CHAPTER 1

Modeling of Asphalt Concrete

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Introduction

Asphalt concrete pavement, one of the largest infrastructure components in the United States, is a complex system that involves multiple layers of different materials, various combinations of irregular traffic loading, and varying environmental conditions. Therefore, a realistic prediction of the long-term service life of asphalt pavements is one of the most challenging tasks for pavement engineers. The performance of asphalt concrete pavements is closely related to the performance of asphalt concrete. It is performance models of asphalt concrete that provide the links among various processes involved in asphalt mixture design, pavement design, construction, and rehabilitation.

Various factors affect the deformation behavior and performance of asphalt concrete, including time (i.e., rate of loading, loading time, rest period), temperature, stress state, mode of loading, aging, and moisture. Models have been developed to capture the effects of these factors on asphalt concrete performance. Most of these models, developed prior to the Strategic Highway Research Program (SHRP), are empirical in nature. The primary reason for the empirical nature of these models is the lack of computing power necessary to calculate the long-term performance of asphalt concrete and, therefore, asphalt pavements. The SHRP recognized the importance of mechanistic models for material specifications, mixture design, and pavement design and developed a range of research products based on the principles of mechanics. The paradigm shift from empiricism to mechanics during the SHRP made a significant impact on the role of models in asphalt pavement engineering.

Development of a fundamentally sound performance model serves two important purposes. For pavement engineers, such a model can provide accurate information about the performance of asphalt concrete under realistic loading conditions, thus leading to a better assessment of the service life of a new pavement or the remaining life of an existing pavement. For materials engineers, the performance model founded on basic principles of mechanics provides relationships between material properties (chemical or mechanical) and model parameters, which can be used for the selection or design of better performing binders or mixtures.

Performance Characteristics

Performance of asphalt concrete can be categorized into two major types of distress: cracking and permanent deformation. Cracking of asphalt concrete can be caused by mechanical loading from repetitive traffic and/or thermal loading from changes in temperature. When the asphalt concrete is subjected to repeated loading, whether it is mechanical or thermal, distributed microstructural damage occurs primarily in the form of microcracks. A microscopic video image of the cracking area in asphalt concrete is presented in Fig. 1-1 to display the formation of micro- and macrocracks under tensile stress. As shown in this figure, microcracks exist ahead of the macrocrack tip, forming a so-called *damage zone*. Propagation, coalescence, and rebonding of these microcracks in the damage zone affect the macrocrack growth and healing and, thus, the fatigue behavior of asphalt concrete. That is to say, the modeling of the fatigue behavior of asphalt concrete requires an evaluation of the effects of both micro- and macrocracks and their interaction on the global behavior of the mixture.

At high temperatures and/or slow loading rates, the asphalt binder becomes too soft to carry the load and, thus, the principal type of damage is permanent deformation due to volume change (i.e., densification) and rearrangement of aggregate particles caused by shear flow. The degree of aggregate interlocking and anisotropy in asphalt concrete caused by aggregate orientation under compaction become important factors in the accurate prediction of the permanent deformation behavior of asphalt concrete.

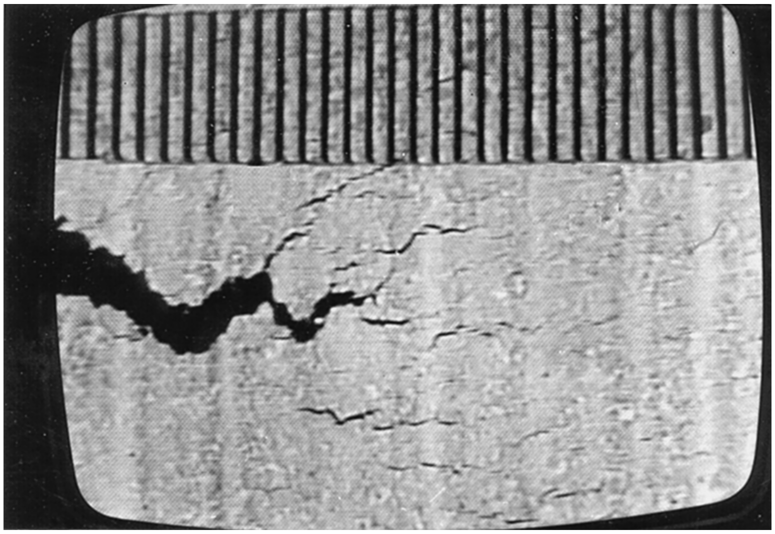

Figure 1-1 Microscopic surface image of cracking area in asphalt concrete. (Kim et al. 1997, with permission from International Society for Asphalt Pavements.)

Future of Asphalt Concrete Modeling

The modeling of asphalt concrete is an evolving subject. Continuing developments and improvements in computational power and test techniques will allow asphalt materials and pavement engineers to use more realistic, powerful models to predict the performance of asphalt materials and pavements. The following subsections attempt to shed some light on the possibilities for future models of asphalt concrete.

Pavement Response Model versus Performance Model

A traditional approach to asphalt pavement performance prediction is divided into two steps: pavement response prediction and pavement performance prediction. In this approach, responses of an undamaged pavement (e.g., tensile strain at the bottom of the asphalt layer) are estimated from a structural model (e.g., the multilayered elastic theory) using initial, undamaged properties of the layer materials. Asphalt concrete performance models are developed using laboratory test results and relate the initial response of the asphalt concrete specimens to the life of those specimens. The responses estimated from the structural model are then input to the performance model to determine the life of the pavement. This approach is the state-of-the-practice method that is adopted in most recent mechanistic-empirical pavement design methods, including the *Mechanistic-Empirical Pavement Design Guide* (MEPDG) developed under the NCHRP project 1-37A (2004).

These models are simple to use because the only measured response of the mixture is at the initial stage of fatigue testing. Such models deserve credit for the basic foundation of current mechanistic-empirical pavement designs. However, there are several weaknesses in this traditional approach. First, damage evolution in complex structures and modified materials may not be captured accurately. For example, complex combinations of layer material types and thicknesses in perpetual pavements make it more difficult to accurately predict the failure mechanisms using conventional hot mix asphalt (HMA) performance prediction models and pavement response models.

Secondly, most performance models used in the two-step approach are mode-of-loading dependent. These models are developed using results obtained from laboratory tests, which are conducted either in controlled stress mode or in controlled strain mode. Currently available two-step approaches do not have the ability to discern the mode of loading in a mechanistic manner and, therefore, could result in an unreliable performance prediction.

Thirdly, the laboratory test methods used in the traditional two-step approach are designed to simulate the boundary conditions of pavement structures rather than to define the material's constitutive behavior in the representative volume element (RVE). Often these laboratory test methods predict the performance under only some selected pavement conditions. So, because the test methods simulate the pavement boundary conditions rather than capture the behavior of the RVE, the number of tests needed to cover the wide range of pavement conditions that are expected in the field is undesirably large.

The weaknesses of the two-step approach can be overcome using a mechanistic approach that combines HMA material models and the pavement response model. In this approach, the material model describes the stress-strain behavior of the material in the RVE. The material model is then implemented into the pavement response model where boundary conditions of the pavement structure in question are applied. This approach allows the accurate evaluation of the effects of changes in layer stiffnesses due to damage growth on pavement performance. Prediction of multiple performance characteristics and their interactions is possible in a realistic manner, although the material models in both tension and compression are needed.

The lack of computing power needed to calculate damage evolution for the entire life of the pavement forced earlier researchers to develop the two-step approach to pavement performance prediction, as opposed to the more realistic one-step integrated approach. However, improvements in computing power and numerical techniques now allow modelers to implement more powerful material models into the pavement response model and to predict the pavement performance directly from the integrated model.

Multiscale Model

Two general approaches in mechanics can be used for modeling the changes in the stress-strain behavior of asphalt concrete: a micromechanical approach and a continuum approach. In the micromechanical approach, defects that constitute the damage are described by microscopic geometrical parameters, such as microcrack size, orientation, and density. These parameters are evaluated through an appropriate microstructural evolution law, such as the microcrack growth law. Mechanics is then applied typically on an idealized RVE to determine the effects of the distribution of microdefects on the macroscopic constitutive parameters, such as the effective stiffness of the damaged body. Such analyses are, in general, difficult to perform because of the intrinsic complexity of the microstructure and the micromechanisms and also due to the interactions among the defects. Therefore, without proper simplifications and assumptions both in modeling and analysis, the micromechanical approach may fail to provide realistic information about the macroscopic constitutive framework for modeling the progressive degradation of the mechanical properties of solids (Park et al. 1996).

On the other hand, in the continuum approach, or so-called *continuum damage mechanics*, the damaged body is represented as a homogeneous continuum on a scale that is much larger than the flaw sizes. The state of damage is quantified by internal state variables (ISVs) within the context of the thermodynamics of irreversible processes. That is, the growth of damage is governed by an appropriate damage evolution law. The choice and interpretation of the ISVs are somewhat arbitrary, and the functional form of the thermodynamic potential (typically Helmholtz or Gibbs free energy) and the resulting stress-strain relations are postulated usually on a phenomenological basis. The stiffness of the material, which varies with the extent of damage, is determined as a function of the ISVs by fitting the theoretical model to the available experimental data. The phenomenological continuum damage models thus provide a viable constitutive framework for the efficient modeling of macroscopic mechanical behavior of materials with distributed damage without requiring explicit descriptions of microstructural evolution kinetics (Park et al. 1996).

Recently, significant advancements in the modeling of asphalt concrete have been made in both micromechanics and continuum damage mechanics. In future models of asphalt concrete, micromechanical and continuum damage models will be coupled to describe the behavior and performance of asphalt pavements using the properties of their component materials (i.e., binder and aggregate). This *multiscale model* will take advantage of the strengths of both micromechanics and continuum damage mechanics, that is, the ability of the micromechanical model to describe mixture behavior using component material properties and that of the continuum damage model to describe the global stress-strain behavior of asphalt concrete in predicting the pavement performance. The challenge in this combined approach is to determine the material properties at the proper scales, as it is expected that some material properties are scale dependent.

Virtual Testing of Asphalt Concrete

One of the fastest growing techniques that can aid asphalt concrete modeling is the imaging technique, including digital imaging, laser, and x-ray tomography, to name a few. These techniques allow engineers to view and construct two- and three-dimensional microstructures of the mixture. The imaging techniques can be combined with advanced models of asphalt concrete and provide the tools to perform virtual testing of asphalt concrete. In this approach, virtual microstructures of asphalt concrete are generated from the imaging technique, and virtual testing is conducted on the virtual microstructure using the advanced numerical models. These virtual testing techniques will help asphalt material and pavement engineers to evaluate the effects of any change in the component material properties on the mixture behavior and performance without any laboratory testing. The virtual testing will also be an efficient tool in undergraduate and graduate asphalt materials courses to demonstrate the effects of changing testing conditions and mixture design parameters on the behavior and performance of asphalt concrete.

Organization Summary

Part 1 (Chap. 2) is dedicated to asphalt binder modeling. Various aspects of the stiffness characterization of asphalt concrete are described in Part 2 (Chaps. 3 through 6). Part 3 (Chaps. 7 to 9) presents different constitutive modeling approaches for asphalt concrete. Part 4 (Chaps. 10 and 11) examines models for rutting. Part 5 (Chaps. 12 and 13) addresses models for fatigue cracking and moisture damage. Last, Part 6 (Chaps. 14 and 15) addresses models for low-temperature cracking.

Note that this book does not necessarily describe all the models that are currently available within each aspect of asphalt concrete modeling (as outlined in the six parts, accordingly). However, it should provide sufficient information about a wide range of models that are available. The following descriptions provide a summary of the contents of each part.

Part 1—Asphalt Binder Rheology

Part 1 of this book deals with issues pertaining to asphalt binder rheology. The historical use of rheological indices in the asphalt industry is discussed to provide perspectives on the development and rationale for the findings from the SHRP project. The influence of binder properties on mixture performance is discussed. Background on polymer modification of asphalt binders is presented and, subsequently, an argument for the enhancement of asphalt binder performance by adding polymer-modifying agents is given. A rheological modeling approach capable of capturing the beneficial aspects of polymer-modified binders is presented along with results from an accompanying experimental study. Since the focus of this book is the modeling of asphalt concrete, only one chapter is allotted to a discussion of asphalt binders.

Part 2—Stiffness Characterization

Part 2 of this book focuses on asphalt concrete stiffness. Stiffness is critically important for mechanistic modeling of both the pavement response and the pavement performance. Chapter 3 discusses explicitly the importance of this factor for such analysis and also details the major factors affecting the material stiffness. Particular attention is paid in Chaps. 4 and 5 to the stiffness characterization of asphalt concrete via the complex modulus. Two different test methods are demonstrated. The first is part of the proposed simple performance test protocol and involves testing cylindrical asphalt concrete specimens in the axial direction. The second method strives to overcome shortcomings associated with using the geometry of the first method to evaluate the stiffness of field cores using the indirect tension test. There are numerous advantages to assessing material stiffness via the dynamic modulus in the frequency domain; however, many of the mechanistic models presented in this book require stiffnesses in the time domain. Linear viscoelastic theory and mathematical manipulation are used in Chap. 6 to demonstrate different methods of converting the dynamic modulus into time domain functions such as creep compliance and the relaxation modulus.

Part 3—Constitutive Models

Part 3 of this book focuses on the constitutive modeling of asphalt concrete. Three approaches are presented in detail in this part. These approaches utilize different principles to describe the deformation behavior and performance of asphalt concrete, but are similar in that they attempt to form a unified model encompassing different performance characteristics by accounting for various constitutive factors.

Chapter 7 in this part incorporates the theory of viscoelasticity, continuum damage mechanics, and the theory of viscoplasticity to arrive at a so-called viscoelastoplastic continuum damage (VEPCD) model as a constitutive relationship for the behavior of asphalt concrete. Implementation of the VEPCD model into the finite element program is discussed. Chapter 8 presents a constitutive model based on the hierarchical disturbed state concept (DSC). The chapter describes the capabilities of the DSC for various pavement distresses such as permanent deformation and different types of cracking. Analysis of both two- and three-dimensional pavement problems is given using the DSC model, and a unified methodology with DSC for design, maintenance, and rehabilitation of pavement structures is proposed. Chapter 9 uses the DBN (Di Benedetto and Neifar) law to describe the behavior of asphalt concrete under a broad range of conditions. It explains how the different types of behavior can be modeled using the same formulation.

Part 4—Models for Rutting

In this part, the mechanisms of permanent deformation are described and modeled in two chapters. Information documented in Chap. 10 is the result of the SHRP A-003 study and illustrates that shear deformation contributes a significantly greater portion of total permanent deformation (rutting) in asphalt concrete than volume change. Based on these findings, the shear test was proposed to measure the propensity of a mix for rutting. The issue of sample size is discussed in the light of RVEs. The data presented illustrate the efficacy of the simple shear test, performed in the repeated load, constant height mode, for mix design and performance evaluation. Chapter 11 summarizes the findings from the more recent NCHRP 9-19 project. This chapter is composed of three main sections: (a) a review of mechanistic-empirical modeling approaches, and in particular the permanent-to-resilient strain ratio model adopted for the NCHRP 1-37A MEPDG; (b) the VEPCD model for the compression behavior of asphalt concrete; and (c) a simple performance test to identify the rutting potential of mixtures during the design process, based on the measurement of fundamental engineering responses and properties. It is noted that the VEPCD model adopted in this chapter employs the same principles as found in Chap. 7 in Part 3, except that the HiSS-Perzyna model is used to describe the viscoplastic strain of asphalt concrete instead of the strain-hardening model used in Chap. 7.

Part 5—Models for Fatigue Cracking and Moisture Damage

The detrimental effects of moisture and fatigue damage are discussed in Part 5 of this book. Chapter 12 focuses primarily on the fatigue damage mechanisms with a particular interest in the acceleration of such damage growth with additional moisture damage. Surface energy principles, fracture mechanics, and continuum damage mechanics are utilized for this argument. In Chap. 13 more attention is given to the moisture damage phenomenon. A review of current procedures for moisture damage assessment is given as a precursor to more advanced, objective techniques for the assessment of moisture damage.

Part 6—Models for Low-Temperature Cracking

Part 6 of this book discusses thermal cracking of asphalt concrete pavements. Mechanisms and events leading to thermal cracking are discussed in detail in Chaps. 14 and 15. Chapter 14 presents the TCMODEL, which has been implemented into the NCHRP 1-37A MEPDG to predict thermal cracking performance. The second chapter, Chap. 15, casts the phenomenon in the light of fracture mechanics and presents experimental results of multiscale modeling efforts encompassing binder, mastic, and mixture modeling.

Concluding Remarks

This book attempts to document models of asphalt concrete and should be regarded as an evolving document, as some of the models are still being refined and improved. It also may be noted that this book focuses mostly on continuum models in order to maintain a reasonable length. Significant advancements in micromechanical modeling of asphalt concrete have also been made. Nonetheless, this book should provide a fair presentation and sufficient review of mechanistic models that are currently available at the time of publication.

References

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