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The extended shift model as a mechanistic-empirical approach to simulating confined permanent deformation of asphalt concrete in compression

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HIGHLIGHTS

- A mechanistic-empirical model is proposed for simulating permanent deformation.
- The extended shift model consists of an incremental function and a shift function.
- The shift factor depends on reduced pulse time, vertical stress, and confinement.
- Model characterization requires four triaxial stress sweep tests.
- The model fits in state-of-practice framework to predict pavement rutting.

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ABSTRACT

The extended shift model is presented as a convenient and effective mechanistic-empirical approach to simulating the densification induced permanent deformation of asphalt concrete under repeated loading. The model is composed of an incremental function that provides a reference deformation curve, and a shift factor function expressed in terms of three variables: reduced pulse time, confining pressure, and vertical stress. The model can be characterized by four triaxial stress sweep tests, and it fits in the state-of-practice frameworks to predict pavement rutting with improved reliability.

1. Introduction

Rutting is one of the major distress types found in flexible pavements, and it usually presents as a channel that is created by repeated vehicle traffic. Rutting may lead to rideability and even safety issues, especially when water collects at the bottom of the rut. The possible coexistence of surface cracks that allow the water to penetrate down through the structure and soften the subgrade may further deteriorate the condition of the pavement. In order to optimize the material and structural design, it is thus of critical importance to first understand the deformation characteristics of asphalt concrete under repeated traffic loading.

In the laboratory, the rutting resistance of asphalt concrete can be evaluated by subjecting a cylindrical specimen to repeated creep and recovery (RCR) testing. The loading profile of the RCR test is a large number of repeated cycles, each consisting of a haversine-shaped load pulse followed by a rest period. Therefore, this test is able to simulate field traffic loading patterns in a realistic manner compared to the continuous loading under monotonic or cyclic test conditions. The strain that is measured at the end of the rest period in each cycle, which is deemed the permanent strain, is extracted and plotted versus the cycle number. The resulting permanent deformation history resembles common creep curves and is divisible into three segments: the primary, secondary, and tertiary regions. In the first two regions the material is mechanically stable and is considered to experience plastic hardening, whereas in the tertiary region the deformation grows rapidly at an

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increasing rate due to the material's instability, and softening dominates the material's behavior.

A considerable amount of effort has been devoted to simulating the permanent deformation behavior of asphalt concrete under the RCR-type test conditions. The phenomenological investigations can be categorized generally into two aspects: mechanistic-empirical and mechanistic modeling. In mechanistic-empirical modeling, power functions have been adopted to represent the deformation curve in the primary and secondary regions, whereas for the tertiary region exponential functions are commonly applied. For example, in the Mechanistic-Empirical Pavement Design Guide (MEPDG) [1] the permanent strain is expressed as a power function of temperature and cycle number. In order to describe the complete deformation history, Zhou et al. [2] proposed a model that represents the three regions in a piecewise fashion using a power, linear, and exponential function of the cycle number, respectively. In the actual implementation, however, Zhou et al. found the model to be sensitive to the algorithms used to determine the cycle number at turning points. After evaluating several available options, Biligiri et al. [3] recommended the use of the Francken model [4] in which the three-stage permanent strain is expressed as a single continuous function (i.e., a combination of a power and exponential functions) of the cycle number.

In modeling the permanent deformation of asphalt concrete under RCR-type test conditions, the significant independent variables are commonly identified as load pulse time, temperature, deviatoric stress, confining pressure, and cycle number. The rest period also plays an important role in the material's overall response. In the present study, a long rest period is implemented because only irreversible deformation is concerned. Mechanistic-empirical models are able to provide an intuitively straightforward approach to the macroscopic deformation history of asphalt concrete. Most mechanistic-empirical models, however, do not incorporate all the significant factors, in particular the confining pressure. For example, the Francken model [4] is a function of cycle number only. The MEPDG model [1] attempts to capture the effects that are due to factors other than temperature and cycle number via the resilient strain, but the resilient strain is computed by assuming elastic or viscoelastic material properties, and thus, the model's capability is questionable in describing the strong nonlinearity that is due to changes in stress or temperature conditions in plastic deformation. In addition, as a result of this general deficiency in mechanistic-empirical models, i.e., not including all the variables, the model parameters are implicitly dependent on the missing factors, and thus supplementary experiments and functions may be required for a complete characterization. Moreover, due to the models' empirical nature, success in seeking consistent relationships may in general not be guaranteed between the model parameters and the changes in the test conditions or material rutting resistance.

By contrast, mechanistic models are able to reveal the underlying mechanisms in the deformation process through a combined effort of experimental observation and theoretical hypothesis. In this category, the Perzyna-type plastic flow rule [5] is usually adopted using various yield criteria coupled with hardening and/or softening laws (e.g., [6–9]). Another type of mechanistic model abandons the concept of yield surface and assumes, for example, that the viscoplastic deformation can be described via a stress-based convolution integral enclosed in Macaulay brackets [10,11].

Mechanistic models can provide a solid approach to the fundamental understanding of material behavior. Yet, manipulation of such models is theoretically demanding and requires advanced numerical techniques. In the theoretical aspect, the direct application of existing yield criteria for metallic or other geotechnical materials to asphalt concrete, which is a pressure-dependent and viscous material, lacks concrete support due to inadequate experimental evidence. In the numerical implementation, the material's state typically must be updated at every time step, which is a computationally expensive and time-consuming process given the need for hundreds or thousands of load cycles. Furthermore, certain parameters associated with the internal state variables and hardening/softening functions can be obtained only through numerical optimization on the experimentally observable quantities, which essentially constitutes an inverse or ill-posed problem and thus may lead to non-unique solutions and perhaps even thermodynamic inconsistency [12].

The shift model proposed by Choi and Kim [13] seems to have the potential to help mitigate the above-described dilemma. The model is developed based on the incremental model [14], which is derived from a viscoplastic theory [10] with simplifications on the evolution of material's hardening state. Compared to other functions (including the Francken model), the incremental function has been demonstrated to have the advantageous capability in fitting the individual experimental curves from various test conditions. In the shift model, the parameters in the incremental function have been expressed as functions of deviatoric stress, temperature, and load pulse time. The shift model is able to predict permanent strain conveniently in a cyclic manner, while the nonlinear effects of deviatoric stress, temperature, and pulse time are described explicitly by the shift functions. In addition, the model parameters can be obtained easily through straightforward regression analysis.

The shift model applies to the primary and secondary permanent deformation regions. It then follows that in this study the focus is only on the densification-induced permanent deformation. The evolution of the material's state in the tertiary region is unstable and highly complicated, and may involve cracking and material plastic flow (e.g., large distortions of asphalt binder, and translation and reorientation of aggregate particles), which are usually deemed the mechanisms associated with severely rutted pavements. Therefore, more advanced experimental and analytical techniques for unstable deformations would be required, which is beyond the current scope of the mechanistic-empirical modeling effort. For the time being, it is suggested that quality design and construction of materials and structures should be guaranteed to avoid or to delay entering the unstable state within the pavement's design life.

The shift model is essentially a convenient and effective mechanistic-empirical approach, and yet one major limitation is that it does not consider the effects of confining pressure. The state of the practice typically uses a single confinement level, for example, 10 psi (69 kPa), as in the MEPDG method. It is, however, well recognized that asphalt concrete, as a porous composite material, exhibits significant pressure dependence just like other geomaterials such as cement concrete, rock, and soil. Therefore, by adopting the aforementioned merits of the shift model, this paper aims to enhance the modeling methodology in the state of the practice by extending the shift model via introducing the effects of confining pressure explicitly into the mechanistic-empirical scheme.

2. Materials and methods

2.1. Specimen preparation and test set-up

The material used in this study is an asphalt mixture with PG 52-34 binder and a nominal maximum aggregate size of 9.5 mm. It was designed originally for use in the state of Vermont. All specimens were compacted using the Superpave Gyratory Compactor to a height of 178 mm and a diameter of 150 mm. In order to achieve smooth surfaces and a relatively uniform distribution of air voids, all specimens were then cored and cut into dimensions of 150 mm in height and 100 mm in diameter. The target air void content for the final test specimens is 6% with an allowable variability of ±0.5%.

As previously stated, the goal of this research project is to incorporate confining pressure as an additional variable in the current modeling framework of the shift model. Hence, material testing was conducted under confinement at a few selected