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Flexible Pavement Design
Summary of the State of the Art

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Contained within this paper is a summary description of the state of the art in flexible pavement design along with a look to the future in terms of some specific technical needs, the translation of the new technology into practice, and making flexible pavement design (or pavement engineering in general) a more credible discipline. Since the scope of the Committee on Flexible Pavement Design focuses upon the improvement of flexible pavement design (with particular emphasis on closing the gap between the state of the art and the state of the practice), these are issues that can be well addressed at this time.

OVERVIEW

Keeping in mind that flexible pavement design deals primarily with structural aspects (i.e., the selection of appropriate materials, characterization of strength or load-carrying properties, layer thickness determination), it can be said that the state of the art in flexible pavement design is manifested in mechanistic, or mechanistic-empirical (M-E), based design procedures that incorporate the treatment of life-cycle costs and design reliability. State-of-the-practice methods, on the other hand, tend to rely more on empirical correlations with past performance, index-value-based characterizations of material properties [layer coefficient, *R*-value, California bearing ratio (CBR), etc.], and engineering judgment for design strategy selection. [Note: In this context, mechanistic design procedures refer to those methods that incorporate models based on fundamental engineering mechanics to evaluate the state of stress in a pavement and predict response, behavior, and performance. Empirical procedures are those that rely more on models developed from experience or observations of past performance.] In addition, these procedures have been used at traffic load levels and in environments well beyond their observational base. The *Guide for Design of Pavement Structures* published by the American Association of State Highway and Transportation Officials (AASHTO) is commonly used to design pavement with traffic loadings greater than 50 million equivalent single-axle loads (ESALs), but the basic design equations were developed from traffic loadings of less than 2 million ESALs.

The primary advantage of the modern procedures is that they are inherently better suited to treat the variety of environmental and wheel loading conditions than their state-of-the-practice counterparts (including the 1993 AASHTO Guide). These procedures can have several other important advantages, including

- Better capability to characterize material properties and assess existing pavement structural capacity (through laboratory testing, nondestructive testing, and backcalculation, or all three);
- Ability to evaluate and compare different design alternatives on a fair (defensible) basis; and
- Ability to account rigorously for stochastic variability or uncertainty in the design process.

The primary disadvantage of the modern procedures (as reported by the users) is that they tend to be more complicated, time-consuming, and costly to apply.

The philosophy of M-E-based design for flexible pavements has been around for roughly half a century; however, it is only in the last decade that full-fledged procedures that could be used outside the academic or research environment have been developed. NCHRP Project 10-26, titled *Calibrated Mechanistic Structural Analysis Procedures for Pavements*, completed in 1990 (*1*), helped usher in a whole new era of advancing the state of the art in pavement design technology. The best examples of some of the new M-E-based procedures used by the states are those that have been developed for the Washington State Department of Transportation (WSDOT) (*2*) and the Minnesota Department of Transportation (MnDOT) (*3*). The WSDOT procedure has been incorporated into a series of design manuals, Microsoft Windows-based computer programs (EVER series software), and supporting documentation that have been accepted and now are routinely used by all six district offices within the state. The documented first version was completed in 1989, but WSDOT had implemented the procedure several years before that date. However, the software has undergone several enhancements since then. The MnDOT ROADENT procedure is a research edition that was also incorporated into a Microsoft Windows-based software package. The first version of ROADENT was completed in 1998 and is now undergoing beta testing and trial implementation.

The anticipated 2002 AASHTO *Guide for Design of New and Rehabilitated Pavement Structures* will advance the state of the art over the WSDOT and MnDOT procedures on several key aspects, including the use of load spectra for traffic modeling, the use of finite-element (FE) analysis for response prediction in certain situations, and the incorporation of reliability in life-cycle cost assessment. However, because of its reliance on off-the-shelf models, the 2002 AASHTO Guide will probably only be a moderate step forward on the technology side. Its greatest benefit is that, as the new guide, it will likely add much more credibility to the use of M-E-based design than in the past.

KEY COMPONENTS

Following is a brief description of the key components that constitute the state-of-the-art flexible pavement design procedure.

Analytical Models

A number of different types of models (mostly computer based) can be used to predict the state of stress in a pavement under simulated wheel and environmental loading conditions. The models that primarily fall into this category are those based on multilayer elastic (MLE) theory and FE analysis. The MLE models are considered satisfactory for predicting flexible pavement response under external wheel loads and are also relatively easy to operate, fast-executing, and widely used. They are not capable of predicting pavement response associated with any environmental loading (i.e., that due to daily temperature changes, temperature gradients, moisture variations, etc.). FE models are also very good for predicting pavement response and are capable of considering both wheel and environmental loading. Unfortunately, they are complicated to operate and time-consuming, and therefore are not typically used for M-E flexible pavement design. Another emerging analytical modeling approach, fracture mechanics, may eventually find its way into future M-E design procedures.

Transfer Functions

A multitude of relationships have been developed to relate the state of stress in a pavement to its overall performance. In current M-E design procedures for flexible pavements, the primary transfer functions are those that relate (*a*) maximum wheel load tensile strain in the hot-mix asphalt (HMA) surface layer to eventual fatigue cracking and (*b*) wheel load compressive stress (or strain) at the top of the subgrade layer to rutting at the surface. These models are typically derived through statistically based correlations of pavement response with observed performance of laboratory test specimens, full-scale road test experiments (such as that conducted by the American Association of State Highway Officials), or by both methods. Transfer functions are the most important component of an M-E design procedure; unfortunately, a lot of models are available that do not show good agreement. (It is hoped that the planned 2002 AASHTO Guide will establish the best models for nationwide application.)

Traffic Loading Simulation Models

One component of the state-of-the-art flexible pavement design procedure that is very similar to the state-of-the-practice methodologies is traffic load simulation. The variety of wheel loads in the traffic stream and their cumulative applications are converted into a single number of 80-kN ESAL applications using a load equivalency factor (LEF) concept that was developed over 40 years ago. This methodology still has some validity; however, it has several weaknesses when it comes to considering the impacts of higher tire pressures and new tire types and axle configurations. Also, the current AASHTO LEFs were developed only on the basis of how wheel load affected pavement serviceability. At least one recent study (*4*) has demonstrated that the LEFs should also be dependent upon the type of distress being predicted. The new load-spectra approach planned for the 2002 AASHTO Guide should address some of these problems.

Material Characterization Methodologies

One of the benefits of the M-E methodologies (ideally) is that they rely primarily on a fundamental engineering property of the individual pavement and soil layers to determine the state of stress and predict pavement performance. That property is the elastic modulus, and its benefit over other index properties such as AASHTO layer coefficients, *R*-value, and CBR is that it is a direct effect in the analytical models used to predict the state of stress. Despite this key advantage, there are some significant problems associated with its use. One is that pavement materials are not elastic. Accordingly, a surrogate for elastic modulus (resilient modulus) is used to characterize a given layer material's bending resistance under the state of stress it will experience in situ. Another problem (which is still minor in comparison with the characterization of index properties) is that it is difficult to accurately measure resilient modulus in the laboratory while loading conditions are being simulated in the field. Although improvements to the laboratory-based resilient modulus test method are anticipated, a second method involving the use of nondestructive testing and backcalculation analysis holds more hope. In this latter approach, measurements of surface deflection are obtained nondestructively in the field and then evaluated mechanistically (using a computerized process known as backcalculation) to determine each layer's in situ resilient modulus. This process is especially useful for rehabilitation design but also has some application for new pavement design (if the nondestructive test measurements are obtained along the planned road alignment).

Life-Cycle Cost Model

Life-cycle cost (LCC) analysis is considered a state-of-the-art component in a pavement design procedure, although it is not at all tied to the M-E design principles discussed thus far. LCC analysis provides a sound basis for economically evaluating a number of feasible pavement design alternatives to identify one that may be the most cost-effective to build and maintain. The candidate costs that can be considered in a LCC analysis are

- Initial construction,
- Maintenance,
- Rehabilitation,
- Salvage value,
- User delay (during future maintenance or rehabilitation), and
- Vehicle operating cost.

The first four are agency costs that typically have the most impact on strategy selection. However, when considered, the last two user costs have been shown to have a major effect on the selection of a strategy that is most cost-effective overall.

Reliability Model

Reliability is a feature that was incorporated into the AASHTO Guide published in 1986 in order to account for much of the uncertainty in determining design inputs and predicting pavement performance. Like LCC analysis, it is not a process that is related to the M-E pavement design principles. However, it is a process that complements M-E design well and is planned for use in the 2002 AASHTO Guide. The process associated with reliability involves an assessment of stochastic variability of the design inputs as well as prediction error in the transfer functions so that a structural design can be established in which there will exist some level of confidence that the design will survive the intended service life.

A LOOK TO THE FUTURE

A look to the near future (as discussed above) indicates that one key step in the improvement of flexible pavement design is already taking place, that is, development of the 2002 AASHTO *Guide for Design of New and Rehabilitated Pavement Structures*. This step will not only result in a major enhancement over the current 1993 AASHTO Guide, but will also help establish some badly needed credibility for the use of modern pavement design procedures by both state and local highway agencies.

There are four other key areas of flexible pavement design that this committee believes ought to be addressed as the industry moves into the new millenium.

Incorporation of LTPP Findings

Under the current schedule, field data collection associated with the Long-Term Pavement Performance (LTPP) studies will be completed within the next seven or eight years. Although some preliminary data analyses are envisioned or are already under way, completion of field monitoring and finalization of the LTPP database will set the stage for a whole new round of comprehensive data analyses. These future research efforts will have a variety of different goals, including the development of new transfer functions, prediction models, and M-E design procedures that would likely be incorporated into a new version of the AASHTO *Guide for Design of New and Rehabilitated Pavement Structures*. A plan for these research and development efforts is on the drawing board, and this committee is poised to participate in whatever conceptualization, marketing, and implementation efforts will be required.

Accelerated Pavement Testing

There is a strong belief that more field experiments will be required to investigate various paving treatments, construction practices, and quality control processes that do not currently have a well-accepted basis in design. Among these are

- Geosynthetic materials (placed either in the subsurface layers or in the HMA surface itself),
- South African inverted pavement design, and
- Control of construction variability.

Some of these processes can be modeled mechanistically. However, good field data are necessary to verify or calibrate the resulting methodologies.

The kind of experiments envisioned here are those that can be carried out either under an accelerated-load facility (ALF) or in a full-scale test facility. Examples of the first type of facility include FHWA’s ALF, the California Department of Transportation heavy vehicle simulator (HVS), or the Texas Department of Transportation mobile load simulator (MLS). Examples of a full-scale test facility include Nevada Automotive Test Center’s WesTrack and the new track being constructed at the National Center for Asphalt Technology in Alabama.

Vehicle-Pavement Interaction

Vehicle-pavement interaction is an issue that has received some attention over the years but that has yet to have any significant impact on flexible pavement design. Past studies have focused either on the effect of vehicle dynamics on accelerated pavement deterioration or on the damaging effects of rough pavements on trucks. Considering the hundreds of billions of dollars that are spent every year on both the preservation of the highway infrastructure and the transport of goods (by trucking) throughout the nation, would it not be a good idea to determine the combination of maximum axle load (or gross vehicle load) and pavement structural cost that produces the least overall cost to the U.S. taxpayer?

Closing the Gap

As mentioned previously, closing the gap refers mainly to the need to bring the state of the practice in flexible pavement design closer to the state of the art. Although there is always going to be resistance to the adoption of any new technology in any field of engineering, it has been especially difficult in the specialized field of pavement engineering. The primary reason for this is the perception by much of the highway community that pavement structural design can be adequately accomplished using simplistic design procedures involving index values to represent material properties, traffic, environment, and pavement condition. This perception is difficult to change because premature failure of a pavement is not considered catastrophic (as in the collapse of a bridge or the failure of a dam). Although there are certainly situations in which simplified procedures are appropriate (i.e., low-volume roads, residential streets, etc.), they are definitely inappropriate for situations in which pavement construction costs are going to be in the millions of dollars.

One of the ways of closing the gap is to provide comprehensive training on the use of the new technologies and the benefits they provide in terms of avoiding premature failures and maximizing cost-effectiveness. Training offered through FHWA's National Highway Institute is one of the best examples of this process. Unfortunately, training by itself does not usually change practice, especially when policy and the level of practice are established at the higher administrative levels of highway agencies.

Another potential way of addressing the problem is to heighten the perception of pavement engineering as a discipline by having AASHTO or FHWA certify individuals as having achieved a certain level of pavement engineering training and experience. Once the program is established, and assuming that they will be thoroughly trained on the use of state-of-the-art methodologies, certified pavement engineers will very likely become the individuals who will be responsible for pavement design in the future. Accordingly, highway agencies and the public in general would have some assurance that the billions of dollars being spent nationally on highway design and construction are being spent wisely.

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