TRANSPORTATION RESEARCH

CIRCULAR

Number E-C209 July 2016

Integrating Asphalt Mixture Design, Structural Design, and Construction Quality Control

TRANSPORTATION RESEARCH BOARD

TRANSPORTATION RESEARCH CIRCULAR E-C209

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For the
Standing Committee on Characteristics of
Asphalt Paving Mixtures to Meet Structural Requirements

July 2016

Transportation Research Board
500 Fifth Street, NW
Washington, D. C.
www.TRB.org

TRANSPORTATION RESEARCH CIRCULAR E-C209
ISSN 0097-8515

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Preface

This e-circular provides an overview of some of the benefits and issues related to integrating asphalt mixture and structural design under the low-bid process in the United States. The e-circular is grouped into five areas:

1. An overview of the mechanistic–empirical (M-E) structural design process for both new pavements and overlays, focusing on the *Mechanistic–Empirical Pavement Design Guide* (MEPDG).
2. Potential benefits of the integrated design procedure, in terms of pavement performance and in terms of complexity and equipment costs.
3. A listing and discussion of some of the practical issues and impediments for adopting an integrated design system related to materials characterization and structural design.
4. Asphalt mixture properties that are common to the structural and mixture design process and how those properties affect distortion, fracture, and other pavement distresses.
5. Potential costs and time to complete an integrated design and the commercial resources that will be needed on a day-to-day basis; in other words, the practical complexities of the process, and the equipment needed in support of that integrated design procedure.

This volume is targeted for agency, consultant, and industry engineers involved in pavement design, asphalt materials, and construction specifications for flexible pavements and asphalt overlays.

The opinions and recommendations are those of the authors of this e-circular and not of the standing committee sponsoring this document or of the Transportation Research Board.

Contents

Introduction

The asphalt mixture design process most common in the United States is to have the contractor responsible for the asphalt mixture design, while the agency maintains responsibility for the structural design and confirming the mixture design. Researchers and consultants have recommended for decades that asphalt mixture and structural design be integrated into one system (*1–2*). Unfortunately, these two operations remain independent functions—even when both are the responsibility of the agency or same organization on a day-to-day basis.

The major reason for this independence is that most agencies use the 1993 AASHTO *Design Guide* for structural design and the Superpave–gyratory volumetric method for mixture design (*3*). These design procedures are based on and use different material properties and design criteria. As a result, it is difficult to determine or know what impact asphalt mixture volumetric properties have on the structural layer coefficients. Thus, some asphalt mixtures placed have not performed as expected and the reliability of the structural design is unknown.

Presently, there is a move to use structural design procedures that are based on M-E principles. The latest one was developed under NCHRP 1-37A: *Development of the Structural Design Procedure for New and Rehabilitated Pavement Structures*; referred to as the *M-E Pavement Design Guide*. These procedures use both volumetric and fundamental material properties, such as modulus and strength, to characterize the asphalt mixture.

There has been extensive work over the years to optimize the asphalt mixture properties for maximizing service life of new flexible pavements and asphalt overlays of both flexible and rigid pavements. The new MEPDG is one procedure that has the capability to tie mixture design to structural design to performance-related specifications.

Benefits of an Integrated Design System

The following list includes some of the benefits that are likely to come from implementation of an integrated structural and asphalt mixture design system, assuming that the specifications are enforced during construction.

1. Comprehensive approach to pavement design considering structural and material properties, as opposed to a thickness design procedure that provides the ability to directly consider different design features and their impact on reducing surface distress.
2. Application of structural and mixture design to construction operations and material specifications.
3. Performance that is based on distress and on ride quality that can be quantified. Performance-related specifications can be developed from measurements used in the design procedure and failure criteria used.
4. Ability to incorporate available paving materials and innovative materials and determine the effect of noncompliance of materials on performance. The system also provides agencies with the ability to extrapolate from limited field and laboratory studies.
5. Establishment of acceptance criteria and specification limits that are based on the design procedure giving weight to the design criteria and specification limits, allowing an agency to quantify pay factors—both incentives and penalties.
6. Assistance in development of performance-related or -based specifications and the criteria used in the specifications. This benefit can also be used to help establish policy decisions on technical as well as nontechnical issues.

Mechanistic–Empirical Design Methodology and Overview

Figure 1 is a conceptual schematic of the three-stage design process of the MEPDG. The general logic of the pavement prediction system is a combination of five basic modules that are common to most M-E design procedures:

1. Climatic module;
2. Traffic module;
3. Material characterization module;
4. Structural response module; and
5. Transfer functions and the distress–performance prediction module.

The above modules, the input scheme, and calibration parameters are discussed in the following sections of this e-circular.

INPUTS MODULE

The MEPDG uses a hierarchical approach for determining the inputs that are required to execute the program and predict pavement deterioration over time. There are three hierarchical levels of input for most parameters, which are defined below.

- **Level 1**. Level 1 input values are used when the designer has specific measures of the input parameter for the project. Level 1 input values are site specific inputs and considered the most accurate, because they are determined from actual measurements from the site or project. Obtaining Level 1 input values require more resources and time than the other levels. As an example, Level 1input values would include laboratory measured dynamic modulus of asphalt mixtures.
- **Level 2**. Level 2 input values are used when the designer has a modest or moderate indications of the input parameter for the project. This level could be used when resources or testing equipment are not available for tests required for Level 1. Level 2 input values are determined from regression equations or the use of regional values—they are not project specific. As an example, Level 2 input values would include calculating the dynamic modulus for an asphalt mixture from volumetric and material properties.
- **Level 3**. Level 3 input values are used when the designer has limited information regarding the input parameter for the project. Level 3 input values are the least accurate because they are determined from default values—a best-guess value provided in the program. As an example, Level 3 input values would include estimating the dynamic modulus for an asphalt mixture from the performance grade of the asphalt and gradation.

This hierarchical approach for defining the inputs to the program was adopted to simplify and facilitate the implementation process of the MEPDG. This approach will allow agencies with little experience in more-advanced materials characterization to use the program with a relatively low investment cost—a definite advantage. The hierarchical approach, however, complicates the calibration–validation process and definitely increases the number of data elements that need to

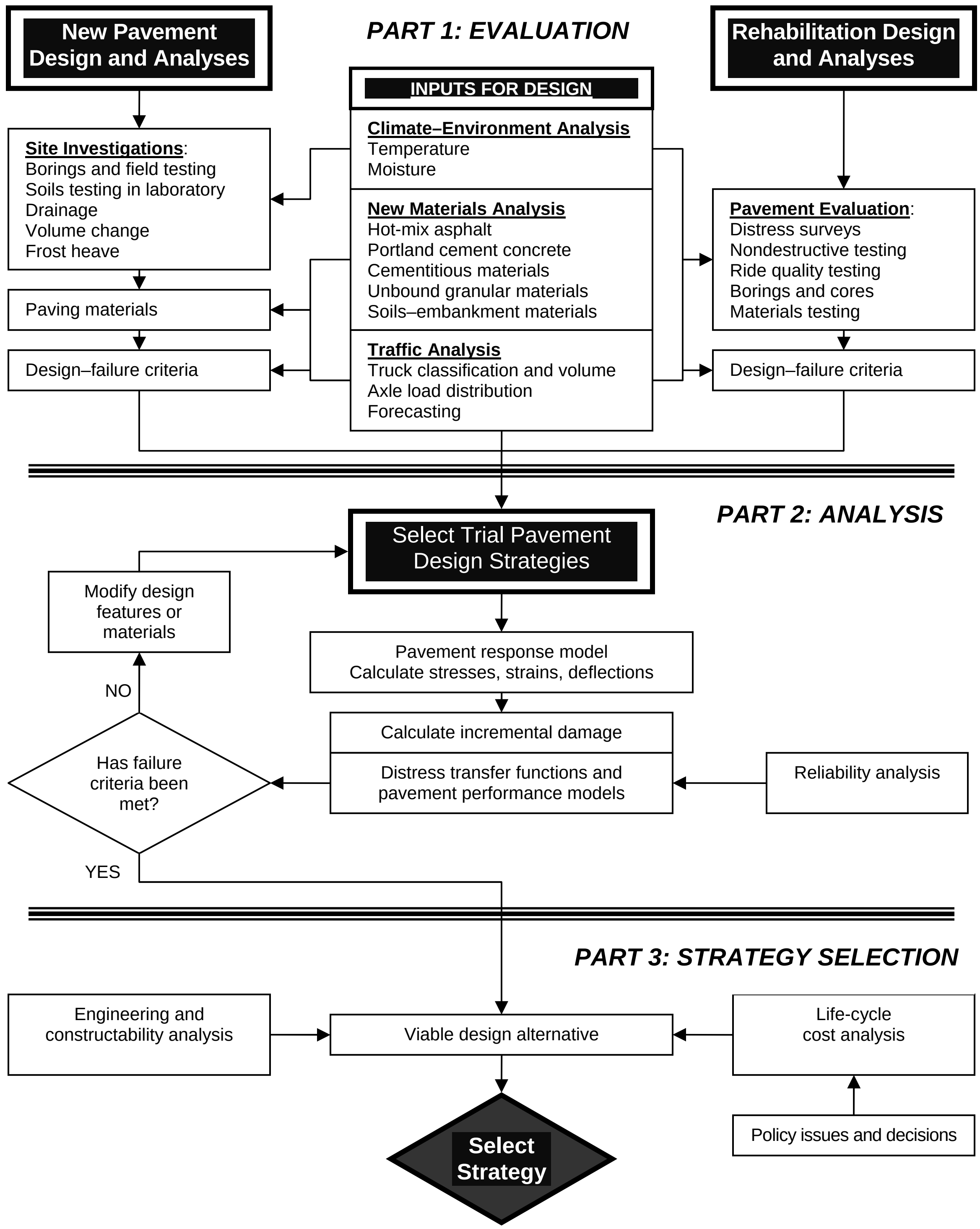

FIGURE 1 Conceptual schematic of the three-stage design process for the MEPDG.

be considered in developing the schema for the global database for refining M-E design and analysis procedures.

CLIMATIC MODULE

The climatic module predicts the spatial and temporal variations of temperature and moisture content within the pavement structure and foundation. The climatic or environmental effects model embedded in the MEPDG is the Enhanced Integrated Climatic Model (EICM), developed by the University of Illinois. The climatic data needed for this model comes from actual or virtual weather stations.

TRAFFIC MODULE

The MEPDG considers truck traffic loading in terms of axle load spectra for each axle type (single, tandem, tridem, and quadruple axles). The truck traffic module is used to compute the axle load spectra: the number of axle applications within each axle load increment for each axle type. The model uses the FHWA standard axle load increments for each axle type and the standard truck classes 4 through 13. The number of axle applications by axle type within each load interval is determined within specific time intervals on a daily basis. The number of axle loads is increased by a growth factor for each year in the design–analysis period.

MATERIALS CHARACTERIZATION MODULE

The material characterization module describes how the various materials in the pavement system respond to traffic loading and environmental changes. Different material characterization models are required for the different categories of materials in the pavement cross section (e.g.; asphalt mixture, unbound materials, stabilized layers). The major material characterization models for flexible pavements include the following:

- Asphalt mixture—loading rate, temperature, and aging-dependent linear elastic material as characterized by the complex modulus (E^*), phase angle (ϕ), and Poisson's ratio (ν). The materials that are applicable to this category include dense- and gap-graded asphalt mixture; asphalt-treated or stabilized materials; open-graded or asphalt-treated permeable base; and cold-mix asphalt.
- Unbound materials (base, subbase, subgrade)—either a linear elastic material characterized by Young's modulus (E) and ν or a stress-dependent nonlinear elastic material characterized by stress-sensitivity parameters k_1, k_2, k_3, Poisson's ratio (ν), and a tension cut-off criterion. The materials that are applicable to this category include crushed stone, pit run aggregate, sand and other base and subbase aggregates, as well as subgrade soils.
- Stabilized materials (base, subbase)—a stiffness-degrading linear elastic material characterized by E and ν and a stiffness degradation function. The materials that are applicable to this category include portland cement concrete (PCC), cementitious treated or stabilized base, and open-graded or cement-treated permeable base.

The material characterization module is generally considered to be the most important to the performance predictions because it affects, to some degree, all components of the system. This one module must also be tied to the asphalt mixture design method in preparation for an integrated design system.

STRUCTURAL RESPONSE MODULE

The structural response module calculates the stresses, strains, and deflections due to traffic loads and environmental influences. Environmental influences may be direct (e.g., strains due to thermal expansion or contraction) or indirect via effects on material properties (e.g., changes in stiffness due to aging, temperature, or moisture effects).

The MEPDG contains two pavement response models for flexible pavements. The JULEA multilayer elastic theory program is used in cases where all of the unbound layers in the pavement are treated as linear elastic. The DSC2D nonlinear finite element program is used in cases where stress dependency of the unbound material is to be considered in the performance or distress calculations. The JULEA program was used in calibrating the distress prediction models, because it is likely to be used for most pavement designs and analyses. These structural response models require several inputs, including:

- Traffic loading in terms of the axle load distribution for each axle type, and the wheel load location and tire pressure;
- Pavement cross section, including material type and layer thickness;
- Poisson's ratio for each layer;
- Young's modulus for each layer (determined from the dynamic modulus master curve for asphalt mixture materials, resilient modulus for unbound materials, and the elastic modulus for PCC materials);
- Interface friction between adjacent layers; and
- Coefficient of thermal expansion [for asphalt concrete (AC) and PCC surface materials].

Given these inputs, the structural model calculates stresses, strains, and displacements at critical locations in the pavement and foundation layers. Air temperatures, rainfall, and other climatic parameters are also needed and extracted from actual weather stations to calculate some of the above inputs. For example, the elastic modulus of asphalt mixtures varies with depth and season.

This approach allows the use of an elastic modulus within a given time period, such as a month, that is representative of that time increment. Thus, the dynamic modulus of asphalt surface layer is much lower in the summer than in winter. This procedure also allows for the asphalt materials to age or oxidize with time. This is modeled so that the dynamic modulus ($|E^*|$) of the asphalt mixture is constantly increasing with time. The resilient modulus of an unbound base course and fine-grained soil vary with degree of saturation. The EICM calculates the change in moisture content over time and uses this change in moisture content to vary the resilient modulus of the unbound materials and soils.

DISTRESS PREDICTION MODULES AND TRANSFER FUNCTIONS

The distress prediction modules utilize the transfer functions to convert the calculated pavement responses into predicted performance. This operation represents the backbone of the M-E design and analysis procedure, as well as any other model based on M-E principles.

As a simple example, to illustrate the concept of integrating structural design and mixture design, the following two Asphalt Institute models are utilized.

For fatigue, the number of strain repetitions to failure (N_f) is determined by the following equation. A model similar to this one is used in the MEPDG.

$$N_f = 18.4\,(C)\,(0.004325)\,(\varepsilon_t^{-3.291})\,(|E^*|^{-0.854}) \tag{1}$$

where

ε_t = the maximum horizontal tensile strain created at the bottom of the AC layer (in./in.);
$|E^*|$ = the dynamic modulus of the AC (psi);
C = a factor used to incorporate the effect of the volumetric mix design parameters of the AC = 10^M, M = 4.84 [(V_b/V_v+V_b) – 0.69];
V_b = the percent volume of asphalt binder in the mixture; and
V_v = the percent volume of air voids in the mixture.

For subgrade rutting, the number of strain repetitions to failure is determined by the following equation:

$$N_f = 1.365 \times 10^{-9}\, \varepsilon_c^{-4.477} \tag{2}$$

where ε_c is the maximum vertical compressive strain created at the top of the subgrade.

For dynamic modulus, the following default relationship is included in the MEPDG for the user to utilize if no dynamic modulus is available:

$|E^*|$ = f (asphalt binder viscosity, load frequency, percent air voids, percent effective bitumen content, percent aggregate retained on the 19-mm sieve, percent aggregate retained on the 9.5-mm sieve, percent aggregate retained on the 4.75-mm sieve, percent aggregate passing the 0.075-mm sieve)

An integrated design process would work by doing numerous iterations of running models such as these. To start, the stress–strain pavement structural analysis model (i.e., layered elastic, finite element) would be used to calculate the critical strains in the pavement (ε_t, ε_c) using relevant traffic inputs as well as the material characteristics adjusted by the climactic model. The asphalt mixture stiffness would either be measured $|E^*|$ data or a calculated $|E^*|$ from the default model, using the specific asphalt binder grade (viscosity), aggregate gradation, asphalt binder content, and percent air void information obtained from the mix design. Next, the fatigue life would be determined utilizing ε_t from the structural analysis model, the $|E^*|$, and the V_b and V_v obtained from the mix design in the fatigue equation into the fatigue transfer function. The $|E^*|$ used also affects the magnitude of ε_t. Then the subgrade rutting service life would be determined based on the ε_c from the structural analysis model, which is also affected by the $|E^*|$ of the AC layers, the overall structural cross section, traffic loads, and the temperature.

If the resulting service lives obtained (for fatigue or subgrade rutting) are not adequate for the pavement facility to be constructed, then the design team has many options at their disposal to adjust. The thicknesses of the various layers could be increased as in the past. However, now that an integrated design system is available, the team could also discuss making changes to the mix design, such as asphalt binder content, air voids, binder grades, aggregate gradation. An integrated design system provides the tool to investigate how each of these parameters impact the ultimate performance of the pavement.

Eventually, with time and experience, a feedback loop of information resulting from these iterative designs may lead to changes in the way an agency operates. After observing how performance is directly affected by the mixture volumetrics, the agency may change the way they do mix design by modifying the mix design criteria, the targets which are used to create the ultimate job mix formula. The team could also look at other more innovative materials in the AC component of the entire cross section to change the volumetric requirements, $|E^*|$ (and indirectly the calculated critical strains), or the performance prediction equation itself.

Ultimately, with this information feedback, the agency may become more aware of which mix and structural design parameters are more sensitive to causing an impact on performance and how sensitive each parameter is. By knowing this sensitivity and verifying the accuracy of the design method, the design team may want to institute or modify the construction quality assurance pay factor system used to penalize or award bonuses to the paving contractor. Different parameters may come to light or the existing parameters may need to be weighted differently. All of this development would take time and verification of course, but the evolving tool to assist with making these important decisions, the integrated design system, would be available for all departments in an agency to work together and learn together.

The MEPDG is an even more complete procedure, which includes the capability to accumulate damage on a monthly basis (or bimonthly, depending on frost conditions) over the entire design period. This approach attempts to simulate how pavement damage occurs in nature, incrementally, load by load, over continuous time periods. By accumulating damage monthly, the design procedure is comprehensive.

The MEPDG includes transfer functions for permanent deformation or rutting, load related cracking, and nonload related cracking. Smoothness is predicted from regression equations. The final output from the prediction system is magnitude of pavement distress versus time. The following items are brief descriptions of the prediction models relative to the calibration of the MEPDG and the future refinement of that model.

- **Distortion or rutting**. The rut depth prediction models are based upon empirical relations between rut depths measured at the surface and mechanistically computed elastic strains in each pavement layer and foundation. The prediction model for asphalt mixture uses the concept of resilient to plastic strain ratio with number of load repetitions. The rutting model considers both volumetric rutting (that is, the predominately linear relationship between the logarithm of the inelastic strain and number of load cycles) in each layer and the important behavior associated with tertiary flow (or plastic flow) of asphalt mixtures. Permanent deformations are computed in each layer interval and then summed to predict the rutting observed at the surface.

- **Fatigue cracking**. The load-related cracking prediction models are based upon empirical relations between area and longitudinal cracking in the wheelpaths and a computed critical strain in the AC layers. The fatigue-cracking prediction model is based on the classical concept of microfracture propagating from the bottom of the AC layer, but also considers the ongoing developments to include more-recent concept of fatigue cracking initiating at the surface and propagating downward under NCHRP 1-52.
- **Thermal cracking**. The thermal cracking prediction model is based on an enhanced version of the model developed under the SHRP. This model is based on fracture mechanics and crack propagation law, which is also one of the model forms considered for fatigue cracking. The growth of thermal cracks in the AC layer is predicted using the Paris law from fracture mechanics.
- **Ride quality**. Pavement deterioration is quantified in terms of individual distresses (rutting, fatigue cracking, thermal cracking), and in terms of roughness or ride quality. Ride quality, as measured by the international roughness index (IRI), is calculated from these predicted and other distresses.

GLOBAL AND LOCAL CALIBRATION PARAMETERS

Although the MEPDG provides for an accurate simulation of the pavement cross section, the calibration and validation of the prediction models was an essential step in giving the design analysis credibility. The calibration and validation of the above prediction models was considered by many to be the most important activities to establish confidence in the design procedure and facilitate its implementation, acceptance, and adoption. Furthermore, it is commonly believed that the prediction models and design analysis procedure will not be accepted for routine use by the highway community if the validation results do not demonstrate reasonable correspondence between the field-observed and predicted distress levels.

The calibration–validation process for each of the distress prediction models was completed using test sections within the long-term pavement performance (LTPP) program. Although the LTPP database is one of the most comprehensive databases that have been put together on a global scale, it does have some limitations regarding validation of M-E distress prediction models. A few of the limitations are noted below.

- **Rutting**. Trenches needed to accurately determine the precise rutting components within the AC layer, all unbound paving layers, and foundation were not conducted as a part of the LTPP program and were outside the scope of work for NCHRP 1-37A. Thus, the surface rutting contribution from each layer was not confirmed through the calibration studies under NCHRP 1-37A. Further revisions and verification of the rutting models have been conducted through NCHRP Projects 1-40 and 9-30A.
- **Fatigue cracking**. Field-coring studies needed to ascertain the presence and frequency of both types of load-related cracking were not conducted as a part of the LTPP program and any field studies were outside the scope of work of NCHRP 1-37A. Thus, the type and direction of crack propagation could not be confirmed through the calibration studies under NCHRP 1-37A. Additional considerations of the top-down cracking evaluation are being considered through the efforts of NCHRP 1-52.

- **Thermal cracking**. The calibration–validation plan for thermal cracking considered how materials and structural factors affect the initiation and propagation of thermal cracks and the relative importance of single, large excursions in temperature compared to smaller temperature cycles. The question of how the age of a pavement and the rate of aging of asphalt mixes affect thermal cracking was considered, but that detail of data is not available for most of the LTPP test sections. This detail of data was measured on some of the earlier calibration–validation studies sponsored by the SHRP in developing the model and in recent updates to the thermal cracking prediction model. The number of LTPP test sections with sufficient data, however, is relatively small (less than 30). No additional calibration work was completed under NCHRP 1-37A for the thermal cracking model using Level 1 input values.
- **Roughness**. The calibration–validation plan for roughness or ride quality considered the potential impact of different distresses and site features on reducing the smoothness of asphalt overlays and pavements over time. The data from the general pavement study test sections were used for calibration and the data from the special pavement study test sections were used for validation. The SPS test sections are relatively new and most have exhibited only low levels of distress. Thus, validation of the IRI prediction equation needs to be updated as these sections begin to exhibit higher levels of distress.

The error of the prediction equation has a significant effect on the predicted distress at different confidence intervals. A large prediction error means that the design will be overly conservative and the cost of construction will increase for increasing confidence intervals. Local calibration parameters are used within the MEPDG software to minimize the error terms for predicting distress. All local calibration parameters were set to 1.0 for the global calibration using the LTPP test sections, but need to be defined by individual agencies. The local calibration effort needs to be clearly defined for the implementation of an integrated structural and mixture design system.

Impediments to Implementing an Integrated Design System

Figure 2 shows a simplified flow chart of the minimum steps needed to integrate a structural and asphalt mixture design procedure. The following is a description of the anticipated impediments to implementing such an integrated design system.

INSTITUTIONAL AND COMMUNICATION BARRIERS (TURF PROTECTION)

Structural and asphalt mixture designs are usually performed within different departments or by completely different organizations for some agencies. Institutional or communication barriers that exist at any level and for whatever reason will result in frustration and potential problems for the agency, contractor, and material suppliers.

Departments, as well as other organizations involved in highway design and construction, need to know what data are needed and how those data will be used and interpreted to establish the input values for structural design and criteria for mixture design. To minimize misinterpretation of data between departments within an agency, between the agency and industry, and reduce any "turf protection," a committee could be established—similar to the process used by some agencies in revising construction specifications to ensure industry support. This committee would consist of individuals from each department and organization who are responsible for providing data to establish inputs to the structural and mixture designs—to establish universal support across all departments within an agency for the integration plan.

A truly comprehensive pavement engineering effort would also include construction and management. Therefore it is also important to include personnel from the construction and pavement management functions within a given organization in the committee charged with integrating structural design and mixture design–material characterization. It is imperative that all pavement engineering stakeholders recognize the interrelated nature of the life cycle of a pavement—relative to materials, design, construction and rehabilitation—and the appropriate influential weight of their roles in that cycle.

RELUCTANCE OR RESISTANCE TO CHANGE FROM STANDARD PRACTICE: INSUFFICIENT CONFIDENCE IN NEW METHODS

Most agencies find it difficult or become nervous when adopting changes to the way they are accustomed to doing business on a day-to-day basis. For example, the 1993 AASHTO *Design Guide* requires the use of repeated load resilient modulus tests for characterizing paving materials and foundation soils. Resilient modulus test procedures have been available for multiple decades. Few agencies, however, require resilient modulus tests for design—correlations are used, which have been accepted without extensive data (*4*). Adoption of an M-E–based structural and mixture design method will be no different, in terms of resistance to change. The question is "Why?"

A major reason for this resistance to change is that the new method is not understood so the user has little confidence in that method and is worried about those embarrassing premature failures. To minimize the resistance to using M-E–based methods, training, and education

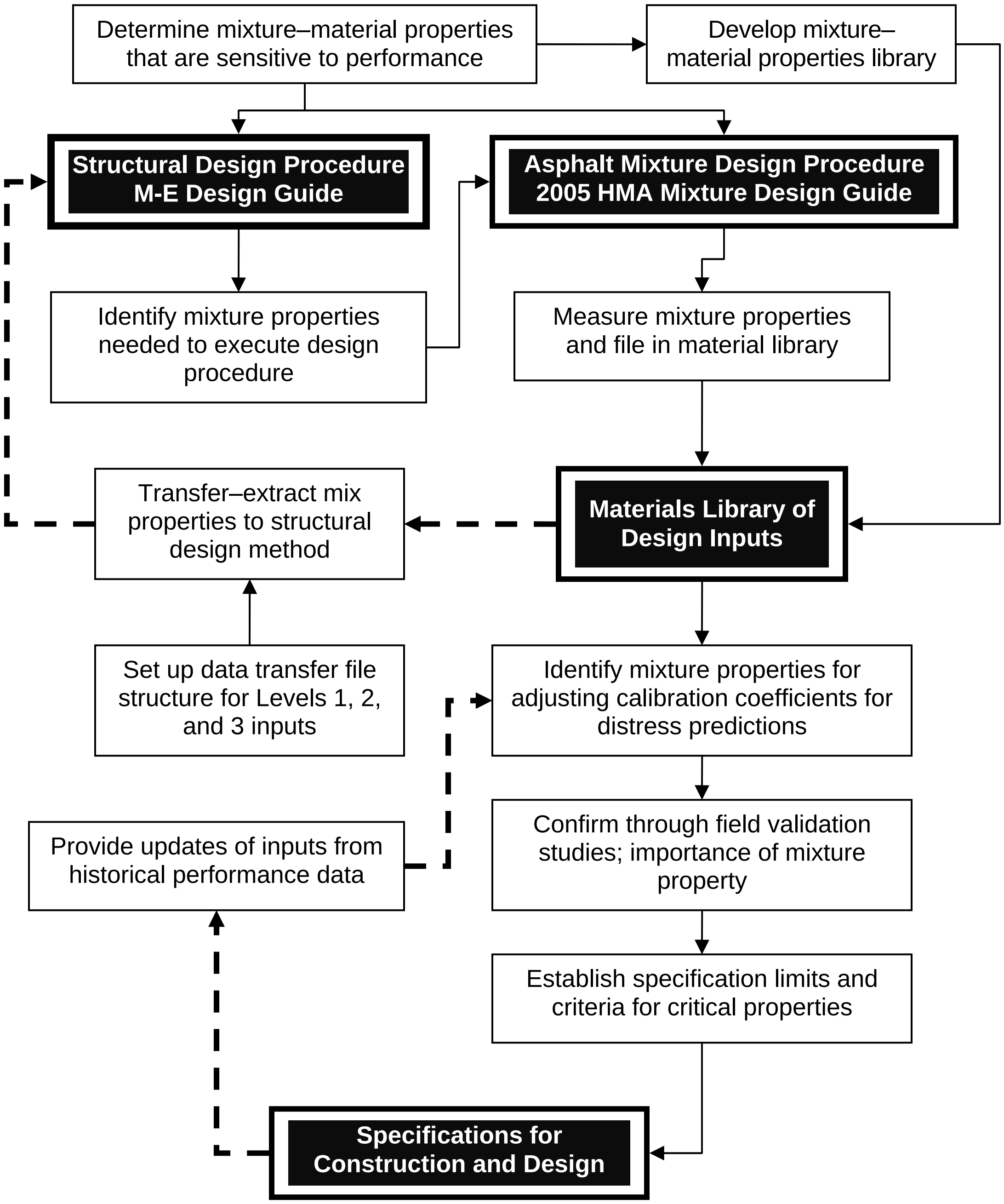

FIGURE 2 Simplified flow chart of the minimum steps needed to integrate a structural and asphalt mixture design procedure.

initiatives need to be at the forefront of the integration effort. Demonstration projects should also be planned over time, because they allow all parties of the structural and mixture design and construction teams to become familiar with and understand the process. A major component of the comfort level with the methodology should include confidence measures and limitations resulting from local calibration efforts to provide the users with highly applicable feedback from the design process. More importantly, the asphalt industry (contractors, consultants, and material suppliers) should be invited to attend seminars and open houses for these demonstration projects.

INCREASED COMPLEXITY OF DESIGN METHODS AS COMPARED TO TRADITIONAL PROCEDURES

One of the definite advantages of the 1993 AASHTO *Design Guide* is its simplicity and ease of use as a thickness design tool. The level of effort and costs to complete a new pavement design or rehabilitation design using the M-E–based methods will likely be greater. The M-E–based methods require many more inputs and material properties for pavement and mixture designs. Another impediment is that there is no manual solution to a specific design project. Agencies are used to being able to complete manual solutions with the 1993 AASHTO *Design Guide,* which can be made in a short time period. This restricts an agency's ability to do a quick check of a design through the older more familiar existing AASHTO structural design software (i.e. Darwin).

These impediments will be difficult to overcome based on the current programs and design methodology. The committee and champion of the M-E–based design method within an organization should clearly acknowledge these facts but also acknowledge the benefits that can be achieved by implementing and integrating the design system. Training programs to educate and therefore help reduce the time needed for determining the input values and executing the software will reduce but not eliminate the frustration with these two impediments.

Regarding training for M-E–based structural design procedures, a word of caution is warranted. Training a pavement design engineer (or mix design engineer) simply to generate an input value or to run an M-E computer program is not the goal. To aid the long-term implementation and acceptance of an M-E design system, design personnel need to understand the concepts of M-E design and the interrelated nature of materials, structural design, and construction. Indeed, M-E design procedures offer the design professional the opportunity to truly design a pavement system—if the concepts are fully understood. Thus, training efforts should seek to both educate key personnel about the background of the material and pavement models involved and then train them on the practical use of these models in the software.

ADDITIONAL COSTS AND TIME FOR PAVEMENT AND MIXTURE DESIGNS

One of the more significant impediments to using M-E–based design software and implementing an integrated design system is the amount of computational run time for analyzing flexible pavements and asphalt overlays. Most 10-year designs require less than 5 min of computational time and more than 10 min for 20-year designs.

In addition, some M-E–based methods do not compute the required layer thickness for specific site conditions. M-E–based methods compute the magnitudes of various performance indicators. A series of software runs is usually needed to optimize multiple design features. To make these computations, more laboratory testing (test specimens and different tests) will be needed. Initially, agency personnel will have minimal experience and knowledge in many areas required by M-E–based methods. This issue of more costs and time will likely hamper and impede the support of an integrated design system.

A method that agencies can use to minimize the number of design iterations and reduce the frustration with having to rerun many problems is to produce a catalog of trial structural designs and rehabilitation strategies that satisfy the failure criteria adopted by the agency. This catalog of designs should be based on an agency's previous experience, the performance of their traditional designs, policy decisions, and M-E–based software.

Some agencies will have insufficient funds to purchase the field and laboratory equipment needed for materials testing to determine the input values for structural design (*7*). Obtaining the equipment will necessarily occur over time, especially in decentralized agencies. Significant training and education efforts will be required for performing the tests and operating the software.[1] Thus, implementation of an integrated design system needs to be planned over a period of time.

The field and laboratory equipment purchases should be planned so that training can occur simultaneously among the different departments and industry. Those agencies that allow contractors and consultants to complete the structural and mixture designs will also need to communicate and coordinate with the asphalt industry. The training and educational plans should be developed by both the agency and industry groups working together and the benefits of the integrated system should be documented.

USE OF PROOF TESTS FOR CONFIRMATION OF MIXTURE DESIGNS (COMPLETED BY CONTRACTOR OR AGENCY ITSELF)

More agencies are beginning to use proof tests to confirm the adequacy of asphalt mixture designs, as part of their day-to-day practice. For the prevention of premature rutting, these proof tests include the asphalt pavement analyzer (APA) [Missouri Department of Transportation (DOT)] and Hamburg wheel loading devices (Texas DOT). Selected agencies have stated that they plan to retain the use of proof tests because they are perceived as being successful in identifying inferior mixtures (susceptible to stripping or distortion) prior to being placed by the contractor. Results from proof tests will probably be different for some conditions from the results of M-E–based mixture design tests that are used for measuring selected properties for structural design (see page 17, "Controversy on which Transfer Function Is the Best for Predicting Pavement Distress"). When this occurs, an agency may have less confidence in the M-E–based method.

Results from proof tests and M-E–based mixture properties likely will be different, because they are measuring different mixture responses under different laboratory conditions. The intent of the proof tests can still be retained in day-to-day practice, but this difference specific to each proof test will need to be explained and documented as part of the integrated design system. The use of proof testing was included under NCHRP Project 9-30A in terms of noting the differences between the results from the proof tests and M-E–based transfer functions used to predict rutting. Some of the demonstration field projects, referred to above, should include the use of proof testing as part of the day-to-day design practice of the agency.

MIXTURE PROPERTIES UNFAMILIAR OR NOT UNDERSTOOD BY AGENCY AND CONTRACTOR PERSONNEL

Unknowns Create Uncertainty or Reluctance to Support Integration

Under the low-bid system, the materials for pavement construction and asphalt-mixture design are usually not known when the structural designs are completed, except for bids submitted under the design–build and similar concepts. Agency and contractor personnel have little historical experience with the mixture property inputs needed for the structural design procedure or how to establish mixture-specific design criteria for those properties. With the implementation of any new structural design process, agency and industry personnel will need time to understand the mixture properties and their effects on the mixture and structural design process. In other words, agency and contractor personnel need to know how changes in a volumetric property or mix component that are controlled by the contractor affect the fundamental properties assumed and used for structural design.

Asphalt material and mixture property libraries will need to be established within agencies to support the use of the structural design method, which are consistent with those parameters, criteria, and construction requirements used in the mixture design method and quality assurance (QA) program. A feedback plan or data storage capability needs to be included so that an agency can update or confirm the properties being used for structural design and identify any necessary changes in those properties over time. As suggested previously, construction is a vital component of the pavement engineering system. It is important that data feedback and storage systems include provisions for construction-related as-built material properties and structural section (e.g. as-constructed layer thickness) data.

Agencies should also take full advantage of work performed by other agencies in support of M-E–based procedure implementation. In this context, it is imperative that design personnel get acquainted with and remain aware of all work performed to characterize the relationship between material mixture properties and M-E design outputs. Historically, there has been a tendency for many agencies to discount or dismiss work performed elsewhere, because a given study “didn’t use our materials.” Taking advantage of the complete body of applicable knowledge available will allow agencies to more efficiently invest monies and effort in those areas having the greatest additional benefit to implementing an integrated design system.

CERTIFICATION OF PERSONNEL AND EQUIPMENT

Most of the test procedures being used to measure the asphalt mixture properties that are needed for structural design are not included in the AASHTO Materials Reference Library certification program. Personnel need to become proficient in the new structural property test methods that will be used in the integrated system for structural and mixture design. The certification issue becomes critically important for those agencies where the contractor is responsible for the mixture design and the agency confirms that design, as well as for QA programs. This impediment can be overcome with time provided some funding is dedicated for this additional training.

CONTROVERSY ON WHICH TRANSFER FUNCTION IS THE BEST FOR PREDICTING PAVEMENT DISTRESS

Because pavement behavior and performance is complicated, a perfect model for predicting pavement distress over time does not exist. All prediction models have errors. More importantly, multiple transfer functions are typically available for use in predicting the same distress. When any new design method is developed, there is debate within the research community regarding the model errors and applicability of the model: model A versus model B. Debate and discussion on the model limitations and statistical error is good, but to the practicing engineer, this debate can reduce confidence in all prediction models, increasing the reluctance of some agencies for adopting any of the design methods.

However, agencies must remain open to new methods and not become paralyzed, avoiding all advancement while waiting for a given design system to be perfect. One of the strengths of an M-E design is that the basic concepts are relatively consistent, regardless of the specific models or transfer functions used within a particular design system. This advantage implies that certain material property and structural inputs are generally applicable to any M-E–based system. An agency can make real progress towards implementation of an integrated design system even in the midst of discussions revolving around specific model forms and coefficients.

UNREASONABLE PREDICTIONS FROM EXPERIENCE CREATE MISCONCEPTIONS AND REDUCE CONFIDENCE IN DESIGN PROCESS

As noted previously, all predictive models have errors and limitations. The transfer functions embedded in M-E–based software are no exception. An important impediment often observed comes from getting unreasonable predictions with the software as compared to an individual or agency's experience. Unreasonable predictions create frustration and reduce the confidence in the design process.

It is impossible and cost-prohibitive to include all possible materials and design scenarios used across the United States within the calibration and validation process of any national M-E–based design system. Agencies and organizations would benefit from sponsoring a local or regional calibration effort to reduce the error terms, as a part of the implementation plan for the integrated design system. The calibration and validation of the prediction models within an M-E design system is an essential step in giving the design analysis credibility. The calibration and validation of the M-E–based prediction models is considered by many to be the most important activity to establish confidence in the design procedure and facilitate its implementation, acceptance, and adoption. Furthermore, it is generally believed that the transfer functions (or prediction models) and design analysis procedure will not be accepted for routine use by the local highway community if the validation results do not demonstrate reasonable correspondence between the field-observed and predicted distress levels.

The M-E–DPM database developed under NCHRP 9-30 was created for this specific purpose (*6*). This database can be used to assist agencies in their local–regional calibration efforts and is a feature that agencies can use to store their calibration data for future use. In addition, an agency's pavement management database should not be overlooked as an additional resource for assisting in the local calibration effort.[2] The effectiveness and use of the pavement management database will depend on the specific details of the information included and maintained within that database. As part of the regional calibration and validation process, agencies would benefit from developing libraries of inputs to support the M-E–based design method and implementation efforts. Those libraries that will likely provide the greatest benefit and use include traffic, asphalt mixture materials, unbound aggregate base materials and soils, and construction QA data.

FUTURE CHANGES TO THE M-E–BASED MIXTURE TESTS: REPLACING TRANSFER FUNCTIONS OR M-E–BASED TEST PROCEDURES

Various agencies have recognized the benefit of implementing an M-E–based structural design procedure (such as the MEPDG) and sponsored projects to complete local calibration studies for the MEPDG. Some of these implementation projects have been completed or are nearing completion. Revisions–improvements eventually are expected to be made to the software and impact the local calibration parameters determined from some of the implementation studies, especially if different transfer functions are included in version 2.0 of the software.

Replacing transfer functions that require different tests will require additional validation–calibration activities, because the computational–test revision may also result in different local calibration parameters, particularly if the model better represents the real in-situ pavement. Changes to the computational methodology or test procedures should be accompanied by a briefing that discusses the impact that those changes will have positively on the bias and standard error of the transfer function and calibration coefficients. The overall issue is how to reduce the negative financial impact on agencies currently undergoing aggressive implementation activities and having the software changed or revised in the future. One of the greatest negative impacts for example, would be where a different test procedure is recommended for use in measuring a mix property and the agency has to purchase different test equipment and retrain their staff.

CLIMATIC EFFECT ON TEST CONDITIONS FOR STRUCTURAL AND MIXTURE DESIGN

Historically, the asphalt mixture design process or method has used one single test temperature for measuring specific mixture properties for selecting the target asphalt content for an asphalt mixture that will be used in any climate or environment. For example, both the Marshall and Hveem mixture design methods use this approach. The use of one test temperature may be insufficient for modeling mixture behavior within the integrated design process for projects located in various climates particularly with the implementation of material formulations which create asphalt mixtures that behave significantly different from the industry standard of unmodified or neat asphalt mixtures.

APPLICABILITY TO QUALITY ASSURANCE PROGRAMS AND TEST PLANS AND FORENSIC INVESTIGATIONS

Stated simply, there can be a bias between the structural, mixture, and forensic mixture tests and those tests used in QA programs. Calibration must mitigate this potential bias for project success.

For example, a good modulus for one project might be an inferior value for another project under different traffic, structural and climatic conditions. Figure 3 shows some of the calibration steps in the integrated design system approach to ensure that the flexible pavement will meet the desired expectations, such as reducing fracture, distortion, rutting, disintegration, and surface roughness over the design period.

Calibration of field and laboratory equipment is also important to reduce the error and variability in test results. However, calibration of the system (and operator) is equally important but often overlooked or confused with equipment calibration in many mixture and structural design projects. Various researchers have found that proper calibration of all aspects of the testing will be a critical element to the successful implementation and integration of mixture and structural designs.

Design Time and Effort

Is It Worth the Added Effort?

As noted previously, the level of effort and equipment needed to complete an integrated design will be greater than what has been required in the past. This section of this e-circular lists some of the additional laboratory and field testing equipment that will be needed for supporting the use of the MEPDG software, as an example of an M-E–based structural design system, to be integrated with, for instance, the Superpave mix design system. It should be understood that the MEPDG uses many more inputs to consider different pavement design features. Volumetric mix design and fundamental properties of each layer are considered to predict the performance and distress of trial pavement sections and materials.

The MEPDG has much more versatility and can incorporate more pavement features than most of the structural design procedures in existence today. These added beneficial features, however, require more design and testing time.

The test equipment needed to measure the mixture properties shown in Figure 3 is more complicated and sophisticated than typically used in an agency's laboratory. The test equipment and interpretation of the test results require extensive training for both agency and industry personnel. The following mechanical or engineering properties will either need to be measured or correlated through surrogate testing to implement the MEPDG, at a minimum:

- Fatigue cracking and rutting predictions:
  - Dynamic modulus master curve for asphalt mixture (triaxial or uniaxial testing) and
  - Repeated load resilient modulus for unbound materials and soils (triaxial testing).
- Thermal cracking predictions (at cold temperatures):
  - Creep-compliance master curve for asphalt mixture (indirect tensile testing) and
  - Indirect tensile strength for asphalt mixture.
- Local calibration of fatigue cracking and rutting predictions. Mixture tests and measured pavement condition data with time will be needed to determine the local calibration factors and values for different asphalt mixtures. These laboratory and field tests, which will be agency-dependent, have yet to be defined on a global basis, but could include the following on a local basis
  - Rutting torture tests: APA, Hamburg loaded wheel testers;
  - Triaxial repeated load permanent deformation tests and flow number determination;
  - Triaxial creep-compliance tests and flow time determination; and
  - Indirect tensile strength and failure strain at intermediate temperatures.

There is a shortage of laboratory test equipment and personnel within most agencies—at least in the beginning. Thus, advisory commercial resources may be needed for design services initially. Agencies would benefit from universities and other resource centers to establish initial mixture libraries that can be used for structural design purposes.

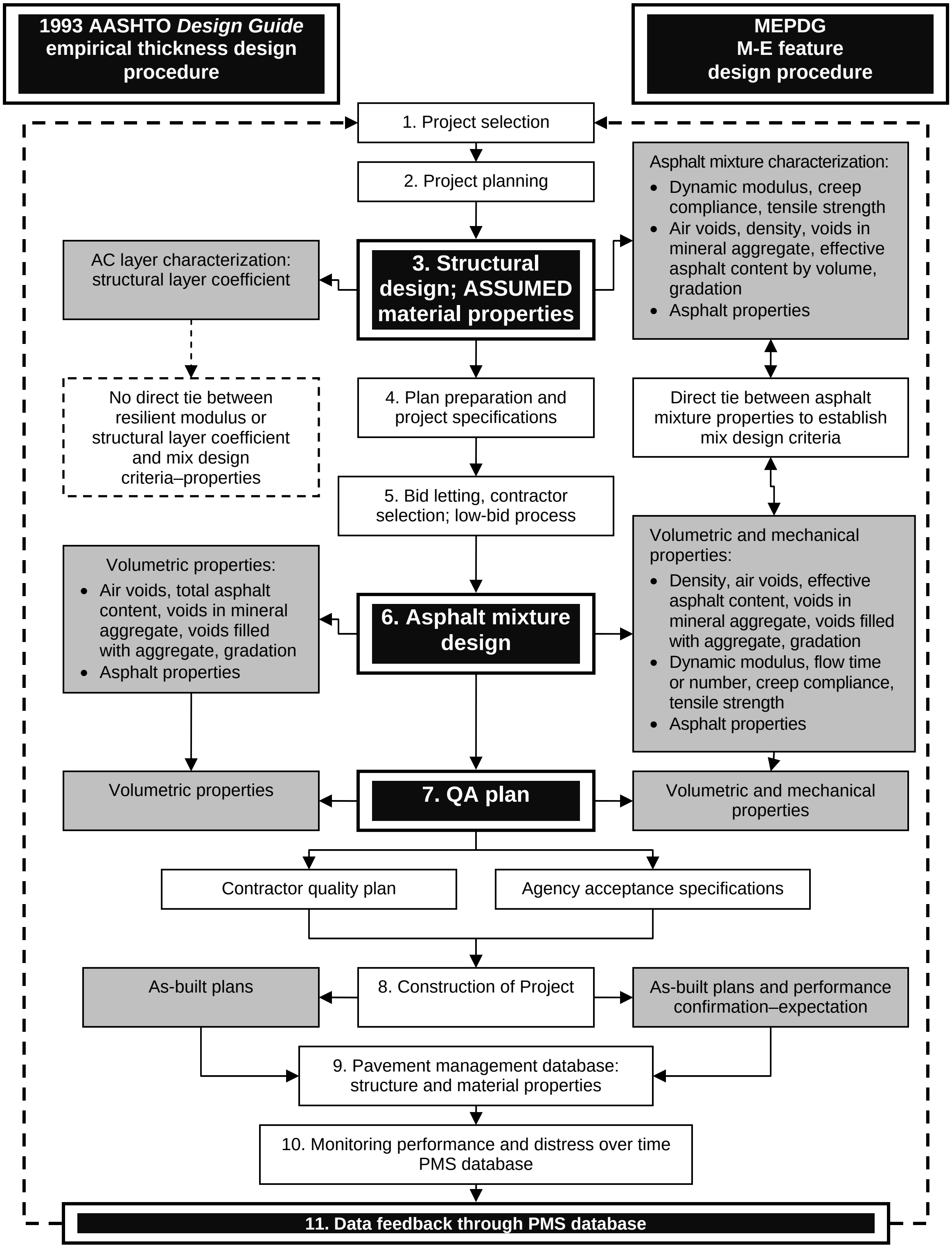

FIGURE 3 Typical steps involved in the design–construction process and the differences between an empirical–separate design process to that of an integrated M-E design system in terms of material characterization.

Design and Construction

Important Parameters

A key aspect of the successful implementation of the MEPDG necessitates that the final asphalt mixture produced meet the quality requirements initially assumed in the design stages of the project. While QA test results may permit the verification of individual test measures, most agencies do not have protocols in place to permit the retroactive adjustments to the design of a particular project dependent upon production mixture characteristics. This may initially appear as a significant limitation to M-E–based design systems, however the longevity of an agency's usage with the system will provide beneficial information. Continued verification of the predicted performance will help to account for overall variation at the agency level. However, project-specific variation or alteration to the typical production or construction processes will require more concentrated efforts.

Further, significant policy changes at the agency level may also produce bias into the effectiveness of the performance predictions. As an example, implementation of specification changes such as percent within limit specifications may substantially alter the consistency of typical asphalt production within a region. This may result in a shift in the performance of pavement sections produced following such an event, and may justify focused evaluations to quantify such impacts. The cost of such periodic evaluations may be offset by cost saving realized through optimized construction and rehabilitation schedules arising from the improvement in the production and construction practices.

Summary

Implementation of the MEPDG will not be a simple or easy activity. Implementation of the MEPDG and integration of the design system with mix design and construction activities will take time and effort. This e-circular has attempted to identify some of the more common impediments to this design process. Figures 3, 4, and 5 present a preliminary vision of an integrated design system in a low-bid process.

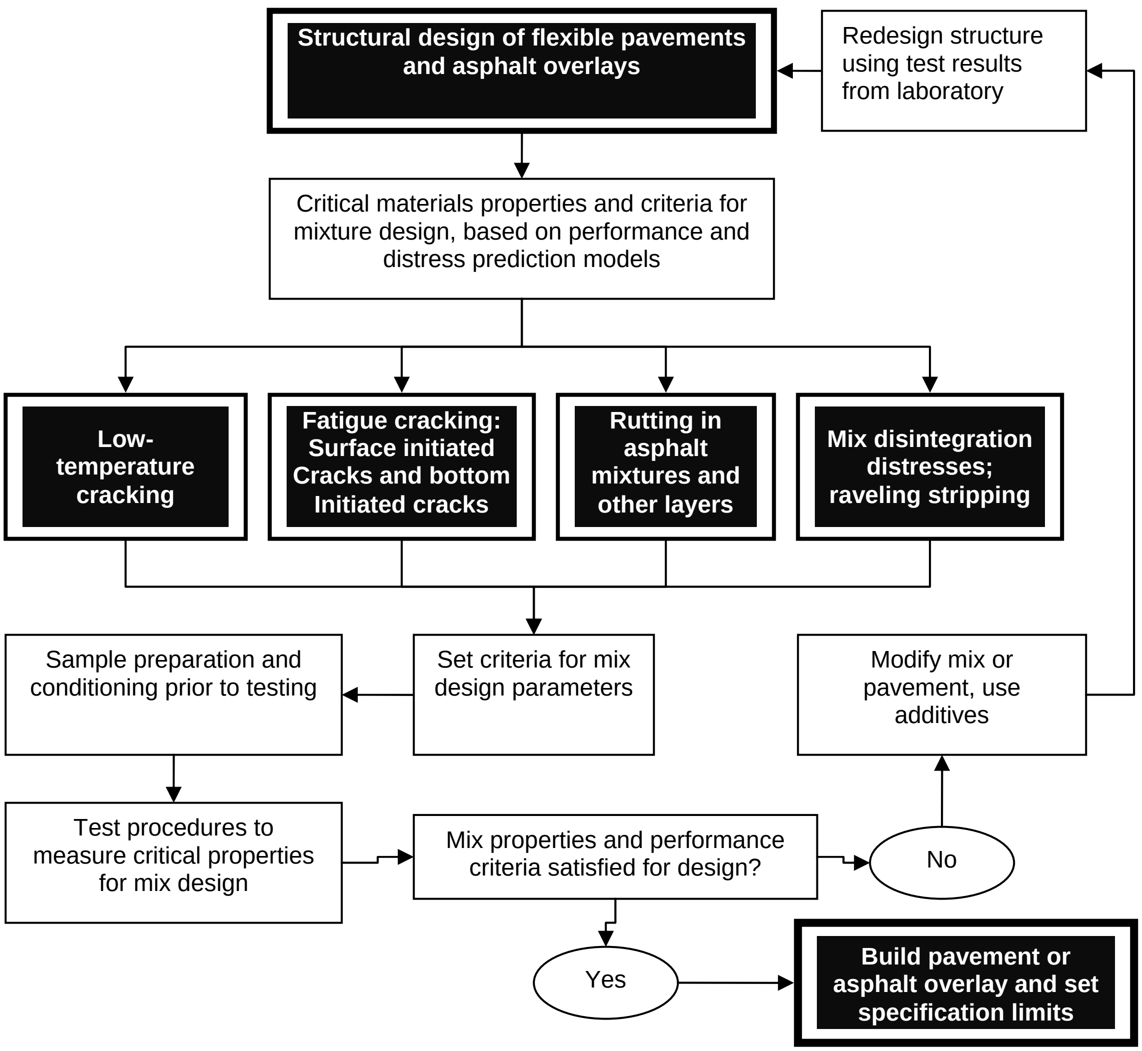

FIGURE 4 Flow chart illustrating the different steps of an integrated mixture and structural design system.

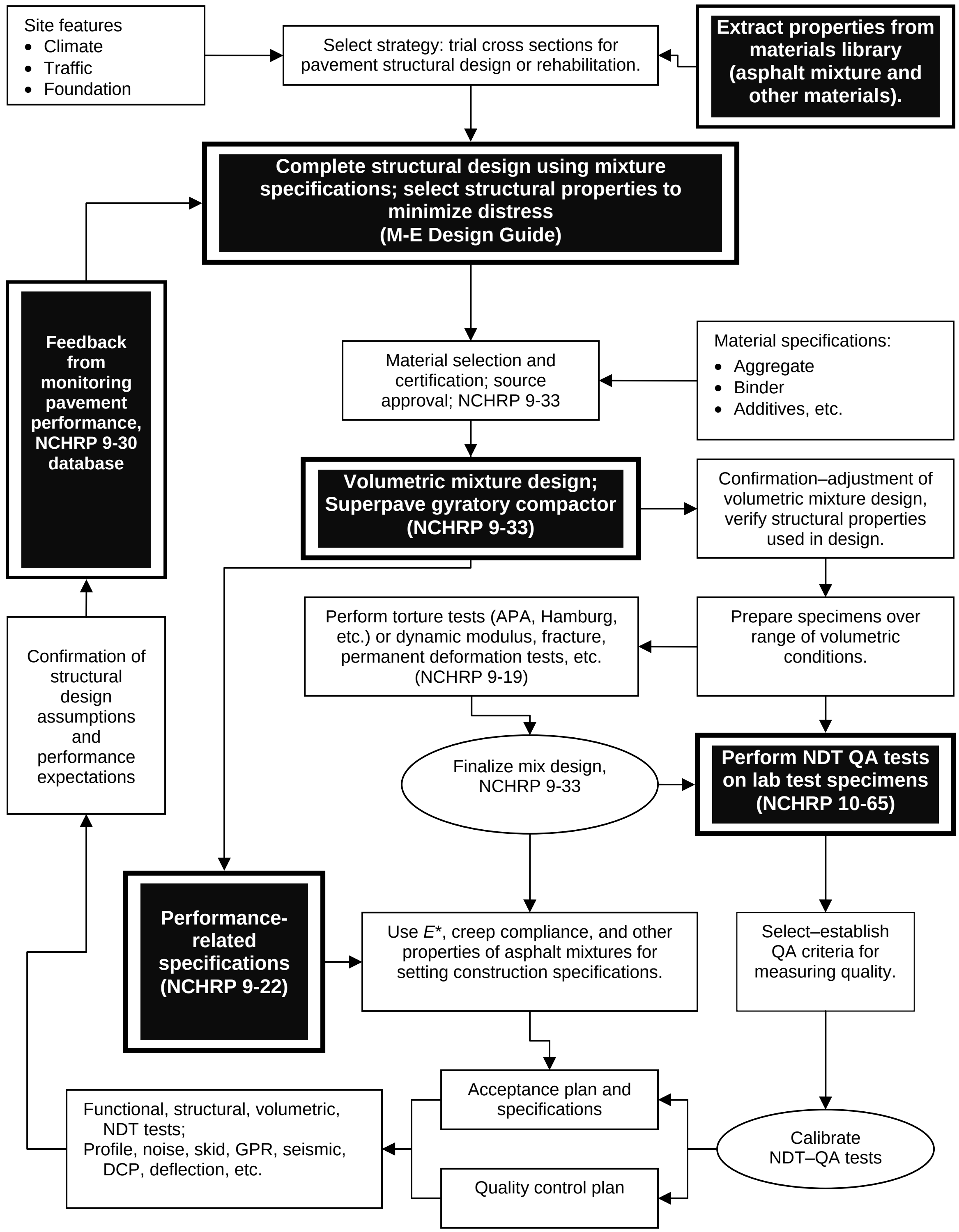

FIGURE 5 Flow chart for the systems approach for designing, specifying quality asphalt mixtures and flexible pavements using an integrated design approach. (NDT = nondestructive testing; GPR = ground-penetrating radar; DCP = dynamic cone penetrometer.)

As agencies consider adopting and using the MEPDG in terms of answering the question, “Is it worth the effort?”, they should also realistically consider and compare the errors and limitations of their current design system to that of the MEPDG. Based on the findings from the LTPP data analysis project, the errors associated with the current 1993 AASHTO *Design Guide* relative to actual performance are much larger than those from the MEPDG software (*6*). In addition, the MEPDG software is a much more powerful design system that can be used to optimize many more pavement design features particularly with the continued introduction of new technologies and materials; it is not just a thickness design procedure. As such, agencies are encouraged to begin the implementation process as soon as possible and not underestimate the costs and efforts that will be required.

Endnotes, References, and Resources

ENDNOTES

1. NHI Course 1310118 on the simple performance test is being developed and will be available in 2009. Training and certification programs need to be available for all test methods that are used for structural and asphalt mixture designs.
2. FHWA is sponsoring a project for using agency PMS data to assist in the calibration and validation of the transfer functions in an M-E–based structural and mixture design system.

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