Meso-Scale Study on Shear Creep Behavior and Characteristic of Asphalt-Aggregate Interface

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ABSTRACT: To investigate the effects of asphalt–aggregate interface creep behavior, an interface creep constitutive model under the coupled compression and shear loading is established in term of the viscoelasticity theory. The model parameters were calibrated by the oblique interface shear creep tests with the nonlinear multiple variables fitting method. The results show there is a good agreement between the theory model curve and the experimental results, which reflect the three stages creep deformation characteristic of the asphalt–aggregate interface. The research gives some better insights into the meso-scale analysis of asphalt-aggregate interface viscoelastic behavior.

INTRODUCTION

Interface bonding condition between asphalt and aggregate plays an important role in determining the overall mechanical properties of asphalt mixture. Asphalt-aggregate interface is often considered the weakest link in asphalt mixture with respect to its formation, strength and durability (Wang, Lin et al. 2015). Mathematically speaking, for a perfect interface the displacement and traction fields are both continuous across the boundary of two phases, while for an imperfect this is not the case (Li and Sun 2013). The asphalt-aggregate interfacial zone contains a thin layer of asphalt binder, which is a typical viscoelastic material, its deformation shows a time-dependent effect. Namely interfacial failure behavior is not instantaneous load of action, but with the creep deformation of the material increase to a certain extent before failure. Efforts have been made to study the asphalt-aggregate imperfect bonding, Zhu and Yang (2011) established a micromechanical model and a numerical method, taking into account of imperfect bonding between aggregate-asphalt, to predict the elastic modulus of AC. Recently, Zhu et al. (2014) also presented a methodology to research the influence of interface imperfection on the viscoelastic characteristics of asphalt-based multi-phase particle-reinforced composites. Gao et al. (2015) investigate the effect of imperfect between asphalt mastic and aggregates on the viscoelastic properties of asphalt concrete. The linear spring layer model is introduced to characterize the interface imperfection. However, very few experiment studies have been involved in asphalt-aggregate interface viscoelastic behavior. Viscoelastic interface issues are the fundamental basis for evaluating the asphalt-aggregate interface failure behaviors. Therefore, it is of great significance to do further research on the asphalt-aggregate viscoelastic interface problems.
CONSTITUTIVE RELATIONS FOR VISCOELASTIC INTERFACES

In order to investigate the interface viscoelastic behavior, to describe the course of additive effect and material stress-strain corresponding process of the interface, an idealized asphalt-aggregate interface system was introduced, see Fig.1(left). The constitutive relations of the asphalt-aggregate interface were studied by the combination of the viscoelasticity theories and the experimental study. And the constitutive relations were expressed in a form of integral. The mechanical analysis of asphalt-aggregate interface is under the normal and shear loading, see Fig.1(right). The stress tensor and the strain tensor are $\sigma$ and $\varepsilon$ respectively.

\[
\sigma = \begin{pmatrix}
\sigma_{11} & \sigma_{12} & \sigma_{13} \\
\sigma_{21} & \sigma_{22} & \sigma_{23} \\
\sigma_{31} & \sigma_{32} & \sigma_{33}
\end{pmatrix}, \quad 
\varepsilon = \begin{pmatrix}
\varepsilon_{11} & \varepsilon_{12} & \varepsilon_{13} \\
\varepsilon_{21} & \varepsilon_{22} & \varepsilon_{23} \\
\varepsilon_{31} & \varepsilon_{32} & \varepsilon_{33}
\end{pmatrix}
\] (1)

Using stress tensor and its trace to represent the strain tensor. Linear elastic constitutive relation of the interface can be written in the following form (Yang 2004).

\[
\varepsilon = \int_0^1 \left[ I \varphi_1(t-\xi)\tilde{\sigma}(\xi) + \varphi_2(t-\xi)\tilde{\sigma}(\xi) \right] d\xi
\] (2)

Where $\tilde{\sigma}$ is the strain rate, and its trace of the tensor can be represented as $\tilde{\sigma}_{ii}$. Based on Eqs. (2), the nonlinear creep constitutive equation can be obtained by considering the effect of quadratic and cubic term of stress, which can be written as the following mathematical form:

\[
\varepsilon = \int_0^1 \left[ I \varphi_1(t-\xi)\tilde{\sigma}(\xi) + \varphi_2(t-\xi)\tilde{\sigma}(\xi) \right] d\xi_1 + \int_0^t \int_0^t \left[ I \varphi_3(\xi_1)\tilde{\sigma}(\xi_2) + I \varphi_4(\xi_1)\tilde{\sigma}(\xi_2) + \varphi_5(\xi_1)\tilde{\sigma}(\xi_2) + \varphi_6(\xi_1)\tilde{\sigma}(\xi_2) \right] d\xi_1 d\xi_2 + \\
\int_0^t \int_0^t \left[ I \varphi_7(\xi_1)\tilde{\sigma}(\xi_2)\tilde{\sigma}(\xi_3) + I \varphi_8(\xi_1)\tilde{\sigma}(\xi_2) \cdot \tilde{\sigma}(\xi_3) + \varphi_9(\xi_1)\tilde{\sigma}(\xi_2)\tilde{\sigma}(\xi_3) + \varphi_{10}(\xi_1)\tilde{\sigma}(\xi_2)\tilde{\sigma}(\xi_3) + \varphi_{11}(\xi_1)\tilde{\sigma}(\xi_2)\tilde{\sigma}(\xi_3) + \varphi_{12}(\xi_1)\tilde{\sigma}(\xi_2)\tilde{\sigma}(\xi_3) \right] d\xi_1 d\xi_2 d\xi_3
\] (3)

where $I$ is the unit matrix, $\varphi_i$ is the creep function.

It can be seen from the Fig.1 that the stress state of asphalt aggregate interface is a combination of normal stress and shear stress, the tensor of stress can be written as follows.

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Figure 1. Schematic of the interface (left), the state of stress on the interface (right).
The following related equations can be calculated by the tensor method

$$\sigma = \begin{pmatrix} \sigma(t) & \tau(t) & 0 \\ \tau(t) & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

(4)

The following related equations can be calculated by the tensor method

$$\sigma\sigma = \begin{pmatrix} \sigma^3 + \tau^2 & \sigma\tau & 0 \\ \sigma\tau & \sigma^2 + \tau^2 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \sigma\sigma\sigma = \begin{pmatrix} \sigma^3 + 2\sigma\tau^2 & \left(\sigma^2 + \tau^2\right)\tau & 0 \\ \left(\sigma^2 + \tau^2\right)\tau & \sigma\tau^2 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

(5)

$$\bar{\sigma} = \dot{\sigma}, \ddot{\sigma} = \sigma^2 + 2\dot{\sigma}^2, \dddot{\sigma} = 3\dot{\sigma}^2$$

Each of the strain component $\varepsilon_{ij}$ can be obtained by substituting the above sub Eqs. (5) into the derived creep constitutive equation, i.e. Eqs. (3). Wherein, the study focuses on the interface shear creep behavior, so the shear strain is needed, and it can be written as

$$\varepsilon_{12} = \int_0^t \bar{G}_1 \xi d\xi + \int_0^t \bar{G}_2 \sigma d\xi \bar{d}_2 + \int_0^t \bar{G}_3 \bar{d}_3 d\xi + \int_0^t \bar{G}_4 \sigma \sigma d\xi d\xi d\xi,$n

(6)

where $\bar{G}_i$ is the function of $(t - \xi_j)$ which can be expressed as

$$G_1(t - \xi_j)$$

$$G_2(t - \bar{\xi}, t - \bar{\xi}_2, t - \bar{\xi}_3)$$

$$G_3(t - \bar{\xi}_1, t - \bar{\xi}_2)$$

$$G_4(t - \bar{\xi}_1, t - \bar{\xi}_2, t - \bar{\xi}_3)$$

(7)

However, it is hard to determine material functions $G_i$ and conduct data analysis through experiment design according to the Eqs. (6). Therefore, the approximate theory is adopted to simplify the Eqs. (6). In which the kernel functions as well as the creep function and the relaxation function are quite significant. Materials integral function approximation is that material function containing the time variable is equal to the product of each function of time variable, namely Eqs. (7) can be written as

$$G_1(t - \xi_j) = R_1(t - \xi_j)$$

$$G_2(t - \xi, t - \xi_2, t - \xi_3) = R_2(t - \xi)R_2(t - \xi_2)R_2(t - \xi_3)$$

$$G_3(t - \xi_1, t - \xi_2) = R_3(t - \xi_1)R_3(t - \xi_2)$$

$$G_4(t - \xi_1, t - \xi_2, t - \xi_3) = R_4(t - \xi_1)R_4(t - \xi_2)R_4(t - \xi_3)$$

(8)

If a sudden shear stress was imposed on the specimen, that is, static load shear creep test. According to state of stress on the interface (see Fig. 1) in a form of oblique shear, and assuming that the shear angle is $30^\circ$, follow functions can be derived.
where $\tau_0$ is the initial shear stress, $H(t)$ is the unit step function and $(t)$ is the unit impulse function.

\[
H(t) = \begin{cases} 
1 & t \geq 0 \\
0 & t < 0 
\end{cases}
\]

\[
\int_{-\infty}^{\infty} \delta(t) dt = \int_{-\infty}^{\infty} \delta(t) dt = 1 \quad \forall \epsilon > 0
\]

Interface shear creep constitutive model can be obtained by substituting the Eqs. (8) and (9) into the Eqs. (6), then the $\varepsilon_{12}$ can be written as

\[
\varepsilon_{12} (t) = \tau_0 R_1 (t) + \sqrt{3} \tau_0^3 R_3^2 (t) + \tau_0^3 R_3 (t)
\]

where $R_2(t) = \sqrt{3} R_4^3 (t) + R_2^3 (t)$, $\tau_0$ is the shear stress applied to the specimen, $R_i(t)$ is the material functions, which is determined by experiments.

**VALIDATION OF INTERFACE MODEL**

In order to verify the derived interface creep constitute model, interface shear creep tests were carried out. A sandwich-like cylindrical specimens were utilized to simulate the asphalt-aggregate interfacial bonding behaviors, see Fig. 2(left). The specimens consisted of two granite aggregate columns with a thin layer of asphalt in between. Aggregate columns with 30mm diameters and 25mm height were sanded and polished to maintain a constant surface roughness. After polished, aggregate columns and asphalt were heated to 160°C and glued together using a servo hydraulic frame. More detailed for sample preparation can be found elsewhere (Al-Haddad and Al-Khalid 2015). Then, sandwich-like specimens were confined in oblique shear device, see Fig.3 (left). The oblique shear device includes loading plate, bearing plate, roller, weight and linear variable differential transformer(LVDT), see Fig.2(right), and the strain of the interface with time was recorded and analysed by DH2817 static and dynamic strain measurement system. As shown in the Fig.3, when the weight is loaded, a constant stress will impose on the loading plate and then covey stress to interface, the shear stress is proportionally to the compression stress during the test, shear stress can be express as follow.

\[
t = \frac{F \cdot \sin \alpha}{A}
\]

where $\tau$ is the shear stress(MPa), $F$ is the pressure(N), $\alpha$ is shear angle(degree), $\alpha$ presented in this study was 20°, $A$ is the area of the interface (mm²).
According to the interface shear creep constitutive model, material functions, of the constitutive model, i.e., $R_1(t)$, $R_3(t)$ and $R_5(t)$, can be determined by conducting shear creep experiment under 3 kinds of different shear stress. The strain-time relation under different shear stress can be obtained by fitting the curve respectively. Then by substituting the $\varepsilon_0$ and $\varepsilon_{12}(t)$ into the Eqs.(12). Then, three equations with three unknowns were got, and materials function can be obtained by solving these equations.

Interface shear creep tests were performed under three kinds of shear stress(0.015MPa, 0.030MPa and 0.045MPa) at a temperature of 35°C. The shear creep curves are shown in Fig.3. Three different model-fitting methods including polynomial method, rational fraction method and exponential method were used to fit the creep curves, it shown that the cubic polynomial method was more suitable for fitting curves, due to its high efficiency and correlation to the curves. Table 1 shows the fitting results.

Table 1. Cubic polynomial fitting results of shear creep curves.

<table>
<thead>
<tr>
<th>Shear Stress (MPa)</th>
<th>Function</th>
<th>$R^2 \alpha^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau_0 = 0.015MPa$</td>
<td>$2 \times 10^{-12}t^3 + 8 \times 10^{-9}t^2 + 1 \times 10^{-5}t + 0.0005$</td>
<td>0.9728</td>
</tr>
<tr>
<td>$\tau_0 = 0.030MPa$</td>
<td>$8 \times 10^{-11}t^3 - 1 \times 10^{-7}t^2 + 7 \times 10^{-5}t - 0.001$</td>
<td>0.9656</td>
</tr>
<tr>
<td>$\tau_0 = 0.045MPa$</td>
<td>$3 \times 10^{-10}t^3 - 2 \times 10^{-7}t^2 + 0.0001t + 0.0003$</td>
<td>0.9069</td>
</tr>
</tbody>
</table>
It is assumed that the fitting results of the interface are equal to the theoretical interface constitutive solutions at a certain initial shear strain and temperature. Then, the following Eqs. (13) can be obtained

\[ a_i t^3 + b_i t^2 + c_i t + d_i = \tau(i)_0 R_i(t) + \sqrt{3} \tau(i)_0^2 R_i^2(t) + \tau(i)_0^3 R_i(t) \]  

where \( i = 1, 2, 3 \). \( \tau(i)_0 \) is the initial shear stress corresponding to \( i \).

Simultaneous the above three equations, the following results can be obtained

\[
\begin{cases}
R_1(t) = -9.3333 \times 10^{-10} t^3 + 7.1556 \times 10^{-9} t^2 - 0.0027778 t + 0.20667 \\
R_2(t) = 0.5 \left( 5.132 \times 10^{-8} t^3 - 0.0012317 t^2 + 0.66716 t - 34.898 \right)^{0.5} \\
R_3(t) = 3.2593 \times 10^{6} t^3 + 0.0061235 t^2 - 3.9506 t + 237.04
\end{cases}
\]

Therefore, the interface shear creep model strain can be written as

\[
\varepsilon_{12}(t) = \tau_0 \left[ -9.3333 \times 10^{-10} t^3 + 7.155610^{-9} t^2 - 0.0027778 t + 0.20667 \right] + \\
\sqrt{3} \left( \frac{5.132 \times 10^{-8} t^3 - 0.0012317 t^2 + 0.66716 t - 34.898}{\tau_0^2} \right) + \\
\tau_0 \left( 3.2593 \times 10^{-6} t^3 + 0.0061235 t^2 - 3.9506 t + 237.04 \right)
\]

where \( \tau_0 \) is the initial shear stress and \( t \) is the creep time.

Figure 3. Shear creep curves under different shear stress (T=35℃).

Figure 4. The comparison between experimental and model curve.
It should be noted that the obtained $\varepsilon_{12}(t)$ is under a relatively certain temperature and a constant surface roughness, then the materials function can be deduced by conducting three kinds of shear stress. Therefore, model validation can be perforated by conducting differences shear stress. Fig.4 shows an example model validation at a shear stress of 0.25MPa. As can be seen from the Fig.4, model shows a good agreement with the experimental curve before interface creep failure.

CONCLUSIONS

A viscoelastic interface model has been proposed in this study based on viscoelastic mechanics theories, which take account for combined compression and shear stress. Furthermore, solving method of model parameters and experimental procedures was proposed according to the characteristic of the interface constitutive model. Polynomial fitting method was applied to obtain the relationship of model parameters under different initial shear stress. Finally the proposed model has been verified by comparing with experimental data, the model can be represented on asphalt-aggregate interface creep behavior.

Further investigations will be carried out to extend the present viscoelastic interface model for different shear angle and a larger range of temperature. Besides, the consideration of the interface roughness, asphalt binder type can be carried out by a more comprehensive mechanical test. Therefore, it is possible to make use of this model to study the interface effect on the overall properties of the asphalt mixtures.

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