Mechanistic-Based Flexible Overlay Design System

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ABSTRACT

This study presents a mechanistic-based overlay design procedure which incorporates the in-situ pavement layer moduli values evaluated by non-destructive testing using Falling Weight Deflectometer. The developed overlay design procedure is mechanistic-based where it makes use of the stresses and strains developed under traffic axle loads to assess the pavement induced damage. The method addresses the effect of seasonal variation on the accumulated damage along the pavement life. For each season, the pavement layer moduli values are adjusted to reflect the variation in pavement temperature and the subgrade moisture including the effects of freeze and thaw if exist. The design method allows for the calculations of the stresses and strains in the pavement layers at each season, and then sum all the damage occurred along the pavement life. Damage is estimated in terms of accumulated fatigue and/or rutting damage along the designated service life. Due to the complexity of the calculation process and the iterative nature of the procedure, the developed overlay design system has been implemented in an event driven user friendly computer program named “FLEXOLAY”. The program is tested and compared with overlay design methods using pavement sections from the state of Idaho. It is found that the overlay thickness determined by the FLEXOLAY was close to some of the existing methods and far from others depending upon the existing pavement conditions.

INTRODUCTION

The mechanistic approach to design flexible overlays mandates good assessment of the existing pavement bearing capacity and determination of past and expected future traffic. While these are two essential categories of design inputs, they represent the most difficult and challenging task to pavement design engineers. The problems stem from the need to accurately model the pavement response to traffic loads and environmental changes. To assess the moduli values of existing pavement layers, non destructive techniques based on deflection measurements are used. Computer programs to backcalculate moduli values from measured deflections are available (e.g. MODULUS 4.0 [1] and EVERCALC [2]. These two programs, for instance, are based on elastic analysis of the pavement system. Although elastic theory has shortcomings when it is applied to pavement systems, design methods which are based on elastic analysis have been used and proven reasonable from the practical viewpoint [3]. Efforts are continued to develop and refine mechanistic design systems for pavement overlays. For example, the 1996 AASHTO Guide, while it is not mechanistic based, it established a framework for mechanistic analysis. The Washington State Department of Transportation adopts EVERPAVE program, an empirical-mechanistic system developed at the University of Washington [4]. The Idaho Transportation Department Materials Manual refers to the Asphalt Institute manual MS-17 when overlay design is to be based on deflection analysis [5]. Idaho Transportation Department decided to develop its own overlay design method. Such method has been developed and tailored to account for the environmental variation all over the state of Idaho. Hardcastle [6] has established six climate zones in Idaho and a method for moduli seasonal adjustment which has been utilized in the development of the Idaho overlay design method. While this method was developed for Idaho, it can be applied to other environments once the appropriate seasonal factors have been determined. Details of the development of the Idaho overlay design method are documented by Bayomy, et. al [7] and Bayomy et. [8]. In this paper, a brief description of the methodology and design criteria adopted in the Idaho overlay design system and its implementation in the computer program “FLEXLOAY is presented.
OVERLAY DESIGN PROCEDURE

Concept. The concept adopted in the development of this overlay design procedure is the use of non-destructive testing by FWD to evaluate the structure capacity of the existing pavements. Assessment of the remaining life of the existing pavement and the required overlay thickness to resist future traffic is based on fatigue and rutting failure criteria. The method is developed assuming the pavement as a multi-layer elastic system. It incorporates the effect of seasonal variation on the change of pavement layer properties and accounts for non-linearity of material properties. The main features of the method includes: determination of design inputs, modeling pavement response and establishing failure criteria. The method is implemented in a computer code to facilitate stress and strain calculations which are essential in the calculation of the pavement service life.

Design Inputs. Design inputs are divided into three categories: material properties, traffic, and environmental factors.

Material Properties. The materials considered are subgrade soils, bases and subbases, asphalt mixtures for surface and base courses and cement treated bases. Since the pavement has been regarded as a multi-layered elastic system, the elastic moduli and Poisson’s ratios of any layer must be specified. In this study, moduli values are determined from non-destructive testing (NDT) using Falling Weight Deflectometer (FWD). Poisson’s ratios could be constant for each type of layer without significant effect on the design, [9]. For stress dependent materials (e.g., granular subgrade and base materials), moduli values can be estimated from the state of stress and the material properties using the following equations:

For granular materials

$$M_r = K_1 \theta K_2$$  \hspace{1cm} (1)

in which $K_1$ and $K_2$ are material constants and $\theta$ is the bulk stress, which is the sum of the principal stresses, i.e., $\theta = \sigma_1 + \sigma_2 + \sigma_3$.

For fine-grained soils

$$M_r = K \sigma_d^n$$  \hspace{1cm} (2)

in which $K$ and $n$ are material constants and $\sigma_d$ is the deviatoric stress, $\sigma_d = \sigma_1 - \sigma_3$.

For asphalt concrete layers, FWD is used to estimate the moduli values of the existing layers. For new overlay, the modulus can be estimated by laboratory testing. Some equations are available to estimate the modulus of the asphalt mixture based on aggregate and asphalt properties. An example of such equation is one like that developed by Rada et. al [10].

For cement treated materials, moduli values are considered linearly elastic and independent of stresses. The modulus of cement treated bases approximately ranges from 3,000 to 7,000 MPa. However, in most cases this modulus will decrease considerably towards the end of the service life of the pavement structure. Therefore, the cement treated base is treated as stress independent unbound material.

Traffic. The design method uses 80-kN ESALs for traffic input. In Idaho, traffic prediction is estimated using weigh-in-motion (WIM) scales.
Environmental Factors. To include the effect of environmental changes on the material properties, this method assumes that the initial moduli values are the normal values on the basis that it is most likely that all field tests will be performed in the “good” weather conditions. Then, the normal modulus is multiplied by an adjustment factor (seasonal factor) to obtain a representative modulus during that season. For example, if a normal modulus of subgrade is 70 MPa, and the seasonal factors for winter and spring-thaw are 7 and 0.65 respectively, the subgrade modulus during the winter season would be 490 MPa and during the spring-thaw period would be 45.5 MPa. In Idaho, intensive studies have been conducted to evaluate seasonal factors for all climate zones. Details of these studies are reported by Hardcastle [6] and Bayomy et al. [8]. Results of such studies have been used to develop the environmental data base of the FLEXOLAY overlay design program. For asphalt mixtures, the adjustment of the modulus is related to the temperature. A modulus-temperature relationship is established and is used to adjust the modulus of the asphalt layer for the season once a representative temperature of the season is determined.

Allowable Traffic and Failure Criteria. The overlay design system under consideration, considers two major distresses in flexible pavements, fatigue and rutting.

Fatigue Failure. Several investigations, for example Finn et. al., [11,12], and Hall et. al., [13], have shown that fatigue failure is best related to the horizontal tensile strain, $\varepsilon_t$, at the bottom of the asphalt layer. Most of the transfer functions found in the literature have the following form for fatigue failure:

$$N_f = f_1 \varepsilon_t^{-f_2} E_1^{-f_3}$$

where $N_f$ is the allowable number of load repetitions to prevent fatigue cracking from reaching a certain limit defined by the agency, $\varepsilon_t$ is the tensile strain at the bottom of the asphalt layer, $E_1$ is the modulus of the asphalt layer, and $f_1$, $f_2$ and $f_3$ are coefficients which can be determined from fatigue tests. The factor $f_1$, however, is to be modified to account for the shift from laboratory results to actual ESALs for applied field conditions. Shift factors may range from 5 to 700 folds. The Asphalt Institute adopted a fatigue model developed by Finn, et. al., [14], and modified it to reflect the effect of both volumetric air void content, $V_a$, and the volumetric asphalt content, $V_b$. The final form of the equation used by Asphalt Institute which is adopted in this design system is [15]:

$$N_f = 10^{4.04(1.84)M + 0.0434} (\varepsilon_t^{3.293} E_{ac}^{0.854})$$

where

$$M = 4 \beta 4 \left( \frac{V_a}{V_b} \right)$$

The factor of 18.4 in equation (4) has been replaced by a variable defined as Shift Factor, SF to account for the transfer from lab based model to the real number of 80- kN ESALs. The user can enter the appropriate SF number based on local experience.

Rutting Failure. Permanent deformation or rutting in flexible pavements has been related to the rutting in subgrade as a function of the vertical strain at the top of subgrade in the form:

$$N_d = f_4 \varepsilon_c^{-f_5}$$

where $N_d$ is the allowable number of load repetitions, $\varepsilon_c$ is the compressive strain at the top of the subgrade and $f_4$ and $f_5$ are material constants. As with the fatigue model, the AI model was adopted to predict rutting failure.

Modeling Pavement Response. The pavement is considered a multi-layer elastic system in which stresses and strains can be calculated by means of any of the existing multi-layer elastic
analysis computer programs (e.g. CHEVRON, BISAR, ELSYM5 and WES5) [9]. The load of 80-kN single axle is considered to estimate the critical strains at the bottom of asphalt layers (for fatigue analysis) and at the top of subgrade layer (for rutting analysis). The superposition principle is used to determine the stresses and strains due to dual load of 40 kN on each tire set.

**Damage Analysis.** Pavement is considered to have failed when the total damage has reached 100% whether it is due to fatigue or rutting or other distress combinations.

**For fatigue:** To perform the damage analysis, the expected future ESAL applications and the past ESAL applications, on the pavement are to be known from analysis of traffic load data. Also the allowable number of ESALs for a given season, i, \( N_{\text{(allow)}} \), is to be determined from Eqn. (4). The ratio of the future and past ESAL applications to \( N_{\text{(allow)}} \) is then calculated. These ratios are the damage ratios for the past and future traffic. By comparing these ratios to a failed pavement, one of the following cases may be existing:

- The existing pavement has failed under the past traffic. In this case, an overlay is needed to accommodate all the expected future traffic, or
- There is some remaining life in the existing pavement, but the future traffic exceeds the fraction of remaining life. In this case an overlay is needed for only that part exceeding the remaining life, or
- If the future traffic does not exceed the existing pavement remaining life, the existing pavement is structurally adequate to sustain the future traffic without overlay. In this case no overlay is needed.

**For Rutting.** Since rutting is of more concern at the surface of the overlay, it can be assumed that the existing rut, if any, will be filled and that the development of rutting will only be a function of the future traffic to be applied on the “new” pavement structure with the overlay. The allowable number of ESAL applications is determined using Eqn. (6) with the compressive strain determined at the top of the subgrade layer.

The final overlay thickness is the one that satisfies both fatigue and rutting requirements.

**FLEXOLAY PROGRAM DEVELOPMENT**

The overlay design procedure was implemented in a computer program named “FLEXOLAY”. The program allows for friendly data input and simple output and printed design report. Two programming languages were used to develop the overlay design program. The main routine, FLEXOLAY.EXE, was developed using VISUAL BASIC language to handle the input-output and file operations. The second routine, SYSAN.EXE, which include the multi-layer elastic program CHEVRON, was developed using FORTRAN language and compiled by POWER STATION FORTRAN which produces 32 BIT programs, hence, breaking the 640 KB barrier imposed by the DOS. SYSAN.EXE handles the intensive analysis and calculations, and works interactively with the main routine, FLEXOLAY.EXE. The program also includes a third routine, DOSXMSF.EXE which comes with the POWER STATION FORTRAN and can be distributed royalty free to enable the 32 BIT programs produced by the compiler to run under DOS.

The program structure is quite complicated to discuss in a comprehensive way. Therefore, the program blocks are shown in a flow chart, Figure 1, which shows briefly the function of each module in the FLEXOLAY design program and the links between the program modules (blocks).
The user interface main menu has four selections. These are File, Data, Results and About. Figure 2 shows the components of the main menu bar (Block 1). The following is a brief description of each menu selection.

The File menu allows the user to input new file, load an existing one and save a loaded file. Files are saved with extension .INP to indicate that they are input files.

The Data menu bar allows the user to select one of three forms; Pavement, Material Parameters and General. The Pavement form allows the user to input moduli values of the exiting pavement as determined form backcalculation of the deflections, information on the overlay material, testing temperatures and a description of the design case. It also allows for selecting a minimum overlay thickness and an increment for design iterations. The Material form allows the user to input information related to the classification of the different materials used in base and/ or subbase and subgrade as well as non-linear stress dependency parameters. The program uses this information to set codes for each type of materials. These codes are used later in establishing the damage level in each layer. The General form allows the user to input information related to traffic, fatigue shift factors and seasonal factors. The FLEXLOAY program has a data base for seasonal factors that are related to the different climate zones in the state of Idaho. For other locations, the program allows the user to input the seasonal factors appropriate to local conditions.

The Results menu allows the user to run (execute) the program to determine the required overlay design thickness, show the results on screen and/or print them on a printer or in a file. The Run command is used to run a single design case that is loaded manually while the RunFile command is used to run a design case with multiple mileposts. For such condition, the program will prompt the user to enter the data file that contains the moduli values (E’s) and test temperatures (T’s) for each mile post. The latter file is a text file with extension .ETF to indicate that it is an E and T File.

The About menu is for information on the program and documentation of ownership.

The rest of the program blocks (2 to 6) are calculation modules which are hidden to the user. They basically perform the stress-strain and damage analysis for each season and optimize on the overlay thickness based on the adopted failure criteria.

CONCLUSION

A flexible overlay design system was developed based on mechanistic analysis using multi-layer elastic theory. Failure criteria were used based on the established Asphalt Institute empirical equations for fatigue and rutting evaluation. Design parameters including material properties (evaluated by non-destructive testing), traffic (ESALs evaluated by weigh-in-motion) and environmental factors (evaluated for the six climate zones in Idaho) were established. The system is implemented in a computer software, FLEXOLAY. The program shows comparable results with other similar working programs.

REFERENCES

1. MODULUS 4.0 User Manual, Texas Transportation Institute, College Station, TX, 1990.


Data Input and Output System

Initialize Control Variables and Read Data File Created in Block 1.
Adjust Moduli Values to Account for Seasonal Variations.

For Non-Linear Layers:
Determine Layer Moduli Values Using Equations 1 and 2 with Stresses Calculated at 0.3 of the Depth of Granular Base/Subbase and 1.5 Total Pavement Thickness for Subgrade Modulus.

- Remaining Life Calculations
- Allowable Fatigue and Rutting Calculations.

Perform Damage Analysis
Design Satisfactory
Store Results
Increase Overlay Yes No

Figure 1 Description of the Different Blocks (Modules) of the FLEXOLAY Program

Figure 2 A Schematic of the FLEXOLAY Program Main Menu Features.