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# Creep and recovery behavior characterization of asphalt mixture in compression

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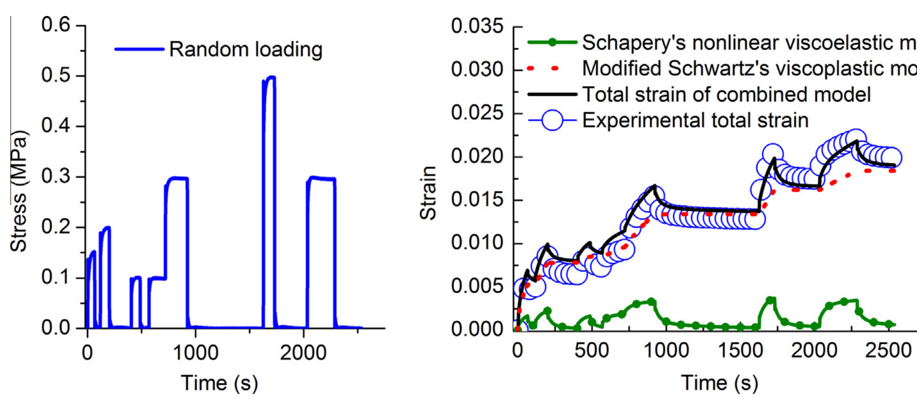
## HIGHLIGHTS

- The creep and recovery behaviors of the asphalt mixture are tested.
- The asphalt mixture exhibits obvious nonlinearity.
- The simplified Schapery's viscoelastic model is used for recoverable strain.
- The modified Schwartz's viscoplastic model is used for irrecoverable strain.

## GRAPHICAL ABSTRACT

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## ABSTRACT

A simplified Schapery's nonlinear viscoelastic model and a modified Schwartz's viscoplastic model with a proposed stress function are combined to characterize viscoelastic and viscoplastic behaviors of compressed asphalt mixture. In this combined model, the simplified Schapery's model is used for describing the recoverable strain, and the modified Schwartz's model is for the irrecoverable strain. The model parameters are determined with the multiple-stress repeated creep–recovery test and the one-hour creep test, and then the combined model is validated with some other tests, including the one-hour creep test at a different stress, the fixed-stress repeated creep–recovery test and the random loading test. Compared with the Perzyna's viscoplastic model, the modified Schwartz's model can fit the experimental viscoplastic strain response better in a wide stress range, so that the combined model can predict the creep and recovery behaviors of asphalt mixture under uniaxial compression well.



## 1. Introduction

Due to permanent deformation accumulation caused by repeated traffic loads, rutting is one of the major failure modes in asphalt concrete pavements. It is extremely important to assess and improve the resistance of asphalt concrete to permanent deformation before making a desirable design. The laboratory wheel tracking test is the most direct and frequently-used method to investigate the rutting resistance, but it is empirical and cannot give a deep understanding of the material properties. It has been well known that asphalt concrete is a time-dependent material which exhibits noticeable viscoelastic and viscoplastic characteristics [1,2]. These characters can be reflected by a creep–recovery test [3]. When asphalt concrete is subjected to a constant load, deformation occurs and develops with time. After the load is removed, the deformation can partly recover. To clarify how much the irrecoverable part is in the total strain, Ossa et al. [4,5] proposed an empirical method to measure the ratio of the recoverable part to the total axial strain. They found the ratio to be a constant

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which was independent of the total axial strain and scarcely influenced by the confining pressure. Some other researchers preferred to decompose the total strain into a viscoelastic strain and a viscoplastic strain and to model them separately [6–12]. The viscoelastic strain described by a viscoelastic model was used to represent the recoverable part of total strain, while the viscoplastic strain described by a viscopalstic model was used to describe the irrecoverable part.

The purpose of this paper is to find a simplified method to investigate the viscoelastic and viscoplastic characteristics of asphalt mixture in compression. In this method, proper models are used to describe the mechanical behaviors, and as few experiments as possible are carried out to determine the model parameters.

There have been many methods to model the viscoelastic strain. When the strain is very tiny, the Boltzmann superposition principle is often applicable, and the linear viscoelastic theory can be used [13]. However, in most cases, especially at high stress and high temperature, asphalt mixture exhibits obvious nonlinearity with respect to load because of its complicated composition. Schapery's nonlinear viscoelastic model [14], originated from the Boltzmann superposition integral by introducing four stress-dependent parameters, is still widely used today. The other useful method to model nonlinear viscoelasticity is the pseudo strain and stress theory [11,15–17]. It can model viscoelasticity as nonlinear elasticity by applying the correspondence principle to eliminate the time dependence. Theoretically, the strain could be partially recoverable in a viscoelastic model because a plastic component is often included. For example, a free dashpot can produce plastic strain in the Maxwell spring-dashpot model [18]. So complete recoverability must be imposed on the viscoelastic model, if it is used to describe the recoverable strain only.

To model the irrecoverable strain, many viscoplastic models are expressed in differential formulas which define the viscoplastic strain rate as a function of the current stress and internal variables. Perzyna's viscoplastic model is one of them and has been wildly used [6,19,20]. It assumes that only when the stress exceeds a threshold can the permanent strain be produced. The threshold corresponds to the yield surface in the three-dimensional space, so the model can be extended into three-dimensional cases easily. However, sometimes the stress threshold is too low to measure, especially at high temperature cases. Different from Perzyna's viscoplastic model, Schwartz's viscoplastic model [8] uses a stress function to describe complex nonlinear relationship between stress and viscoplastic strain rate without the necessity of defining a stress threshold. In addition, recently, a new viscoplastic model based on the convolution integral was proposed by Subramanian et al. [9]. This model is expressed in an integral formula and hypothesizes that the viscoplastic strain rate depends not only on the current values of stress and viscoplatic strain, but also on the loading history. No matter which formula is used, a viscoplastic model must embody the strain hardening effect of the material, and ensure the viscoplastic strain rate to be zero when the current stress vanishes.

This paper combines a simplified Schapery's nonlinear viscoelastic model and a modified Schwartz's viscoplastic model with a proposed stress function to characterize viscoelastic and viscoplastic behaviors of compressed asphalt mixture. The model parameters are determined with the multiple-stress repeated creep–recovery test and the one-hour creep test. The multiple-stress repeated creep–recovery test can exhibit the nonlinear viscoelasticity and viscoplasticity, while the creep test can reflect the long-term response to loading. Both the strain and stress in this paper are compressive but measured in positive sign.

## 2. Combined viscoelastic–viscoplastic model

### 2.1. Strain decomposition

Fig. 1 schematically shows a typical viscoelastic–viscoplastic response in a creep–recovery experiment. Before the recovery point $t'$, the asphalt mixture sample creeps because of being subjected to a constant load. The creep strain can be decomposed into a recoverable part and an irrecoverable part, which will be described by the viscoelastic and viscoplastic models, respectively. The decomposition of the strain can be expressed as

$$\varepsilon = \varepsilon_{ve} + \varepsilon_{vp}, \tag{1}$$

where $\varepsilon_{ve}$ and $\varepsilon_{vp}$ denote the viscoelastic and viscoplastic strain components, respectively. At $t'$ the load is removed instantaneously and the creep strain begins to be partly recovered. When the recovery time lasts long enough, only the irrecoverable creep strain $\varepsilon_{vp}(t')$ remains. The recoverable creep strain $\varepsilon_{ve}$ at $t'^-$ will be totally recovered after $t'^-$. The instantaneous strain decrement at time $t'$ is defined as $\Delta\varepsilon_e = \varepsilon_{ve}(t'^-) - \varepsilon_{ve}(t'^+)$, which is also called the instantaneous recovered strain. During the recovery period, the strain is gradually recovered with time elapsing. The strain decrement from time $t'^+$ to $t(t > t'^+)$ is defined as $\Delta\varepsilon_v(t) = \varepsilon_{ve}(t'^+) - \varepsilon_{ve}(t)$, which is also called the retarded recovered strain. As shown in Fig. 1, the recoverable creep strain at $t'^-$ can be decomposed into two parts: $\Delta\varepsilon_e$ and $\Delta\varepsilon_v(\infty)$.

### 2.2. Simplified Schapery's nonlinear viscoelastic model

The simplified Schapery's nonlinear viscoelastic model is expressed as

$$\varepsilon_{ve} = g_0 D_0 \sigma + \int_{0^-}^{t} \Delta D(t-\tau)\frac{d(g_2\sigma)}{d\tau}d\tau, \tag{2}$$

where $D_0$ and $\Delta D(\psi)$ are the instantaneous compliance and the transient compliance, respectively. $g_0$ and $g_2$ are the stress-dependent parameters.

In the creep–recovery test shown in Fig. 1, the viscoelastic strain response can be theoretically expressed according to Eq. (2) [14]. When $0^+ \leqslant t \leqslant t'^-$, $\sigma = \sigma_0$ (namely a constant creep stress), so that

$$\varepsilon_{ve}(t) = (g_0 D_0 + g_2 \Delta D(t))\sigma_0, \tag{3}$$

but when $t \geqslant t'^+$, $\sigma = 0$, so that

$$\varepsilon_{ve}(t) = (\Delta D(t) - \Delta D(t-t'))\sigma_0 g_2. \tag{4}$$

Because the viscoelastic strain is totally recoverable, the strain in Eq. (4) should be zero when $t \to \infty$. To this end, the following Prony series is used to represent the transient compliance.

$$\Delta D(t) = \sum_{i=1}^{n} D_i(1 - \exp(-\lambda_i t)), \tag{5}$$

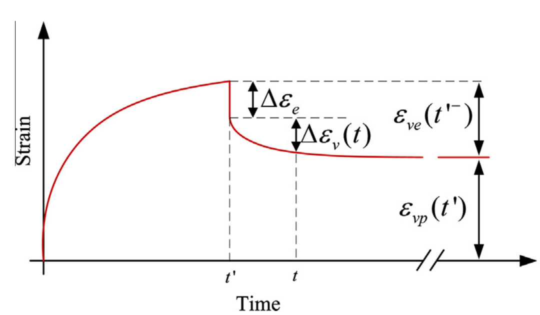


**Fig. 1.** A typical viscoelastic–viscoplastic response in a creep–recovery experiment.