Mechanistic Overlay Design Procedures Available to the Design Engineer

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ABSTRACT

This paper is based on the first of a three-volume report on overlay design procedures. The basic report contains a summary of major overlay design procedures documenting their development and conceptual basis, and analyzes their sensitivity to required input data. Contained in this paper is a description of mechanistic overlay design procedures that are available to design engineers. Overlays or resurfacings are used by agencies more often than any other type of rehabilitation technique. This paper was prepared to provide highway engineers with assistance in determining what mechanistic overlay design procedures are available for adoption, implementation, and use by an agency. The full report documents the development and basis of the major overlay design procedures that are in use or are being implemented in the United States at the present time. Contained in this paper is an abbreviated description of the more common mechanistic overlay design procedures.

The most commonly used overlay design procedures include engineering judgment, standard thickness, empirical, deflection, mechanistic, and mechanistic-empirical. Each of these is described in some detail in the original report (1-3). Engineering judgment (or engineering experience) has often been used to design overlays (4) and, in many ways, it is still a part of most current overlay design procedures. Standard thicknesses have been developed for use by some agencies, either formally or informally (5). For a given existing pavement type, traffic level, pavement thickness, and other factors, a standard overlay thickness is prescribed. Purely empirical procedures base overlay thicknesses on known data such as age, traffic, construction, structural section, and environmental factors. A relationship is developed between performance of overlay thicknesses and these quantities, normally using regression techniques. Empirically developed deflection-based overlay design procedures have gained wide acceptance and are currently used, for example, in California, Utah, Texas, and Louisiana. The basic concepts are that similar pavements with higher deflections will fail more quickly than those with lower deflections under the same loading.

Mechanistic design procedures differ from others in that they characterize the response of the pavement to a load in terms of strains, stresses, or other responses based on mechanistic models. A fatigue relationship between that response and number of load repetitions to a designated failure criterion is used to determine pavement life. Most procedures use calculated stress or strain level based on deflection testing as the pavement response that is related to performance.

When mixed-load levels are encountered, which is the case in normal pavements, some method of combining the effects of mixed traffic must be considered. Miner's hypothesis is the one that is most often used, which allows an accumulation of damage from the various load levels to be combined into one damage number (6). The damage is a measure of the total fatigue caused by all previous traffic loadings. The damage from projected future traffic loadings is also calculated and combined with the damage from previous traffic loadings. When this damage is greater than the allowable damage, an overlay is required. By applying additional thicknesses of overlay to the surface, the strain (or stress) in the existing pavement will be decreased. The overlay thickness required is determined by trying various thicknesses of overlay and selecting the thickness that decreases the strains or stresses in the layers to a level that results in an acceptable damage level throughout the projected pavement life.

The strain at the bottom of the existing asphalt layer is normally used in flexible pavements for fatigue damage. In some instances, the stress or strain at the top of the subgrade has also been used for rutting damage. The strain or stress is normally calculated with layered elastic- or stress-dependent analysis programs. Stress in the concrete slab layer is normally used in rigid pavements. This is best calculated by finite element programs that can calculate stress for center, edge, and corner loads. Programs that will model several adjacent slabs with varied load transfer are available to analyze rigid pavements (7). However, some agencies use elastic-layered programs that can only determine stress from center slab loads, and an adjustment factor is used to convert the center slab stress to an edge stress. The stresses and strains calculated by different models will be somewhat different. The stresses and strains for analysis and fatigue models should be calculated with the same model to remain consistent.

Failure is normally defined in terms of a specific distress type. This is usually fatigue cracking and rutting in flexible pavements and fatigue cracking in rigid pavements. For the system to be fully mechanistic and theoretically correct, fracture mechanics should be used to determine the relation between strain or stress and cracking, and soil mechanics concepts should be used to determine the relation between subgrade stress and deformation. The current state of the art does not allow the use of such a theoretically based procedure. The load-

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and fatigue-caused distress provide an adequate substitute that can be economically collected. In any of these relations, the type, amount, and severity of the distress considered as failure must be carefully defined.

The basic assumptions are that

- The stress or strain can be accurately calculated,
- The stress or strain controls performance of the pavement,
- A relationship between the stress or strain and loadings to failure can adequately be defined, and
- Mixed loads can be accurately considered.

This requires a method for characterizing the existing layers in terms of stiffnesses or other parameters either from field sampling and laboratory tests or by back-calculating from deflection basins. When based on laboratory tests, the assumption is made that the tests provide field values. When calculated from deflection tests, the assumption is made that the layers can be accurately determined from deflection tests.

The major advantage of this approach, even when an empirical relation between calculated strain or stress and number of applications to failure are used, is that the overlay requirements can be determined for any pavement for which the strain or stress can be calculated. The user is not limited to only pavements with which he has extensive experience; instead, he can analyze the expected performance of new designs and the influence of new materials. Another significant advantage of this approach is that past and projected damage can be more accurately calculated. In some environmental areas, there are significantly different subgrade support conditions throughout the year. This affects the stress or strain in the pavement. A mechanistic procedure will allow the damage in the various seasons of the year to be calculated and used in the analysis.

The major shortcoming of mechanistic overlay design procedures is that to properly characterize the pavement structure and materials properties, either (a) extensive materials testing and evaluation or (b) back-calculation of materials properties from deflection measurements are needed to determine all of the required inputs. If the materials testing approach is used, this requires retrieval of many samples from the existing pavement and much laboratory testing to determine the required parameters. Programs are available that back-calculate the dynamic elastic moduli of up to 4 pavement layers. They generally give reasonable estimates of field conditions and work best with heavy load deflection equipment. However, there is some difficulty in determining the in-place properties of some materials such as granular subgrades and thin asphaltic concrete surfaces.

The long-term effects of environment on material properties and the geometry of joints and cracks often make it difficult to accurately characterize the in-place pavements with deflection testing alone. In addition, most of the procedures do not explicitly analyze the influence of cracks and other distress in the existing pavement on the performance of the overlay. As a result, most mechanistic procedures rely on an empirical relationship between the calculated strain or stress and the failure criteria. This is usually some type of fatigue cracking or rutting in flexible pavements and some level of fatigue cracking in rigid pavements. In any of these relations, the amount and severity of the distress considered to be failure must be carefully defined.

SUMMARY OF CURRENT MECHANISTIC DESIGN PROCEDURES

Shell--Flexible Overlays of Flexible Pavements

The pavement is modeled as a three-layer linear elastic system consisting of an asphaltic concrete surface layer, an unbound or cemented base layer, and a subgrade with infinite thickness (8-10). The materials are assumed to be homogeneous and isotropic, which allows them to be characterized by a modulus of elasticity and Poisson's ratio. With this information, the stress and strains can be calculated for the pavement section. Relationships for asphalt tensile strain fatigue and subgrade strain for traffic loadings have both been developed for use in predicting performance.

The Shell method uses results from a nondestructive evaluation conducted with a Falling Weight Deflectometer (FWD) to establish the effective thickness of the surface layer and the elastic modulus of the underlying subgrade. The surface modulus is determined by using the surface type and the surface temperature during FWD testing in a stiffness modulus chart developed for FWD loading conditions. The base layer thickness is assumed, taken from construction records or measured from cores. Poisson's ratios for all layers are assumed or are measured in laboratory tests. The elastic modulus of cemented base material must be either measured in laboratory tests or assumed. The modulus of unbound base material can be calculated using the relationship

$$E_2 = k\,E_3$$

Where

$k = 0.206\,(h_2)^{0.45}$,
h_2 = base thickness (mm),
E_2 = base modulus (MPa), and
E_3 = subgrade modulus (MPa).

(This relationship was developed using the BISAR elastic-layered program.)

The response of the pavement is characterized by the maximum deflection and the shape of the deflection bowl, which is expressed as the ratio of the deflection at a designated distance from the load to the deflection under the center of the load. The distance at which this is measured is selected based on the type of construction. A series of graphs were developed that allow the determination of the effective surface thickness and the subgrade modulus as a function of the center point deflection and ratio deflection at the given distance to the center point loading for a given surface modulus, base thickness, and base modulus. The deflections used for this determination can be selected for any desired reliability factor; however, the 85th percentile is suggested.

Deflections are normally measured between the wheel paths or other areas that have not been subjected to severe traffic loadings. This allows the calculation of the needed values of the pavement before significant damage has developed. The original available design life based on fatigue can then be calculated for use in the fatigue analysis. The residual life is determined based on asphalt strain fatigue. The residual life is calculated as the difference between the design life, calculated from the Shell design curves (8), and the traffic sustained to date. If the residual life is less than the projected traffic, an overlay is required.

The required overlay thickness is selected as the most conservative value determined from subgrade strain or asphalt strain fatigue. The future fatigue is adjusted for the decrease in strain at the bottom of the asphalt layer because of the overlay. If the pavement is extensively cracked, the existing pavement is analyzed as a granular layer and the overlay selected on that basis.

If the overlay material is the same as the original construction, the overlay design can be derived directly from the Shell design charts. If the maximum asphalt strain is expected to occur in the new overlay rather than in the original surface, it can be derived from BISAR elastic layer solutions. If the overlay material type differs from the original type, a thickness equivalency must be established and the design performed as though the material were the same.

Pavement sections are selected using the deflection data by computing a 3-point moving average that is plotted for the whole length of road. The operator selects characteristically different sections and statistically verifies the difference in these sections using a nonchalant t-test at a confidence level selected by the highway agency.

The procedure is established for specific asphaltic concrete mix types and cement grades. The design life is expressed in terms of 18-kip (80 kN) ESALs (equivalent single-axle loads). The pavement temperature during testing must be measured in the center of the asphalt layer. Climatic differences are based on a weighted mean annual air temperature. This is used to indicate the daily and monthly temperature gradients in the asphalt layer for the climate.

Eleven Amsterdam area pavements were used to check the procedure. The effective thicknesses compared well with actual thicknesses based on cores and wave-propagation tests. No information is available on verification through feedback of actual design data. The procedure requires manipulation of several charts and graphs making the solution rather complex and difficult to complete. The procedure uses the FWD with a heavy impact load as the required input for deflection. Because this device simulates a moving-wheel load deflection basin, it should be compatible with the design concept.

POD--Flexible Overlays of Flexible and Rigid Pavements and Rigid Overlays of Rigid Pavements

The procedure, developed by Austin Research Engineers, Incorporated (ARE) (11-13), uses an elastic-layered analysis (ELSYM5) of the pavement to determine the stress or strain created in the pavement by loadings for both flexible and rigid pavements. For rigid pavements, the SLAB49 discrete element program was used to develop stress adjustment factors for edge and corner loads. An empirical relationship for the pavement life was developed based on AASHO Road Test data. Pavement life was based on fatigue cracking and rutting for flexible pavements and fatigue cracking only for rigid pavements. For flexible pavements, the strain is calculated at the bottom of the surface for fatigue cracking, and stress is calculated at the top of the subgrade for rutting. In rigid pavements, the horizontal tensile stress in the rigid layer is used; it is assumed to occur at the corner in jointed pavements and at the edge for continuously reinforced pavements. (It is important to note that this was a regression analysis of data that was based on accelerated testing and may not reflect the performance under normal traffic conditions.)

The NDT evaluation allows use of the Dynaflect and other deflection equipment such as the Road Rater, Benkelman Beam, Deflectograph, and the FWD. The NDT data are first used in conjunction with distress data to locate design sections by determining adjacent sections that have statistically significant different deflections based on the t-test. The deflection mean and standard deviation for each design section are used to determine a design deflection based on desired design reliability. It is recommended that NDT testing be conducted during the season that gives the largest deflections. User-developed corrections should be applied to those measured during other seasons.

The modulus of elasticity for each of the pavement layers above the subgrade is determined from laboratory testing of pavement layer materials. However, the program does have default values if none are entered. The subgrade modulus is determined using a combination of laboratory test data and deflection-matching procedures based on elastic-layer analyses. If the deflection device uses the design load [9,000 lb (40 kN)], the subgrade modulus can be determined directly from the deflection measurements. If the deflection device uses a load less than the design load, such as the Dynaflect [which only applies a 1 000 lb (4.4 kN) load], an approximate procedure is used to correct the modulus for the change in stress from the Dynaflect load to the design wheel load.

The ELSYM5 program is used to determine relationships between the resilient modulus as deflection and between resilient modulus and deviator stress. The laboratory curve of resilient modulus versus deviator stress is then adjusted to reflect the relationship found above, and the existing resilient modulus is then selected from this adjusted curve at the design load. The deviator stress used in laboratory testing is the axial stress minus the confining pressure. The deviator stress for deflection testing is that calculated by the elastic layer program for the test load.

A detailed condition survey is conducted to determine the remaining fatigue life classification of the existing pavement. The type of overlay to be placed, the type of existing surface material, and remaining fatigue life are used to select a subsystem for overlay design and the appropriate fatigue model. A total of 18 different design subsystems are available for use for flexible and rigid pavements combined.

The stress and strain for a series of overlay ticknesses are computed. These values are used to calculate the allowable fatigue life for the flexible and rigid pavements and the number of repetitions to produce failure by rutting in flexible pavements. These results are used to develop a design curve for the appropriate failure criteria. The projected traffic [18,000 lb (80 kN) ESALs] is then used to determine the required overlay thickness to meet the most severe criteria. The procedure was validated and adjusted for field data for the Texas Department of Highways and Public Transportation (14). A procedure was also developed for reflective cracking; however, it was not included in the latest version.

For the procedure to be effective in analyzing an existing pavement, a large amount of field and laboratory data are needed. Although default data can be used, the results would be much less reliable. The procedure is computerized and requires a mainframe computer for operation and sophisticated analysis to determine the required input data as well as the reasonableness of output data.

Although the manual says that any NDT device can be used, the procedure was developed for use with the Dynaflect. Use of other NDT equipment should be carefully monitored. The use of light-load devices to design overlays for heavy truck loads has been questioned. A regional factor is used to account for the effect of various environmental regions. This factor is applied by adjusting the projected traffic. The original system, including the one analyzed in this study, would not allow the design of flexible overlays for pavements that were determined to have no remaining fatigue life. It would also only allow the use of one modulus of rupture for the portland cement concrete overlay and base material. These were corrected in the later versions used by Texas.

OAF--Flexible Overlays of Flexible Pavements

The overlay design method developed by ARE was reviewed and revised (15) in several aspects by Resource International, Incorporated (RII). Among the revisions was a reanalysis of the AASHO Road Test data originally used by ARE as the basis of the fatigue relation for the design of the overlay. Using the same data used by ARE, RII found a fatigue relation for horizontal tensile stress in the asphalt layer that was considerably different from the one reported by ARE.

Another revision was the method in which the deflection measurements were used to calculate moduli values. A three-layer (sometimes four-layer) elastic-layer analysis program is used with deflection basin matching techniques to calculate moduli values. The computer program uses an iterative approach to match measured deflections to those computed by the ELSYM5 procedure for a three-layer system. Layer moduli are adjusted in the model until the computed basin matches the measured basin. If an adequate fit cannot be achieved with a three-layer analysis, the fitting process is rerun using a four-layer system.

Two basic strategies are employed to determine the moduli in the three-layer system. In the first, the computed deflection at the center of the load, or maximum for the Dynaflect, and at a 1-ft (305-mm) distance from the center along with the spreadability are matched to those measured. The second strategy matches the computed deflection at the center and at a 2-ft (610-mm) distance from the center along with the spreadability to those measured. Spreadability is defined as

$$SP = 100 * \left(\sum_{i=1}^{N} W_i\right)/NW_1$$

where

W_i = measured deflections,
W_1 = maximum deflection, and
N = number of sensors.

If convergence is not achieved using the first strategy, the convergence criteria is relaxed and a solution is sought with readout notification of this step. Convergence is achieved when the computed deflections differ from the measured deflection by 3×10^{-6} in. (8×10^{-5} mm) for normal and 1.5×10^{-6} in. (4×10^{-5} mm) for relaxed criteria, respectively. If convergence is still not achieved, a four-layer solution is attempted. In this procedure, the second deflection strategy is used. If a solution still cannot be achieved, a default solution is applied, and notification is given.

It is important to realize that several solutions to a three- or four-layer system may provide an adequate basin match. Certain constraints are placed on derived moduli values to try to limit errors in calculated values. The temperature-corrected asphalt modulus must be at least 100,000 psi (689 MPa), and the computed base stiffness must be no more than 65 percent of that value for uncracked pavements. For pavements with fatigue cracking, the computed asphalt modulus must be at least 70,000 psi (482 MPa), and the computed base stiffness must be no more than 65 percent of the surface value.

Once the match is achieved, the calculated moduli values are adjusted for temperature. The moduli values are then calculated for the base, subbase, and subgrade for the state of stress under the design load of a 9-kip (40-kN) dual wheel load at the design temperature. These materials have stress-dependent moduli values; therefore, an iterative process is employed using a modified Newton-Raphson procedure to determine the new values of the layer moduli. Convergence criteria are achieved when the moduli values change less than 2 percent for the base, 3.5 percent for the subbase, and 5 percent for the subgrade.

When the wheel-load radius is greater than the thickness of the surface layer, the elastic layer model predicts tensile stresses in the base and/or subbase layer for some combinations of layer moduli and thicknesses. This will occur when the surface layer is relatively thin. The situation is compensated for by assuming that the base and subbase moduli values are essentially stress independent when the bulk stress (sum of the principal stresses) is less than 1 psi (7 kPa). This reduces the chance of calculating high strains for the condition.

The layers are characterized by thickness, modulus of elasticity, Poisson's ratio, and layer density. The layer thicknesses, Poisson's ratios, and material stress sensitivities are assumed to be known. These are entered into the program by the designer and must be derived from test results or estimates. The analyzed load is assumed to be distributed uniformly over a circular area. The procedure recognizes the nonlinear relationship of stress to strain in granular and fine-grained layers in response to load. The program uses the designer-supplied stress sensitivity to adjust the calculated moduli values to reflect those found in the layers under a design load if the deflections were measured with other than the design load. Tables of typical stress sensitivity values are provided for guidance.

The strains for the layers are calculated, and the remaining life is determined. The remaining life is based on an "effective stiffness" concept. The existing pavement is characterized using the as-built thicknesses; however, they are characterized with the derived stiffnesses. This section is then assumed to have all of its life remaining, and an analysis of previous traffic is not required. The only traffic information required is future traffic data.

The strain is calculated at the bottom of the existing slab for pavements that are uncracked and that have a surface modulus greater than 70,000 psi (482 MPa). If the pavement is badly cracked or if the surface moduli is less than 70,000 psi (482 MPa), the tensile strain is calculated at the bottom of the overlay and at the bottom of the existing layer, and the larger value is used. When thin layers are encountered, the strain is calculated under two thicker pavements and then extrapolated for the thin pavement. This is checked against that calculated in the normal method above, and the larger of the two values selected as the design value. A special check is made on sections for which the base or subbase moduli approaches that of the surface by calculating the remaining life after adding a 1-in. (25-mm) overlay to assure that a reliable analysis has been made.

The overlay design is based on the fatigue analysis. If the required life is greater than the remaining life in terms of 18-kip (80-kN) ESALs, an overlay is required. A trial overlay thickness is selected based on the difference between the required life and the remaining life. The addition of the overlay changes both the stress state and the corresponding moduli values. An iterative procedure is used to select the overlay thickness that will provide the required life by calculating the moduli values, the resulting strain, and the resulting fatigue life.

Unlike the ARE procedure, a required overlay thickness is calculated for each deflection point entered into the analysis. This is required because the full deflection basin is used to back-calculate the layer properties. When only the maximum deflection is used in an analysis, a "design deflection" can be selected; however, it is more difficult to select a design basin. To take advantage of the more complex analysis procedures, moduli values are calculated and the full fatigue and overlay design procedure is completed for each measured deflection point. The variation in required thicknesses is then statistically analyzed to determine sections that should receive the same overlay thickness.

For pavements with cement-treated bases, the system is modeled as a two-layer equivalent full-depth asphalt layer resting directly on the subgrade. If the base layer is cracked, the program treats the base as a granular layer. An analysis can be completed using laboratory-determined layer properties for either the three- or four-layer system. An analysis can also be made with the three-layer system using default layer properties. A regional and a seasonal factor are used to account for differences in performance that are due to different environmental regions. This is used to adjust the traffic inputs to provide equivalent performance.

During development, the procedure was compared to other procedures on data from fifteen projects. The required overlay thicknesses were similar to those calculated by the California and Utah methods but were thinner than those required by the Louisiana and Mississippi methods. The weak subgrade and temperature adjustments were felt to cause the difference. It was compared to performance on two in-service sections and reported to provide reasonable agreement. (This procedure is currently being evaluated by highway agencies in California, Illinois, Minnesota, and Texas under Task Orders with the FHWA Office of Implementation.)

Because of the problems discussed earlier in modeling thin layers [less than 2 to 5 in. (51 to 127 mm)], this system may not give reliable overlay designs for thin asphalt sections. The assumption that a pavement system can be modeled with a moduli derived from current conditions while neglecting previous traffic in the analysis may not be valid. Other studies have shown that moduli values for a given load and at a given temperature tend to remain constant for a majority of the useful life of the pavement and then decrease only near the end of the pavement life (8). The procedure used in OAF does not seem to include recognition of this fact, however. The basin matching system has produced unreasonable layer moduli and should be carefully monitored. This can be a problem with any procedure that uses computerized basin matching techniques to determine moduli values.

The data needed to use the system are somewhat less complicated than that needed for the POD procedure. They do require deflection testing and at least a good knowledge of the layer materials. Generally, some testing will be required to determine typical material properties of the various layer materials used by an agency. Because the system, which operates on a mainframe computer, uses iteration to analyze the overlay needs for every deflection point, a considerable amount of computer time is used. The free-format input system simplifies the input of data. A knowledgeable person is needed who is capable of analyzing the inputs and results, including moduli values, so that reliable results may be obtained.

University of Illinois--Flexible Overlays of Flexible Pavements

This procedure has been developed for designing flexible overlays on flexible pavements (16). At present, it has only been used with pavements on cohesive, fine-grained subgrades.

A condition survey is used to determine pavement sections that are candidates for overlay and should receive NDT testing. The testing is then conducted using a Road Rater Model 2008 with an 8,000-lb (36-kN) load or an FWD with a 9,000-lb (40-kN) load. Pavement temperatures are recorded to allow temperature adjustments. Equations and nomographs have been developed for determining remaining life and designing overlays for conventional flexible pavements and full-depth asphalt; however, only pavements on fine-grain subgrades are addressed.

A relation between the deflection and strain at the bottom of the asphalt surface layer is used with a fatigue relation to determine the total number of loads that can be carried in the spring and in the summer-fall periods. Numerous computations with the ILLI-PAVE finite-element computer program were used to establish the equations for maximum deflection and the normalized cross-section area (AREA) of the deflection basin out to the sensor at a 3-ft (0.9-m) distance from the center of the loading plate. Nonlinear stress-strain characteristics of the granular base course and cohesive subgrade were incorporated into the analysis.

With the thicknesses known, the equations can be used to determine the asphalt modulus and the subgrade resilient modulus. The granular layer modulus is assumed and included in the nomographs. Other algorithms are being developed in continuing research efforts. The asphalt concrete modulus is corrected for temperature and adjusted for two different seasons, the spring and the summer-fall periods. The subgrade modulus is corrected by tabulated multiplying factors for freeze-thaw and moisture effects to give typical values in the same two seasons.

To design an overlay, the existing pavement is analyzed to determine if it is structurally adequate for the past and projected traffic based on strain in the asphalt layer and a fatigue relationship. If it is deficient, an overlay thickness is assumed and Odemark's assumption is used to determine the equivalent total thickness of the existing asphaltic-concrete and the overlay. Then, the equation for maximum deflection is used to predict the deflection of the overlaid pavement. The percentage of life that is used in each season is calculated to determine if the life of the overlaid pavement is consumed within the design period. If so, the overlay thickness is increased, and the percent of life consumed is calculated again. The iterative process is repeated until an adequate overlay thickness is found.

This overlay design method uses design load levels as input and incorporates the nonlinearity of the base course and subgrade directly into the NDT data interpretation and the overlay design phases. The ILLI-PAVE computer program was used to develop the equations.

The FWD is used as the standard NDT device. A 9,000-lb (40-kN) impulse load applied to a 12-in. (305-mm) diameter plate is the standard load. For devices that apply a load other than the design level [9,000 lb (40 kN)], the procedure would have to incorporate a method for correcting the measured basin deflection to what would be produced by the design load.

This procedure is currently being tested. No information is available on its effectiveness at the current time. The required inputs are relatively simple compared to other mechanistic models. It uses a chart and nomograph system to produce reasonable layer parameters for use in the overlay design. The Illinois and Minnesota Departments of Transportation are evaluating it for use.

OAR--Flexible and Rigid Overlays of Rigid Pavements

This is a computerized overlay design procedure for flexible, rigid bonded, and rigid unbonded overlays of rigid pavements, which was developed by RII (17). The program, designated as OAR, generates recommended overlay thicknesses to limit load-induced fatigue cracking, but is not yet fully able to address the problem of reflection cracking at this time. Overlay thickness determination is based on elastic layer theory, modified by influence functions based on finite-element analysis to account for edges, joints, cracks, and other discontinuities. Adjustment factors based on finite-element analysis were determined for edge and corner voids as well. The failure criterion is fatigue cracking.

The relationship between critical stress in the rigid slab and failure was based on an analysis of AASHO Road Test data using number of traffic loadings required to reach a serviceability level of 2.0 with traffic adjusted by a traffic distribution factor. A finite-element program coupled to a multilayer elastic solid foundation (RISC) was used to calculate the stress with the critical loadings applied. The actual fatigue relationship was developed using stress ratio (flexural strength/stress) and number of 18-kip (80-kN) axle loads to failure.

A visual distress identification system was recommended to assist with the pavement evaluation. The Pavement Condition Rating (PCR) system assigns an index value of 100 to a pavement with no observable distress. Points are deducted from this value for various types of distress, weighted according to extent and severity. A scale assists in interpreting PCR value (90 = good, 75 = fair, etc.). Other required inputs to the design procedure include existing pavement thickness, concrete modulus and flexural strength, subbase, and subgrade moduli, predicted design life in terms of traffic loading, and estimated previous traffic loading. The OAR program can accommodate input data obtained from construction records, field tests, lab tests, NDT results, or estimates assigned within accepted guidelines.

The subgrade modulus can be adjusted from NDT measurements; however, the procedure is a "self-calibrating" system that requires subgrade moduli values from soil testing or classification. A separate calculation is made for each deflection point to determine the subgrade modulus using a two-term regression equation. The coefficient of variation of the derived subgrade modulus is calculated. The design subgrade modulus is then determined from the equation

$$E_{SD} = E_{SO} (1 - Z\ CV_S)$$

where

E_{SD} = design subgrade modulus,
E_{SO} = original subgrade modulus from test or classification data,
CV_S = coefficient of variation of subgrade modulus derived from NDT data, and
Z = a constant depending on the confidence level desired.

As can be seen from the equation, the effect on the subgrade modulus from deflection testing has been largely eliminated except for the variability found.

It should be noted that unlike OAF, OAR does not consider stress dependency in the base and subgrade moduli. NDT measurements are made at the center of the slab and across joints and cracks, or both, to measure load transfer that is used in determining the presence of voids. It is recommended that these measurements be taken during the early morning hours or on a cloudy day when the vertical temperature gradient is small. Because load transfer efficiency is temperature-dependent, it is recommended that these measurements be made when the slab temperature is near the average annual air temperature.

Normally, the critical stress is calculated for the bottom of the rigid slab, and the fatigue relationship is used to determine remaining life. If a stabilized layer is used, an alternate procedure is used. The elastic layer program (ELSYM5) is used to determine the critical strain in the bottom of the stabilized layer and the critical stress in the bottom of the rigid slab. Both are modified for edge or corner conditions, and the remaining life is calculated based on the fatigue equations. Remaining life of each is then calculated and the results combined together for flexible bases. For cement-treated bases, an equivalent thickness approach is used. If the remaining life is less than that required for the expected traffic, an overlay is designed using current conditions.

The fatigue life of the overlay and the existing pavement are both considered in the analysis. When the existing slab is expected to fail before the overlay, a reduced stiffness is assigned to the slab. This is most prevalent in flexible overlays. When the user indicates the presence of edge or corner voids, the void adjustment factor is applied in the stress calculation. If the load transfer (deflection of the unloaded slab divided by the deflection of the loaded slab) is less than 0.72, a corner void is assumed unless overridden by the user.

An iterative approach is used to determine the overlay thickness, which provides the desired design life. This requires an analysis of the total available life, the life used by traffic to the time of the analysis, and future traffic. The design life is calculated (a) based on a stress calculated with no voids, (b) for edge stress in jointed-reinforced and continuously reinforced pavements, and (c) for corner stress in plain-jointed pavements.

When the remaining life analysis indicates that an overlay is required, then the overlay thickness required is based on the stress calculated from current conditions with the edge voids and corner voids, if present. The fatigue life of both the overlay and the original pavement are considered. This allows the original pavement to fail and still leave the overlay with some remaining life. When an existing pavement is analyzed as having no remaining life, a reduced modulus value of 70,000 psi (483 MPa) is assigned to the rigid slab and an overlay is designed. Environmental effects are taken into account by applying a regional factor to the projected traffic. This is supposed to provide equivalent performance.

The model was checked by analyzing unfailed sections in the AASHO Road Test data. It provided an indirect indication of model validity. The system has not been fully verified at this time; however, it is currently being evaluated by highway agencies in Illinois, Minnesota, Ohio, and Texas.

The OAR program requires a fairly sophisticated computer system to operate. A person who is knowledgeable in both material characterization and elastic layer analysis is necessary to operate the system and achieve reasonable results. The amount of data required is less than that required for the POD procedure; however, unless some material testing is used to determine the material moduli values, the resulting overlay designs are going to be of questionable value. The deflection testing suggested in this procedure may be needed to evaluate the pavement by the designer; however, it provides little, if any value in the actual overlay design procedure as conducted by OAR.

CALCULATED OVERLAY THICKNESSES

A set of pavements was selected for which the overlay design procedures were used to calculate required overlay thicknesses. The pavements had a range of conditions, deflections, traffic, and subgrade support. The complete inputs and results are presented in the basic report. Only abbreviated conclusions are presented here. The mean calculated overlay thickness from each of the procedures and the ratio of the mean overlay thickness to the lowest mean thickness calculated by the selected procedures were determined. The ratio provides a relative comparison of overlay thicknesses required by each of the design methods. This is not meant to be used to judge one procedure better; neither thickness nor thinness should be used to judge the relative value of an overlay design. This analysis is meant to point out significant differences and identify causes.

The OAF overlay design method required the thinnest mean asphalt overlay thickness for flexible pavements. The University of Illinois mean calculated thicknesses were the greatest; however, they were only for the sections with fine-grain subgrades. The POD and Shell procedures gave similar calculated thicknesses that were generally between the other two thicknesses. Low traffic levels seem to have more influence on the University of Illinois and OAF procedures than others.

For the flexible overlays of rigid pavements, POD required the lowest mean overlay thickness for the flexible overlays of rigid pavements. However, six sections had high levels of preoverlay traffic. The POD computer program calculated that the sections had already used up the design life and could not calculate an overlay design thickness for the existing pavement. The OAR procedure calculated overlay design thickness much greater than the POD procedure when the POD would calculate a required thickness and, in general, would range from 3.5 to 5 in. (9 to 13 mm) thick with little variability. This probably is due to the procedure's reliance on selected moduli values rather than measured field values.

For the rigid overlays of rigid pavements, the POD overlay design procedure resulted in the lowest mean overlay thickness. The POD procedure calculated required overlays for all sections including those the other procedure indicated were structurally adequate. This may reflect that the POD procedure is more sensitive to low traffic levels. The OAR procedure resulted in the largest mean calculated overlay thickness; however, it also had the largest number of sections requiring no overlay. This indicates considerable variability.

SENSITIVITY ANALYSIS

A sensitivity analysis was performed on selected parameters for each of the overlay design procedures to demonstrate the reasonableness of the procedure and to identify the design inputs that influence the overlay thickness calculated by each overlay design procedure most heavily. This allows the user to establish the priority of the importance of design inputs for a particular overlay design procedure and allocate time and money to each input accordingly. For example, since POD's overlay design thickness changes drastically with a change in traffic, but only slightly for a change in the overlay design modulus of elasticity, it could be argued that the designer should spend more effort obtaining accurate traffic data than exact moduli values.

The sensitivity analysis was conducted by varying the major inputs for each of the overlay design methods one at a time while holding all others constant. Sections with the most complete field data available were selected for use in this analysis. For each design input, low, medium, and high values were selected to check the sensitivity of the input to the design procedure. The medium value was generally selected to be the actual mean data used from the selected pavement sections and, where feasible, this value was increased and decreased by 50 percent to get the low and high values, respectively. Although one design input was being varied in the design procedure, the rest of the inputs were held constant. This enables the user to see how much effect the input has on the overlay design thickness.

In some instances, all of the inputs could not be analyzed. Some of the variables are interdependent and cannot be varied without changing another variable. For instance, when deflection and a subgrade support were interdependent inputs, only one of the variables was analyzed. (A full set of sensitivity figures is provided in the report.)

The sensitivity of the Shell flexible overlay procedure for flexible pavements was analyzed using subgrade modulus of elasticity, unbound layer thickness, design traffic, and air temperature. The calculated overlay thickness was most sensitive to subgrade modulus. The thickness of the base material, the design traffic, and the air temperature have somewhat less impact in the range of data analyzed. Because it is a mechanistic procedure, it would be expected to be most sensitive to layer moduli and thicknesses.

The sensitivity of the POD overlay design procedure for flexible overlays of flexible pavements was analyzed using overlay modulus of elasticity, existing asphalt concrete thickness, deflection, and design traffic. The calculated overlay design thickness was most sensitive to design traffic. Surprisingly, overlay modulus of elasticity, existing asphalt concrete thickness, and deflection produced little change. This may reflect the level of design traffic that was relatively small, and the other factors could be more sensitive in a different data range.

The sensitivity of the POD overlay design procedure for flexible overlays of rigid pavements was analyzed using overlay modulus, existing PCC modulus, slab thickness, deflection, traffic, and crack type. However, the selected data had to be modified by reducing past traffic. This was required to allow the procedure to calculate an overlay as the procedure would have otherwise assumed that all remaining life had been used. The calculated overlay design thicknesses were most sensitive to the concrete modulus of elasticity, existing slab thickness, and deflection and design traffic. This sensitivity was expected because this is a mechanistic procedure and these are the main parameters to characterize the pavement and predict performance. It was somewhat less sensitive to past traffic and overlay modulus. Crack type had little influence on overlay thickness in the range of data analyzed.

The sensitivity of the POD overlay design procedure for rigid overlays of rigid pavements was analyzed using overlay modulus, existing PCC modulus, slab thickness, deflection, traffic, and bond type. The calculated overlay design thickness was most sensitive to the overlay modulus of elasticity and the design traffic. The calculated overlay thickness is less sensitive to slab thickness, deflection, and bond. It is practically insensitive to existing PCC modulus and past traffic in the range of data analyzed.

The sensitivity of the OAF flexible overlay design procedure was analyzed using modulus of elasticity of existing asphaltic concrete test temperature, the subgrade modulus of elasticity, existing asphaltic concrete thickness, deflection, and traffic. The calculated overlay design thickness is most sensitive to the modulus and thickness of the existing pavement. This would be expected because it is a mechanistic procedure and uses these to characterize the existing pavement. It is moderately sensitive to deflection and traffic in the range of data analyzed.

The sensitivity of the University of Illinois flexible overlay design procedure was analyzed using asphalt concrete modulus of elasticity, subgrade modulus of elasticity, surface thickness, granular base thickness, deflection, and traffic. It is most sensitive to deflection and is somewhat less sensitive to the effects of moduli values, layer thicknesses, and traffic.

The sensitivity of the OAR flexible overlay design procedure for rigid pavements was analyzed using overlay modulus, slab thickness, deflection, traffic, regional factor, directional factor, and lane distribution. The calculated overlay thickness is most sensitive to existing slab thickness. It is somewhat less sensitive to overlay modulus, traffic, and directional factor in the data range analyzed. It is surprising that the overlay thicknesses calculated by OAR are nearly insensitive to regional factor and lane distribution because they directly affect traffic. As would be expected, the calculated overlay design thicknesses are completely insensitive to deflection data because only the deflection coefficients of variation are used in the calculations.

The sensitivity of the OAR rigid overlay design procedure for rigid pavements was analyzed using overlay modulus, slab modulus, slab thickness, deflection, traffic, load transfer, traffic growth factor, lane distribution, bond type, and directional distribution. The calculated overlay thickness is most affected by the existing slab thickness. The overlay modulus of elasticity and the traffic-related items have somewhat less of an impact on the calculated overlay design thickness. As expected, the deflection and load transfer across joints has practically no influence on the overlay thickness because of the way they are used in the procedure. It is surprising that the type of bond and modulus of the existing pavement have so little effect.

CONCLUSIONS

No conclusions are presented to identify specific overlay design procedures as being good or bad. They are directed at general points found in all procedures. It is hoped that such a review of available systems will encourage the highway engineer to use the available mechanistic procedures. The conclusions are as follows:

1. Studies in California (18) and Texas (19) have shown that overlays designed with more technically correct design procedures perform in a more consistent manner with more reliable life expectancies. Fault can and should be found with all existing mechanistic overlay design procedures; however, the problems found should be used to identify areas for further study and improvement as in all phases of pavement design. The available mechanistic overlay design procedures provide better analysis tools than the more subjective approaches used in the past.

2. More technically correct overlay design procedures often require more time, testing, and effort to complete than subjective procedures. However, the cost of conducting such an evaluation for an overlay design is small compared to the cost of either failure or over-design.

3. Models should be developed for the microcomputer that can adequately characterize both flexible and rigid pavements. This should include modeling the joints and cracks of rigid pavements.

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Project Evaluation for Overlay Selection and Design

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ABSTRACT

Overlays or resurfacings are used by agencies more often than any other rehabilitation technique. It has been suggested that they have been used in some instances when a different rehabilitation technique would have been better suited. This paper contains a description of an evaluation procedure to determine whether an overlay is required and whether other rehabilitation techniques might be substituted for the overlay. The description focuses on how to use an overlay design procedure in this evaluation. It is based on portions of the third volume of an FHWA report, Pavement Overlay Design Procedures and Assumptions (Report FHWA/RD-85/006-008), developed to provide a ready reference on overlay design for use by highway agency engineers. It was designed to provide assistance in determining what overlay design procedures are available for adoption, implementation, and use by an agency as well as to provide guidance on the use of an overlay design procedure. Pavements are rehabilitated to return damaged pavements to a condition that can continue to provide the desired level of service to the using motorists. Project evaluation is conducted to identify rehabilitation alternatives that meet this goal. In overlay design, the goal is directed more specifically to identifying the type of overlay that would be the most effective, the thickness of the needed overlay, and problems that would indicate that some other rehabilitation technique would be more suitable.

The basic objective of project evaluation is to identify and develop cost-effective rehabilitation techniques for the pavement while meeting imposed constraints such as available funds. In many cases, overlays are among several alternatives available to rehabilitate the pavement. Overlays only add layers of materials to the surface and may need to be combined with other techniques to develop an effective solution. In some cases, other techniques may be more cost effective than an overlay.

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FUNCTIONS OF AN OVERLAY

Overlays are used to either (a) strengthen existing pavements to support future traffic loadings or (b)