Guide for the Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures

Materials Characterization

Is your Agency Ready?

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Paper prepared for presentation
at the
Soils and Materials Session
on
Material Characterization for Inputs into AASHTO 2002 Guide

of the 2004 Annual Conference of the
Transportation Association of Canada
Quebec City, Quebec

ABSTRACT

Implementation of the first AASHTO Design Guide in the early 1960's was a major paradigm shift in the pavement design process and required highway agencies to undertake several efforts over a period of many years to implement the new design procedures. These efforts included training of staff, analysis of truck axle load and traffic data, laboratory testing of materials, establishing correlations with the new material inputs, field testing for establishing the initial serviceability index of new construction, and selection and monitoring of field test sections for calibration of local conditions.

The implementation of the Guide for the Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures (Design Guide) as a standard design practice will also require significant changes to pavement design procedures, testing procedures and equipment, traffic data input, climatic data input, performance criteria, and others. The Design Guide performance models are calibrated using data from the Strategic Highway Research Program (SHRP) Long Term Pavement Performance (LTPP) Program. To maximize the benefits of the Design Guide, agencies will need to embark on an implementation process to ensure that all of the input parameters are acceptable and practical for their location.

The Design Guide provides a hierarchical methodology with three levels of design ranging from Level 1 (detailed project specific inputs) to Level 3 (default regional inputs). This paper presents the material characterization input and testing required for use in the Design Guide.

Introduction

The *AASHTO Guide for Design of Pavement Structures* is one of the most commonly used methods of pavement design in North America. A 1996 survey completed as part of NCHRP Project 1-32 found that 80 percent of states use the 1972, 1986, or 1993 AASHTO Guides [1]. In Canada, a 2002 survey found that approximately 70 percent of provinces use a portion of the 1993 AASHTO Guide [2].

The 1972 version of the AASHTO Guide relies heavily on performance equations based on the results of the AASHO Road Test, which was conducted near Ottawa, Illinois in the late 1950s/early 1960s [3]. The original pavement design equations were developed for a fairly limited set of pavements, subgrade conditions and traffic. Later versions of the Guide rely extensively on extrapolated data from the original AASHO Road Test results with revised Guides published in 1986 and 1993, along with a supplement to the 1993 Guide published in 1998 [4,5]. While each of the revised Guides advanced the state of pavement design technology, the basis of the design procedure was still empirical.

Advancements in computer and modeling technologies coupled with the significant pavement performance information now available from the Strategic Highway Research Program (SHRP) and the Long Term Pavement Performance (LTPP) Program initiatives has permitted the development of more rigorous pavement design procedures. The Guide for the Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures (Design Guide) incorporates a mechanistic-empirical design approach and will allow pavement designers to improve design reliability, predict specific failure modes (which can minimize premature failures), better characterize seasonal/drainage effects and reduce overall life cycle costs.

Through the use of mechanistic principles and more comprehensive input data, the new design procedure is capable of producing more reliable and cost-effective designs, even for design conditions that vary significantly from previous experience (e.g., much heavier traffic loadings). The Design Guide contains procedures for the design and analysis of all types of new and rehabilitated pavement systems (e.g., flexible, rigid, and semi-rigid pavements). The mechanistic-empirical design procedure included in the Design Guide allows the designer to evaluate the effect of variations in materials (both inherent and due to construction procedures) on pavement performance.

While the Design Guide is new, the technology behind the Guide is not. The Design Guide applies existing, validated, state-of-practice technologies/methodologies into a single tool for the design of pavement structures. The Design Guide is the culmination of NCHRP Project 1-37A, *Development of the 2002 Guide for Design of New and Rehabilitated Pavement Structures: Phase II* [6].

This paper provides an abbreviated version of the material characterization requirements of the mechanistic-empirical (M-E) design approach adopted by the Design Guide.

Material Characterization

The material properties and changes caused by loading and the environment are required to predict the characteristics and performance of the pavement. The primary characteristics (mechanistic properties) used to evaluate the performance of pavement materials under various loading and environmental conditions are the resilient modulus (E) and Poisson's ratio (μ) of the materials. The mechanistic properties of the pavement materials and subgrade are used to calculate the stresses, strains and displacements within the pavement under vehicular loading. These stresses and strains are then 'translated' into pavement surface distresses using transfer functions developed through a regression of the LTPP database and pavement performance information supplemented by several specific full scale pavement studies such as the Minnesota Test Road.

The pavement materials and subgrade have been divided into nine primary categories for the Design Guide. These include:

- Hot mix asphalt materials (all layers bound with asphalt cement including stabilized bases, open graded drainage layers, etc.
- Portland Cement Concrete (used as a pavement surfacing)
- Chemically or cement stabilized materials (cement, flyash and lime stabilized materials)
- Unbound materials (granular base/subbase and subgrade)
- Recycled concrete (crack and seal)
- Recycled hot mix asphalt (used in new asphalt concrete mixes)
- Recycled cold mix asphalt concrete (plant or in-situ recycled)
- Recycled asphalt pavement (used as a granular base/subbase)
- Bedrock.

The material characterization input parameters for each of the above categories are summarized in Table 1.

As seen in Table 1, a significant amount of information is required to characterize the pavement and subgrade materials for input to the new mechanistic-empirical design procedure. While many agencies in Canada routinely test pavement and subgrade materials, this testing typically consists of items such as aggregate gradation, subgrade optimum moisture content, concrete modulus of rupture, etc. Very few agencies collect test data such as asphalt dynamic modulus, aggregate and subgrade modulus of elasticity, concrete thermal conductivity, etc. Those collecting 'non-routine' material information are doing so on a limited basis either in-house (limited) or at local universities (more common).

Table 1. Primary Material Property Input Requirements

Material	Required Information
Hot Mix Asphalt	• Dynamic modulus • Poisson's ratio • Tensile strength • Coefficient of thermal expansion • Creep compliance • Thermal conductivity • Asphalt binder stiffness • Aggregate properties
Portland Cement Concrete	• Modulus of elasticity (adjusted for strength gain with time) • Poisson's ratio • Unit weight • Coefficient of thermal expansion • Mix properties (aggregate blend, w/c ratio, compressive strength, etc. • Aggregate type • Thermal conductivity • Heat capacity
Chemically Stabilized Material	• Elastic Modulus • Poisson's ratio • Unit weight • Modulus of rupture • Thermal conductivity • Heat capacity
Unbound Material	• Resilient modulus[1] • Poisson's ratio • Unit weight • Gradation • Hydraulic conductivity • Optimum moisture content • Plasticity index
Recycled Concrete	• Resilient modulus • Poisson's ratio • Thermal conductivity • Heat capacity
Recycled Hot Mix	• Dynamic modulus • Poisson's ratio • Tensile strength • Coefficient of thermal expansion • Creep compliance • Thermal conductivity • Asphalt binder stiffness • Aggregate properties

Table 1. Primary Material Property Input Requirements

Material	Required Information
Recycled Cold Mix Asphalt	• Dynamic modulus • Poisson's ratio • Tensile strength • Coefficient of thermal expansion • Creep compliance • Thermal conductivity • Asphalt binder stiffness • Aggregate properties
Recycled Asphalt Pavement	• Resilient modulus • Poisson's ratio • Unit weight • Gradation • Hydraulic conductivity • Optimum moisture content • Plasticity index
Bedrock	• Elastic modulus • Poisson's ratio • Unit weight

1. The resilient modulus is adjusted for seasonal variations.

Hierarchical Design Concept

Recognizing that the complexity and cost of providing complete, detailed information for all pavement designs is not practical, the Design Guide uses a hierarchical approach which allows the designer flexibility in selecting the design inputs based on the importance of the project and available information. Three levels of design are provided as follows:

Level 1 – Requires detailed testing of specific materials to be used in a project, e.g. complex modulus testing of an asphalt concrete mix. A Level 1 design would typically be used for a research test section or very high volume road. A Level 1 design typically has the highest confidence level of performance.

Level 2 – This level is intended for use for routine pavement designs. While still required as a key input, complex testing such as resilient modulus determination is not required. Rather, resilient modulus values are determined through correlations with other more standard testing procedures, such as, California Bearing Ratio (CBR), aggregate gradation, plasticity index and moisture content. For Level 2 designs, regional correlations between pavement material properties and pavement performance would be used. Level 2 designs have a moderate confidence level of performance.

Level 3 – This level has the lowest level of accuracy and would typically be used for lower volume roadways. Level 3 designs are based on typical material property default values derived from the LTPP database.

It is possible for a designer to mix and match the levels of input for a specific project or region. For example, a designer may select a Level 2 input for the subgrade because the subgrade in a particular region is well characterized by other tests such as CBR. However, detailed commercial vehicle data (axle load spectra) is unavailable and therefore, Level 3 defaults would be selected. This same concept translates to the other non-material required input data such as environmental data, traffic loadings and distribution, etc.

Changes in Material Properties due to Climate and Load

Regardless of the input level selected, the variation in the properties of the pavement and subgrade materials due to environmental change is modeled using the Enhanced Integrated Climate Model (EICM). The EICM uses a master climate database (currently only based on U.S. continental weather stations) to determine the impact of a change in climate on a specific material property. For example, hourly temperature, solar radiation and cloud cover are used to model the changes in the modulus of the asphalt concrete. This is very important because asphalt concrete is a visco-elastic material and as the temperature goes up, its modulus goes down. This property may affect the performance characteristic of an asphalt concrete under heavy loads and high temperatures. Similarly, precipitation and temperature data is used to model the resilient modulus seasonal variations of the subgrade soils to determine the load carrying capacity at various times during the year.

Some pavement materials, such as asphalt concrete, react differently depending on the speed at which they are loaded. For example, the modulus of elasticity of an asphalt material will be higher under a traffic speed of 100 km/h than it would be under slower moving traffic. This is one of the reasons that asphalt concrete rutting occurs on uphill grades and approaching stop bars at urban intersections. Granular base/subbase and subgrade materials can also exhibit stress dependent behaviour. Fine grained subgrade such as silts and clays are typically stress softening. As the stress level increases, the ability of the material to accommodate the load decreases. Materials such as sands and gravels are typically stress hardening therefore their ability to carry load increases corresponds to their stress level increasing.

An overview of the input requirements and testing required to characterize the materials for the nine primary materials is provided in the following sections.

Asphalt Concrete Materials Characterization

The characterization for asphalt concrete materials is the most complex in the Design Guide. The primary input parameter is the dynamic modulus of the asphalt concrete mix. Dynamic modulus testing (NCHRP 1-28A), asphalt binder complex shear modulus and phase angle testing (AASHTO T315) are used to develop a master curve that represents the time vs. temperature performance. The master curve is developed for a standard mix temperature of $21^{o}C$ and then shifted as necessary to represent other temperature conditions within the tested temperature range. The asphalt concrete materials characterization procedure used in the Design Guide accounts for short term binder aging during asphalt concrete mixing and placement at initial construction and due to age hardening as the asphalt concrete pavement gets older.

For a Level 1 rehabilitation project, the master curve for the asphalt concrete is developed by using the Falling Weight Deflectometer (FWD) and laboratory testing on extracted cores. The FWD testing is used to measure pavement surface deflections with the asphalt modulus calculated through backcalculation. The sensitivity of the backcalculated asphalt modulus to changes in temperature is calculated based on the range of temperatures during the FWD testing, this develops a temperature/modulus curve. Cores are extracted from the pavement and subjected to standard asphalt concrete testing (air voids, asphalt cement content and gradation) to develop an undamaged master curve for the aged asphalt concrete. A damage transfer function then combines the results of the backcalculation and laboratory testing to develop a field master curve. The Level 2 project eliminates the FWD testing and uses some additional resilient modulus testing while the Level 3 analysis uses a typical asphalt concrete master curve and the results of a visual distress survey to determine the field master curve.

The asphalt concrete master curves are used as inputs to the distress prediction equations to determine the amount of fatigue cracking and rutting. Additional testing is necessary to predict the amount of thermal cracking that will occur for a particular pavement. The additional testing includes:

- Tensile strength (AASHTO T322);
- Creep compliance (AASHTO T322); and
- Thermal conductivity and heat capacity (ASTM E 1952 and ASTM D2766).

In addition, it is necessary to determine the coefficient of thermal contraction. This value is computed internally in the Design Guide based on the volumetric properties of the as-built asphalt concrete mix and the coefficient of thermal contraction of the aggregates. The results of the above tests and calculations are used to determine the amount of thermal cracking with time.

Finally, the distresses (thermal cracking for instance) and the timing of occurrence are used, in part, to calculate the progression of roughness on the pavement.

Portland Cement Concrete Materials Characterization

Similar to the asphalt concrete, the Portland Cement Concrete (PCC) modulus of elasticity is used as an input to characterize the performance of the PCC. For a Level 1 design, the PCC modulus of elasticity and Poisson's ratio are determined through laboratory testing (ASTM C 469). The modulus of elasticity of PCC will generally increase with time as the cement in the PCC continues to hydrate. As the modulus strength increases, so does the ability of the PCC to carry loads and therefore, it is important to account for this increase in load carrying capability. For Level 2 and 3 designs, the modulus of elasticity is estimated from other concrete material testing such as compressive strength.

PCC flexural strength is also an important parameter in the design of PCC pavements. For Level 1 design, the flexural strength is determined in the laboratory using beams and three point loading (AASHTO T97) for beams of age 7, 14, 28 and 90 days. Level 2 uses compressive strength cores taken at various ages (7, 14, 28 and 90 days) and applies a correlation equation. Level 3 uses a correlation equation and the specified 28-day strength of the concrete.

Other important parameters of PCC materials considered by the Design Guide include:

- Coefficient of thermal expansion (AASHTO TP 60)
- PCC shrinkage (AASHTO T160)
- Thermal conductivity (ASTM E 1952)
- Heat capacity (ASTM D 2766).

These properties are very import in modeling the effects of temperature and moisture variations on the properties of the PCC slabs. Shrinkage and thermal expansion can cause significant curling and warping in PCC slabs, resulting in pavement cracking.

Chemically Stabilized Materials Characterization

Chemically stabilized materials covered in the Design Guide include lean concrete, cement stabilized, cement treated open graded drainage layers, soil cement, lime, cement and flyash treated layers. The elastic modulus of the layer is the primary input parameter for chemically stabilized materials. For lean concrete and cement treated materials in new pavements, the elastic modulus is determined using ASTM C 469. For lime stabilized materials, AASHTO T 307 protocols apply. For each of the stabilized materials, relationships between the elastic modulus and compressive strength have been developed. Recommendations for all the stabilized materials are provided in the Design Guide.

For rehabilitation projects, the elastic modulus of the stabilized layer is determined through the use of a backcalculation program and FWD test results or through the use of dynamic cone penetrometer testing and correlation equations.

The flexural strength of a stabilized layer is an important input parameter for flexible pavements only. Level 1 test procedures for chemically stabilized materials include:

- Lean concrete and cement treated aggregate layers (AASHTO T 97)
- Lime, cement and flyash treated layers (AASHTO T 97)
- Soil cement (ASTM D 1635).

Level 2 test procedures use correlations to develop the flexural strength for stabilized materials as follows:

- Lean concrete and cement treated aggregate layers (AASHTO T 22)
- Lime, cement and flyash treated layers (ASTM C 593)
- Soil cement (ASTM D 1633)
- Lime stabilized soil layers (ASTM D 5102).

Other important parameters of stabilized materials considered by the Design Guide include:

- Thermal conductivity (ASTM E 1952)
- Heat capacity (ASTM D 2766).

Unbound Granular Materials and Subgrade Materials Characterization

The Design Guide uses the AASHTO soils classification as described in AASHTO M145 or the Unified Soils Classification (USC) definitions as described in ASTM D 2487. Unbound materials are categorized by grain size distribution, liquid limit and plasticity index value. The designer selects the primary unbound material type using one of the classification systems and then provides further input to determine appropriate material properties to be used for design.

The primary input parameter used for design is the resilient modulus. For Level 1 designs, the resilient modulus values of unbound granular materials, subgrade, and bedrock are determined from triaxial tests (AASHTO T307)

As indicated previously, unbound materials can be either stress hardening or stress softening and therefore, the nonlinear behaviour of the material must be established for design. The model used to characterize the resilient modulus behaviour of unbound materials is described in NCHRP 1-28A.

While it is expected that resilient modulus testing is to be completed for Level 1 designs, very few agencies in Canada are equipped to complete resilient modulus testing. Therefore, for Level 2 designs, correlation equations have been developed with more commonly used testing protocols to estimate the resilient modulus of the unbound materials. These correlations are summarized in Table 2.

Table 2. Test correlations for the Determination of Resilient Modulus Values.

Test	Correlation Equation	Test Procedure
California Bearing Ration (CBR)	$M_r = 2555(CBR)^{0.64}$ M_r, psi	AASHTO T193, "The California Bearing Ratio"
R-value	$M_r = 1155 + 555R$ (*20*) M_r, psi	AASHTO T190, "Resistance R-Value and Expansion Pressure of Compacted Soils"
AASHTO layer coefficient	$M_r = 30000\left(\frac{a_i}{0.14}\right)$ M_r, psi	AASHTO Guide for the Design of Pavement Structures
Plasticity Index (PI) and Percent of Material Passing the 75 µm sieve size (w)	$CBR = \frac{75}{1 + 0.728(wPI)}$	AASHTO T27. "Sieve Analysis of Coarse and Fine Aggregates" AASHTO T90, "Determining the Plastic Limit and Plasticity Index of Soils"
Dynamic Cone Penetrometer (DCP) value	$CBR = \frac{292}{DCP^{1.12}}$	ASTM D 6951, "Standard Test Method for Use of the Dynamic Cone Penetrometer in Shallow Pavement Applications"

Note: 1 MPa ~ 145 psi, 1 psi ~ 0.0069 MPa.

Resilient modulus for rehabilitation projects is determined using the procedures outlined in ASTM D 5858, Standard Guide for Calculating in Situ Equivalent Elastic Moduli of Pavment Materials Using Layered Elastic Theory. While there are many computer programs available, it is cautioned that each program makes certain assumptions regarding the response of pavement layers under load and the user should be very careful to ensure that the backcalculated modulus values are reasonable and representative of the pavement.

For Level 3 designs, the resilient modulus of unbound materials is selected based on the unbound material classification (AASHTO or USC). The Design Guide provides a general range of typical modulus values (based on LTPP averages) for each unbound material classification at their optimum moisture content.

Other important parameters of unbound materials considered by the Design Guide include:

- Atterberg Limits (AASHTO T 89/90)
- Grain size distribution (AASHTO T 27)
- Moisture/density relationship (AASHTO T 99).

Recycled Concrete Materials Characterization

Recycled concrete materials are treated similarly to unbound materials. The recycled concrete is tested to determine its resilient modulus by laboratory testing (if broken to aggregate sized pieces) or through FWD testing if broken in the field into fractured slabs.

Recycled Hot Mix Asphalt Materials Characterization

Central plant recycled hot mix asphalt is treated the same as new asphalt concrete materials with inputs required to determine the modulus for each temperature and shift factors obtained by data shifting from master curves.

Cold Recycled Hot Mix Asphalt Materials Characterization

Cold recycled hot mix asphalt pavement, either in-situ or at a central plant location is treated as a stabilized material with the resilient modulus and temperature sensitivity used to define the stabilized layer characteristics.

Cold Recycled Hot Mix Asphalt (Aggregate) Materials Characterization

When cold recycled hot mix asphalt is used or blended with other natural aggregates it is treated the same as an unbound material with the exception that the recycled material is not expected to be moisture sensitive (resilient modulus will not change substantially with a change in moisture content).

Bedrock Materials Characterization

As with other data input requirements for the Design Guide, the resilient modulus of the bedrock is the most important parameter to be selected. As actual resilient modulus testing of bedrock is very rare for pavement design, the Design Guide provides the following default resilient modulus values for bedrock:

- Uniform, solid bedrock, 1000 ksi (~ 7,000 MPa)
- Highly fractured, weathered bedrock, 500 ksi (3,500 MPa).

The Poisson's ratio for bedrock is selected as 0.15 for uniform, solid bedrock and 0.30 for highly fractured and weathered bedrock.

Conclusions

The Guide for the Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures incorporates a mechanistic-empirical design approach that will allow pavement designers to improve design reliability, predict specific failure modes (which can minimize premature failures), better characterize seasonal/drainage effects and reduce overall life cycle costs.

There are many other specific input parameters and the Design Guide calculated values that are used to characterize pavement materials for design. This paper provides an overview of the materials' characteristics that have the largest influence for the design of pavement structures.

The mechanistic-empirical design procedure outlined in the Design Guide will allow the designer to evaluate the effect of variations in materials (both inherent and due to construction procedures) on pavement performance. However, as presented, the mechanistic principles will require more comprehensive input data which, in turn will require more comprehensive test data.

Will your agency be ready?

References

[1]. Darter, M.I., Von Quintus, H., Jiang, Y.J., Owusu-Antwi, E.B., Killingsworth, B.M., *Catalog of Recommended Pavement Design Features*, 1997. National Cooperative Highway Research Program, NCHRP Project 1-32, Washington, DC.

[2]. *Pavement Structural Design Practices Across Canada*, 2002. Canadian Strategic Highway Research Program, C-SHRP Technical Brief # 23, Ottawa, Ontario.

[3]. *AASHTO Interim Guide for Design of Pavement Structures,* 1972. American Association of State Highway and Transportation Officials, Washington, D.C.

[4]. *AASHTO Guide for Design of Pavement Structures,* 1986. American Association of State Highway and Transportation Officials, Washington, D.C.

[5]. *AASHTO Guide for Design of Pavement Structures,* 1993. American Association of State Highway and Transportation Officials, Washington, D.C.

[6]. *Development of the 2002 Guide for Design of New and Rehabilitated Pavement Structures: Phase II*, 2004. National Cooperative Highway Research Program, NCHRP Project 1-37A, Washington, DC.

[7]. *Minnesota Test Road,* Maplewood, MN