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A thermodynamic framework for constitutive modeling of coupled moisture-mechanical induced damage in partially saturated viscous porous media

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ABSTRACT

A general thermodynamic-based framework is proposed to derive coupled moisture-mechanical induced damage constitutive relationships for multi-phase viscoelastic porous media. The well-known (Kachanov, 1958) effective (undamaged) configuration and the concept of effective stress space are extended to moisture-susceptible materials to couple the detrimental effects of moisture to the mechanical response of materials. A physically-based moisture-induced damage internal state variable is introduced within the proposed framework to account for the moisture aggravation effect, and to couple moisture-induced damage with mechanical responses. The principle of virtual power, Clausius–Duhem inequality and maximum rate of energy dissipation are constructed for multi-phase porous media. These principles are used to obtain the main macroscopic and microscopic balance laws, the general framework, and the constitutive relationships. The thermodynamic conjugate forces are decomposed into energetic and dissipative components, obtained from Helmholtz free energy and the rate of energy dissipation, to accurately estimate the rate of energy dissipation. The proposed thermodynamic framework is used to develop a comprehensive viscoelastic model, which takes into account the effect of pore water pressure, a constitutive relationship to model the detrimental effect of moisture diffusion inside the solid phase, Darcy's law, Fick's second law and, the Fourier heat conduction equation. The resulting constitutive relationships describe the coupled effects of mechanical loading and moisture-induced damage and accurately predict the response of partially saturated viscous porous media under various mechanical loading and environmental conditions.

1. Introduction

Moisture in the form of liquid or vapor diffuses through the solid skeleton or flows through the interconnected cracks and voids of porous media. The infiltrating moisture degrades the material integrity through thermodynamic, chemical, physical, and mechanical mechanisms. The combined effects of mechanical loading and moisture conditioning intensify the aggravation of the moisture-susceptible materials. Time- and rate-dependent (viscous) materials—such as polymers, bituminous materials, and soft materials—are especially moisture sensitive. Robust and comprehensive constitutive relationships are required to predict the response of such materials under moisture and mechanical loading. The constitutive relationships should consider the coupling between viscoelastic,

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moisture-induced damage, mechanical damage, and the temperature-dependent response of the material in a simple yet robust manner while satisfying the laws of thermodynamics.

The constitutive relationships that violate thermodynamic laws cannot describe the behavior of materials under general conditions and may produce thermodynamically unreasonable results. Enforcing the energy conservation and entropy increase laws provides a tool for developing general governing equations for physical phenomena. The general relationships can be particularized to more specific material behavior and conditions once a better understanding of the physics of such materials is achieved. Much effort has been put into developing the thermodynamic-based formulations to model the detrimental effects of environmental conditions on such materials as polymers, soft materials, granular materials, asphalt concrete, concrete, rocks, and bio-inspired materials (e.g., Biot, 1956; Shi et al., 1981; Weitsman, 1987; Collins and Houlsby, 1997; Rajagopal, 2003; Coussy, 2004; Loret and Simões, 2005; Arson and Gatmiri, 2012 and references therein). In particular, Weitsman (1987) introduced a general thermodynamic framework to formulate coupling between moisture diffusion and mechanical response in polymeric composites, the material moduli in the proposed model depend on thirty-two invariants, which makes it impossible to use in practice. Rajagopal (2003) conducted a review of literature on the effect of liquid diffusion through polymers undergoing large deformations. He discussed inherent difficulties associated with specifying boundary conditions within the context of mixture theory, a practice which has been used in the literature.

Geo-mechanicians conducted studies to predict the effect of flow of water through interconnected cracks and voids in geo-materials (e.g., Biot, 1956; Collins and Houlsby, 1997; Coussy, 2004; Arson and Gatmiri, 2012). Coussy (2004) developed a thermodynamic framework for partially saturated porous media. He proposed relationships to consider extra stress induced by liquid flow and the effect of suction on the elasto-plastic response of the solid skeleton. Arson and Gatmiri (2012) proposed a thermodynamic-based damage model for a non-isothermal unsaturated porous elastic skeleton. The developed models for geo-materials mostly assumed the material to be elastic and did not incorporate the degradation of the solid phase due to moisture diffusion, as should be done for moisture-susceptible viscous materials.

Kringos et al. (2008) introduced a moisture damage parameter and developed a thermodynamic framework to model moisture-induced damage in asphalt concrete. They theorized a three dimensional elasto-visco-plastic constitutive relationship for mastic (i.e., mixture of asphalt binder and fine aggregates) that considered the moisture-induced damage effect. They added the moisture damage variable as an internal state variable to the Helmholtz free energy. They did not enforce the first and second laws of thermodynamics for all phases of a multi-phase medium. Also, the developed moisture damage variable was time-independent and allowed for full moisture damage recovery upon drying, which is controversial.

Most of the available moisture-induced damage constitutive relationships either were developed based on simplified assumptions regarding the material properties that affect moisture susceptibility or did not consider all possible detrimental effects of moisture. Furthermore, most of the available models were developed based on ad-hoc conditions and while they can explain one or more experiments, they are not flexible enough to handle more general cases. To address these shortcomings, this paper does the followings:

1. Develops a general and robust thermodynamic framework that can be applied systematically to formulate constitutive relationships that incorporate the effect of moisture in viscous porous media.
2. Incorporates the Continuum Moisture-Mechanical Damage Mechanics (CMMDM) theory to overcome the complexities associated with defining mixture boundary conditions and moisture-mechanical couplings.
3. Unlike previous studies, integrates both the detrimental effect of moisture diffusion and presence inside the solid phase, as well as the effect of pore water pressure inside interconnected cracks and voids.
4. Proposes strong two-way coupling between moisture effect and mechanical response of moisture-susceptible materials.

In doing the above, the intrinsic characteristics of all phases are incorporated into formulating the principle of virtual power and the first and second laws of thermodynamics using the mixture theory context. The internal energies and entropy productions of different phases and the interactions between phases are the intrinsic characteristics that are considered in formulations. Formulating the principle of virtual power for such multi-phase media yields general balance equations that govern the wet viscoelastic solid, liquid, and visco-damage (i.e., moisture damage and mechanical damage) responses. The effective stress concept of CMMDM theory developed by Shakiba et al. (2014a) is used to define a physically based moisture damage variable and couple it to the mechanical damage and response of the media. This approach enables the framework to overcome the difficulty of defining boundary conditions in the context of mixture theory. Therefore, this study combines the micro- and macro-mechanical approaches to get a simple and robust framework to model moisture effects in porous viscous media. The developed framework is based on the use of independent state variables and it emphasizes, as Ziegler (1977) initially proposed, the decomposition of thermodynamic conjugate forces into energetic and dissipative components. A systematic procedure is used in this study to determine energetic and dissipative components of conjugate forces, respectively, from the Helmholtz free energy and the rate of energy dissipation functions. The evolution of natural configuration needs to be determined by a thermodynamic criterion and this study uses the maximization of the energy dissipation rate. Several examples in this study show the capabilities and robustness of the presented thermodynamic framework.

In order to keep the constitutive relationships tractable, several natural simplifying assumptions are adopted in this