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Mechanistic modeling of healing in asphalt mixtures using internal stress

Xue Luo [a,*], Rong Luo [b,1], Robert L. Lytton [c,2]

[a] Texas A&M Transportation Institute, Texas A&M University System, 3135 TAMU, CE/TTI Bldg. 508B, College Station, Texas 77843, United States
[b] Texas A&M Transportation Institute, Texas A&M University System, 3135 TAMU, CE/TTI Bldg. 503C, College Station, Texas 77843, United States
[c] Zachry Department of Civil Engineering, Texas A&M University, 3136 TAMU, CE/TTI Bldg. 503A, College Station, Texas 77843, United States

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ABSTRACT

Healing of a material refers to a process of the restoration of original material properties to a damaged material. There are currently phenomenological methods and mechanism-based methods to characterize healing in asphalt materials. The phenomenological methods are based on the change of some kind of material property due to healing. The mechanism-based methods describe healing as a combination of a wetting process and a diffusion process. In addition to these two types of models, the paper aims at presenting a mechanical view of the healing process and developing a mechanistic approach to model healing in asphalt mixtures.

A new perspective of studying healing is proposed in this paper by relating it to the recovery of a material, based on which the mechanics of healing is well explained. The relationship between healing and recovery is clarified by defining the apparent recovery and true recovery. The apparent recovery of a bulk damaged material is driven by the apparent internal stress. The true recovery of the intact material is driven by the true internal stress. The apparent recovery involves two simultaneous processes: the true recovery and healing.

By studying the energy redistribution around cracks during healing, it is found that the true internal stress and the interfacial force of attraction are the two driving forces for healing. Under their actions, the direct result of healing is the decrease of damage density as a result of the growth of the contact area between crack surfaces. The energy-based mechanistic (EBM) approach is used to conduct mechanical analysis on the healing process and model healing by the progression of damage density. The creep and step-loading recovery (CSR) test is utilized to measure the apparent and true internal stresses.

By using the EBM approach to analyze the CSR test data, cracking is modeled in the creep phase of a CSR test, and healing is modeled in the recovery phase of the same CSR test. The analysis produces a damage density progression curve in the both phases. The initial damage when healing starts is represented by the damage density at the end of the creep phase; the damage at any time during the healing process is represented by the damage density in the recovery phase. The difference between the initial damage when healing starts and the damage at an arbitrary time point during recovery thus quantifies the extent of healing that occurs during this rest period.

1. Introduction

Healing of a material refers to a process of the restoration of original material properties to a damaged material. In asphalt pavements, healing of asphalt mixtures accompanies all kinds of cracking processes, such as fatigue cracking under repeated loading or creep fracture due to extensive creep deformation. Many approaches have been developed to quantify the effect of healing in damaged asphalt mixtures. Si et al. (2002) conducted cyclic load tests and added a series of rest periods (2, 5, 10, and 30 min) at 1000 cycle intervals to study the effect of healing. A healing index is defined as follows:

$$HI = \frac{\psi_{after} - \psi_{before}}{\psi_{before}} \tag{1}$$

* Corresponding author. Tel.: +1 (979) 458 8535.
E-mail addresses: xueluo@tamu.edu (X. Luo), rongluo@tamu.edu (R. Luo), r-lytton@civil.tamu.edu (R.L. Lytton).
[1] Tel.: +1 (979) 845 9897; fax: +1 (979) 845 0278.
[2] Tel.: +1 (979) 845 9964; fax: +1 (979) 845 0278.

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where HI is the healing index; ψ_{before} is the pseudo stiffness before a rest period; and ψ_{after} is the pseudo stiffness after a rest period. Pseudo stiffness is the slope of the linear regression of the hysteresis loop of stress versus pseudo strain. It decreases with the accumulation of fatigue damage as the loading cycles increase, and increases in the rest periods due to healing of the asphalt mixture. Thus, the recovery of the pseudo stiffness in the rest period, $(\psi_{after} - \psi_{before})$, represents the effect of healing. Kim et al. (2003) investigated the effect of healing of fine asphalt mixtures (asphalt binder mixed with fine aggregates) using the dynamic mechanical analyzer (DMA). Two-minute rest periods were executed ten times in a cyclic loading test. Healing was measured by the recovery of dynamic modulus in the rest period. Carpenter and Shen (2006) described the effect of healing from the change of fatigue resistance of an asphalt mixture. A constant rest period was inserted between every two adjacent loading cycles of a cyclic loading test to measure healing. They found a plateau region in the plot of the ratio of dissipated energy change versus the number of loading cycles, and defined the magnitude of the ratio of dissipated energy change in this region as plateau value. The fatigue resistance of the asphalt mixture was quantified by the plateau value. Change of the plateau value after the rest period thus represents the effect of healing. Kim and Roque (2006) conducted resilient modulus tests with a series of rest periods on different asphalt mixtures, and used the recovered dissipated creep strain energy per unit time to quantify healing. All of the methods just mentioned have the commonness of quantifying healing by its effect on some property, such as the change of the modulus or strain energy. This is a phenomenological way to describe healing by relating it to other phenomena that occur during rest periods.

Besides the phenomenological methods, mechanism-based models have also been proposed to predict healing in asphalt materials. Before discussing such a kind of model, it is useful to briefly review the mechanisms underlying occurrence and progression of healing. Extensive studies of healing have been carried out for polymer solids (Kausch et al., 1987). The physical mechanisms involved in a healing process include:

(1) Approach of two surfaces of a crack.
(2) Contact and adhesion between two crack surfaces.
(3) Deformation of surface irregularities.
(4) Interchange of molecular segments across the interface.
(5) Formation of new entanglements at the interface.

Healing starts when the two surfaces of a crack approach to get in touch with each other. Once the surfaces are brought in contact, an immediate adhesion arises from the change of the surface work. For most solids, their surfaces contain irregularities like hills and valleys, commonly called asperities. When the surfaces are in contact, the contact first takes place at the tip of the surface irregularities or asperities. The asperity regions continuously deform under the load, which leads to a gradual increase of the contact area. When the two crack surfaces are in complete contact, a diffusion process occurs accompanied by molecular interchange across the interface and random entanglement formation. In general and for simplicity, the first three physical mechanisms are called "wetting"; the last two are called "diffusion". Thus, healing is a combination of two processes: a wetting process and a diffusion process.

Wool and O'Connor (1981) proposed a convolution integral function to describe healing in polymers as a result of these two processes:

$$R = \int_{\tau=-\infty}^{\tau=t} R_h(t-\tau)\frac{d\phi(\tau,X)}{d\tau}d\tau \tag{2}$$

where R is the macroscopic recovery of a property, which is defined as the ratio of a property of the healed state to that of the virgin state at certain healing time, temperature, and pressure; $R_h(t-\tau)$ is the intrinsic healing function for wetting and diffusion; $\phi(\tau,X)$ is the wetting distribution function; X is a domain in the crack interface; t is the time; and τ is the running variable on the time axis. This theory was later used by Bhasin et al. (2008) to model healing of asphalt materials. The wetting distribution function is determined based on a crack closing relationship developed by Schapery (1989). This relationship predicts the crack closing speed of viscoelastic materials using material properties. The intrinsic healing function still employs a similar formulation in Wool and O'Connor (1981). The parameters of the intrinsic healing function are obtained through testing asphalt binders using the dynamic shear rheometer (DSR). However, healing of asphalt binders is different from that of asphalt mixtures since a mixture is a composite that consists of binder, aggregates, and air voids or cracks.

In addition to the aforementioned phenomenological and mechanism-based methods, this paper aims at presenting a mechanical view of the healing process and developing a mechanistic approach to model healing of asphalt mixtures. To achieve this objective, the mechanics of healing and the mechanistic approach to model healing are first discussed in Section 2. Investigation of the mechanics of healing will help identify the driving forces for healing in an asphalt mixture. Then the experimental design to measure the driving forces and acquire the necessary data to determine healing are introduced in Section 3. Detailed procedures of the proposed mechanistic approach are presented in Sections 4 and 5 step by step. The final section summarizes the major findings of this paper and presents the ongoing work on this topic.

2. Mechanics of healing

In order to mechanically model healing in asphalt mixtures, the mechanics concerning with healing need to be clarified. Specifically in this paper, three aspects are discussed:

(1) Healing under intermolecular forces (Section 2.1).
(2) Healing under internal stress and intermolecular forces (Section 2.2).
(3) Model healing using energy-based mechanistic approach (Section 2.3).

The contents in Section 2.1 are mechanical analyses of healing from literatures. The new perspective and approach proposed in this paper to study healing are introduced in Sections 2.2 and 2.3, respectively.

2.1. Healing under intermolecular forces

Studies pertaining to healing in damaged materials can be traced to the work of so-called autohesion of polymers in the 1960s (Anand and Karam, 1969; Anand and Balwinski, 1969; Anand, 1969). Autohesion refers to self-adhesion of two surfaces of the same material: the two surfaces are gradually closed and the contact area between them increases correspondingly. Anand and coworkers proposed a two stage theory for autohesion in polymers. The first stage involved contact establishment and the second stage involved bond formation through intermolecular forces. Similarly, Schapery (1989) formulated the bonding speed of a crack in linear viscoelastic materials using the interfacial forces of attraction (or surface energy). The interfacial force of attraction acts on the adjacent separated crack surfaces and tends to draw the