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Constitutive modeling of coupled aging-viscoelastic response of asphalt concrete

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HIGHLIGHTS

- Proposed an oxidative-aging constitutive relationship for aging-susceptible materials.
- Coupled oxidative-aging to viscoelastic response of asphalt concrete.
- Calibrated and validated the coupled aging-viscoelastic constitutive relationship.
- Conducted finite element simulations on aged asphalt pavements.

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ABSTRACT

Oxidative aging is one of the most important processes affecting the time-dependent response of asphalt concrete materials, which subsequently results in brittleness of the material and fatigue damage. This paper proposes a mechanistic-based constitutive relationship of oxidative aging based on the evolution of a physically-based aging state variable. The aging constitutive relationship is coupled to the viscoelastic response of asphalt concrete by making both the creep compliance and relaxation time terms a function of the aging variable. The coupled oxidative aging-viscoelastic constitutive relationship is calibrated by analyzing the results of dynamic modulus testing conducted at different temperatures and frequencies on aged and unaged laboratory specimens with different air void contents ranging from 4% to 10%. The coupled constitutive relationships is validated against multiple repeated creep-recovery tests conducted on aged and unaged specimens at different stress levels, temperatures, and air void contents. The results illustrate the capabilities of the coupled oxidative aging-viscoelastic constitutive relationship to predict the viscoelastic response of aged asphalt concrete materials. Finally, the effect of oxidative aging on viscoelastic performance of aged pavement structures is investigated by: (a) applying a state-of-the-art experimental-computational method to determine oxygen diffusivity of asphalt concrete mixtures, and (b) conducting 2D finite element (FE) simulation of aged and unaged pavements.

1. Introduction

Oxidative aging of asphalt concrete is the consequence of chemical reactions within the asphalt binder phase with oxygen. Oxidative aging is one of the major contributors to premature failure of asphalt pavements as it affects the time-dependent response of asphalt concrete leading to brittleness of binder and eventually fatigue damage. The chemical reactions alter the physical properties of asphalt concrete, which typically results in increased viscosity, stiffness, and brittleness of the material. The brittle asphalt concrete is more susceptible to fatigue cracking; therefore, its performance is significantly influenced by oxidative aging.

The complexity of the asphalt binder, a mixture of relatively high weight molecules, has made the study of the chemistry of asphalt oxidation a difficult task. Asphalt is composed primarily of carbon and hydrogen, with nitrogen and sulfur at lower percentages and with other trace elements. These elements combine to form the main fractions of asphalt (i.e., asphaltenes, saturates, naphtene, and polar aromatics). Saturates and aromatics together make up the maltene phase. In other words, asphalt can be deemed as the dispersion of asphaltene particles in the continuous maltene phase. Due to oxidation, new asphaltene phases are produced by oxidizing the maltene phase [1,2]. The asphaltene phase undergoes

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progressive reactions with oxygen to form carbonyl and sulfoxides functional groups [3–5]. Such chemical reactions gradually increase viscosity and stiffness of asphalt concrete [3,4,6,7] Several studies have shown that the carbonyl formation is linearly correlated with oxygen content during oxidation [8]. Such observations have rendered the carbonyl functional groups a surrogate for measuring the level of asphalt oxidation [6,9].

Despite extensive studies on the chemistry and mechanisms of the oxidative aging, few studies are available on constitutive modeling of oxidative aging and its effect on the mechanical response of asphalt concrete. Since asphalt oxidation increases the viscosity and stiffness of the material, any constitutive model must consider such changes in physical and rheological properties. The common practice is to do this through the use of an aging-time shift factor. Struik [10] used this approach to incorporate reversible physical hardening effects in polymers. Using this approach viscoelastic functions at multiple ages were measured with one age selected as the reference. Then retardation or relaxation times for other ages were shifted by a constant factor such that they fell in line with the curve at the reference age. A number of other researches also used the same concept [11–16].

The linear viscoelastic response of asphalt concrete is governed by dynamic modulus in which a master curve of asphalt concrete is constructed by shifting the dynamic modulus in frequency domain at different temperatures with respect to a reference temperature. Studies have shown that aging of asphalt concrete does not affect the master curve in the same manner at all frequency ranges (later, this will be supported by experimental data). Consequently, this results in non-uniform changes in the master curve of the aged asphalt concrete with respect to the unaged material. The shift factor to accommodate aging effects fails to predict such observations [17] and assumes the opposite, i.e., that the influence of aging over all frequency ranges and temperatures is identical.

Alternatively, the aging effects on the viscoelastic response was considered by modifying creep compliance/relaxation moduli as a function of the age of the material as well as the loading period [18–23]. In this case, the integral form of the viscoelastic functions was expressed in two time domains, aging time and loading time. The former occurs on the order of years while the latter is at a much smaller time scale. Computationally, solving the viscoelastic integrations that are defined at two different time scales requires a great deal of computational cost and time.

Continuum-based modeling of asphalt concrete has gained popularity and importance using mechanistic-based constitutive relationships. The objective of such studies has been to utilize realistic physio-rheological properties to formulate constitutive relationships that properly describe the material behavior in an attempt to predict damage and plastic deformation that defines the service life of asphalt pavements. Such an approach, Pavement Analysis using Nonlinear Damage Approach (PANDA) was developed to include various mechanistic-based constitutive relationships with the ability to predict asphalt concrete performance [24–31]. With the objective of extending PANDA's constitutive relationships to account for the aging process, this paper presents a phenomenological, but physically-based oxidative aging constitutive relationship coupled with the viscoelastic response of asphalt concrete due to the process of aging. The hardening effect of aging is sequentially coupled to the viscoelastic properties in which the result of the oxidative aging analysis is used to assess the effect of mechanical loading on the aged asphalt. The aging constitutive relationship is formulated based on continuum theory such that the aging state variable is correlated to oxygen content via an evolution function.

This paper presents a straightforward procedure to identify the material properties associated with the aging constitutive relationship. Then, the method is validated against different repeated creep-recovery tests at various stress levels to show the capability of the oxidative aging constitutive relationship to predict the viscoelastic response of the aged asphalt concrete. This approach has several advantages over the past efforts to account for aging:

- The effects of oxidative aging are evaluated through introducing the physically-based aging state variable that modifies the viscoelastic compliance terms and relaxation times. Such modifications allow for shifting the dynamic modulus master curve concurrently in both vertical and horizontal directions. This is a substantial improvement over the previously used aging-time shift method.
- Defining the aging state variable at the continuum level allows one to simulate the aging effects at multiple scales. Since the constitutive relationship can be applied at the continuum scale, one can conduct aging-viscoelastic simulations of roadway structures either at macro or micro scales.
- The procedure for identifying material parameters associated with the coupled aging-viscoelastic constitutive relationship is straightforward and easy to apply.
- Since the proposed method is formulated based on a realistic physio-mechanical model of the material, it can be associated with and coupled to any constitutive behavior of aging that exhibits a viscoelastic response.

It should be noted that the response of asphalt concrete under traffic loading is complicated and can be influenced by nonlinear viscoelasticity, plastic deformation and rate-dependent damage. In order to fully account for the aforementioned response of the asphalt concrete, rate-dependent damage and plasticity must be considered in the constitutive modeling. This will be the subject of future studies by the authors and their collaborators.

2. Effect of oxidative aging on viscoelastic response of asphalt concrete

2.1. Oxidative-aging effect on viscoelastic rheology of asphalt concrete

Schapery's [32] viscoelastic constitutive relationship has successfully been used by several researchers [24,33,34] to represent the viscoelastic response of asphalt concrete. As the material ages, the viscoelastic properties of the material (i.e., compliance and retardation time terms) changes. The general form of the Schapery's viscoelastic constitutive relationship for aged materials can be written as:

$$(\varepsilon^{nve,t})^A = g_0 D_0^A \sigma^t + g_1 \int_0^{\psi} \Delta D^A(\psi^t - \psi^\tau) \frac{d(g_2 \sigma^t)}{d\tau} d\tau \tag{1}$$

where the superscript "A" designates the aged material properties. The term $(\varepsilon^{nve,t})^A$ is the nonlinear viscoelastic strain induced in aged material due to applied stress input, σ^t. The term D_0^A is the instantaneous compliance of aged material; ΔD^A is the transient compliance of aged material; and g_0, g_1, and g_2 are the stress dependent nonlinear parameters. The parameter ψ^t is the reduced-time that incorporates temperature and environmental effects. For numerical convenience, the Prony series is used to represent the transient compliance ΔD^A, such that:

$$\Delta D^A = \sum_{n=1}^{N} D_n^A [1 - \exp(-\lambda_n^A \psi^t)] \tag{2}$$

where D_n^A is the nth compliance associated with the nth retardation time λ_n^A, and N is the number of Prony series coefficients. The common practice in the literature is to extract the compliance