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# Microstructural modeling of asphalt concrete using a coupled moisture–mechanical constitutive relationship

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ABSTRACT

The coupled effect of moisture diffusion and mechanical loading on the microstructure of asphalt concrete is studied. The traditional Continuum Damage Mechanics (CDM) framework is modified to model detrimental effects of moisture and mechanical loading. Adhesive/cohesive moisture-induced damage constitutive relationships are proposed to describe the time-dependent degradation of material properties due to moisture. X-ray two-dimensional (2D) computed tomography-imaging technique is used to construct finite element (FE) microstructural representation of a typical dense-graded asphalt concrete. After being calibrated against pull-off experiments, the proposed moisture-induced damage constitutive relationship, which is coupled to thermo-viscoelastic–viscoplastic–viscodamage mechanisms, is used to simulate the microstructure of asphalt concrete. Simulation results demonstrate that the generated 2D FE microstructural representation along with the coupled moisture–mechanical constitutive relationship can be effectively used to model the overall thermo-hygro-mechanical response of asphalt concrete.



## 1. Introduction

Moisture infiltration through moisture susceptible material; such as polymers, particulate composites, geo-materials, and asphalt concrete; combined with mechanical loading gradually degrade their properties. Specifically, moisture is a primary cause of premature failure of asphalt concrete pavements. Once infiltrated, moisture degrades aggregate–binder adhesive and binder cohesive bonds. The combined effects of repeated traffic loading with fluctuating environmental conditions intensify the degradation of asphalt concrete properties, adversely influence serviceability, and lead to early distress formation.

Extensive experimental and analytical investigations on the effects of moisture on different materials have been conducted since 1932 (Nicholson, 1932; Gandhi et al., 1987; Weitsman, 1987; Liu et al., 2005; Hueckel and Hu, 2009; Muliana et al., 2009; Hu et al., 2012). Researchers developed different models to simulate the response of polymers and their composites subjected to environmental effects. These model are either too complicated to use (material moduli depend on thirty-two invariants in Weitsman (1987) model) or the degradation procedure in their model is a linear function of concentration of moisture and allows for full recovery upon drying (Muliana et al., 2009). Geotechnicians developed models to consider the effect of moisture on partially saturated geo-materials (Liu et al., 2005; Hu and Hueckel, 2007; Hueckel and Hu, 2009; Arson and Gatmiri, 2012; Hu et al., 2012). They simulated the effect of flow of moisture inside interconnected cracks and voids and its induced additional stress on elastic solid materials. Liu et al. (2005) used Barcelona basic model formulation to take into account the influence of partial saturation on the response. Hu and Hueckel (2007) studied the mineral dissolution in the vicinity of a stressed grain. Rigid chemo-plasticity was used to simulate the phenomena in the solid phase at the micro-scale, coupled with the reactive-diffusion transport of the dissolved mineral across the grain. Similar approaches can be used to simulate the detrimental effect of moisture due to its diffusion inside the solid phase as both (i.e., diffusion and flow of moisture) cause extra expansion strains. However, these studies coupled the detrimental effects of moisture with the elastic solid material behavior and not a sophisticated thermo-viscoelastic–viscodamage behavior, as it should be for asphalt concrete.

A few relationships are available in the literature to investigate the effect of moisture on the aggregate–binder and aggregate–mastic interfaces of asphalt concrete material (e.g. Youtcheff and

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Aurilio, 1997; Kringos et al., 2008b; Pinto et al., 2009), mastic being defined as the mixture of asphalt binder with aggregates smaller than 2.34 mm. Youtcheff and Aurilio (1997) and Pinto et al. (2009) conducted pull-off tests and investigated the effect of moisture on the aggregate–binder bond strength through developing empirical relationships.

Kringos et al. (2008a) proposed a moisture damage constitutive relationship as a time-independent function of moisture content that allows for full moisture damage recovery upon drying, which is a controversial assumption. Graham (2009) proposed a time-dependent continuum damage-based constitutive relationship for predicting adhesive and cohesive moisture damage in asphalt concrete. This constitutive relationship does not account for moisture damage history effect and has not been verified against experimental measurements.

Most of the available moisture-induced damage constitutive relationships were developed based on simplified assumptions regarding the material properties that affect moisture susceptibility. This study extends the Continuum Damage Mechanics framework to consider the effect of moisture on the response of moisture-susceptible materials. The extended framework is followed to propose a physically-based moisture-induced damage constitutive relationship for particulate composite materials. The proposed moisture-induced damage is time-dependent, captures the moisture history effect, and considers the irreversible phenomena associated with the moisture degradation.

Moisture transport phenomenon and resistance of asphalt concrete to moisture-induced damage depend on aggregate mineral composition, proportions of the constituents (mix design), physical–chemical properties of the constituents, and other microstructural features (e.g., aggregates shape, size, and gradation; asphalt binder type; air void content and size distributions). Therefore, it is desirable to develop a microstructural analysis approach that utilizes a proper unified constitutive relationship and realistic microstructural representation to investigate the fundamental mechanisms governing distress formation in asphalt concrete when subjected to mechanical loading and moisture conditioning.

Paggi and Wriggers (2011a) derived a nonlocal cohesive zone model taking into account the properties of finite thickness interfaces to simulate particulate material at micro-scale. Then, they proposed the numerical applications to Polycrystalline materials, focusing on the constitutive modeling of the finite thickness interfaces between the grains (Paggi and Wriggers, 2011b). However, Paggi and Wriggers (2011a) assumed the material to be linear elastic at the initial stages before damage starts to evolve. Furthermore, the evolution of mechanical damage variable was defined as a monotonically increasing damage variable with time. Finally, they did not consider the degradation due to environmental conditions.

A few attempts have been made to simulate the microstructure of asphalt concrete subjected to mechanical loading and moisture effects since such simulations are computationally expensive. Abu Al-Rub et al. (2011) used X-ray computed tomography (CT) imaging technique to create a 2D FE microstructural representation of a typical dense-graded asphalt concrete composite. They utilized a thermo-mechanical constitutive relationship (Darabi et al., 2011) to simulate the mechanical response of asphalt concrete subjected to mechanical loading. Kringos et al. (2008a) and Graham (2009) simulated an idealized 2D FE microstructural representation of asphalt concrete to investigate the response of moisture-conditioned specimens subjected to mechanical loading. A cohesive zone element approach also was used to simulate the degradation at the aggregate–mastic interface of asphalt concrete materials (Caro et al., 2010a; Abhilash et al., 2011). Caro et al. (2010a) constructed a simple 2D FE microstructural representation of asphalt concrete and subjected it to cycles of moisture diffusion and mechanical loading. They embedded cohesive zone elements to simulate the effect of moisture on damage evolution at the aggregate–mastic interface. One of the main limitations of their method is that they predefined the direction of crack propagation. Although such approaches provide insight into the micromechanical response of particulate material, they cannot be used effectively to predict the overall response of materials at macro scale due to their high computational cost.

The moisture damage constitutive relationship proposed herein is coupled to a unified mechanical constitutive relationship implemented in the Pavement Analysis using Nonlinear Damage Approach (PANDA) model to predict the coupled moisture–mechanical response of asphalt concrete. PANDA is then used to conduct microstructural simulations of realistic 2D FE representation of asphalt concrete subjected to various mechanical and environmental loading conditions. The effect of moisture on the evolution of distresses at microstructural level is demonstrated through several simulations. It is shown that the modeling technique presented herein can predict crack propagation both in the mastic and at the aggregate–mastic interface without prescribing a predefined crack path. This modeling technique is employed to shed the light on the mechanism of damage evolution due to both mechanical and environmental loading conditions.

## 2. Coupled hygro-mechanical constitutive relationship

### 2.1. Continuum Moisture-Mechanical Damage Mechanics framework

This section extends the traditional Continuum Damage Mechanics (CDM) framework (Kachanov, 1958; Rabotnov, 1969) to Continuum Moisture-Mechanical Damage Mechanics (CMMDM) framework to couple moisture and mechanical damage mechanisms. Mechanical loading and moisture conditioning both contribute in degrading the material integrity. Mechanical loading causes evolution and propagation of micro-cracks and micro-voids through the material while moisture diffusion and presence simultaneously degrades adhesive and cohesive strength of the material. Degraded material due to moisture is more prone to mechanical damage. Simultaneously, propagation of micro-cracks and micro-voids causes more moisture diffusion and consequently more degradation. To simplify the numerical implementation and mathematical modeling of coupled moisture–mechanical response of

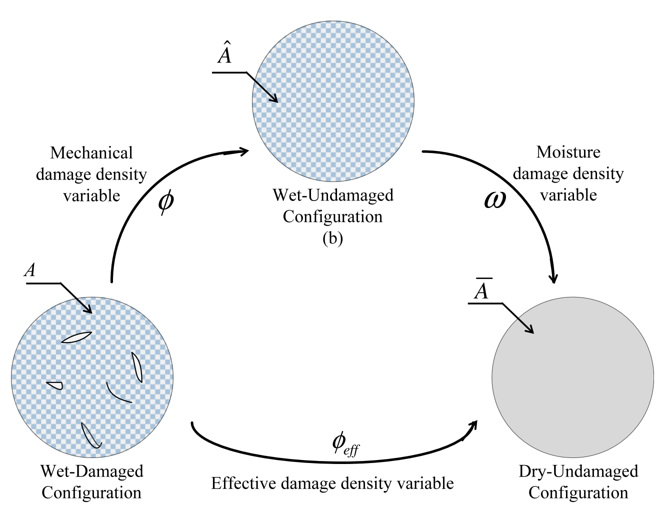


**Fig. 1.** Defined (a) *wet-damaged*, (b) *wet-undamaged*, and (c) *dry-undamaged* natural configurations to enable Continuum Damage Mechanics theories in modeling the response of moisture-susceptible materials.