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Micromechanical finite element modeling of moisture damage in bituminous composite materials

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HIGHLIGHTS

- Computational micromechanical model simulating moisture damage in asphalt concrete.
- Coupled moisture flow and mechanical response.
- Finite element models generated from X-RAY CT images.
- Modeling adhesion and cohesion failure in asphalt concrete due to moisture presence.
- Macroscale homogenized properties from the moisture coupled micromechanical models.

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ABSTRACT

This study numerically investigates the effect of moisture presence on the microscale and macroscale responses of bituminous composite materials such as Asphalt Concrete (AC). A micromechanical modeling framework based on the Finite Element (FE) method was developed. The microstructure of the material was characterized using the non-destructive X-ray Computed Tomography (CT) technique. Images obtained from X-ray CT scans were used to generate FE-based micromechanical models. A computationally efficient hydro-micromechanical framework that bridges the microscale features of AC materials to the corresponding macroscale linear viscoelastic properties was presented. The micromechanical model provides a micromechanical based approach for quantifying the contribution of cohesive and adhesive damage to the overall material response of particulate composite in the presence of moisture.

1. Introduction

Moisture damage in bituminous composite materials such as AC refers to the progressive deterioration in the properties of the composite material under the action of water in liquid and/or vapor state [6]. In addition to reducing the structural load-carrying capacity of the material, the presence of moisture in pavements causes or facilitates the development of several distresses such as raveling. Raveling, which can be defined as the physical separation of the aggregates from the asphalt binder [12,28], generally results from the deterioration of the asphalt binder (a process known as cohesive damage), and/or weakening of the aggregate–mastic interface (referred to as adhesive damage).

Research on moisture damage in AC materials can be traced back to the early studies of Nicholson [39], Field and Phang [11], and Fromm [12]. These studies were the first to underline stripping phenomenon in AC in the field. Until the last couple of decades, the study of moisture damage in AC has been essentially limited to experimental work at a macroscale level. Little information was gained on the fundamental mechanisms that lead to moisture damage in AC, particularly from a microstructural point of view [6].

1.1. Moisture transport in asphalt concrete

Moisture originating from rainfall, humid environments, wet subgrade soils, and wet aggregates moves in AC through various mechanisms. Moisture transport basically occurs through three main mechanisms, namely infiltration of surface water, diffusion of water vapor, and capillary rise of subsurface water [32]. The following sections discuss the first two moisture transport mechanisms.

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1.1.1. Flow through the air voids structure

Moisture infiltrates through the air voids structure of AC. The resulting water flow field gradually washes out the surface of the mastic phase [22]. This phenomenon is essentially related to the permeability of the AC material. Significant experimental research related to characterizing the permeability of AC can be found in the literature [2,19,33]. Fig. 1 shows the relationships found in the literature between the permeability and the air void content of common AC materials. Permeability values for AC were found to range from 10^{-6} cm/s for relatively impervious AC materials to 10 cm/s for highly porous materials. Other studies used analytical approaches for determining the permeability of AC materials using traditional models of flow in porous media such as the Kozeny–Carman equation. Another study presented an empirical approach for predicting the permeability of AC by incorporating several mixture parameters into the Kozeny–Carman model [33,30].

1.1.2. Diffusion due to moisture gradient

Diffusion refers to the transport of moisture at the atomic or molecular levels [6]. Kringos and Scarpas [22] noted that the diffusion of moisture within the mastic, which reduces the latters cohesive strength, ultimately reaches the mastic–aggregate interface, thus causing and/or promoting adhesive failure. The process of moisture diffusion is commonly characterized using Fick's first and second laws for steady and non-steady state diffusion, respectively.

Moisture diffusion in AC has been examined by several researchers. One study [3] presented the diffusion coefficients of AC using both FE and Finite Difference method. The study noted that measurements of diffusion coefficients are strongly dependent, among other things, on the source of the materials in question and the testing procedure adopted. Another study [20] examined moisture diffusion in AC and presented experimental measurements of diffusion coefficients for different mastics with predetermined field performance.

1.2. Review of micromechanical modeling

The use of micromechanical models when dealing with composite heterogeneous materials such as AC is not new. Micromechanical models are essentially used to extract the fundamental material properties of heterogeneous materials such as AC from the properties of individual constituents. The fact that the microstructural features are explicitly discretized renders micromechanicals models particularly attractive for AC materials which exhibit a high level of heterogeneity and complex microscale features.

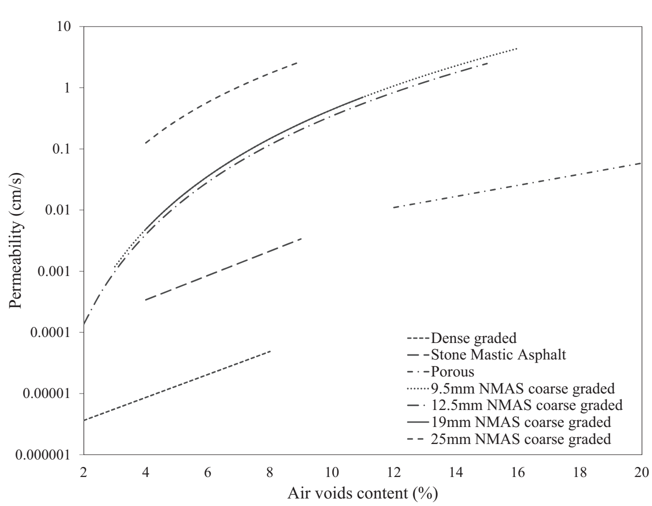

Fig. 1. Summary of major experimental correlations between the permeability of common AC materials and the corresponding total air voids content (%) [19,8].

For AC materials, the bulk response is governed by the microstructural properties of each of the constituents of the composite, namely aggregates, air voids, mastic phase, and aggregate–mastic interface. The mastic phase includes the asphalt binder, fine aggregates, and fillers.

Micromechanical models related to AC can be generally divided into three main categories: statistical, analytical, and computational models.

1.2.1. Statistical models

Numerous statistical-based micromechanical models for AC applications can be found in the literature [17,16,26]. The main limitation of statistical approaches is that such models are only applicable when the parameter values are within the range used in the experiments. Universal statistical models that work for all asphalt and aggregate types are difficult to establish. In addition, aggregate gradation and maximum aggregate size parameters are not included in the statistical models.

1.2.2. Analytical models

Analytical-based micromechanical models for predicting the bulk response of particulate-filled composite materials can be also found in the literature [18,15,9]. Analytical micromechanical models provide, first, a poor prediction of AC fundamental properties, and second, an oversimplification of the microstructure of AC [5]. Despite this fact, analytical and statical models offer the advantage of being relatively simple to implement, as compared to computationally-based micromechanical models.

1.2.3. Computationally-based micromechanical models

In the last couple of decades, a growing number of micromechanical models based on computational approaches have emerged. Such numerical micromechanical models were mostly based on either the Finite Element (FE) method or the Discrete Element (DE) method. The following sections review both the DE- and FE-based micromechanical models.

The first part of computational micromechanical models is based on the DE method [7,38,35,41,42,27]. Chang and Meegoda [7] developed a micromechanical model called ASBAL based on the DE method. The viscoelastic behavior of the asphalt binder was modeled with the Burgers element. Ullidtz [38] used 2D DE-based micromechanical models to predict rutting and failure potential of cohesive particulate media using the Dem2D code, where the particulate sample was digitally fabricated. You and Buttlar [42] presented a 2D microfabric DE approach for predicting the complex modulus of AC using the PFC-2D code. Another study [27] presented 2D DE micromechanical models to predict the dynamic modulus and phase angle of AC, where the mastic was modeled with the Burgers model. The study concluded that the proposed 2D DE model accurately predicts the viscoelastic properties of AC within a 90% confidence range.

The second part of computational micromechanical models is based on the FE method [6,10,21,34]. Dai [10] developed a microstructural 2D and 3D FE computational model to predict the complex modulus and phase angle of stone-based materials under cyclic loading and with varying frequencies. The study concluded that the local maximum strain found from micromechanical FE analysis can be 3.2–13.6 times higher than the nominal maximum strain, which underlines the importance of micromechanical analysis of AC materials. One study [21] used X-ray CT images to develop FE micromechanical models of AC using elastic material properties for the aggregates and the asphalt binder. Another study [34] used a 2D micromechanical FE model to determine the