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Evaporation-induced moisture damage of asphalt mixtures: Microscale model and laboratory validation

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HIGHLIGHTS

- Finite-element model to address evaporation-induced asphalt mixture moisture damage.
- Laboratory validation of the developed model with a comprehensive experimental plan.
- Investigating factors contributing to evaporation-induced moisture damage.
- Effects of environmental conditions, material properties, and aggregate structure.

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ABSTRACT

Moisture damage is a major source of pavement distress and may cause premature failure. In this study, moisture damage due to evaporation was investigated. A microscale finite-element model coupled with comprehensive laboratory testing was developed to simulate and validate the effect of evaporation-induced moisture damage on asphalt mixture load bearing characteristics on indirect tensile (IDT) strength test. In the proposed model, cohesive zone method (CZM) was used to address crack initiation and development at the aggregate-mastic interface. Quadratic nominal strain and BK exponential damage progress curve were considered for failure due to interaction of shear and normal forces. Fick's first law was incorporated into the model to simulate moisture diffusion in asphalt mixtures after hours of curing with saturated cold evaporation. Several tests were carried out to derive mechanical and moisture-related input parameters for the model. These tests included an static creep test on mastic, single-edge notch beam (SENB) on asphalt mixtures, and an evaporation diffusion coefficient test on aggregates and mastic. Appropriate moisture-dependent properties were assigned to mastic and aggregate-mastic interface. For laboratory validation, nine samples were fabricated and IDT strength test was performed on them. Samples were cured for 192, 456, and 672 h and tested at loading rates of 0.05, 0.075, and 0.1 mm/s. Comparison of load–displacement plots obtained from laboratory tests and model results showed a descent match in terms of peak load and plot shape. Analysis of factors influencing IDT strength revealed that aggregate-mastic adhesion had a higher contribution to strength of samples compared to mastic cohesion.

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1. Introduction

Moisture damage is one of the most common distresses in asphalt mixtures. This damage significantly accelerates pavement deterioration and may cause premature failure in severe cases. In 2005, an additional cost of 54 billion dollars was imposed to highway agencies in United States in order to maintain highways due to moisture damage [1]. A moisture sensitivity test was a fundamental requirement of the Superpave mix design system when developed in 1990 [2]. By 2003 about 87 percent of state highway agencies were mandating moisture susceptibility tests and 82 percent were suggesting use of antistrip additives [3].

Early efforts to understand the effect of moisture at aggregate-mastic interface in *microscale* dates back to 1960s and 70s [4]. Over the past decades, moisture damage has been predominantly investigated using a *macroscale* approach [5]. Thus, there has been less effort focused on physical, chemical, and mechanical processes contributing to moisture damage as these processes cannot be

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scrutinized on a macroscale. A robust micromechanical model helps understanding of moisture damage processes (i.e., physical, mechanical, and chemical) and allows for investigating influential parameters including environmental conditions and effect of material properties (e.g. aggregate, asphalt binder) on development of moisture damage.

In a widely accepted definition, moisture damage is the continuous loss of pavement performance due to loss of adhesion bonds at the aggregate-mastic interface or loss of cohesion within the mastic due to reaction with moisture [6,7]. Aggregate-mastic adhesion loss or mastic cohesion loss initiates with moisture diffusion. The moisture damage mechanism is comprised of two stages: 1) a moisture diffusion process; and 2) a mixture mechanical response. The first stage depends on the moisture diffusion type (liquid, evaporation), the means of moisture diffusion in the aggregate or mastic, and the moisture diffusion at the aggregate-mastic interface. The second stage depends on changes in mixture mechanical properties which leads to reduction of asphalt mixture load-bearing characteristics [4]. Environmental conditions significantly influence the moisture diffusion process. For instance, high relative moisture, intensive rainfalls, freeze/thaw cycles, and other environmental conditions increase the exposure of materials to moisture, elevating moisture damage potential.

Several factors contribute to moisture damage initiation and development in asphalt mixtures including air void content and distribution, moisture diffusion mechanisms, asphalt mixture physical properties, and aggregate-mastic cohesion characteristics [7,9–12]. In general, moisture damage begins with moisture diffusion in form of water or evaporation. A moisture damage due to evaporation diffusion is investigated in this study. The Evaporation diffusion rate and amount depend on relative moisture, the evaporation diffusion coefficient, and water storage potential. Relative moisture is an environmental factor while water storage potential and evaporation diffusion coefficient are thermodynamics properties of the asphalt mixture. Asphalt binders with higher water storage potential are more prone to evaporation-induced moisture damage [13]. Furthermore, the evaporation diffusion coefficient is a significant parameter in moisture damage finite-element modeling and needs to be appropriately determined in laboratory [14].

Mathematical modeling of moisture damage is important because it can be employed for evaluating the effect of different aggregate and binder materials and asphalt mixture physical properties on the induced damage [8]. In several studies, water flow in the asphalt mixture has been studied by considering three-dimensional voids in asphalt mixture [15]. Finite-difference and Boltzmann network methods were employed in these studies to estimate flow speed and pressure at any arbitrary points in the asphalt mixture. Flow speed and pressure are significant inputs for numerical modeling of moisture damage at the microscale. In another study, loss of mastic cohesion due to evaporation diffusion, loss of aggregate-mastic adhesion at their interface due to water diffusion, and mechanical loading were investigated [9]. In all of these studies, no laboratory experimental validation of the developed models was conducted. In the current study, however, the effect of evaporation diffusion on moisture damage and mixture strength characteristics of the asphalt mixture was numerically modeled and validated with laboratory experiments.

Several studies have employed the concept of surface free energy to evaluate the moisture susceptibility of asphalt mixtures. Bhasin et al. applied the concept of surface free energy to investigate aggregate-binder adhesion loss and considered adhesive bond energy in the aggregate-binder, as well as reduction of free energy in the system when debonding between aggregate and binder occurs [16]. In another study by Bhasin et al., energy parameters were developed based on surface free energy of materials used for constructing asphalt mixtures [17]. It was observed that the moisture susceptibility of laboratory fabricated asphalt mixtures were well correlated with the developed energy parameters. In this study, our proposed finite-element model accounts for fracture energy release due to loss of aggregate-mastic adhesion.

Once moisture is introduced to the asphalt mixture, it can cause cracks at the aggregate-mastic interface (adhesive crack) or within the mastic medium (cohesive crack). In general, adhesive cracks occur in mastics with low film thickness while cohesive cracks occur at higher mastic film thicknesses. Adhesive cracks are more detrimental to the asphalt mixture compared to cohesive cracks from the prospective of moisture damage development prospective. The proposed finite-element model in the current study accounts for moisture damage due to loss of adhesion and cohesion.

In many moisture damage studies, water has been considered to be the main source of moisture diffusion and other sources have been neglected. In fact, there are three moisture diffusion mechanisms: 1) surface water diffusion, 2) rise of ground water table due to capillary effect; and 3) evaporation diffusion [9]. Surface water diffusion is the main source of moisture, which depends on rainfall, drainage conditions, and material properties. However, field studies have shown that moisture damage may also occur in regions with low rainfall [3]. Moreover, evaporation diffusion is a significant cause of aggregate-mastic adhesion loss [10]. In other words, evaporation diffusion and ground water capillary are also significant means of moisture diffusion. Since modeling and evaluation of model caused by moisture damage due to evaporation diffusion has not been the focus of past research, the objective of this paper is to create and evaluate a numerical model to investigate the effect of evaporation diffusion on moisture damage and strength characteristics of asphalt mixtures using indirect tensile (IDT) strength test.

2. Research approach methodology

The proposed finite-element model considers the combined effect of evaporation diffusion and material response to mechanical loading in ABAQUS software. The model was validated with a comprehensive laboratory experimental plan. Fig. 1 summarizes details of model input and output parameters, as well as the laboratory validation plan. These details are described in the rest of this paper.

3. Model development

The model described in this paper simulates damage initiation and development by considering 1) the linear viscoelastic properties of the mastic; and 2) the aggregate-mastic interface bond strength, to be a function of moisture content. The first and second item represent moisture damage due to mastic cohesion loss and aggregate-mastic adhesion loss, respectively. Though moisture damage development is independent of load type and amplitude, it only occurs in the presence of external mechanical loading. Therefore, mechanical loading was included both in the model and laboratory validation after diffusion occurred.

3.1. Cohesive zone method (CZM)

The Cohesion Zone Method (CZM) was employed in the model to simulate damage in microscale. The most significant aspect of the CZM is the traction-separation law which determines the relationship between applied traction and relative space between the two surfaces or CMOD (crack mouth opening displacement). Fig. 2 schematically presents a bilinear traction-separation law, which is basically traction as a function of CMOD. When an initial

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