Development of Shear-based Rutting Prediction Model for Asphalt Pavements

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ABSTRACT: In this study, a shear-based rutting prediction model is built considering the shear property of structure and materials and the characteristic of traffic and environment, which is not only an essential input for an efficient PMS, but also a pavement design tool. A genetic optimization approach is used to get the parameters of the prediction model by full scale pavement tests and laboratory wheel tests at various conditions in terms of temperatures, pressures and slab thicknesses. Finally, this model is calibrated by the field data.

KEY WORDS: Asphalt pavement; rutting; prediction model; shear factor;

1 INTRODUCTION

Rutting acknowledged as a common concern, defined as longitudinal depressions in the wheel path accompanied by upheaves to the sides, is one of the major distresses formed in asphalt pavements, which usually results from the frequent traffic loads at a high temperature. The accurate prediction of its development is not only an essential input for an efficient pavement management system, but also plays an important role in the mechanistic-empirical pavement design method for the analysis of pavement structure and materials (Archilla et al., 2000). Rutting in asphalt pavements is believed to be due to the combination of densification and shear flow of hot-mix asphalt (HMA), whereas the majority of severe rutting is caused by the shear flow within the asphalt mixtures (Eisenmann et al., 1987, Myers et al., 2002, Su et al., 2009). This is especially true for asphalt pavements compacted well during construction, in which asphalt layer is responsible for most of the deformation. In years past, applying the shear concept into mix design of asphalt concrete was actively pursued by a number of pavement researchers (McLeod, 1951, Monismith et al., 2006). However, research works in this direction have not achieved a widespread accepted result by now, probably due to the complexity of shear test methods. In recent years, this situation is changing with the invention of Static Uniaxial Penetration Test (SUPT), a simple and compact but efficient method to determine the shear resistance for asphalt concrete (Sun et al., 2006). This paper presents a new approach to predict rutting of asphalt pavements with semi-rigid base course, which consider shear properties of pavement structure and materials.

2 FRAMEWORK OF RUTTING PREDICTION MODEL

This study focuses on the shear deformation within asphalt pavements with semi-rigid base course induced by traffic loads. Research indicated that this type of rutting was mainly associated with the properties of pavement structure and material, temperature and traffic in terms of load magnitude, vehicle speed and number of load repetitions. In general, the prediction of the field rutting evolution is based on the widely used empirical equation expressed by power function as shown in Eq. (1). This equation accounts for the incremental development of rutting over time as a function of load repetitions and temperature. Where *RD* is the rutting depth after the load repetitions of N at the temperature of T, α, β and θ are the experimentally determined coefficients.

$$RD = \alpha \times N^{\beta} \times T^{\theta} \tag{1}$$

Recent research indicated that the exponent β of load repetitions in Eq. (1) was closely related to the magnitude of loading level and the strength of asphalt mixtures (Fwa et al., 2004). The results from this study found that rutting was not only affected by the load but also by the pavement structure, in other word the two factors together contributed to the shear stress in the pavement. In order to reflect the combined effect of loads, pavement and materials, β can be adjusted to a function of load magnitude, structure and material properties in this paper. As a result, Eq. (1) is converted to Eq. (2):

$$RD = \alpha \times (N)^{\kappa \cdot \varphi} \times T^{\theta} \tag{2}$$

where $\kappa = (\tau/\tau_0)^{\mu}$, τ = shear stress, reflects the loading level applied to a given pavement structure, which can be calculated by FEM, and τ_0 accounts for the shear strength of HMA determined by SUPT. Since κ is a non-unit parameter, it can minimize the system error resulting from using elastic theory to compute τ_0 and τ. Herein, shear strength is only aimed to differentiate the shear resistance of different asphalt mixtures, and 60°C is designed as the test temperature for SUPT test. Resilient modulus at the temperature of 20°C is used to compute shear stress so that different pavement structures can be differentiated.

In the past, many efforts were devoted to studying the relationship of speed to the rutting with the conclusions indicating that the vehicle speed had a significant effect on the rutting evolution due to the viscous property of asphalt concrete, and in general the rutting and speed were in reverse proportion (Sun et al. 2006, Fwa et al. 2004, Margarita 2006). Taking this result into account, the framework of the rutting prediction model is illustrated in Eq. (3), where *RD* is the rutting depth in mm, V is the vehicle speed in km, N is the number of load repetitions, V^p is V to the pth power and T is the temperature in °C.

$$RD = \alpha \times \left(\frac{N}{V^{p}} \times\right)^{\kappa \cdot \varphi} \times T^{\theta} \tag{3}$$

The shear stress, temperature and strength of asphalt concrete layer vary along the depth in pavement, which in turn results in different deformation at different sub-layer depth. In this study, the asphalt layer is divided into many sublayers with each being 10 mm, and the mid-point of each sub-layer is used as the computational point. Thus, one can obtain the total rutting depth from Eq. (4) by simply summing all sub-rutting through the entire layer, where *i* reveals the sub-layer position number and *n* represents the amount of sub-layer.

$$RD = \sum_{i=1}^{n} \Delta RD_i \tag{4}$$

3 EXPERIMENTAL TEST METHOD

Wheel tracking test: A commonly used wheel tracking tester was used to provide the rutting depth data. It is capable of applying a temperature from 0°C to 70°C, as the lowest and highest, respectively. After the specimens with the size of 300 in length×300 in width and a varied height in mm were held in an environmental chamber at the prescribed temperature for 6 hours to reach the temperature equilibrium, they were tested by a rubber faced tire, which moved back and forth on the middle surface of the HMA specimens. The maximum number of load repetitions is set as 2,520 passes with a constant speed of 1.21 km/h. A tire-specimen contact pressure can be applied up to 1.3MPa. The rutting in the tested specimen consisting of shear flow and small densification is almost consistent with that observed in the field.

Static Uniaxial Penetration Test (denoted as SUPT): In general, rutting occurs mainly along the wheel path, while the rest part of asphalt pavements is not deformed by the repeated load. Therefore, the load-induced deformation can be analyzed at the limited area instead of the whole section. For this limited area, when it receives the same load as that in the whole section, it can deform similar with that occurring in the infinite pavement. This mechanism is adopted by Static Uniaxial Penetration Test. It is conducted on the Material Test System was used as shown in Figure 1, which can directly determine the shear strength of HMA.

Figure 1 Static Uniaxial Penetration Test

During this test, the loading head penetrates into the HMA specimen at a displacement controlled manner with the loading rate of 1 mm/min at the specified temperature of 60 °C.

The steel rod with a diameter of 28.5 mm is suitable for the HMA specimen of 100 mm in height and 100 mm in diameter with a nominal maximum aggregate size (NMAS) less than 16 mm, and 42 mm for the HMA specimen of 100 mm in height and 150 mm in diameter with a NMAS more than 16 mm. Specimens can be easily molded by SGC (Superpave gyratory compactor). The shear strength obtained from SUTP test was defined as Eq. (5):

$$\tau_0 = \tau_c \times (P / A) \tag{5}$$

where τ_0 is the shear strength in MPa of HMA, P is the applied axial load in kN at the failure point of the loading deformation curve, A is the cross section area in m^2 of the steel loading rod, and τ_c *is* named as the strength coefficient with the suggested value of 0.339 for the specimen with NMAS less than 16 mm and 0.350 for NMAS more than 16 mm.

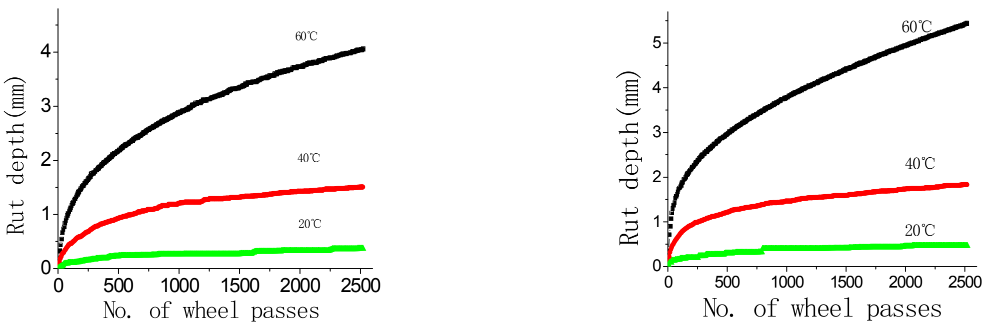
Full scale pavement Test (FSPT):A full scale pavement test with three types of pavement structures and similar materials were conducted in Chongqing Highway Research Institute. The test conditions were described as follows: temperature of pavement surface, 55 °C; axle load, 27.5 kN; tire pressure ,0.70 MPa; loading speed, 37.5 km/h; length of road, 33 m.

4 DETERMINATION OF RUTTING PREDICTION MODEL

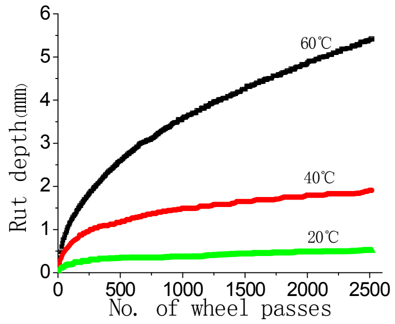
4.1 Laboratory Test Results and Analysis

In the wheel tracking test, a typical asphalt mixture used for surface course in China, referred to as AC-13, was used. Diabase was adopted as aggregates and asphalt used in asphalt concrete was a straight asphalt with the penetration of 60/80.The mix design followed the standard Marshall method, and finally 4.5% was decided as the optimal asphalt content. The properties of the mixture satisfied the specification.

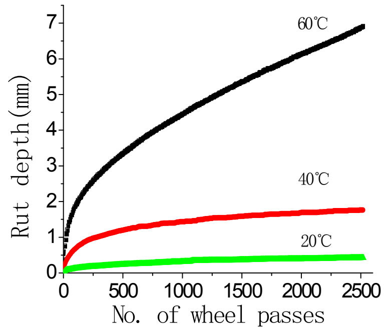
The wheel tracking tests were conducted at three temperatures of 20°C, 40°C and 60°C, three tire-specimen contact pressure levels of 0.56 MPa, 0.72 MPa and 1.10 MPa and two slab thickness of 40 mm and 60 mm, namely, in total eighteen test conditions, and the deformation corresponding to the different number of wheel passes were recorded. The wheel tracking test results are shown in Figure 2.



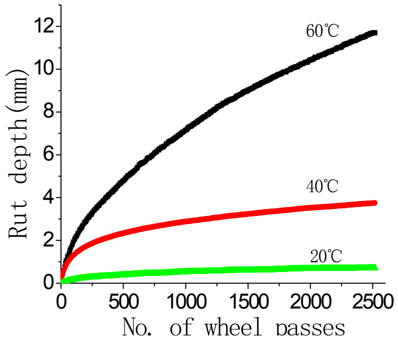
（a）0.56MPa/4cm （b）0.56MPa/6cm



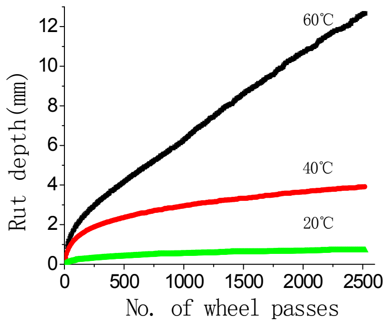
（c）0.72MPa/4cm



（d）0.72MPa/6cm



（e）1.10MPa/4cm



（f）1.10MPa/6cm

Figure 2 Results of wheel tracking tests

The same asphalt and aggregates materials were used to prepare the specimens for SUPT test and resilient modulus test. The number of fabricated specimens for SUPT test and resilient modulus test was, respectively, four and five, and the average of parallel test results was adopted. Prior to testing, all the specimens in the two tests were held in an environmental chamber for at least five hours to reach the temperature thermal equilibrium. The shear strength and resilient modulus are obtained as 1.06 and 1787.2 in MPa, respectively.

The FEM model with the same size as wheel tracking slab sample was established to capture the shear stress in the wheel tracking slab. The displacement constraints conditions were listed below: side planes were fixed in the normal direction, and other directions were free; the bottom side was completely fixed with constraints in X, Y and Z direction. Then, the shear stress in the specimens of wheel tracking test were obtained.

4.2 Full scale pavement Test results and Analysis

The results of the full scale pavement test are presented in Figure 3. The resilient modulus and shear strength of all materials were listed in Table 1. The temperature in FSPT pavement was listed in Table 2. The FSPT FEM model was built to analyze the shear stress in pavement, which was 5 m long, 5 m wide and 8 m deep in foundation, and the boundary conditions were same with that in the wheel tracking slab. By the FEM analysis, the shear stresses in the full scale pavement were obtained.

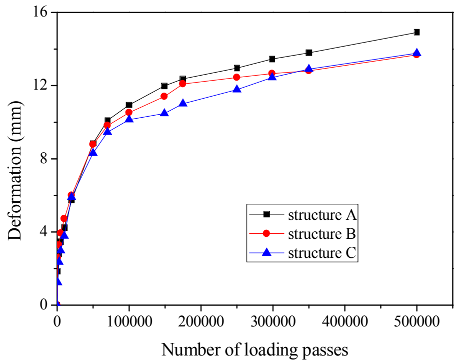


Figure 3 Results of full scale pavement test

Table 1 Material properties in full scale pavement

Layers		Wearing	Binder	Base	Subbase	Foundation
Resilient Modulus (MPa)/Thickness(cm)	Str:A	2000/4	1900/8	2223/8	2457/22	45
	Str:B	2000/5	1900/16	2223/16	350/22	
	Str:C	2000/4	1900/8	2223/15	15000/36	
Poisson ratio	Str:A	0.35	0.35	0.35	0.35	0.40
	Str:B				35	
	Str:C				0.20	
Shear strength (MPa)	Str:A	1.261	0.943	0.797	0.640	--

Table 2 Temperature distribution in full scale pavement

Depth (cm)	0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5
Temperature (°C)	59.4	59.1	58.9	58.5	58.2	57.8	57.4	57.0	56.6	56.1
Depth (cm)	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5	18.5	19.5
Temperature (°C)	59.4	59.1	58.9	58.5	58.2	57.8	57.4	57.0	56.6	56.1
Depth (cm)	20.5	21.5	22.5	23.5	24.5	25.5	26.5	27.5	28.5	29.5
Temperature (°C)	50.5	49.9	49.4	48.9	48.4	47.9	47.4	46.9	46.4	46.0
Depth (cm)	30.5	31.5	32.5	33.5	34.5	35.5	36.5	37.5	38.5	39.5
Temperature (°C)	45.6	45.2	44.8	44.4	44.1	43.8	43.5	43.3	43.1	42.9

4.3 Rutting Prediction Model by Optimization Analysis

With the test and analysis results obtained from the laboratory and full scale pavement tests, the coefficients of rutting prediction model were determined by means of the least square method with a self-developed procedure based on genetic algorithm optimization. Each data corresponded to a rutting depth, a temperature, a shear stress, a shear strength and a number of load passes. The model is finally achieved as shown in Eq. (6). It is highly significant evidenced by a higher determined coefficient of over 0.90.

$$RD = \sum_{i=1}^{n} 10^{-6.989} \cdot T_i^{3.487} \cdot (V^{-2.198} \cdot N)^{0.834 \cdot \left(\frac{\tau_i}{[\tau_0]_i}\right)^{0.622}} \quad (6)$$

Where, i represents the i^{th} sub-layer, T_i, τ_i, $[\tau_0]_i$, respectively, is the temperature, shear stress and shear resistance of the i^{th} HMA sub-layer.

In general, rutting depth is defined as the compressive deformation plus the neighboring upheave as shown in Figure 4 (Hua, 2000).. So in this sense, Eq. (6) can only be called as deformation prediction model. In order to make Eq. (6) adapt to predict the actual rutting, an upheave coefficient, which was defined as dividing the difference of rutting and deformation by deformation, should be introduced in Eq. (6), and then Eq. (6) can be expressed as Eq. (7), where P is the upheave coefficient.

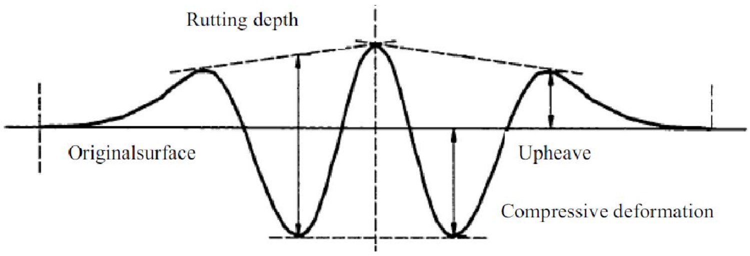


Figure 4 Comparison between rutting and deformation

$$RD = (1+P) \cdot \sum_{i=1}^{n} 10^{-6.989} \cdot T_i^{3.487} \cdot (V^{-2.198} \cdot N)^{0.834 \cdot \left(\frac{\tau_i}{[\tau_0]_i}\right)^{0.622}} \quad (7)$$

To determine the upheave coefficient, a creep analysis was performed by the creep model of Eq. (8), where, ε is the rate of the creep strain, σ is the stress, t is the loading period, C_1, C_2, C_3 is the experimentally determined parameters.

$$\varepsilon = C_1 \sigma^{C_2} t^{C_3} \quad (8)$$

The FEM analysis to simulate the FSPT test was performed. Four side planes and the bottom plane were fixed in the normal direction and free in other directions.

In order to simulate the deformation in the pavement in situ, all creep parameters determined in the field environment were used instead of those obtained from in FSPT test. Table 3 listed the related parameters. The axle load was 27.5 kN with the tire pressure of 0.70 MPa, and the loading speed was set as 80 km/h that was typical in highways.

In addition, the upheave coefficient was strongly affected by the lateral traffic wander, which was generally assumed to follow the normal distribution. Based on the experiences, four typical lateral traffic distributions identified by the standard deviation of 0.445 m, 0.326 m, 0.236 m and 0.156 m were studied. Then, the upheave coefficient were calculated. For different pavement structures, it can be determined from Table 4.

Table 3 Material properties for creep analysis

Item	Materials	Wearing	Binder	Base	Subbase	Foundation
Structure A	Temperatur	43	36	27	10	
	Resilient	554	600	900	2200	45
	Poisson	0.35	0.35	0.35	0.35	0.40
	C_1	1.942E-08	2.369E-011	2.958E-07	2.735E-09	
	C_2	0.721	1.287	0.525	0.810	
	C_3	-0.878	-0.673	-0.658	-0.662	
Structure	Tempe	43	30	11		
Structure B	Resilie	554	752	2200	350	45
	Poisso	0.35	0.35	0.35	0.35	0.40
	C1	1.942E-08	5.601E-08	2.301E-07		
	C2	0.721	0.648	0.449		
	C3	-0.878	-0.744	-0.646		
Structure C	Temperatur	43	36	22		
	Resilient	554	600	1031	15000	45
	Poisson	0.35	0.35	0.35	0.20	0.40
	C1	1.92E-08	2.369E-011	1.509E-06		
	C2	0.721	1.287	0.356		
	C3	-0.878	-0.673	-0.659		

Table 4 Upheave coefficient (P) for different lateral traffic wanders

Structure	Standard deviation	Load repetitions (unit:10^6)						
		1	5	10	15	20	25	30
A	0.445	0.366	0.477	0.521	0.545	0.563	0.577	0.587
	0.326	0.299	0.420	0.463	0.488	0.503	0.515	0.524
	0.236	0.281	0.405	0.449	0.473	0.487	0.500	0.508
	0.156	0.264	0.397	0.446	0.473	0.490	0.503	0.513
B	0.445	0.284	0.317	0.327	0.337	0.351	0.361	0.369
	0.326	0.218	0.225	0.268	0.292	0.311	0.325	0.334
	0.236	0.150	0.232	0.280	0.309	0.325	0.340	0.350
	0.156	0.1234	0.243	0.292	0.316	0.333	0.345	0.357
C	0.445	0.504	0.535	0.540	0.542	0.54	0.544	0.548
	0.326	0.448	0.460	0.460	0.461	0.462	0.462	0.462
	0.236	0.428	0.444	0.450	0.454	0.458	0.462	0.464
	0.156	0.445	0.488	0.509	0.523	0.534	0.542	0.550

5 CALIBRATION OF RUTTING PREDICTION MODEL

Since the gap exists between laboratory and the field, Eq. (7) can not be directly moved to predict rutting of the field pavements. To overcome this limitation, some calibrations are indispensable to make it adapt to the “real world performance”. In this study, the data obtained from the pavement in service was used to calibrate the laboratory model. The rutting depth, vehicle speed and traffic volume unit in ESAL (equivalent single axle load 100 kN) in each section were listed in Table 5.

Table 5 Rutting depth, vehicle speed and traffic volume

Section	A	B	C	D	E	F
Rutting (mm)	6.5	8.0	17.0	25.0	37.0	45.0
Speed (km/h)	50	50	40	50	30	30
Traffic volume (ESAL)	1,3178,027		21,963,386			

The shear strength and modulus of each asphalt concrete layer and temperature in each section were listed in Table 6~Table 8, respectively. As section E, D and F were located at the top of the slope, the horizontal force coefficient was considered with the typical value of 0.2 when computing the shear stress. The pavement temperature was predicted by Eq. (9) as suggested by SHRP Asphalt Research Program.

$$T_{eff} = 30.8 - 0.12Z + 0.92(T_{ave} + K_{\alpha}\sigma) \tag{9}$$

Where, T_{eff} is the predicted temperature inside the pavement, Z is the predicted depth, T_{ave} is the average air temperature and σ is the standard deviation of the air temperature.

Table 6 Shear strength of asphalt concrete

Section		A	B	C	D	E	F
Shear strength (MPa)	Wearing course	1.3015	1.1938	0.9554	0.8777	0.7082	0.7982
	Binder course	1.0808	1.0026	0.8521	0.8353	0.8600	0.8097
	Base course	0.8647	0.7989	0.6817	0.6682	0.6881	0.6478

Table 7 Modulus of each structure layer

Structure	Wearing course	Binder course	Base course	Upper cement stabilized gravel	Lower cement stabilized gravel	Foundation
Resilient Modulus (MPa)	1600	1400	1200	17,000	13,000	35
Poisson ratio	0.35	0.35	0.35	0.20	0.20	0.40

Table 8 Temperature of each structure layer

Depth (cm)	0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5
Temperature (°C)	52.35	51.15	49.95	48.75	47.55	46.35	45.15	43.95
Depth (cm)	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5
Temperature (°C)	42.75	41.55	40.35	39.15	37.95	36.75	35.55	34.35

Based on the above obtained data, Eq. (7) was calibrated and then became:

$$RD = 0.689(1+P)\cdot\sum_{i=1}^{n}10^{-60989}\cdot T_i^{3.487}\cdot\left(V^{-2.198}\cdot N\right)^{0.834\left(\frac{\tau_i}{[\tau_0]_i}\right)^{0.622}} \tag{10}$$

6 CONCLUSIONS

The following conclusions were drawn from this study:

(1) Based on the laboratory and full scale pavement test results and analysis, a shear-based rutting prediction model was put forward. This new approach considered the properties of pavement structure and materials, and the characteristic of traffic and environment.

(2) This new rutting prediction model was calibrated using the data obtained from the service pavement. Further validation was now undergone

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