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Prediction of Permanent Deformation in Asphalt Concrete Using Hierarchical Models

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1. ABSTRACT

A permanent deformation model was developed in this study based on the shear properties of asphalt mixtures such as cohesion and friction angle. Triaxial compressive strength (TCS) and repeated load permanent deformation (RLPD) tests on the three types of asphalt mixtures are performed at various loading and temperature conditions to correlate shear properties of asphalt mixtures to rutting performance. It is observed from the tests results that the ratio of shear stress to strength accurately identifies the mixture rutting performance. It could take care of not only mixture types but also load and temperature conditions dependences. Three different versions of the permanent deformation model based on different input levels are proposed and verified using the tests data. The proposed model based on the ratio of shear stress to strength can successfully predict the permanent deformation of various asphalt mixtures all the way up to the 10% of permanent strain including all three stages of permanent deformation in a wide range of loading and temperature conditions without changing model coefficients.

2. INTRODUCTION

Permanent deformation or rutting due to repeated traffic loading is one of the major distresses in asphalt pavements, particularly in hot regions or during the summer months. In theory, permanent deformation can occur in the upper asphalt concrete (AC) layers, base or subgrade layer or in a combination of these layers. Actually, the AC layers contribute a major part to the surface total rutting among the various pavement structure layers. Thus, it is very important to predict rutting potentials of asphalt mixtures for asphalt-aggregate mix design and pavement thickness design.

Repeated load permanent deformation (RLPD) test has been widely used to characterize the rutting performance of asphalt mixtures since this test can closely simulate field loading conditions (*1*). There have been many attempts to model the permanent deformation of asphalt mixtures using different methods. However, most of the existing models have obvious weaknesses limiting the application to rutting prediction. The regression coefficients of traditional empirical models (i.e., power law model) strongly depend on material properties, temperatures, loading conditions as well as the data range applied to fit these models (*2, 3*). The power law model also has a limit in characterizing the mixture behavior under all the stages of permanent deformation because the regression coefficients derived from the linear (secondary) portion of the cumulative permanent strain against number of load cycles curve ignore the

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tertiary zone of the deformation (*1*).

The AC rutting model adopted in Mechanistic-Empirical Pavement Design Guide (MEPDG) (*4*) incorporated resilient strain to reflect the effects of pavement responses. However, the AC dynamic modulus, which was one of the main material properties for calculating resilient strain, was not a good parameter for describing rutting behavior of asphalt mixtures especially for modified asphalt mixtures (*5*). Besides, the resilient strain is dependent not only on the material properties but also pavement thicknesses and loading conditions. Similarly, the fully mechanistic models are limited due to relatively complicated model forms or difficulties in obtaining accurate model parameters.

Permanent deformation of AC layer is the result of a complex combination of densification and shear flow. The shear flow is a more dominant contributor to the permanent deformation occurred in the AC layer (*6*). Therefore, shear properties play an important role in the development of permanent deformation model for asphalt mixtures and could potentially be incorporated into the model.

Several related researches (*7*, *8*) have given us great insights of the application of shear properties to the permanent deformation prediction of asphalt mixtures However, they have a limit that the power law models can only characterize the secondary stage of the permanent deformation and ignore the tertiary shear flow. Moreover, the WT test is incapable of providing an accurate simulation offield stress states.

The main objectives of this study is to develop a permanent deformation model based on shear properties of asphalt mixtures at a wide range of material, temperature and loading conditions. To accomplish these objectives, the triaxial compressive strength (TCS) and RLPD tests for three different asphalt mixtures were performed. Three different versions of the permanent deformation model based on different input levels were proposed and verified using the tests data.

3. SHEAR PROPERTIES OF ASPHALT MIXTURES

The shear strength of a material is principally developed from two sources (*1*): cohesion c and friction angle ϕ:

$$\tau_f = c + \sigma_f \tan\phi \tag{1}$$

where, τ_f = shear strength at failure, and
σ_f = normal stress at failure.

As seen in Eq. (1), the shear strength of a material is a function of normal stress and shear properties. For a specific point in an AC layer, the shear properties of AC are constant while the normal stress is varying depending on the magnitudes of traffic loading. Thus, the shear strength is varying. For a specific confining pressure, the ratio of shear stress to strength, τ/τ_f, can be calculated as follows:

$$\frac{\tau}{\tau_f} = \frac{(\sigma_1 - \sigma_3)(\tan\phi \sin\phi + \cos\phi - \tan\phi)}{2(c + \sigma_3 \tan\phi)} \tag{2}$$

where, τ = shear stress at the potentialfailure plane,
σ_1 = actual maximum principal stress, and
σ_3 = actual minimum principal stress.

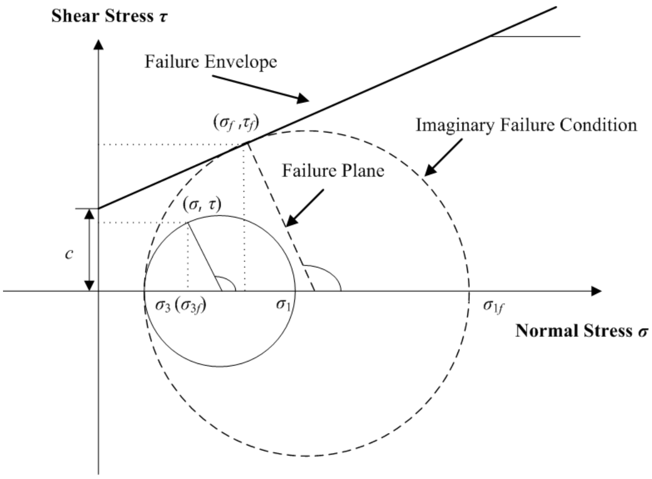


Figure 1. Representation of stress state using Mohr-Coulomb failure theory

Figure 1 illustrates that stress to strength ratio of asphalt mixtures can be represented as how far the actual stress at potential failure plane is from the failure envelope under the same confinement level. It must be noted here that Eq. (2) is only valid when the shear stress and strength are obtained under the same confining pressure.

4. EXPERIMENTAL PROGRAM

The laboratory tests were conducted in two phases. In the first phase, five asphalt contents were planned for each type of mixture to simulate mix design procedure and the RLPD tests were performed at a single loading (the deviatoric stress σ_d of 690 kPa and the confining pressure σ_c of 69 kPa) and temperature condition (50 °C). In the second phase, only the optimum binder content of each type of mixture was selected. Moreover, three different levels of deviatoric stresses σ_d (552, 690, 828 kPa), confining pressures σ_c (0, 69, 138 kPa) and temperatures T (40, 50, 60 °C) were selected in the experimental design. In the tests, only the major testing parameter, whose sensitivity was being examined, was varied while the other testing conditions were maintained at medium levels. In addition, four different load durations (0.1, 0.2, 0.4 and 0.8 seconds) were adopted to evaluate the effects of loading frequency. All the combinations of the tests were provided in Table 1 and 2.

4.1 Materials and Specimen Preparation

Three types of asphalt mixtures were produced in the laboratory. Two of them, AC-19C and AC-19M, were dense graded mixtures with nominal maximum aggregate size (NMAS) of 19mm, and PG 64-22 and PG 76-22 asphalt binders, respectively. The other one, SMA-13, was stone matrix asphalt (SMA) mixture with the NMAS of 13mm and PG 64-22 binder. In the second phase of testing, The target air void contents were 4.0% for the dense graded mixtures (AC-19C and AC-19M) and 3.0% for the SMA-13 mixtures. The binder contents were 5.0%, 5.0% and 6.5%, for the AC-19C, AC-19M and SMA-13 mixtures, respectively.

A Superpave gyratory compactor (SGC) was used to fabricate cylindrical specimens. Test specimens with 100 mm in diameter and 150mm in height were used. The test specimens were cored from the center of the SGC cylindrical specimens with the diameter of 150mm and the height of 175 mm, and each end was sawed to obtain 150 mm long specimens. Two replicates were conducted for each test.

4.2 TCS Test

All tests were conducted on an MTS servo-hydraulic testing system with a triaxial cell. The TCS tests were conducted to measure the shear properties of the mixtures. The TCS tests were run at a load rate of 50 mm/min under three temperatures of 40, 50 and 60 °C. To calculate c and ϕ values based on Mohr-Coulomb failure theory, three confining pressures of 0, 69 and 138 kPa were used in the tests.

4.3 RLPD Test

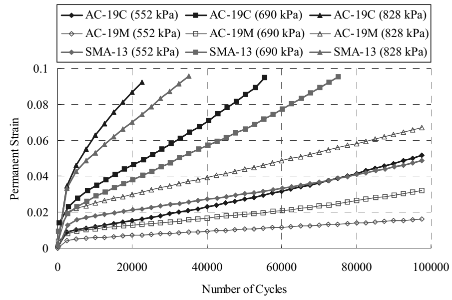
The RLPD tests were performed under a haversine of cyclic loading to evaluate the permanent deformation of the mixtures. Rest periods were introduced between the haversine loadings. The ratio of load duration to rest period is 1 to 9 for all the tests. The tests were continued up to 100,000 cycles of load repetitions or 10% of permanent strain whichever came first.

5. MODELING OF PERMANENT DEFORMATION

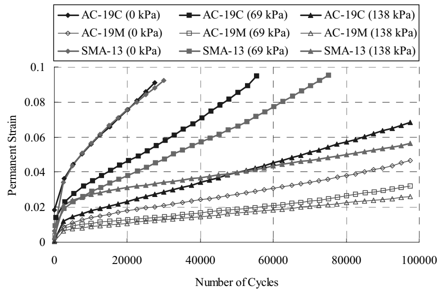
Table 1 and 2 provide a brief summary of the results obtained from the TCS and RLPD tests in two phases for all asphalt mixtures (*9*, *10*). Cohesion c and friction angle ϕ were calculated according to Mohr-Coulomb failure theory. The permanent strain at 10,000 of loading cycles, ε_p, was selected to evaluate rutting performance for asphalt mixtures. Overall, it is observed from the RLPD tests results that the three mixtures have the following ranking order in terms of laboratorial rutting performance (from high to low): AC-19M, SMA-13 and AC-19C. Moreover, rutting potential increases with binder content irrespective of the mixture types. In addition, it is found from the TCS tests results that for a given type of mixture, friction angle decreases as binder content increases whereas the maximum cohesion occurs at approximate optimum binder content obtained from volumetric mix design criteria (i.e., air voids of 4% for AC-19 mixtures and 3% for SMA mixtures) except the SMA-13 mixtures. Both cohesion and friction angle of asphalt mixtures decrease with increase in temperature.

Table 1. Summary of tests results in the first phase

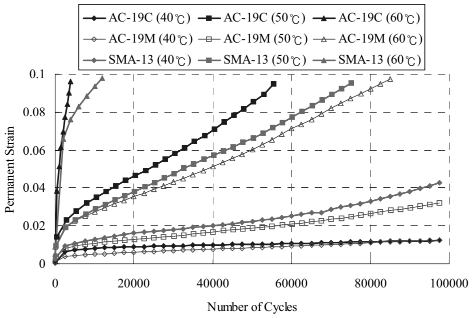
Mix	Mix Design		TCS Test (50 °C)		RLPD Test (50 °C)	
	Air Void (%)	Asphalt Content (%)	c (kPa)	ϕ (°)	ε_p (N=10000)	τ/τ_f
AC-19C	7.2	4.0	367	46.6	0.025	0.311
	4.8	4.5	377	42.9	0.031	0.340
	2.8	5.0	378	41.7	0.035	0.350
	1.7	5.5	376	41.5	0.047	0.354
	1.3	6.0	353	41.5	0.087	0.374
AC-19M	7.7	4.0	558	47.9	0.010	0.208
	5.7	4.5	626	41.0	0.011	0.228
	3.2	5.0	624	38.8	0.011	0.242
	2.1	5.5	611	38.5	0.011	0.249
	1.8	6.0	573	38.5	0.016	0.264
SMA-13	7.2	5.0	367	48.4	0.023	0.294
	5.5	5.5	381	47.2	0.024	0.296
	4.2	6.0	367	46.8	0.024	0.309
	2.8	6.5	348	45.5	0.029	0.336
	2.1	7.0	326	45.5	0.047	0.355



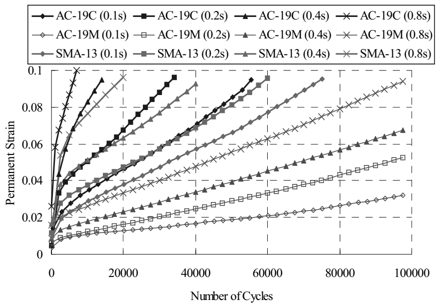
(a) Various deviatoric stress levels



(b) Various confining pressure levels



(c) Various temperature levels



(d) Various load duration levels

Figure 2. RLPD tests results

Table 2. Summary of tests results in the second phase

Mix	T (°C)	TCS Test		RLPD Test				
		c (kPa)	ϕ (°)	σ_d (kPa)	σ_c (kPa)	t (s)	ε_p (N=10000)	τ/τ_f
AC-19C	40	587	43.9	690	69	0.1	0.008	0.211
	50	378	41.7	552	69	0.1	0.012	0.280
				690	69	0.1	0.035	0.350
				828	69	0.1	0.063	0.421
				690	0	0.1	0.056	0.409
				690	138	0.1	0.018	0.306
				690	69	0.2	0.051	–
				690	69	0.4	0.083	–
				690	69	0.8	> 0.1	–
	60	250	39.0	690	69	0.1	> 0.1	0.535
AC-19M	40	847	43.3	690	69	0.1	0.005	0.153
	50	624	38.8	552	69	0.1	0.006	0.194
				690	69	0.1	0.011	0.242
				828	69	0.1	0.025	0.291
				690	0	0.1	0.014	0.265
				690	138	0.1	0.009	0.223
				690	69	0.2	0.012	–
				690	69	0.4	0.018	–
				690	69	0.8	0.026	–
	60	472	37.3	690	69	0.1	0.028	0.325
SMA-13	40	521	48.2	690	69	0.1	0.013	0.219
	50	348	45.5	552	69	0.1	0.018	0.268
				690	69	0.1	0.029	0.336
				828	69	0.1	0.053	0.403
				690	0	0.1	0.057	0.405
				690	138	0.1	0.027	0.286
				690	69	0.2	0.038	–
				690	69	0.4	0.051	–
				690	69	0.8	0.077	–
	60	254	42.4	690	69	0.1	0.094	0.478

Figure 2 shows cumulative permanent strains against load cycles for all mixtures with the optimum binder content obtained from the RLPD tests at various testing conditions. The effects of several factors on rutting performance such as deviatoric stress σ_d, confining pressure σ_c, temperature T and load duration t are discussed below.

As can be seen in Figure 2, for each type of mixtyres, the higher deviatoric stress yields more permanent deformation when the other testing conditions are maintained the same. Moreover, permanent strain is significantly constrained by the confining pressure. Confinement can strengthen the aggregate structure and stiffen the mixtures. Consequently, permanent deformation is sensitive to both the lateral and vertical stresses, strongly signifying that the confining pressure needs to be considered in rutting modeling. The asphalt concrete exhibits a significant temperature and time (or frequency) dependence because of its viscoelastic nature. As shown in the figure, the permanent strain significantly increases with temperature. The softening of the binder increases the rutting potential of the mixture. In addition, larger permanent stain is always associated with longer load duration in each cycle, because the longer load duration can produce more viscous deformation.

Figure 3 gives the correlation between the ratio of shear stress to strength τ/τ_f and the permanent strain ε_p at 10,000 of loading cycles measured from the RLPD tests. The tests data in two phases were used for plotting this figure. As shown in Figure 3, the ε_p is closely correlated to the τ/τ_f, and the coefficient of determination R^2 of the exponential regression function is 0.94. The rutting potential of asphalt mixtures rapidly increases with the τ/τ_f. The mixtures with similar τ/τ_f values achieved from different combinations of loading and temperature conditions have almost the same permanent strain values as seen in Table 1 and 2 as well as Figure 3. This observation implies that the τ/τ_f is a rational indicator of permanent deformation for asphalt mixtures. It could take care of not only mixture type but also load and temperature dependences.

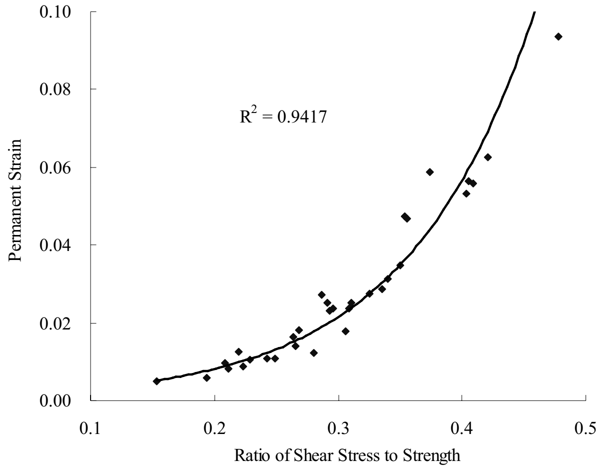


Figure 3. Relation of permanent strain and the ratio of shear stress to strength

A hierarchical approach was employed in this study. After a statistical analysis on the RLPD tests data, different versions of the permanent deformation model based on the τ/τ_f were established for the three levels of material properties inputs:

5.1 Level 1

The following form of a permanent deformation model was proposed for Level 1 inputs:

$$\epsilon_p = 2.9895 \times 10^{-3} e^{6.2807 \times 10^{-6} N} e^{3.6723 \frac{\tau}{\tau_f} N^{0.1032}} t^{0.4224} \quad (3)$$

(R^2 =0.9461, $RMSE$ = 0.0060, Average error =13.34 %)

where, t = load duration of each cycle (s).

The permanent deformation model in Eq. (3) provides the highest level of accuracy. The material properties, c and ϕ, used in the model should be directly measured from the laboratory tests (i.e., TCS tests) at different temperatures. Then, the τ/τ_f values under a given confining pressure can be calculated using Eq. (2) as long as the pavement responses are known.

5.2 Level 2

This level of permanent deformation model can be used when the laboratory tests for determining the shear properties of asphalt mixtures are only conducted at a reference temperature (50 °C in this study). Thus, the temperature term T was incorporated into the permanent deformation model to consider the temperature effects as follows:

$$\epsilon_p = 2.7067 \times 10^{-3} e^{6.8753 \times 10^{-6} N} e^{4.3668 \frac{\tau}{\tau_{fR}} N^{0.0889}} (\frac{T}{50})^{5.9721} t^{0.4224} \tag{4}$$

(R^2 =0.9418, $RMSE$ = 0.0062, Average error =15.08 %)

where, T = temperature (°C), and

τ/τ_{fR} = the ratio of shear stress at an arbitrary temperature to shear strength at a reference temperature of 50 °C under the same confining pressure.

5.3 Level 3

The permanent deformation model for the Level 3 is the same as the Level 1 model in Eq. (3). (R^2 =0.9418, $RMSE$ = 0.0062, Average error =15.08 %). However, the material inputs, c and ϕ, are predicted from the following two equations:

$$c = \alpha_0 + \alpha_1 T + \alpha_2 V_b + \alpha_3 A_v \tag{5}$$

$$\phi = \beta_0 + \beta_1 T + \beta_2 V_b + \beta_3 A_v \tag{6}$$

where, c =cohesion (kPa),

ϕ = friction angle (°),

V_b = binder content in weight (%),

A_v = air void (%), and

α_0, α_1, α_2, α_3, β_0, β_1, β_2, β_3 = regression coefficients provided in Table 3.

The prediction equations for c and ϕ in Eqs. (5) and (6) were established from a forward stepwise multivariate linear regression conducted on the laboratory tests data.

Table 3. Regression coefficients in Eqs. (5) and (6)

Mix	α_0	α_1	α_2	α_3	R^2	β_0	β_1	β_2	β_3	R^2
AC-19C	1694.20	-15.98	-84.96	-26.58	0.9846	54.24	-0.39	0.93	1.09	0.9458
AC-19M	2299.09	-17.53	-129.12	-42.90	0.9785	62.95	-0.46	-0.64	1.18	0.8450
SMA-13	2379.28	-13.36	-178.96	-62.81	0.9713	45.40	-0.29	1.70	1.27	0.9914

6. CONCLUSIONS

A permanent deformation model of asphalt concrete based on shear properties is developed in this study. Some of the important observations and conclusions made in this study are as follows:

1. Both cohesion and friction angle of asphalt mixtures decrease with increase in temperature.
2. Loading and environmental conditions, such as deviatoric stress, confining pressure, test temperature and load frequency, significantly affect the permanent deformation of asphalt mixtures and are needed to be incorporated in the permanent deformation model.

3. The ratio of shear stress to strength could be utilized as a parameter to identify the rutting performance and as a rutting criterion for a performance based mix design.
4. Three different versions of the permanent deformation model based on different input levels are proposed and verified using laboratory tests data. The proposed model based on the ratio of shear stress to strength can successfully predict the permanent deformation of various asphalt mixtures all the way up to the 10% of permanent strain including all three stages of permanent deformation in a wide range of loading and temperature conditions without changing model coefficients.
5. Since the prediction models for the c and ϕ values are developed from a regression analysis using a limited amount of tests data, a further study is needed to increase the accuracy of the prediction models.

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