Rut Prediction for Semi-rigid Asphalt Pavements

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Abstract

A new rutting prediction model for semi-rigid asphalt pavements is put forward based on the shear deformation mechanism. The most notable feature of this model is the efficient consideration of shear factors, namely, shear-strength is employed to evaluate the anti-deformation capacity of asphalt mixture and shear stress is used to represent the resistance of pavement structure to rutting. Four asphalt mixtures are used to carry out wheel tracking tests at different temperatures and contact pressures, and then the model is determined by the optimization analysis method. Meanwhile, the vehicle speed, which has a pronounced influence on rutting, is successfully introduced into the model by means of Boltzmann’s linear superposition principle. Finally, the model is calibrated using accelerated pavement test results.

Introduction

Accurate estimates of rutting are an essential input for the efficient pavement management systems. Rutting in asphalt pavement includes densification and shear flow of hot-mix asphalt, whereas the majority of severe rutting is caused by the shear flow within the asphalt mixtures (Eisenmann et al. 1987 and Myers et al. 2002). This is especially true for semi-rigid asphalt pavements as a result of their stiffer stabilized base: in this case, asphalt layer is responsible for most of the shear deformation. In the past, efforts have been made by a number of pavement researchers to apply the shear concept to the mix design of asphalt concrete (McLeod 1951 and Monismith et al. 2006). However, researches in this direction
have not achieved a widespread accepted result by now, probably due to the complexity of the test methods, such as triaxial tests and repeated simple shear test at constant height.

The paper presents a new mechanism-empirical approach to predict rutting in semi-rigid asphalt pavements. A simple and practical shear test method is employed to take into account the shear properties of asphalt concrete: Static Uniaxial Penetration Test (SUPT) (Sun et al. 2006). This work aims to lay the foundation for putting forward appropriate design procedures to control rutting in the future.

**Framework of Rut Prediction Model**

Much research (Eisenmann et al. 1987, Sousa et al. 1994 and Myers et al. 2002) has indicated that shear deformation is mainly associated with pavement structure characteristic, pavement materials properties, temperature and traffic (vehicle speed, load magnitude and repetitions). Traditionally, predictions of rutting progress have been based on the most widely used power equation as shown in Equation (1) (SHRP 1993), which empirically accounts for the rut depth as a function of temperature and loading repetitions.

\[
RD = \alpha \times N^\beta \times T^\theta
\]  

where \(RD\) is the rut depth after the loading repetitions of \(N\) at the temperature of \(T\), \(\alpha\), \(\beta\) and \(\theta\) are the coefficients of the equation.

However, recent studies indicate that the exponent of loading repetitions generally varies with exposure to different loads or if different materials are used (Su 2006). The value of \(\beta\) in Equation (1) mainly depends on the magnitude of stress and the properties of asphalt mixture. To reflect this, Equation (1) is modified to give Equation (2) by introducing a function for shear stress and shear strength instead of the constant \(\beta\) value above.

\[
RD = \alpha \times N^m \times T^\theta
\]  

where \(m = (\tau/\tau_0)^n\), \(\tau\) is shear stress in the pavement, which can be calculated by the finite element method, and \(\tau_0\) accounts for the shear strength of asphalt concrete measured by SUPT. Note that the ratio of \(\tau\) to \(\tau_0\) can minimize the error resulting from using elastic theory for computing \(\tau_0\) and \(\tau\). In this model, shear stress is used to differentiate the resistance of pavement structures to rutting, and shear strength is only used to evaluate the shear strength of asphalt mixtures, therefore, 20°C and 60°C were respectively designated as their representative temperature.

Because of the viscous property of asphalt concrete, lower speed usually results in greater rut depth, as found on gradients and at intersections. However, it is very difficult to precisely capture the relationship between deformation and
speed due to its complexity. Therefore, the Boltzmann’s linear superposition principle (Guo 2001), that is, that the total rut depth can be directly calculated by summing all the deformation increments at different times, is coupled with another empirical equation stating that the loading duration is the inverse of vehicle speed (Pell and Taylor 1974) to take into account the influence of vehicle speed on rutting. In other words, the rut depth caused by one application of a load operation with the speed of 10 cm/s is equivalent to that caused by ten similar loadings operation at a speed of 100 cm/s. The resulting complete prediction model is illustrated in Equation (3), where $V_{\text{ref}}$ is the reference speed and $N_v$ is the number of load repetitions at the speed of interest $V$.

$$RD = \alpha \times \left( \frac{V_{\text{ref}}}{V} \cdot N_v \right)^m \times (T)^\theta$$  \hspace{1cm} (3)

In reality, the shear stress, temperature and properties of asphalt concrete vary through the depth in asphalt pavement. To take this into account, a method of accumulating all sub-layer deformations as the total deformation was employed. The thickness of each sub-layer is defined as 10mm, and the mid-point of each sub-layer is designed as the computation point. Thus, one can obtain the total rut depth by simply summing all deformation increment through the entire thickness based on the actual temperature, shear stress and shear strength in each sub-layer.

**Laboratory Experimental Program**

**Wheel Tracking Test.** A wheel tracking test with a solid rubber-faced tire was used to provide the data of the rut evolution with the repetitions of loading. The slab specimen used in this test was 300mm wide, 300mm long and had a thickness of 50mm. Tests were carried out at three temperatures, 20°C, 40°C and 60°C at a constant tracking speed of 0.16m/s. Four asphalt mixtures were used, of which aggregate gradations were as shown in Figure 1. Mix A was tested at three pressure levels of 0.56MPa, 0.72MPa and 1.10 MPa, whereas mix B, C and D were tested at the standard pressure of 0.72MPa. The wheel tracking test results are shown in Figure 2. Just as mentioned above, pronounced differences in deformation development trend were observed for different asphalt mixtures or under various load levels.

**Static Uniaxial Penetration Test.** Basically, the shear resistance of asphalt concrete as an intrinsic property of the material and should be constant under given conditions. However, variations in confining pressure mean that triaxial test fails to give a unique value for shear strength. Considering this deficiency and also the complexity of triaxial test, a static uniaxial penetration test (Figure 3) was
employed, named SUPT. This test can directly determine the shear strength of asphalt mixture as verified by Bi (Bi 2004), who showed that the distribution of shear stress in a SUPT specimen agreed perfectly with that in a real pavement structure, and also the damage mechanism in SUPT was mainly dependent on shear forces. Chen has further demonstrated the superior repeatability of SUPT and consistency with triaxial test at 0.3MPa confining pressure (Chen 2006).

In this test, the specimen size was 100mm in diameter by 100mm in height. Such specimens can be easily molded by the Superpave gyratory compactor. The loading head (a steel rod with 28.5 mm diameter) penetrates the SUPT specimen at a strain-controlled loading rate of 1mm/min. The shear strength denoted $\tau_0$ is
defined as:

\[ \tau_0 = k \cdot P_{\text{max}} \]  \hspace{1cm} (4)

where \( P_{\text{max}} \) is the penetration strength provided by the SUPT specimen, and \( k \) is named as the shear strength coefficients with a suggested value of 0.339 based on the ratio of maximum shear stress to the vertical circular pressure of 1MPa applied on a semi-infinite space when the Poisson ratio is 0.35.

Prior to testing, each specimen was held in an environmental chamber for over 5 hours at 60°C. Shear strength tests of mix A, B, C and D were conducted, and the shear strength values were 1.063, 0.861, 1.152 and 0.984 MPa, respectively.

**Finite Element Analysis of Shear Stress.** The shear stress in the slab specimen used for wheel-tracking test was calculated by a three-dimensional finite element method as shown in Table 1. Note that the measured resilient modulus of asphalt concrete was used to compute the shear stress, but the results indicated that resilient modulus had negligible effect on the value of shear stress in this finite element model.

**Determination of Prediction Model by Optimization Analysis**

The model was determined by fitting the wheel-tracking test results using the Solver optimization technique in Excel by minimizing the sum of errors arising from the error (SSE) between the measured and the predicted rutting. In this case, every input data point corresponds to a rut depth, a temperature and a shear stress as well as a shear strength. This model, as expressed in Equation (5), gives an excellent fit as evidenced by a higher value of determined coefficient up to 0.838.

\[ RD = \sum_{i=1}^{n} 10^{-5.342} \cdot T_i^{2.524} \cdot \left( \frac{0.58}{V} \cdot N_V \right)^{0.752} \left( \frac{\tau}{\tau_0} \right)^{0.440} \]  \hspace{1cm} (5)

To shift the model from the laboratory to actual pavement, a full-scale road test was performed to provide confirmatory evidence for the laboratory tests. This calibration not only considers the downward rut depth but also upheaval on the two neighboring sides of rut. Here, Equation (5) becomes:

\[ RD = \sum_{i=1}^{n} 10^{-5.72} \cdot T_i^{2.512} \cdot \left( \frac{0.58}{V} \cdot N_V \right)^{0.743} \left( \frac{\tau}{\tau_0} \right)^{0.472} \]  \hspace{1cm} (6)

**Table 1.** Shear stress in the wheel tracking slab (MPa)

<table>
<thead>
<tr>
<th>Tire pressure</th>
<th>0~1 cm</th>
<th>1~2 cm</th>
<th>2~3 cm</th>
<th>3~4 cm</th>
<th>4~5 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.56 MPa</td>
<td>0.1993</td>
<td>0.1502</td>
<td>0.0999</td>
<td>0.0735</td>
<td>0.0623</td>
</tr>
<tr>
<td>0.72 MPa</td>
<td>0.2395</td>
<td>0.2184</td>
<td>0.1498</td>
<td>0.1114</td>
<td>0.0948</td>
</tr>
<tr>
<td>1.10 MPa</td>
<td>0.3414</td>
<td>0.3676</td>
<td>0.2662</td>
<td>0.2017</td>
<td>0.1729</td>
</tr>
</tbody>
</table>
Conclusions

In this study, a method is developed for the prediction of rutting in semi-rigid asphalt pavements, and the most significant enhancement in this new approach is that the concept of shear is successfully introduced. The new approach takes into account traffic and environmental characteristic as well as the pavement structure and the properties of the materials. The fit of this model when both rutting and local upheavals as well as temperature gradient are taken into account is improved after a calibration using the results obtained in a full-scale road test.

Though this new method looks very promising, considerable efforts are still needed to assess the new rut model before it can be applied to the actual pavements.

References


