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Characterization of recovery properties of asphalt mixtures

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

HIGHLIGHTS

- Recovery of a material is characterized based on causation.
- A novel test is devised to measure internal stress as the driving force for recovery.
- The measured internal stress is simulated by an appropriate model.
- A new type of material property (recovery modulus) is defined using internal stress.
- The recovery moduli of undamaged and damaged asphalt mixtures are different.

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ABSTRACT

Recovery of a material refers to a process that the deformed material reduces its stored energy and restores its deformation after the load is removed. Characterization of recovery plays a significant role in damage measurement and prediction of asphalt pavements. However, major attention has been paid to the loading phase of a material, while much less attention is paid to the unloading phase, or the recovery phase. Even though there is some literature addressing this issue, the testing and analysis methods are empirical or phenomenological which emphasize correlation and not causation. To fill these research gaps, this paper presents a new test and analysis method to obtain the true mechanical properties in the recovery phase and characterize recovery based on its causal relationship.

The internal stress is the key to derive the true mechanical properties in the recovery phase because it is the driving force for the recovery. A creep and step-loading recovery (CSR) test is innovated to measure the internal stress at different points during the recovery of an asphalt mixture specimen. Since such a test method is novel for asphalt materials, its validity and accuracy are examined by comparing the measured value to the theoretical value. The results show that the CSR test is valid and accurate to measure the internal stress for asphalt mixtures.

The internal stress measured by the CSR test is used to define a new type of material property: the recovery modulus, which is an indicator of the material's capability to recover. The characteristics of the recovery modulus is studied at three different nondestructive loading levels and one destructive loading level. It is found that the recovery modulus of the undamaged asphalt mixtures does not change with the change of the loading level. However, the recovery modulus of the damaged asphalt mixtures is different from that of the undamaged asphalt mixtures. This difference is due to the loss by the damaged material of part of its capability to recover.

The CSR test and internal stress model innovated in this paper can be applied to any viscoelastic materials to determine their recovery properties. Because the CSR test has been validated in this study, the entire test procedure can be shortened to two steps including a nondestructive and a destructive CSR tests. Based on the results of the two CSR tests, the internal stress can be simulated using the exponential model developed in this paper, and the recovery modulus is then determined during the recovery phase of the material.

* Corresponding author. Tel.: +1 (979) 458 8535; fax: +1 (979) 845 0278.
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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1. Introduction

Recovery of an asphalt mixture refers to a process that the deformed material reduces its stored energy and restores its deformation after the load is removed. Before removing the load, the asphalt mixture undergoes a deforming process, during which if the load is destructive cracking damage and permanent deformation are generated in the material. Further development of cracks produces alligator cracking and the accumulation of permanent deformation results in rutting, which are two major distresses in asphalt pavements. Most existing research studying damage measurement and characterization in asphalt pavements focuses on reducing the cracking damage and permanent deformation during the loading phase, while much less attention is paid to the unloading phase, i.e. the recovery phase. The recovery of asphalt mixtures, in fact, contributes significantly to the measurement and characterization of damage as well. During the recovery phase, the cracks generated during the loading phase heal to alleviate the cracking damage. It has been proven that healing of asphalt mixtures is a substantially important issue in the field of asphalt pavements, and its significance has been demonstrated in both the laboratory and field [1–4]. As a result, the healing process, which is always accompanied by the recovery process, should be included in order to accurately predict the remaining cracking damage in asphalt pavements. In addition, investigating the recovery ability can help reduce rutting in asphalt pavements. An asphalt pavement that has better recovery ability accumulates less deformation in the asphalt layer, so the occurrence of excessive deformation which produces permanent deformation is less under repetitive traffic loading. This reduction is especially distinct for asphalt pavements under high frequency traffic. A number of State Departments of Transportation (DOTs) have adopted this idea and have used the elastic recovery test as a complement to examine the rutting resistance of asphalt materials [5]. In addition to the elastic recovery test, the creep recovery test has also been used to evaluate the rutting resistance of non-modified and modified bitumen [6].

The elastic recovery test examines the recovery ability of asphalt materials using a ductilometer following the procedure as documented in the American Association of State Highway and Transportation Officials (AASHTO) T301-99 [7] or American Society of Testing Materials (ASTM) D6084 [8]. In this test, a briquet specimen is pulled apart until it reaches a specified elongation of 20 cm [7] or 10 cm [8]. The specimen is then severed at the center and allowed to recover without disturbance for an hour. At the end of 1 h, the two halves are rejoined and the elongation of the recovered specimen is measured. Then the ability of the material to recovery is described as the percentage of recovered length to the specified 20 cm or 10 cm. The elastic recovery test appears to be simple; however, it requires elaboration on sample preparation and testing. Moreover, the result is not very accurate and often fails to discriminate the behavior between different asphalt binders [5]. To fulfill the objective of the elastic recovery test and avoid the associated problems, Shenoy [5] proposed a dynamic test using the dynamic shear rheometer (DSR). In a dynamic oscillatory test, the modulus is a complex number, defined as the complex modulus, which includes two components: the storage modulus and the loss modulus. The ratio of the storage modulus to the complex modulus is used as a measure of the recovery ability of the asphalt material. However, the storage modulus does not represent the total recovery of an asphalt mixture. An asphalt mixture has an elastic response that instantaneously recovers upon load removal. It also exhibits considerable delayed elastic response (viscoelastic response), which non-instantaneously (time-dependently) recovers and is completely recoverable given sufficient time. The elastic and viscoelastic responses constitute the total recovery response of the asphalt mixture. From the viewpoint of the complex modulus, the elastic response and a portion of the viscoelastic response are contained in the storage modulus; the other portion of the viscoelastic response is contained in the loss modulus [9]. Therefore, measuring the storage modulus with a dynamic oscillatory apparatus is not an appropriate method to characterize the recovery of asphalt mixtures.

The creep recovery test is another method to characterize the recovery behavior of viscoelastic materials by recording the recovered strain during the recovery phase of the test. A creep recovery compliance is defined as a measure of such behavior [10]:

$$J_r(t) = \frac{\varepsilon_r(t)}{\sigma_0} \tag{1}$$

where $J_r(t)$ is the creep recovery compliance; $\varepsilon_r(t)$ is the recovered strain in the recovery phase, which is the difference between the maximum strain at the end of the creep phase and the remaining strain in the recovery phase; and σ_0 is the applied stress in the creep phase. Since $J_r(t)$ is defined by σ_0, it is a material parameter that quantitatively describes how the material behaves after removing the load; it is not a material property because the recovery response is not stimulated by σ_0. The actual driving force for the recovery response should be the force present in the recovery phase. Under the circumstance of no external load, the force present in the recovery phase is provided by the material itself, which is defined as internal force or internal stress. As a result, in order to obtain the material properties in the recovery phase, the internal stress must be determined first during the recovery of asphalt mixtures.

The internal stress has been studied by many researchers for metals and polymers using the creep test [11–17]. In the loading phase of the creep test on a metal or polymer, the creep strain is partitioned into two parts: the recoverable part (including the elastic component and the time-dependent component) and the plastic part. Accordingly, the applied creep stress is decomposed into two components, as follows:

$$\sigma = \sigma_i + \sigma_e \tag{2}$$

where σ is the applied creep stress; σ_i is the internal stress, or the recovery stress, responsible for the recoverable strain that restores the deformed material into its original state; and σ_e is the effective stress, responsible for the plastic strain that results in the activated rate process of plastic deformation. According to this partition and definition, the positive creep strain rate is explained as being caused by a positive σ_e since σ is much larger than σ_i in the loading phase. When σ becomes zero in the recovery phase, the rate of recovery is governed only by σ_i, which is proportional to the unrecovered strain [17,18]. These studies define and measure the internal stress in the loading phase of the creep test, aiming at explaining the deformation mechanism of a metal or polymer under the load. In order to study the recovery behavior of an asphalt mixture when it is unloaded, the internal stress of the asphalt mixture in the recovery phase must be measured using a new approach.

The objective of the paper is to design a laboratory test to measure the internal stress of an asphalt mixture in the recovery phase and then to use the internal stress to characterize the recovery properties of the asphalt mixture. The measurement principle of the internal stress is introduced in the next section. Then the following section presents the configuration and procedure of the test designed to measure the internal stress in an asphalt mixture specimen. To ensure the accuracy of the proposed testing method, verification of the test results is conducted by comparing the measured values to the theoretical calculations. Once the testing method is verified, the measured internal stress is used to define the actual recovery properties. Finally, the findings of this paper are summarized and the ongoing work on this research topic is