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A Mechanistic Design Procedure for Fabric-Reinforced Pavement Systems

Un procédé de modèle méchanique pour des systèmes de pavés en tissu renforcé

This paper presents a Mechanistic Design Procedure for fabric reinforced flexible pavement systems. A fabric reinforced pavement structure is one in which an engineering fabric or geotextile is embedded within the asphalt bound layer. For an overlay, the fabric is placed on top of the existing pavement. Purpose of the fabric is to enhance the fatigue life (or cracking resistance) of the pavement. Fatigue and rutting distress functions are the basis of the design procedure. Design for fabric reinforced pavements requires characterization of the fatigue life enhancement of the geotextile, called Fabric Effectiveness Factor (FEF) and determination of the in-situ stiffness of the existing pavement layers including subgrade. A laboratory fatigue testing procedure using a beam on an elastic foundation has been developed to determine a fabrics FEF. The laboratory test procedure is described in detail. Experience with FEF testing is summarized. Required characterization of the pavement layer properties needed for the design model is also presented. A design example demonstrates the design procedure.

Cet article traite un procédé de modèle méchanique pour des systèmes de pavés souples en tissu renforcé. Une structure de pavé renforcé de tissu est celle dans laquelle un tissu industriel ou géotextile est encastré dans une couche d'asphalte. Pour une couverture, le tissu est placé au dessus du pavé existant. Le but du tissu est de réhausser la durée de la détérioration interne (ou du craquage de la résistance) du pavé. Le modèle pour pavé renforcé de tissu demande une définition du réhaussement de la durée de la fatigue du géotextile, appelée Facteur d'Efficacité du Tissu (FEF) et la détermination de la fermeté originale des couches du pavé existant ainsi que la surface. Une procédure d'essai de fatigue en laboratoire, utilisant un rayon sur une fondation élastique, a été développée pour déterminer le tissu (FEF). La procédure d'essai en laboratoire est décrite en détail. L'experience avec le FEF essai est resumée. La caractérisation exigée pour les propriétés de la couche du pavé nécessaire pour la conception du modèle est aussi présontée. Un modèle exemplaire démontre le procédé.

INTRODUCTION

The rational design of pavements must lead to the prediction of their performance during their service life. Overall pavement performance, as measured by its serviceability and maintainability under induced environmental and loading conditions, is directly related to the occurrence of pavement distress and associated pavement roughness. The engineering properties of paving materials and geometrical variables such as thickness and relative position of various component layers greatly contribute to the structural integrity of pavement systems, and thus the occurrence of pavement distress. The pavement material and its structural arrangement need to be selected to provide optimum serviceability so as to resist detrimental forces of load and environment and provide satisfactory performance.

This paper presents a Mechanistic Design Procedure for fabric reinforced flexible pavement systems. The design procedure is based upon the enhancement in fatigue life of asphalt concrete beams reinforced with geotextiles and tested in the laboratory. A fabric reinforced pavement structure is one in which an engineering fabric or geotextile is embedded within the asphalt bound layer. For a new pavement the fabric would be located between intermediate courses of asphalt concrete. For an overlay the fabric is placed on top of the existing surface as illustrated in Figure 1, prior to placement of the new asphalt concrete. Purpose of the fabric is to enhance the fatigue life (or cracking resistance) of the pavement when subjected to traffic loads. Only traffic forces are currently considered by the design procedure. Thermal induced cracking is not considered.

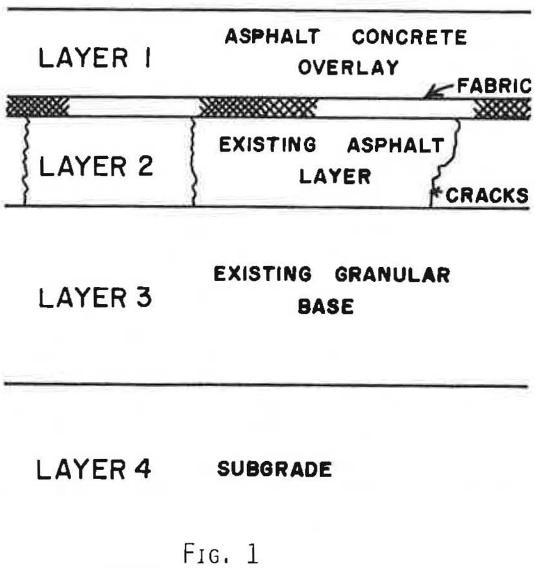


FIG. 1
FABRIC -REINFORCED ASPHALT OVERLAY

However other researchers have developed evidence that fabric reinforced pavements are also more resistant to thermal induced cracking.

DESIGN METHODOLOGY

Both rutting (distortion) and fatigue (cracking) distresses are considered by the design. Distress functions which utilize elastic strains at critical locations in the pavement are the basis of the design. For rutting distress vertical strain at the surface of the subgrade layer is the critical strain. For fatigue cracking distress, horizontal strain at the bottom of the asphalt bound layer is the critical strain. For overlays of severely cracked pavements horizontal strain at the bottom of the overlay is the critical fatigue cracking strain. These critical strain locations are consistent with other flexible pavement design procedures (1).

The phenomenological characterization of fatigue in bituminous mixtures has been extensively studied within the past few decades (2, 3). In this approach, the fatigue life of a flexible pavement, N_f, is related to the maximum tensile stress, ε_h, or tensile strain, ε_h, developed in the under-side of the bituminous layer by semi-empirical relations of the form:

$$N_f = c_1 \left(\frac{1}{\varepsilon_h}\right)^{m_1} \quad \text{for controlled stress tests} \quad (1)$$

and $$N_f = c_2 \left(\frac{1}{\varepsilon_h}\right)^{m_2} \quad \text{for controlled strain tests} \quad (2)$$

where c_1, c_2, m_1, m_2, are constants to be determined experimentally on laboratory beam specimens using prescribed testing procedures. Despite certain inherent limitations, the phenomenological approach provides a reasonably simple procedure which has been widely accepted by various research and pavement design organizations. Recently a sophisticated pavement stress analysis program (1) was utilized to analyze AASHO Road Test data and develop the following fatigue expression:

$$N_f = 7.56\text{x}10^{-12}\ (1/\varepsilon_h)^{4.68} \quad (3)$$

Equation 3 is an improvement over laboratory fatigue equations since full scale field construction and real stress-dependent material properties were considered during development of the expression.

To reflect regional differences in pavement performance resulting from different climates and materials the Regional Factor (RF) defined by AASHTO (4) is applied. Fatigue life of unreinforced pavement structures is thus given by

$$N_{fu} = 7.56\text{x}10^{-12}\ (1/\varepsilon_h)^{4.68}\ /RF \quad (4)$$

In Figure 2, a typical laboratory distress function ε_h -N_f relation for an unreinforced mixture (line A), and a fabric reinforced specimen (line B) are compared. At a given strain level, the life for fabric-reinforced beam (N_{fr}) and life for unreinforced (N_{fu}) are estimated from Figure 2. The Fabric Effectiveness is then expressed as

$$FEF = \text{Fabric Effectiveness Factor} = \frac{N_{fr}}{N_{fu}} \quad (5)$$

Fabric Effectiveness Factor, represents the benefical effect of the fabric in reducing the fatigue distress and prolonging pavement life. Laboratory testing described in subsequent portions of this paper, has shown that FEF is dependent upon fabric location, thickness and stiffness of the asphalt layer, stress level, and fabric type. These variables which affect FEF are reflected in the expression used to calculate fatigue life for fabric reinforced pavements:

$$N_{fr} = N_{fu} \times FEF\ (i,\varepsilon_h) \times GEO \quad (6)$$

where FEF (i,ε_h) = fabric effectiveness factor for fabric i at strain $_h$

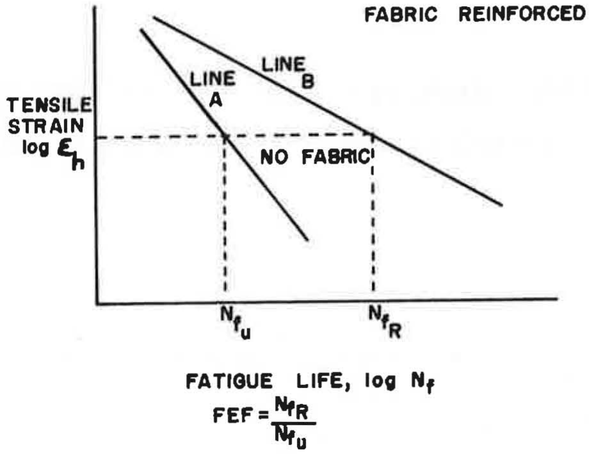


FIG. 2 FATIGUE LIFE VERSUS STRAIN

GEO = geometry correction accounting for the effect of placing the fabric at different depths within the asphalt layer.

The strain dependent FEF function is of the form:

$$FEF = a_1\ (\varepsilon_h)^{a_2} \quad (7)$$

where a_1 and a_2 are constants determined from laboratory testing on beams reinforced with the fabric.

The GEO function is a relationship between the ratio d'/z and reduction in FEF as the fabric is placed higher in the pavement structure (Figure 3). Depth of fabric from the top of the pavement structure is given by d', with z representing the depth of the neutral axis (zero horizontal bending strain) under traffic load. The GEO function currently used is based upon a limited number of experiments with fabrics placed at various positions within the asphalt layer. This function is given by:

$$GEO = 0.64\ (d'/z)^{1.60} \quad (8)$$

and will be updated as additional experimental data becomes available. A limiting GEO value of 1.00 is used to prevent the extrapolation of higher FEF's for pavements which have higher d'/z ratios than that used in the experimental beam study.

The rutting model, which designs against excessive repetitive consolidation and/or shear movements within the subgrade layer, utilizes a relationship between allowable vertical subgrade strain and number of load applications. The Dorman/Metcalf expression (5) was used to develop the relation:

$$N_{f_{rut}} = 1.46\text{x}10^{-10}(1/\varepsilon_v)^{4.98}\ /RF \quad (9)$$

where $N_{f_{rut}}$ = rutting life of pavement
RF = regional factor
ε_v = maximum vertical strain at top of subgrade layer.

Note that the same rutting life equation is used for both reinforced and unreinforced pavements. It is assumed that placement of fabric reinforcement within the asphalt layer does not have a significant affect upon rutting life of the underlying subgrade layer. Rutting considerations are important since the use of fabric reinforcement for fatigue life enhancement will yield a reduction in the required thickness of the asphalt concrete layer. The reduction in bound layer thickness will produce higher vertical stresses on the subgrade

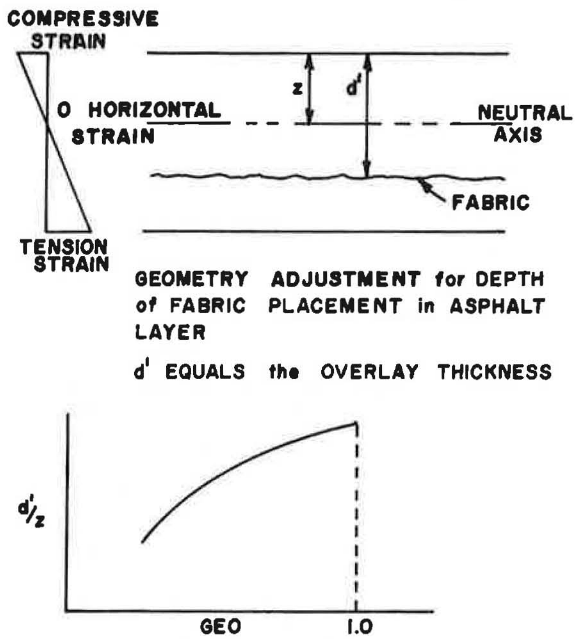


FIG. 3 GEOMETRY ADJUSTMENT TO FEF

which must be below tolerable levels. Use of the rutting distress function should ensure an adequate design.

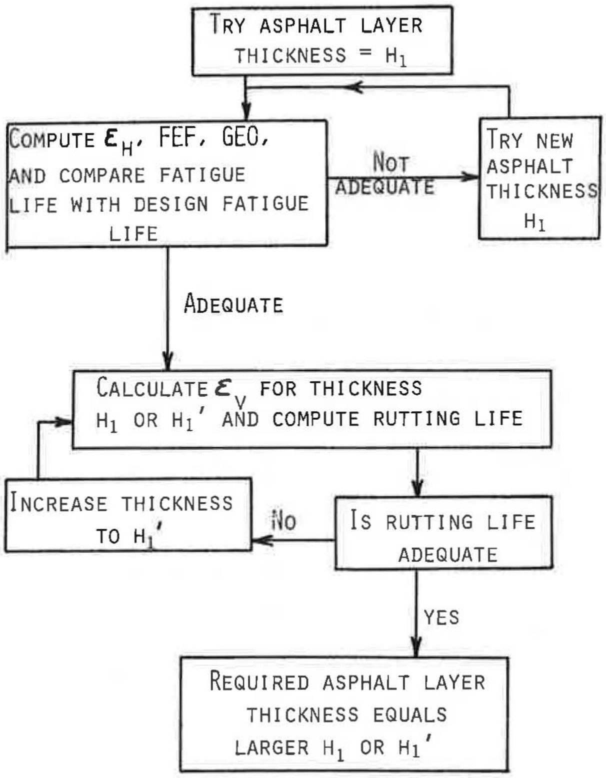
Equations 4, 6, 7, 8, and 9 form the model for design of fabric reinforced pavements. Table 1 summarizes the design methodology. For new pavements h_1 in Table 1 equals the total thickness of the asphalt bound layers while for overlay design h_1 is the overlay thickness. Similar logic is applied for both the unreinforced and fabric reinforced alternatives to permit comparison of required asphalt concrete thickness. Computed pavement strains under traffic load, a single 80 kN(18,000lb.)axle, are required for the procedure. In recent years several computer programs such as CHEVRON, ELSYMS, VESYN, and recently OAF have been developed to compute multilayered pavement stresses and strains (1, 6, 7). Any of these programs could be utilized to compute the necessary strains as input into the distress functions used by the design procedure.

LABORATORY CHARACTERIZATION OF FABRIC EFFECTIVENESS

The fatigue experiments were conducted using a beam on elastic foundation with geometry as shown in Figure 4. The selection of this experimental set-up was based on the two dimensional modeling of a pavement structure, in which a beam representing the pavement is supported on an elastic foundation representing the subgrade. The dimensions of the beam and foundation as well as the stiffness characteristics of foundation are selected with consideration to stress and strain at the bottom of pavement structure subjected to traffic loading. The test setup is the same as that used previously by researchers studying the fatigue properties of asphaltic mixtures (8),(12).

The fatigue tests were performed using a dynamic load function of Haversine shape. An MTS electro-hydraulic testing system was used to generate the load function. To insure complete recovery of the sample before

TABLE 1 DESIGN METHODOLOGY



the next load cycle, a rest period of .4 seconds was allowed between each load application. The duration of load application in all tests was kept constant at .1 seconds. All tests were conducted at a temperature of 22°C with tests conducted at a minimum of three stress levels per fabric. Tests were repeated to obtain statistically based FEF versus strain relationships.

The asphalt mixtures used in the preparation of fatigue specimens were selected to meet the Ohio Department of Transportation specifications for asphaltic concrete surface course, Item 404. The asphalt mixtures were prepared using limestone aggregate and an AC-20

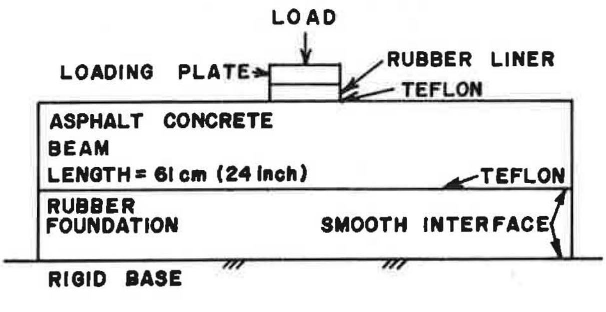


FIG. 4 SET-UP for FATIGUE TESTS

asphaltic cement. The asphaltic mixtures were prepared using an optimum asphalt cement content of 6.6% of total mix basis. The preparation of asphaltic mixtures followed recommended standard procedures for mixing and compaction of bituminous mixtures.

The fatigue specimens used in this investigation were beams with dimensions of 7.6 cm (3 in.) thick, 7.6 cm (3 in.) wide, and 61 cm (24 in.) in length. These specimens were prepared as laminated beams of 2.5 cm (1 in.) and 5.1 cm (2 in.) in thickness. The 5.1 cm (2 in.) layer is compacted on top of the previous manufactured 2.5 cm (1 in.) thick layer. Beams are compacted in steel mold by a testing machine. The compaction pressure is increased until the asphaltic mixture is compacted to desired thickness. The pressure is then maintained constant for about 2-3 minutes, until pressure stabilizes and asphaltic mixture attains constant density. The compacted test specimen is then removed and placed at room temperature for a minimum of 24 hours prior to testing. The lower part of the fatigue specimen, a beam 2.5 cm x 7.6 cm x 61 cm (1 in. x 3 in. x 24 in.) is manufactured first. If the sample is to be a fabric reinforced specimen, the surface of the 2.5 cm (1 in.) thick beam is tack coated as per fabric manufacturers published recommendations. AC-20 at an application rate of 1.1 liter/m^2 (.25 gallon/sq. yd.) was the most commonly used tack coat. Precut 7.6 cm x 7.6 cm x 61 cm (3 in. x 3 in x 24 in.) fabric strips were placed on the sticky tack material.

After the placement of fabric on the top of tack coated base beam, the fabric surface is smoothly brushed to bring it into complete contact with the binder. The prepared base beam (2.5 cm thick beam, tack coat and the fabric) is then placed back into the mold and sufficient amounts of asphaltic mixtures required for fabrication of 5.1 cm (2 in.) thick specimens are weighed and placed into the mold. A leveling device is passed through the loose material for even distribution of the mixture in the mold. Similar to the procedures used in the fabrication of one inch specimens, the mixture is pressed under steadily increasing load, until a 7.6 cm (3 in.) thick specimen is obtained. The mold is dismantled and the specimen is carefully removed. The fabricated fatigue specimen is placed on a stiff support to await testing. All precautions are taken to prevent bending and any possible damage to the beam sample prior to testing. Control samples without fabric were manufactured in the same manner except no tack coat was used between the 2.5 cm and 5.1 cm layers. Fatigue test data for fabric reinforced beams was compared with that of the control (no fabric) samples to determine the constants a_1 and a_2 for the FEF strain relationship presented in equation (7). Fatigue testing of over 600 fabric reinforced beams indicated the following general conclusions regarding the ability of geotextiles to enhance fatigue life:

1. FEF for most lightweight, about 135g/m^2 (4 oz/sq. yd.) nonwoven or woven fabrics is in the 3 to 10 range;
2. FEF tends to increase as fabric weight increases;(Research is in progress to identify other fabric properties affecting FEF).
3. FEF generally increases as stress or strain level decreases.

and 4. Tack coat quantity and type recommended by manufacturers generally produces optimum FEF performance. However tack coat influence on FEF is being further investigated.

MATERIAL PROPERTIES AND REQUIRED PAVEMENT EVALUATION

Computation of traffic load stresses and strains in a pavement structure requires characterization of the elastic modulli or stiffnesses for each layer of the pavement. For a new pavement laboratory testing of compacted asphalt concrete, granular base (with confining pressure), and undisturbed soil subgrade samples is performed to determine stiffness of the material (7), (11). In lieu of laboratory testing modulli values can be assigned based upon previous tests or experience with similar materials. Assigning of modulli rather than performing laboratory testing should only be done for low volume highways, or small resurfacing projects.

Characterization of existing pavements by laboratory testing is more difficult since undisturbed sampling is expensive and many samples are usually required to reflect actual variability in field conditions. Therefore current state-of-the-art pavement evaluation techniques are based upon nondestructive deflection measurements obtained along the existing roadway. There are several commercially available deflection measuring devices including Dynaflect, Road Rater, and Falling Weight Deflectometer (1, 9, 10). Pavement evaluation can be conducted using any of the devices.

Nondestructive testing is a fast and economical way to obtain a large quantity of test information about a roadway. The development of interrelations between deflection and pavement structural performance data back to the 1950's where the concept of allowable deflections to produce a certain pavement life was formulated by California Highway Department and subsequently at the AASHO Road Test. During the early 70's techniques were developed to "back-calculate" in-situ stiffnesses of pavement layers from deflection measurements (10) for known layer thicknesses. A recently developed U.S. DOT-FHWA flexible pavement overlay design procedure is based upon calculation of pavement layer modulli from deflection measurements (1). For overlay design of high type roadways it is suggested that one of the techniques to back-calculate modulli be used to characterize the existing pavement. In addition to nondestructive testing pavement cores should be obtained at a rate of 1 core per 5000 m^2 of pavement to determine layer thicknesses.

When cracks develop in a pavement there is a reduction in the "effective" stiffness of the pavement from that of the no crack condition. Therefore modulli back-calculated from deflection measurements are usually lower than those calculated for laboratory samples. Therein lies the advantage of the nondestructive technique, since the ability of the materials to perform in pavement system under field conditions is evaluated.

It is likely that nondestrictive will not be readily available or economically feasible for some projects. Although not preferred, visual condition survey of pavement cracking could be used to assign a stiffness to the existing asphalt concrete layer. Tables 2 and 3 present a relationship between effective modulus of an existing asphalt concrete surface and severity and extent of wheel track cracking. There has been very little research relating visual condition of a pavement to effective stiffness. The information in Tables 2 and 3 should be considered as preliminary, subject to verification by future research.

Similarly, Table 4 presents ranges of modulus for granular base, subbase and subgrade materials. Again, it is preferable to use laboratory testing or nondestructive measurements to calculate the modulus values. Once the modulus values are known, and the fabric has been characterized in terms of FEF the methodology presented in Table 1 can be used to design a fabric reinforced pavement.

DESIGN EXAMPLE

The following example illustrates the procedure for design of a fabric reinforced overlay.

1. Conditions

The existing flexible pavement consists of a 150 mm (6 in.) asphalt concrete layer over 75 mm (3 in)granular

TABLE 2. SEVERITY AND EXTENT OF WHEEL TRACK CRACKING

DESCRIPTION

CRACKS LOCATED WITHIN OR NEAR THE WHEEL TRACKS. WHEEL TRACK CRACKING USUALLY STARTS AS INTERMITTANT SINGLE LONGITUDINAL CRACKS PROGRESSING TO MULTIPLE LONGITUDINAL CRACKING, AND EVENTUALLY INTERCONNECTED OR ALLIGATOR CRACKING. WHEEL TRACK CRACKING USUALLY RESULTS FROM FATIGUE FAILURE OF THE ASPHALTIC LAYER. REFLECTION OF UNDERLYING CRACKS IN OVERLAID PAVEMENTS CAN ALSO RESULT IN WHEEL TRACK CRACKING.

SEVERITY LEVEL

SEVERITY IS BASED UPON BOTH CRACK WIDTH AND MULTIPLICITY OF THE CRACKING. BOTH CRITERIA MUST BE SATISFIED WHEN ASSIGNING SEVERITY LEVEL.

LOW: SINGLE OR INTERMITTANT MULTIPLE CRACKING WITH AVERAGE CRACK WIDTH LESS THAN 3 mm (1/8 in.) OR BARELY NOTICEABLE.

MEDIUM: MULTIPLE CRACKING (MAY ALSO INCLUDE REGIONS OF INTERMITTANT ALLIGATOR CRACKING) WITH AVERAGE CRACK WIDTH GREATER THAN 3 mm (1/8 in.) WITH LITTLE SPALLING OR LOOSE PIECES.

HIGH: MULTIPLE CRACKING WITH EXTENSIVE ALLIGATOR CRACKING. SPALLING IS FAIRLY COMMON WITH AVERAGE CRACK WIDTH GREATER THAN 6 mm (1/4 in.) AND SOME ALLIGATOR BLOCKS ARE EASILY REMOVED.

EXTENT LEVEL

EXTENT IS BASED UPON PERCENTAGE OF THE WHEEL TRACK LENGTH WITHIN THE SECTION WHICH EXHIBITS CRACKING:

OCCASIONAL - LESS THAN 20%
FREQUENT - BETWEEN 20 AND 50%
EXTENSIVE - MORE THAN 50%

TABLE 3. REDUCED "EFFECTIVE" MODULUS OF CRACKED ASPHALT LAYERS

	CRACK SEVERITY LEVEL		
EXTENT LEVEL	LOW	MEDIUM	HIGH
OCCASSIONAL	2585 MPa (375,000 PSI)	1550 MPa (255,000 PSI)	1045 MPa (150,000 PSI)
FREQUENT	2080 MPa (300,000 PSI)	1045 MPa (150,000 PSI)	430 MPa (60,000 PSI)
EXTENSIVE	1560 MPa (250,000 PSI)	430 MPa (60,000 PSI)	245 MPa (35,000 PSI)

TABLE 4. SUGGESTED MODULLI OF GRANULAR LAYERS

GOOD QUALITY GRANULAR BASE	245 MPa (35,000 PSI)
LOW QUALITY GRANULAR BASE	175 MPa (25,000 PSI)
GOOD QUALITY GRANULAR SUBBASE	140 MPa (20,000 PSI)
LOW QUALITY GRANULAR SUBBASE	85 MPa (12,000 PSI)
SUBGRADE	
CBR* =10 -	105 MPa (15,000 PSI)
CBR = 6 -	60 MPa (9,000 PSI)
CBR = 3 -	30 MPa (4,500 PSI)

* CBR IS CALIFORNIA BEARING RATIO (11).

base over a silty clay subgrade. Deflection testing indicates in-situ stiffness of the pavement layers of 1045 MPa (150,000 psi) for the existing asphalt concrete, 156 MPa (25,000 psi) for the granular base and 43 MPa (6000 psi) for the subgrade. The design traffic is 80 daily 80 kN (18 kip) axle loadings for a design period of 10 years. The AASHTO Regional Factor is 1.5. The required fatigue and rutting life (DESL) are given by:

DESL = (80) (10) (365) = 292,000 applications

2. Strain and Fatigue Analysis

The multilayer elastic program OAF (1) was used to calculate pavement stresses, strains and neutral axis position for various overlay thicknesses. The modulus for the new asphalt concrete was 3345 MPa (480,000 psi). Only the strains corresponding to the required overlay thickness are presented here.

2a. Unreinforced (No Fabric Design)

With overlay thickness of 76 mm (3.0 in.) the horizontal strain of the bottom of existing asphalt layer is 262 microstrain. The fatigue life given by equation (4) is

$$N_{fu} = 291{,}600 \text{ applications}$$

N_{fu} nearly equals DESL, therefore the required overlay thickness without fabric reinforcement is 76 mm(3.0 in.). Calculation of ε_v with a 76 mm overlay and determination of rutting life by equation (9) indicates that rutting life exceeds DESL, therefore fatigue governs the design.

2b. Fabric Reinforced Design

With overlay thickness of 44 mm (1.7 in.) the horizontal strain at the bottom of the existing asphalt layer is 330 microstrain. The depth of zero bending strain (neutral axis, z) is 38 mm (1.5 in.). The fatigue life given by equation (4) is:

$$N_{fu} = 99{,}030 \text{ applications}$$

For fabric placed on the surface of the existing pavement prior to overlay, GEO is calculated by equation (8) with d' of 44 mm and z of 38 mm:

$$GEO = .80$$

Assume the fabric has a FEF of 3.7 at ε_h of 30 microstrain. Then the fatigue life of the fabric reinforced overlay is given by equation (6) as:

$$N_{fr} = 99{,}030\ (3.7)\ (.80) = 293{,}100 \text{ applications}$$

N_{fr} nearly equals DESL, therefore the required overlay thickness with fabric reinforcement is 44 mm (1.7 in.). Calculation of ε_v with a 44 mm overlay and determination of rutting life of equation (9) indicates that rutting life exceeds DESL, therefore fatigue governs the design.

3. Conclusions

For the conditions given in the design example, a savings of 32 mm (1.3 in.) in asphalt concrete thickness is indicated by using a fabric to reinforce the overlay. The actual decision of whether or not to utilize fabric reinforcement should consider not only fatigue life enhancement but also other considerations including fabric cost, fabric laydown and handling characteristics, and bonding properties between the asphalt and fabric. Also the methodology presented for design of fabric reinforced pavement structures is based upon laboratory data. Future correlation with field test results is needed to verify or calibrate the design procedure.

ACKNOWLEDGEMENTS

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