Finite Element Analysis of Coir Fiber Reinforced Bituminous Pavements

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***Abstract:* - The maintenance of rural roads is becoming an increasing challenge as a result of the rapid growth of the network and increase in traffic volume. Fiber reinforcement of bituminous mixes can be easily adopted in rural road construction without any appreciable increase in construction cost. Only limited studies are there in the field of thin bituminous mixes used for rural road. Coir fiber has been used as the reinforcement for bituminous mix based on laboratory studies. A three layer pavement system was considered for the study comprising of subgrade, base and surface course. The pavement system was modelled using two dimensional finite element method and the tensile strain in the interface between bituminous layer and base and compressive strain above the subgrade are determined; which are the design criteria for design of pavement in M-E method. The increase in service life of the pavements is expressed as Traffic Benefit Ratio (TBR). This study has shown that coir fiber reinforcement when correctly introduced can reduce the rutting and improve the life of pavements even in thin bituminous pavements.**

***Key Words:* - Coir fiber, Finite element method, Mechanistic – Empirical method, Traffic benefits ratio, Service life**

I. INTRODUCTION

Mechanistic - Empirical method of design is based on the mechanics of materials that relates input, such as wheel load, to an output or pavement response. In pavement design, the responses are the stresses, strains, and deflections within a pavement structure and the physical causes are the loads and material properties of the pavement structure. The relationship between these phenomena and their physical causes are typically described using some mathematical models. The most common of them is layered elastic model. The pavement has been modeled as a three layer structure and stresses and strains at critical locations have to be computed. Failure criteria adopted are fatigue cracking and rutting failure of bituminous mixes.

As stresses and strains are used more and more to predict pavement distresses, and thus the relative condition of the various layers in the pavement structure, the need for consideration of non-linear material behavior becomes increasingly important. Finite element analysis tools are increasingly viewed as the best approach to answering certain fundamental questions about pavement performance.

A great deal of research has been conducted over many years on the use of fibers in asphalt. Test results showed a marked increase in reinforcing effect with increasing fibers up to a critical fraction. Also various studies have shown that, fibers have the potential to increase the dynamic modulus which indicate the improvement in fatigue and rutting-resistance properties. Much of this research has focused on the laboratory and field behavior of fibermodified asphalt binders and mixtures. Research is needed to clarify the use of mechanistic – empirical pavement design with fiber-reinforced mixtures. This paper is a study in this direction.

II. LITERATURE REVIEW

Finite Element techniques have been successfully used to simulate different pavement problems that could not be modelled using simpler methods for the past several years. Mechanistic method was used for modelling flexible pavements with fiber reinforced soil as subgrade (4). This study shows effective application of finite element method in modelling flexible pavements by mechanistic empirical method. Two dimensional axisymmetric elastoplastic finite element analysis was done on the pavement sections. The stress and strains developed were used for quantifying the effect of fiber reinforcement of subgrade.

Using finite element method, studies are done to observe the effect of various types of loading on flexible pavements (8). The method is capable of simulating the observed responses of pavements subjected to axle loads with different tire pressures, axle loads with different configurations, and axle loads traveling at different speeds. A variety of material constitutive models such as linear elastic, nonlinear elastic, and viscoelastic are employed in the analyses to describe the behavior of the pavement materials. Finite-element modeling of pavements, if validated, can be extremely useful, because it can be used directly to estimate primary response parameters without resorting to potentially costly field experiments. If accurate correlations between the calculated and the measured primary response parameters can be obtained, then the analytical model can be used to calculate primary response load equivalency factors, utilizing deflection-based or strain-based equivalency factor methods

ABAQUS software is used to design 3 D finite element models of flexible pavements to determine the effect of tire loading on pavements (17). From the study it was found that for effective stress distribution, tire imprint area should be a rectangle with two semicircles at both sides.

Thickness various layers of bituminous pavements were analyzed using a computer program FPAVE developed by authors, which is based on mechanistic approach (2). Pavement was modelled considering it as a layered elastic structure consisting of various sub layers. Practical thickness charts for bituminous pavements were developed.

2.1 Objectives of Present Study

1. To model fiber reinforced bituminous pavements using Mechanistic Empirical method
2. To determine the effectiveness of fiber reinforcement in reinforcing the bituminous mix.
3. To determine the effect of fiber reinforcement in low volume roads
4. To determine the traffic benefits ratio of reinforced pavements over unreinforced pavements

III. MECHANISTIC – EMPIRICAL PAVEMENT DESIGN [11]

The IRC 37(IRC 2012) considers considered the design life of pavement to last till the fatigue cracking in bituminous surface have been restricted to 20 per cent of the area for design traffic and 20mmfor 20 percentage length for rutting upto 30 million standard axles. Tensile strain, ε_t, at the bottom of the bituminous layer and the vertical subgrade strainε_v, on the top of the subgrade are conventionally considered as critical parameters for pavement design to limit cracking and rutting in the bituminous layers andnon-bituminous layers respectively. The equation for the conventional bituminous mixes for fatigue designed by Marshall method are given below:

$N_f = 2.21 \times 10^{-04} \times [1/\varepsilon_t]^{3.89} \times [1/M_R]^{0.854}$……………….. (1.1)

where,

N_f– fatigue life in number of standard axles

ε_t-Maximum tensile strain at the bottom of the bituminous layer

M_R -resilient modulus of the bituminous layer.

Rutting is the permanent deformation in pavement usually occurring longitudinally along the wheel path. The rutting may partly be caused by deformation in the subgrade and other non-bituminous layers which would reflect to the overlying layers to take a deformed shape. The bituminous mixes also may undergo rutting due to secondary compaction and shear deformation under heavy traffic load and higher temperature. Excessive rutting greatly reduces the serviceability of the pavement. The equation for the conventional bituminous mixes for rutting designed by Marshall method are given below

$N = 4.1656 \times 10^{-8} (1/\varepsilon_v)^{4.5337}$…. (1.2)

Where,

N = Number of cumulative standard axles,

ε_v= Vertical strain in the subgrade

The Traffic Benefits Ratio (TBR)[4] gives the extension in the service life of pavement due to fiber reinforcement and can be written in the equation form as the benefits of fiber-reinforced mixes in terms of extension in service life of a flexible pavement can be expressed as

$TBR = N_R/N_U = (\varepsilon_{vR}/\varepsilon_{vU})^{-B}$

Where, N=number of traffic passes required for producing rutting up to the allowable rut depth and expressed in mm; and Rand U denote reinforced and unreinforced pavement sections and B=constant, equal to 4.533

3.1 Methodology

Two types of pavements were considered for the present study, control section, and Coir Fiber Reinforced Bituminous Pavements (CFRBP). From earlier studies [19], the optimum percentage of coir fiber to be used in the pavement is obtained as 0.2% and optimum fiber length is obtained as 18mm. Marshall Samples of 63mm height are prepared for the above mixes and stiffness modulus of the mixes are determined from dynamic modulus test done with Nottingham Asphalt Testing Machine (NAT).

A three layer pavement system was considered for the study comprising of subgrade, base and surface course. The pavement system was selected as per IRC SP 72 for low volume roads, which is given in figure1. The thickness of the base and subgrade layers are kept constant and the thickness of surface layers were changed. The pavement system was modelled using two dimensional finite element method and the tensile strain in the interface between bituminous layer and base and compressive strain above the subgrade are determined; which are the design criteria for design of pavement in M-E method. The increase in service life of the pavements is expressed as TBR.

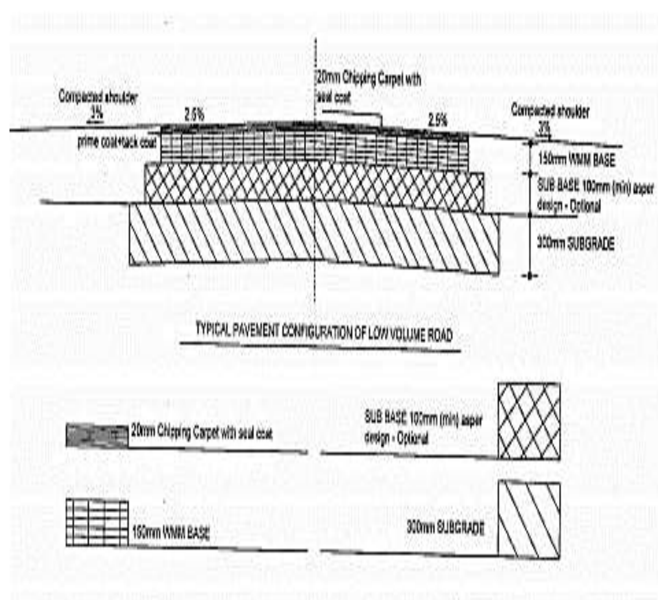

Fig.1.Typical Pavement Configuration of Low Volume Roads (source IRC SP 72-2015)

3.2. Finite element method

Finite element method (FEM) is one of the powerful techniques used in various engineering fields. The aim of this method is to develop a numerical solution for complex engineering problems. It divided the complex structure into tiny small parts, then it analysis the small parts and by summing the solution of the small parts. The general approximate solution of the complex structure can be obtained from this. ABAQUS, a commercial finite element modeling (FEM) program, has been widely applied for pavement analysis. For the finite element analysis, the finite element commercial code ABAQUS 6.1 is used. The mechanical properties of the base and subgrade layers were given in table1. The modulus value of subgrade was determined by assuming the subgrade having a CBR of 5.

Table 1: Mechanical properties of base and subgrade layers (Source: Ref 8)

Section	Thickness (mm)	Modulus of elasticity (Mpa)	Density (KN/m3)	Poisons Ratio(μ)
Subgrade	300	50	21	0.3
Base	150	95.33	23	0.3

3.3 Material Modelling

The modulus of bituminous mixes are determined from laboratory studies by doing dynamic modulus test on samples. The results are given in table2.

Table 2: Mechanical properties bituminous layer

Specimen	**Modulus (Mpa)**	**Density (KN/m^3)**	**Poisson's ratio**
Control mix	1622.05	23.1	0.35
CFRBM	2320.25	23.75	0.35

In the study, the thickness of subgrade and base layers are kept constant.The thickness of various layers considered for study is given in table 3.

Table 3: Thickness of layers

Layer	**Thickness (mm)**		
Subgrade layer	300	300	300
Base layer	150	150	150
Surface layer	20	30	40

3.4 Finite Element Configuration

The different pavement layers are modelled using axisymmetric 4 node two dimensional quadrilateral elements (CAX4R). The modelling is done based on the assumption that the flexible pavement is subjected to static loads and material behavior is elastic. For application of finite element model in analysis, the infinite pavement system has been reduced to a system having finite dimensions. Fig.2shows the 2D axisymmetric model used in the study.

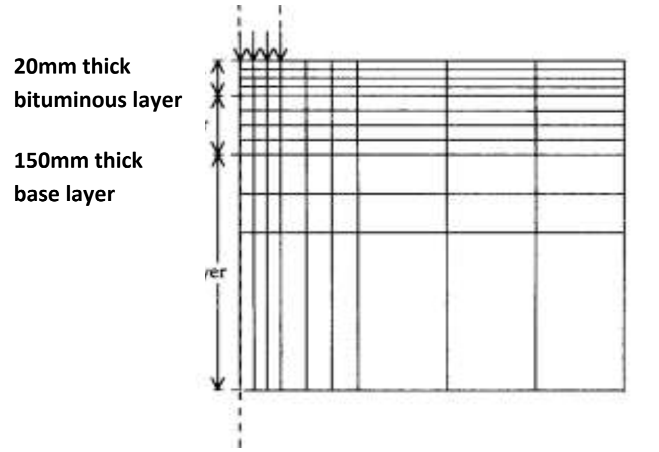

Fig2. Finite Element Model

3.5 Boundary Condition

The pavement section is considered symmetrical about Y axis and constant pressure of 0.55Mpa is applied through 32cm diameter plate of negligible weight corresponding to an axle load of 81.6KN i.e., 40.8KN on each wheel. Roller supports are assumed in X and Y direction preventing motion to achieve the condition of both zero displacement and radial displacement. Also the right boundary is placed at a distance of 500mm from the outer edge of loaded area so as to have negligible deflection in the radial direction. Encastre boundary condition is provided at the bottom to prevent all displacement and rotation.

3.6. Validation of model

The finite element model considered for the study has to be analysed to verify the correctness of the finite element discretization, the applied load and the boundary conditions. For this, the three layers are assumed the same elastic moduli, thereby transferring the three layer system into an equivalent single layer system. This was analysed in ABAQUS and was verified with Boussinesq's 'close form solution' for a circular loaded area as described by Hewany Sam et al (1998). The results are shown in figure3.

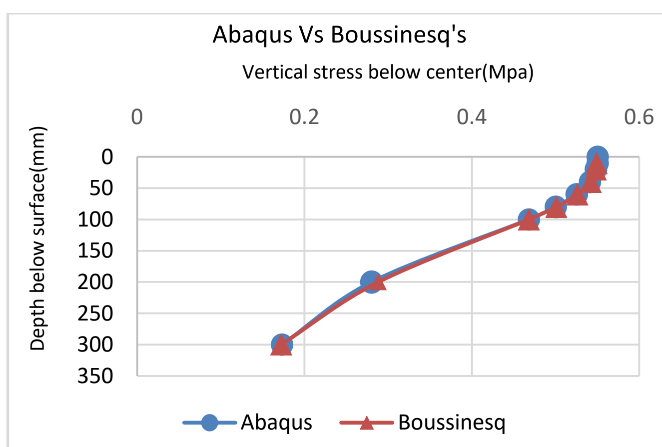

Fig.3 .Validation of Finite element analysis

This shows the accuracy of the model and the applicability of the software.

3.7. Results of the study

Deformed finite element mesh showing the strain values is given in figure.4.

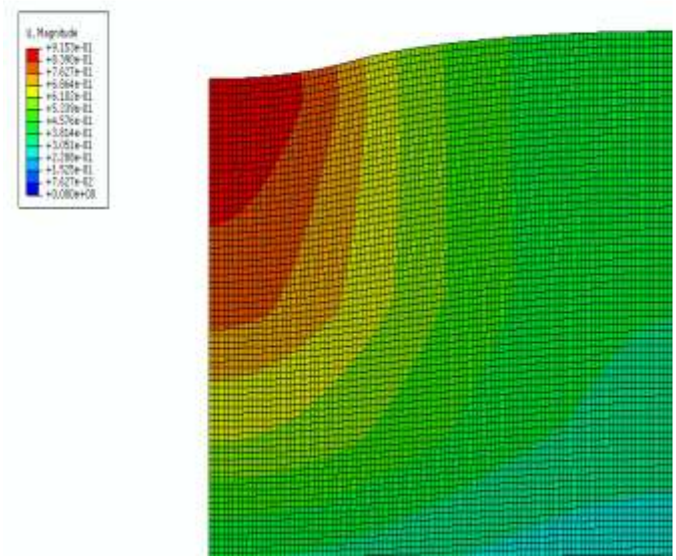

Fig.4 .Deformed mesh

The service life of the pavements based on fatigue for various pavement thicknesses considered is given in figure5.

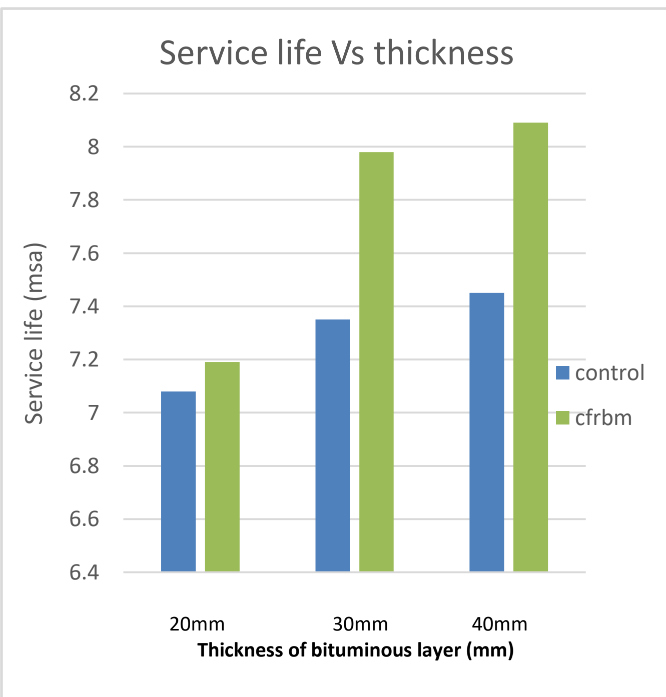

Fig.5. Service life of pavement sections in fatigue

The service life of CFRB pavements for various thickness with respect to rutting is given in figure 6.

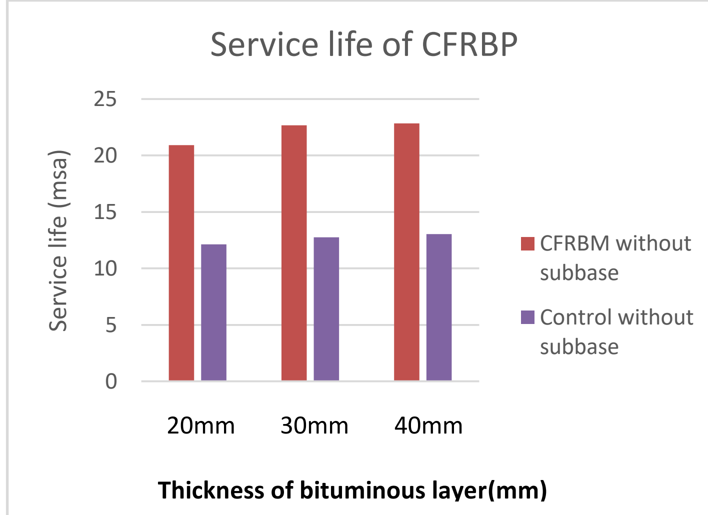

Fig.6 . Service life of pavements in rutting

The increase in service life of pavement structure is usually evaluated by using the Traffic Benefit Ratio (TBR). The TBR defined as the ratio of the number of load cycles to achieve a particular rut depth in the reinforced section to that of unreinforced section of identical thickness, material properties, and loading characteristics. The TBR values obtained at 20 mm rutting depth for the different sections studied in this research project were calculated and summarized in table 4.

Table 4: Benefits of reinforcement

Pavement	Thickness (cm)	Traffic Benefits ratio
PPFRB with sub base	20	1.86
PPFRB without sub base		1.75
PPFRB with sub base	30	1.95
PPFRB without sub base		1.81
PPFRB with sub base	40	1.98
PPFRB without sub base		1.8
CFRB with sub base	20	1.83
CFRB without sub base		1.72
CFRB with sub base	30	1.91
CFRB without sub base		1.78
CFRB with sub base	40	1.96
CFRB without sub base		1.75

IV. DISCUSSION

From the results it can see that as the stiffness and thickness of the bituminous layer increases, the strain decreases. The observed strains are within the allowable limit by comparing it with equation 1.1 and 1.2.

From the results of tensile strain below bituminous layer, itis seen that, as the stiffness of bituminous layer increases, the strain decreases. Also the strain decreases as the thickness of the bituminous layer increases. For a bituminous layer thickness of 20mm, the increase in stiffness does not produce any difference in strain. The maximum service life is obtained for CFRB pavements with 40mm thickness.The service life of CFRB pavements increases 1.1% to 8.6% From the results of compressive strain above subgrade, it is seen that, as the stiffness and thickness of the bituminous layer increases, the strains decreases. For pavement thickness of 20mm, by using CFRBM, the strains can be reduced to 18.76%.

Considering the traffic benefit ratio, it can be observed that the TBR values for all thickness is greater than 1.5. This means that the life of pavements using CFRBM will be more than one and a half times of that of pavements with unreinforced mix. Increasing the thickness of pavements beyond 40mm does not produce any appreciable reduction in strain.

V. CONCLUSIONS

In the study, the pavement configuration for low volume rural roads were considered for study. From the results, it can be inferred that using a stiffer mix does not appreciably reduce strains below bituminous layer, but there is a definite decrease in case of strains above the subgrade. For low volume roads, the main type of distress will be the bottom up cracking rather than the top down cracking induced by heavy traffic loads.The pavement configuration can be effectively used for catering heavier loads by increasing the thickness of bituminous layer. Maximum thickness of bituminous layer is observed to be 40mm for reinforced and unreinforced mixes; above which there is no marked benefit. So from the results it can be concluded that using CFRMB increases the service life of pavement without increasing the cost of construction for low volume rural roads.Also as we are using a natural fiber, it is an environmental friendly modification.

VI. LIMITATIONS OF THE STUDY

The results reported in the study are based on experiments done under controlled laboratory conditions. The pavement system is modelled in finite element method based on various assumptions. Results of finite element analysis are to be extended to field studies to better understand the properties of the reinforced mixes; which is yet to be done. This study is done using VG10 bitumen, considering the pavement configuration for low volume roads. Experiments are to be conducted using other grades and for other traffic conditions for further refinement of results.

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