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Characterization of linear viscoelastic, nonlinear viscoelastic and damage stages of asphalt mixtures

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HIGHLIGHTS

- Linear viscoelasticity was strictly differentiated from the nonlinearity.
- Material properties in linear viscoelastic stage were the reference properties.
- Viscoelastic stress, reference modulus & pseudostrain were rigorously established.
- The sole linear viscoelastic effect was eliminated to determine pseudostrains.
- Dissipated pseudostrain energies were determined for representative loading cycle.

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ABSTRACT

It has been demonstrated that asphalt mixtures experienced linear viscoelastic stage, nonlinear viscoelastic stage and damage stage when subjected to controlled-strain repeated direct-tension (RDT) tests with increasing strain levels. However, the linear viscoelastic properties of asphalt mixtures are usually muddled up with their nonlinear viscoelastic properties. These confusions directly lead to the incorrect determination of the pseudostrains and dissipated pseudostrain energies (DPSEs) in the nonlinear viscoelastic stage and damage stage. This study investigated the material properties of fine aggregate mixture (FAM) specimens in all three stages. These three stages were differentiated and characterized in terms of the viscoelastic stress, pseudostrain and DPSE. The definitions of viscoelastic stress, reference modulus and pseudostrain were rigorously established to assure that the material properties in the linear viscoelastic stage were the reference properties and that the sole linear viscoelastic effect was eliminated when determining the pseudostrain and DPSE in the three stages. The characteristics of the DPSE in the three stages were found to be: (1) the DPSE of any loading cycle was zero in the linear viscoelastic stage; (2) in the nonlinear viscoelastic stage, the DPSE of each loading cycle remained approximately the same with the growth of the number of loading cycles, and the DPSE increased to a larger value when the strain level of the RDT test increased to a higher level; (3) in the damage stage, the DPSE of the loading cycle increased as the number of loading cycles increased. This study strictly distinguished the linear viscoelasticity from the nonlinear viscoelasticity of the asphalt mixtures, which is critical for the accurate determination of the DPSE spent in overcoming the nonlinear viscoelasticity and in developing damages, such as cracking and permanent deformation, in the asphalt mixtures.

1. Introduction

Paving asphalt mixtures are complex composite materials that may exhibit different properties at different strain levels. It has been demonstrated that, when subjected to typical controlled-strain repeated direct-tension (RDT) tests, an asphalt mixture experiences multiple stages as the strain level increases, which include: (1) undamaged stage, consisting of the linear viscoelastic stage and the nonlinear viscoelastic stage; and (2) damage stage [1,2]. These stages have the following characteristics:

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(1) Undamaged stage:
  a. At any specific strain level, the material properties stay constant despite of the increase of the number of loading cycles;
  b. The deformation of the asphalt mixture is completely recovered after unloading;
  c. As the strain level varies, the asphalt mixture has different properties in the linear viscoelastic stage from those in the nonlinear viscoelastic stage:
  i. Linear viscoelastic stage: the material properties remain unchanged if the strain level varies within this stage;
  ii. Nonlinear viscoelastic stage: the material properties change as the strain level varies;

(2) Damage stage:
  a. At any specific strain level, the material properties vary with the increase of the number of loading cycles;
  b. The deformation of the asphalt mixture cannot be completely recovered after unloading; and
  c. The material properties change as the strain level varies.

If using the pseudostrain defined in Eq. (1) to eliminate the linear viscoelastic effect [3], these stages can be illustrated via the stress-pseudostrain curve, as shown in Fig. 1.

$$\varepsilon_R = \frac{\sigma_{VE}(t)}{E_R} = \frac{\int_0^t E(t-\tau)\frac{\partial \varepsilon(\tau)}{\partial \tau} d\tau}{E_R} \quad (1)$$

where ε_R = pseudostrain, $\mu\varepsilon$; $\sigma_{VE}(t)$ = viscoelastic stress corresponding to the measured strain history, Pa; E_R = reference modulus, MPa; t = loading time, s; τ = a dummy variable, indicating any arbitrary time between 0 and t, s; $E(t)$ = relaxation modulus in the linear viscoelastic stage, MPa; and $\varepsilon(t)$ = measured strain history, $\mu\varepsilon$.Based on the identification of these distinct stages, testing to determine the mechanical properties of asphalt mixtures is made simpler and more precise by using pseudostrain concepts in analyzing the test data. However, these advantages are diminished or even lost if the analysis does not make clear distinctions and boundaries between these stages. In fact, the nonlinear viscoelastic properties are usually muddled up with the linear viscoelastic properties [1,2,4,5]. For example, $\sigma_{VE}(t)$ has been considered to be the same as the measured stress in the nonlinear viscoelastic stage, and E_R has been chosen to be the magnitude of the complex modulus at the critical nonlinear viscoelastic point (Point B) shown in Fig. 1 when calculating the pseudostrain in the nonlinear viscoelastic stage [1,2]. These confusions directly lead to the incorrect determination of the pseudostrains and pseudostrain energies in the nonlinear viscoelastic stage and in the damage stage. Using these incorrectly determined results could hardly make accurate prediction of the development of the damages in the asphalt mixture, such as the fatigue cracking and permanent deformation, which are driven by the corresponding dissipated pseudostrain energies (DPSEs). As a result, there is an urgent need to rigorously determine the nonlinear viscoelastic properties of the asphalt mixture in typical controlled-strain RDT tests and to characterize the associated DPSEs in the nonlinear viscoelastic stage and damage stage.

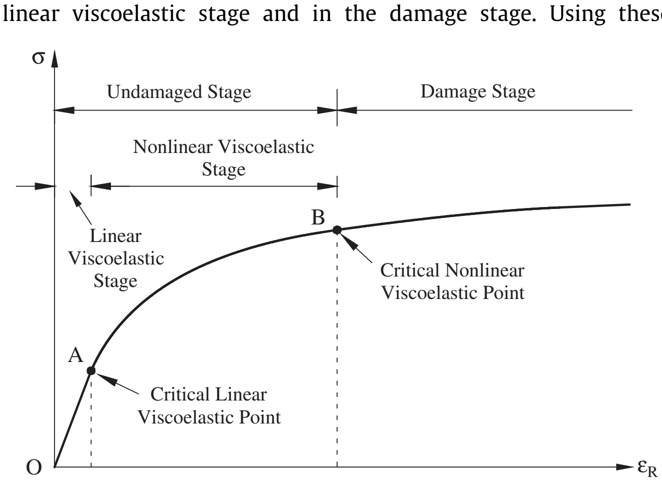

Fig. 1. Stress-pseudostrain curve of an asphalt mixture in controlled-strain RDT tests (after [1,2]).

To address this research need, this study employed a Dynamic Mechanical Analyzer (DMA) to perform controlled-strain RDT tests on fine aggregate mixture (FAM) specimens in order to investigate their material properties in the linear viscoelastic stage, nonlinear viscoelastic stage and damage stage. The DPSEs in these stages were also characterized for future applications to the prediction of the damage development in asphalt mixtures. The next section describes the configuration and procedure of the controlled-strain RDT tests. The subsequent section presents the determination of the asphalt mixture properties in different stages based on the test data. The following section details the differentiation and characterization of the linear viscoelastic stage, nonlinear viscoelastic stage and damage stage in terms of the viscoelastic stress, pseudostrain and DPSE. The final section summarizes the major findings of this study and briefs the authors' ongoing research on this subject.

2. Configuration and procedure of the controlled-strain RDT tests

2.1. Specimen fabrication

FAM specimens for the controlled-strain RDT tests were fabricated in the laboratory using an unmodified #70 petroleum asphalt binder (graded based on the penetration) and fine limestone aggregates passing No. 16 sieve with the opening of 1.18 mm. The gradation of the fine aggregates is listed in Table 1. The asphalt binder content was calculated to be 8.97% by weight of aggregates using the aggregate surface area method with the optimum asphalt content of the corresponding full asphalt mixture [6–9].

The procedure of fabricating and preparing the FAM specimens for testing was composed of five major steps as follows:

(1) Mixing and compaction: the aggregate batch was mixed with the asphalt binder at the temperature of 135 °C; after being cured at 121 °C for 2 h, the asphalt mixture was compacted using the Superpave Gyratory Compactor (SGC) into a cylindrical raw specimen 150 mm in diameter and 70 mm in height, as shown in Fig. 2(a);
(2) Cutting: the upper and lower part of the raw specimen were cut off using an automatic saw into a shorter specimen 40 mm in height, as presented in Fig. 2(b);
(3) Coring: the shorter specimen were cored following the pattern illustrated using red circles in Fig. 2(c) to obtain cylindrical specimens to be tested, which were 12 mm in diameter and 40 mm in height; Fig. 2(d) shows an example of the FAM specimen;
(4) Gluing: each end of a FAM specimen was glued to an end platen using a 2 ton epoxy with the aid of a specially designed gluing jig, as presented in Fig. 2(e), to assure the

Table 1
Gradation of the fine aggregates in FAM specimens.

Sieve No.	No. 16	No. 30	No. 50	No. 200	PAN (-No. 200)
Sieve size (mm)	1.18	0.60	0.30	0.75	<0.075
Individual retaining (%)	0	44.23	23.46	18.85	13.46