of subgrade layer, and the geometric and engineering properties of the geosynthetics. Loui et al(2013) found that introduction of coir geotextile improve the shear resistance between the pavement layers up to 8 fold than unreinforced section.

<table>
<thead>
<tr>
<th>Particulars</th>
<th>Coir Geotextile Type</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CCM 400</td>
</tr>
<tr>
<td>Mass / unit area (g/m²)</td>
<td>390</td>
</tr>
<tr>
<td>Thickness (mm)</td>
<td>6.96</td>
</tr>
<tr>
<td>Tensile Strength</td>
<td></td>
</tr>
<tr>
<td>Warp</td>
<td>5.40</td>
</tr>
<tr>
<td>Weft</td>
<td>4.00</td>
</tr>
<tr>
<td>Failure Strain (%)</td>
<td></td>
</tr>
<tr>
<td>Warp</td>
<td>24.16</td>
</tr>
<tr>
<td>Weft</td>
<td>21.30</td>
</tr>
<tr>
<td>Elastic Modulus (kN/m)</td>
<td>90</td>
</tr>
</tbody>
</table>

(Source : Central Coir Research Institute India)

5. FINITE ELEMENT MODELING - METHODOLOGY

Flexible pavements in India are designed on the basis of California Bearing Ratio (CBR) of soil subgrade and traffic loading. Indian Road Congress code entitled ‘Guidelines for the design of flexible pavement’ (IRC 37:2001) is being used in the present study to find out the layer composition and overall pavement thickness of the soil subgrade of 7% CBR value and cumulative traffic loading of 10 million standard axles (msa), during the design life. The pavement is modeled as a multi layer structure of linear elastic material subjected to circular loading under static condition. Bituminous concrete (BC) and Dense Bituminous Macadam (DBM) was clubbed together and considered as a single layer for finite element modelling.

Two dimensional axisymmetric pavement response models were developed for unreinforced and coir geotextile reinforced pavement. A typical axis symmetric model with their material properties and boundary conditions are shown in Figure 1. Table 2 shows the physical and mechanical properties of the pavement response model.

Optimum location and type of coir geotextile required for the bituminous layer is evaluated on the basis of fatigue distress criteria. The composition of pavement parameters adopted for the analyses of pavement sections with 100 mm asphalt layer are shown in Table 3. Similar composition of pavements were analysed for sections with bituminous layer thickness of 75 mm and 50 mm. Prediction of Service life of unreinforced and coir geotextile reinforcement pavement sections were based on the horizontal tensile strain and fatigue damage ratio.
**Figure 1:** Developed axisymmetric pavement response model

**Table 2:** Physical and mechanical properties of pavement response model adopted in this study

<table>
<thead>
<tr>
<th>Section</th>
<th>Thickness (mm)</th>
<th>Unit weight (kN/m$^3$)</th>
<th>Young’s modulus E (MPa)</th>
<th>Poisson’s ratio (µ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bituminous layer</td>
<td>100</td>
<td>22.8</td>
<td>2579</td>
<td>0.3</td>
</tr>
<tr>
<td>Granular base</td>
<td>480</td>
<td>21.2</td>
<td>225</td>
<td>0.35</td>
</tr>
<tr>
<td>Subgrade</td>
<td>6420</td>
<td>19.6</td>
<td>70</td>
<td>0.4</td>
</tr>
</tbody>
</table>

**Table 3:** Composition of pavement parameters analysed

<table>
<thead>
<tr>
<th>Sections</th>
<th>Asphalt Layer Thickness (mm)</th>
<th>Type of coir geotextile</th>
<th>Location of coir geotextile</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 A</td>
<td>100</td>
<td>CCM 900</td>
<td>Bottom</td>
</tr>
<tr>
<td>1 B</td>
<td>100</td>
<td>CCM 900</td>
<td>Middle</td>
</tr>
<tr>
<td>1 C</td>
<td>100</td>
<td>CCM 900</td>
<td>One third</td>
</tr>
<tr>
<td>1 D</td>
<td>100</td>
<td>CCM 700</td>
<td>Bottom</td>
</tr>
<tr>
<td>1 E</td>
<td>100</td>
<td>CCM 700</td>
<td>Middle</td>
</tr>
<tr>
<td>1 F</td>
<td>100</td>
<td>CCM 700</td>
<td>One third</td>
</tr>
<tr>
<td>1 G</td>
<td>100</td>
<td>CCM 400</td>
<td>Bottom</td>
</tr>
<tr>
<td>1 H</td>
<td>100</td>
<td>CCM 400</td>
<td>Middle</td>
</tr>
<tr>
<td>1 I</td>
<td>100</td>
<td>CCM 400</td>
<td>One third</td>
</tr>
</tbody>
</table>
5.1. Boundary condition and meshing

Conventional kinematic boundary conditions were adopted, i.e. roller support on all vertical boundaries of the mesh and fixed support at the bottom of the mesh. Such boundary conditions have been successfully used by Saad, Mitri and Poorooshab (2006). The modeled domain must be large enough to avoid any edge error. Domain size analysis was carried out by various researchers to find out the optimum size of pavement response model that yield desirable pavement responses with reasonable degree of accuracy. It has been found that domain size exceeding 25 times the radius of contact area in horizontal direction and 35 times the radius of contact area in vertical direction yield the critical pavement responses. Accordingly pavement response model of 5 m length in horizontal direction and 7 m in height in vertical direction has been selected for axisymmetric analysis. Pavement layers were modeled using four noded quadratic elements, while quadratic axisymmetric membrane element with thickness of 1 mm was used for the coir geotextile reinforcement.

5.2. Material behaviour

Flexible pavements can be viewed as layered system. In layered elastic analysis, the system is divided into an arbitrary number of horizontal layers. The thickness of the individual layer and material properties may vary from one layer to the next and the material is assumed to be homogeneous and linearly elastic with an elastic modulus, $E$ and a Poisson’s ratio, $\mu$. According to the concept of layered system the flexible pavement may be constructed in a number of layers and the top layer has to be the strongest. The simple way to characterize the behaviour of bituminous layer is to consider it as linear elastic material.

Although the unbound granular materials are highly complex and definitely show non linear, stress dependent, elastic behaviour, but for many purpose it is sufficient to assume a constant modulus. Linear elastic material model based on Hook’s law is considered for modelling of granular layers and subgrade. Under low stress-strain conditions the linear elastic material model can reflect soil behaviour with reasonable degree of accuracy.

In this study the coir geotextile reinforcement membrane is considered as an isotropic elastic material. Material models which include components of plasticity, creep, and directional dependency of the coir geotextile may be more realistic, however, these models require many parameters for numerical simulation. Therefore in this study the coir geotextile was assumed to act as a linear elastic isotropic material. Such a model proved to be efficient as used by other researchers; e.g. Ling and Liu (2003).

5.3. Loading conditions

To model the surface load of the dual wheel, the total load is transferred to the pavement surface through an average contact area of 200 mm radius. The stiffening effect of the tire wall is being neglected.

6. LATERAL STRAIN DISTRIBUTION

The lateral strains profiles at different distances from the center of the wheel load predicted from the finite element analysis for a typical unreinforced and reinforced section is shown in Figure 2.
In these sections, different types of coir geotextile layers were placed at the interface of bituminous layer and base course layer. It can be seen that the coir geotextile layer significantly constrained the lateral strains within the base course layer and subgrade layer. CCM 400 type coir geotextile has shown about 33% reduction in lateral strains in the reinforced sections at 80 kN axle load.

It was also noted that the constraining effect was mainly below the wheel loading area and it decrease with increasing distance from the center of the wheel load. The reduction of lateral strain provided by coir geotextile reinforcement was more appreciable in section with thick bituminous layer build on top of medium subgrade layer compared to sections built with thin bituminous layer. Figure 3 presents the lateral strain profiles computed at different distances from the center of the wheel load for unreinforced section, and section reinforced with one layer of CCM 400 coir geotextile placed at different locations such as interface of bituminous layer and base course layer, middle and one-third from bottom of bituminous layer.
In general, for pavements, coir geotextiles placed at middle of bituminous layer offer least lateral strain reduction; while, coir geotextile placed at the interface of bituminous layer and base course layer has the greatest strain reduction. Beyond a distance of 400 mm and 1 m away from the wheel load center, the location of coir geotextile has almost no effect on the lateral strain reduction when compared to that of unreinforced section.

7. ANALYSIS OF DISTRESS

Field observations for evaluation of pavement surface conditions of roads network in India, showed that, rutting and fatigue cracking are the most important pavement distresses due to high severity and density levels, and accordingly their high effects on the pavement condition. Cracking in the bituminous layer is due to fatigue, caused by repeated application of load by moving traffic. Rutting is developed due to accumulation of pavement deformation in various layers along the wheel path. Horizontal tensile strain ($\varepsilon_t^{\text{max}}$) developed at the bottom of bituminous layer (or the vertical compressive strain ($\varepsilon_z^{\text{max}}$) developed at the top of sub grade, respectively) have been considered as indices of fatigue and rutting of the pavement structure. Indian Roads Congress code entitled
Guideline for the Design of Flexible Pavement (IRC:37:2001) specifies the following fatigue life relations for Indian conditions:

\[ N_f = 2.21 \times 10^{-4} \left( \frac{1}{\varepsilon_t} \right)^{3.89} \left( \frac{1}{E} \right)^{0.854} \]  

(1)

- \( N_f \) = number of cumulative standard axles to produce 20% cracked surface area
- \( \varepsilon_t \) = tensile strain at the bottom of BC layer
- \( E \) = Elastic modulus of Bituminous surfacing (MPa)

### 7.1. Damage Ratio

Damage to a pavement occurs more rapidly under heavy loads than under light loads since every part of the structure will experience higher stresses. To study the effect of coir geotextile reinforcement on fatigue in pavement, higher axle loads were applied and corresponding fatigue life of unreinforced and coir geotextile reinforced pavement is determined using Equation 1.

The prediction of pavement life for unreinforced and coir geotextile reinforced pavement sections is based on the cumulative damage concept in which a damage factor is defined as the damage per pass caused to a specific pavement system by the load in question. The damage \( (D_i) \) caused by each application of single axle load is depicted in Equation 2

\[ D_i = \frac{1}{N_i} \]  

(2)

Where \( N_i \) is the minimum number of load repetitions required to cause fatigue failure, as given by Equation 1.

Estimated fatigue damage ratios at 80 kN axle load were presented in Figure 4 for unreinforced and coir geotextile reinforced flexible pavement. Remarkable reduction in fatigue damage ratio was noticed in reinforced pavement ranging 12 to 66% for different axle loads.

![Figure 4: Estimated fatigue damage ratios for unreinforced and coir geotextile reinforced flexible pavement sections at 80 kN axle load](image)

### 7.2. Prediction of pavement fatigue life

Prediction of pavement service life on the basis of fatigue strain as shown in Figure 5 is based on the minimum number of load repetitions required to cause fatigue failure over the pavement life time. The majority of Indian bituminous pavements fail due to fatigue strain attributed by heterogeneous traffic conditions and seasonal variation of temperature, therefore fatigue life is the
governing criteria for prediction of pavement service life. Coir geotextile reinforced pavement sections showed considerable improvement in pavement fatigue life for varying axle loads when the coir geotextile was placed at the interface of asphalt layer and base course.

Coir geotextile type CCM 400 placed at the interface of asphalt layer and base course layer showed increase in service life when compared with CCM 700 and CCM 900 type coir geotextiles. Improvement in fatigue life was more pronounced at lower magnitude of load (10 to 33%) whereas at higher load magnitudes beyond 110 kN, the contribution of coir geotextiles to retard the fatigue damage gradually diminishes.

Figure 5: Predicted Design Fatigue life of unreinforced and coir geotextile reinforced pavement sections at 80 kN axle load

8. DISCUSSION
8.1 Effect of axle load on service life
The series of finite element analysis showed that pavement service life depends on the intensity of axle load applied. Axle load ranging from 40 to 110 kN were applied on the pavement sections taken for study.

Figure 6: Axle load Vs Service life of unreinforced and coir geotextile reinforced pavement section
Figure 6 shows that as the load increases the beneficial effect of inclusion of coir geotextiles on pavement layers diminishes. Similar trend was observed for all other pavement response models analyzed. In general, when higher axle loads are applied, the service life of pavement decreases which did not influence the benefits provided by coir geotextiles in reducing the lateral strains.

8.2 Effect of Tensile Modulus

Previous Studies on geogrid reinforcement showed that higher geogrid tensile modulus resulted in larger reduction in lateral strain values. But in the case of coir geotextiles taken for the present study, lower geotextile tensile modulus resulted in larger reduction in lateral strain. This may be due to the fact that CCM 900 and CCM 700 type coir geotextiles will act as membrane element whereas CCM 400 coir geotextile with an increased mesh size will act as a geogrid.

8.3 Effect of bituminous layer thickness

Figure 5 showed the predicted fatigue life of unreinforced and coir geotextile reinforced pavement sections with 100 mm, 75 mm and 50 mm asphalt layer. It is clearly seen that as the bituminous layer thickness increases service life of pavement increases. Asphalt layer of 100 mm thickness showed increased service life when coir geotextile was placed at interface of asphalt layer and base course layer, middle and one third from bottom positions of bituminous layer. Since pavement bituminous layer thickness could not be increased beyond a limit, it is obvious to identify the optimum layer thickness as per design requirements. From the analyses, it is seen that coir geotextiles were an efficient reinforcement material and inclusion of coir geotextiles could effectively reduce the bituminous layer thickness.

9. CONCLUSION

A series of 30 pavement response models were analyzed. Predicted strain profiles showed that coir geotextile layer significantly constrained the lateral strains within the base course layer and subgrade. CCM 400 type coir geotextile has more reduction in lateral strains developed in the reinforced sections. Thick bituminous layer performed better than thin bituminous layer in reducing lateral strain. Pavement response models showed remarkable reduction up to 33 % in fatigue strain. Estimated fatigue damage ratios showed a reduction of 12 to 66 % in reinforced pavement sections for different axle loads. Service life of pavement increased with increase in asphalt layer thickness. Coir geotextiles placed at the interface of asphalt layer and base course layer performed better than geotextiles placed at one-third from bottom followed by middle locations of bituminous layer. Optimum location of coir geotextile was identified to be at the interface of asphalt layer and base course layer. Improvement in fatigue life was more pronounced at lower magnitude of load. At higher load magnitudes beyond 110 kN, contribution of reinforcement to retard fatigue damage gradually diminishes. Predicted fatigue life chart gives the optimum thickness of AC layer the location and type of coir geotextile to be used for required service life of pavement.

10. ACKNOWLEDGMENT

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11. REFERENCES


