Comparison of Mixture Rutting Estimators Based on Binder Stiffness

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INTRODUCTION

The rutting potential of asphalt mixtures is evaluated through many dynamic or repeated-loading tests, such as wheel tracking (WT), asphalt pavement analyzer (APA) and repeated-load creep (RLC) test, among many others. A static-loading test, Kim Test, is lately introduced as a potential tool for the same purpose. The binder rutting property is represented by G*/sin d and the mixture rutting potential is dependent upon the G*/sind level if the same aggregate and gradation are used. Therefore, it is hypothesized that the rutting property of the binder is reflected in the rutting test of the mixture and the test method producing highly correlated data with binder property is a reliable method for predicting rutting even though there is some variation due to aggregate.

The APA, RLC and Kim Test were selected for comparison and finding the most reliable rutting estimation method. Regression analyses were performed between mixture rutting property and binder G*/sin δ values, and between one mixture rutting test and another. Specifically, the objective of this study was to examine the correlation of the mixture rutting property data with G*/sinδ values and to suggest the most powerful test technique which can be comparable to WT for predicting rutting tendency of asphalt mixtures at a high temperature.

EXPERIMENTAL PROGRAM

Materials

Aggregates from two sources and eight binders were used to prepare the dense-graded and gap-graded asphalt mixtures, with each having maximum size of 13mm. The two aggregates were a gneiss and a granite, and the eight binders include a base asphalt PG 64-22 (CO), a PG 76-22 (76) and six laboratory-blended polymer-modified asphalt (PMA) binders. The polymers used for the PMAs included a low-density polyethylene (LDPE), a styrene-butadiene-rubber (SBR), a styrene-butadiene-styrene (SBS), a recycled LDPE (RLDPE) and a recycled high-density polyethylene (RHDPE). The content of each polymer, selected based on earlier studies [1,2], are shown in Table 1. A total of 32 mixtures (2 aggregates x 2 gradations x 8 binders) were prepared using Marshall Mix-design with a target air void of 4 % for surface course mixtures using 50-blow compactions per side.

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Table 1. Description of binders used in this study.

Abbreviation	CO[a]	R7	S3	S5	L6	76	RH8	RL8
Polymer	None	SBR	SBS	SBS	LDPE	SBS	RHDPE[b]	RLDPE[c]
Content (%) by wt. of binder	0	7	3	5	6	Un-known	8	8

Note: [a]: control, [b]: recycled HDPE, [c]: recycled LDPE.

DSR test

The dynamic shear rheometer (DSR) was used to obtain the complex shear modulus (G*) and the phase angle (δ) for each binder at a frequency of 10 rad/sec at 64°C, which is the high-temperature PG grade of the base asphalt used in this study. The value of the G*/sin δ is defined as the rutting factor, which represents the high temperature stiffness or rutting resistance of the binder. A high G*/sin δ value is considered desirable from the stand point of rutting resistance [15]. Each binder was tested as the original binder using DSR at 64°C. The binder was then RTFO-aged and tested as an RTFO binder in the DSR at the same temperature. The G*/sin δ values of the original binders and the RTFO-treated binders were separately used in regression analyses.

Kim Test

Kim Test applies a load to the top of specimen through a loading head which has a round edge to create a dimple-shape deformation created with the shear movement of mixture along the sideline at and near the top surface. Earlier studies have found that the diameter (D) of 40mm and edge curvature radius (*r*) of 10mm to be the most reliable size of loading head in rutting estimations [12-14]. Therefore, Equation (1) is used for calculation of the deformation strength or S_D.

$$S_D = \frac{P}{\pi(10+\sqrt{20y-y^2})^2} \quad (1).$$

A set of three cylindrical specimens, with a height of 63mm and a diameter of 100mm, were obtained from the slab by coring for the Kim Test (Figure 1). The specimen is submerged into water at 60_ for 30 minutes, and then removed before being placed on a Marshall loading frame (Figure 2) in which a load at the speed of 50mm/min is applied. A load and deformation curve, similar to the one from Marshall Test, was obtained and the peak load P and the vertical deformation y at P were read from the curve for each sample. A total of 32 slabs were made using 2 aggregates, 2 gradation for each aggregate and 8 binders for the Kim Test.

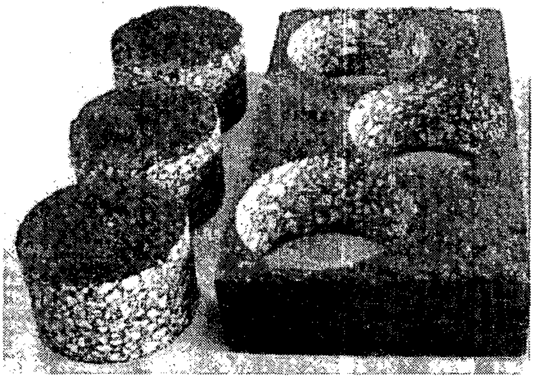

Figure 1. Cored specimens for Kim test from a slab.

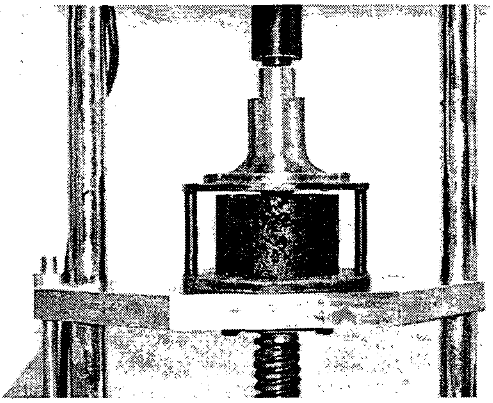

Figure 2. Kim Test set-up on a Marshall loading frame.

Asphalt pavement analyzer (APA) Test

The cylindrical specimens (ϕ=150mm, h=75mm) at the optimum asphalt contents were prepared using a Superpave gyratory compactor with a target air void of 4 ± 0.5 % for the APA test. The test temperature, pressure, speed, vertical load and length were 60℃, 689kPa (100psi), 60 cycles/min, 444.4N (100lbf) and 140 minutes, respectively. The rut depth by cycle was traced and final rut depth (DR) at 8,400cycles was recorded. Since no significant difference was observed between the aggregate sources in the Kim Test, a total of 16 mixtures, rather than 32, were prepared: 8 dense-graded gneiss mixtures and 8 gap-graded granite mixtures. One test used 6 specimens and the average rut depth was used as dependent variable for the regression analysis. The APA system used in this study is shown in Figure 3.

Repeated load creep (RLC) test

The repeated load creep test (RLC) was conducted using mechanical-property testing machine (AMTM). A loading plate was placed on top of the specimen, with two LVDTs being installed on top of it to measure the vertical deformation in an environmental chamber as shown in Figure 4. Three cylindrical specimens (ϕ=100mm, h=63mm) were prepared using a Superpave gyratory compactor for each mixture. In this test also, a total of 16 mixtures were used: 8 dense-graded gneiss mixtures and 8 gap-graded granite mixtures.

The loading cycle consisted of a 2.75kN peak load creating 359kPa (50psi) pressure using a halversine type load at the speed of 1 Hz with a 0.1 second loading time followed by a 0.9 second rest period. The test was conducted at 60°C for up to 3,600 cycles (60 min) or to the strain of 0.065 (4mm of final deformation: FD), whichever occurred first. This strain limit was chosen because most specimens showed rapid strain increments after this level. The deformation by load cycle was traced, and final deformation was recorded for each RLC test.

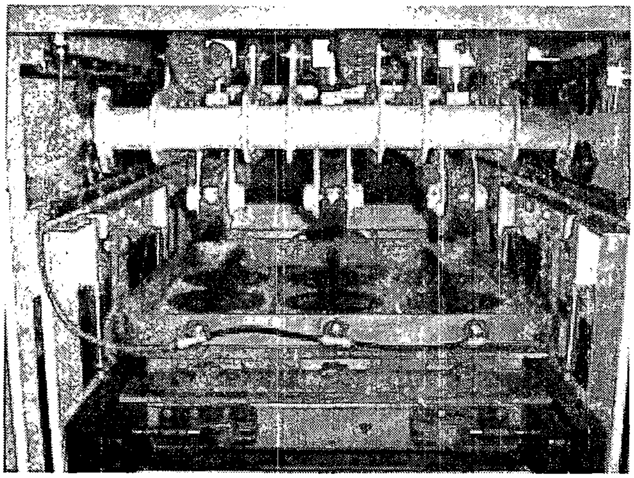

Figure 3. Inside view of APA test system.

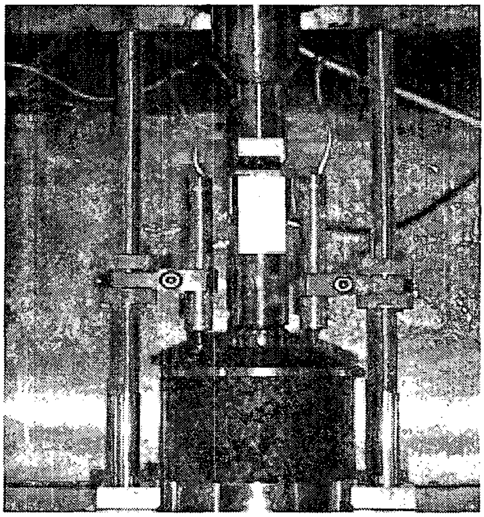

Figure 4. Repeated load creep (RLC) test setup

RESULTS AND DISCUSSIONS

Material Testing Results

In general, the gap-graded mixtures showed higher deformation strength (S_D) values with lower deformations (y) than the dense-graded mixtures, suggesting that gap-graded mixtures have stronger resistance to deformation than dense-graded mixtures. Specifically, the S_D in Table 2 ranges from 2.0MPa for CO to 3.8MPa for RL8 binder mixtures, meaning these two are the weakest and the strongest mixtures, respectively. The number of samples used in this study were three for the DSR, Kim and RLC and six for the APA.

During the RLC test, the CO-gneiss mixture reached the 4mm deformation limit in the middle of test. Since the failure point was specified at 4mm in regard to deformation, the test was stopped at that point for this sample. In addition to the final deformation (FD) value, the number of cycles (2,100) to failure is given in the table as the mixture failure point indication. Except for the CO-gneiss mixture, all other binder mixtures sustained to the final cycle, 3,600.

In general, the higher stiffness binders produced relatively better values in all four rutting tests. In most cases, the gap gradation showed a lower deformation than the dense gradation. In addition, the mixture with the higher S_D exhibited lower rut depth in APA and deformation in RLC. These results suggest that mixtures with a high S_D have a strong rutting resistance.

Table 2. Binder rutting factor and mixture rutting test results.

Binder	G*/sin δ (kPa) by DSR		Aggregate	S_D (MPa) by Kim Test		Rut depth (㎜) by APA		Final deformation by RLC (㎜)	
	ORIG	RTFO		Dense	Gap	Dense	Gap	Dense	Gap
CO	1.613	3.670	Gneiss	2.236	2.705	7.78		4(2100)*	
			Granite	2.438	2.788		6.14		2.74
R7	1.613	3.720	Gneiss	2.006	2.905	7.06		2.268	
			Granite	2.563	2.594		5.74		1.21
S3	3.425	4.500	Gneiss	2.266	2.729	5.59		2.221	
			Granite	2.685	2.715		4.06		1.35
S5	6.585	7.920	Gneiss	2.511	3.289	4.06		0.745	
			Granite	2.896	3.083		3.06		0.90
L6	6.770	7.984	Gneiss	2.704	3.355	4.26		0.934	
			Granite	2.902	3.166		2.84		0.62
76	5.460	8.801	Gneiss	3.031	3.444	3.56		0.632	
			Granite	3.203	3.435		2.35		0.45
RH8	10.950	14.420	Gneiss	3.600	3.570	3.60		0.571	
			Granite	3.270	3.753		2.33		0.39
RL8	10.511	13.621	Gneiss	3.265	3.594	2.94		0.522	
			Granite	3.220	3.801		2.57		0.44

*The number in "( )" is the number of cycle when FD was reached 4mm and disregarded in analysis.

Correlation Analyses

For further investigation, regression analyses were performed on the mixture rutting data and the binder stiffness data. Since the variation of aggregate is fixed by using the same aggregate and gradation for this study, the mixture response to the deforming pressure in each test is mainly a function of the binder stiffness. Therefore, the rutting test data were used for the dependent variable and the G*/sin d value of each binder as the independent variable in the regression model. The typical best-fit regression curves for each property are shown by aggregate in Figures 5 - 7, and the coefficient of determination, R^2, values for all regression results are reported in Table 3.

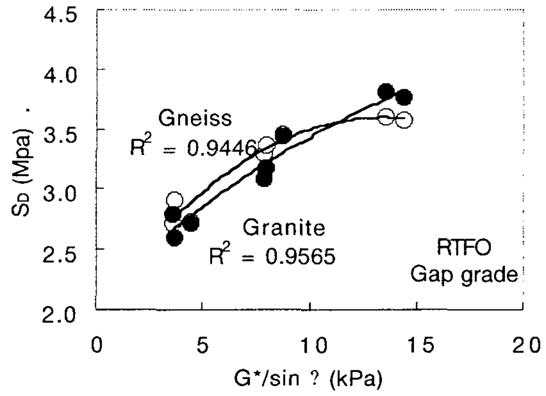

Figure 5. Relationship of S_D by Kim Test and binder stiffness.

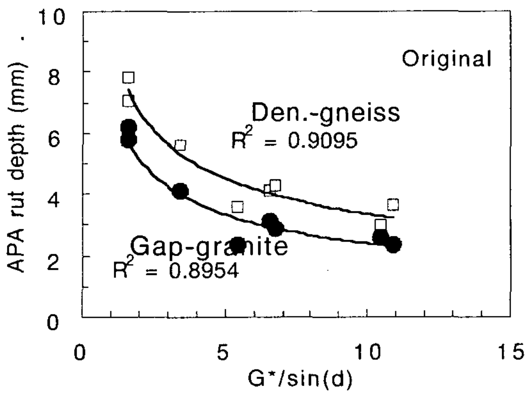

Figure 6. Relationship of rut depth by APA and binder stiffness.

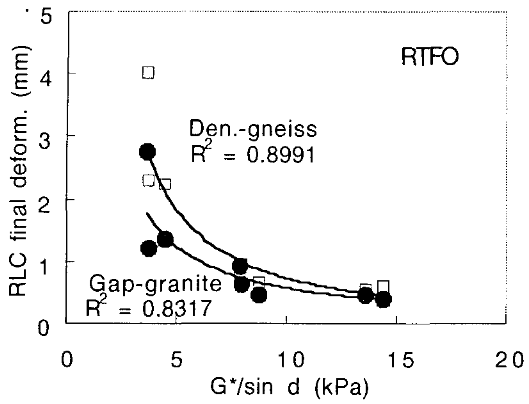

Figure 7. Relationship of final deformation by RLC and binder stiffness.

Table 3. R^2 values from regression analyses between mixture rutting data and binder stiffness.

Mixture rutting test property	Gradation	Gneiss			Granite			Gradation mean & test mean
		Binder condition		Mean	Binder condition		Mean	
		Original	RTFO		Original	RTFO		
S_D by Kim Test	Dense	0.8522	0.9224	0.8873	0.8501	0.9283	0.8892	0.8883
	Gap	0.8423	0.9446	0.8935	0.8719	0.9565	0.9142	0.9039
	Mean			0.8899			0.9017	0.8960
Rut depth by APA	Dense	0.9095	0.9055	0.9075	-	-	-	0.9075
	Gap	-	-	-	0.8954	0.8557	0.8756	0.8756
	Mean			0.9075			0.8756	0.8915
Final deformation by RLC	Dense	0.8099	0.7616	0.7858	-	-	-	0.7858
	Gap	-	-	-	0.9090	0.8317	0.8704	0.8704
	Mean			0.7858			0.8704	0.8281*
Total mean		0.8512	0.8931	0.8721	0.8957	0.9145	0.9051	0.8886

* Significantly different at _ =0.05 among four test means

Most of data were well fit to the regression line, with relatively high R^2 values ranging from approximately 0.76 to 0.96. In most cases, the RTFO binders showed higher R^2 values than the original binder, suggesting that the condition of the binder in the mixture is similar to the condition of RTFO-treated binder.

The test producing the higher correlation with the binder stiffness is potentially the better method for estimating the rutting potential of an asphalt mixture. Based on the R^2 values, the best technique, the one having the highest R^2 on the average, was the Kim Test (R^2 = 0.90). The rut depth of the APA was the second place in R^2 level, showing R^2 approximately 0.89 with the binder stiffness. The R^2 of RLC was 0.83, showing statistically significant difference from the R^2 values of S_D and APA at _ = 0.05 (Table 3). Even though the R^2 values between the S_D and APA test means is not significant, the mean R^2 values between the two aggregates (0.8899 and 0.9017) are more consistent than those [(0.9075 and 0.8756) of the APA. The APA is wellproved rut testers, being widely used in many parts of the United States, but the S_D is a new strength property measured by the Kim Test. The R^2 level of S_D was higher for the mixtures used in this study than those of the APA and RLC, even though it is a static-test property.

Since the two mixture properties from the APA and Kim tests are highly correlated with the binder stiffness, the correlations between these two properties were also evaluated. Figure 8 was drawn to show the relationship of the S_D with the APA using all the data. Figure 8 indicates that the S_D inhibited fairly high correlations with the APA test data, showing an R^2 of approximately 0.785 on average

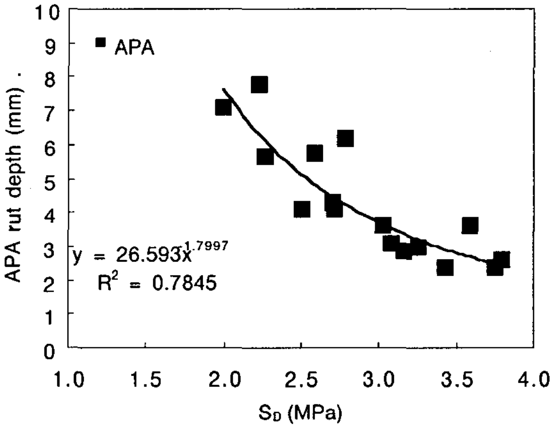

Figure 8. Relationship of rut depths by WT and APA with S_D (all data).

CONCLUSIONS

This study compared three mixture-rutting tests based on binder stiffness (G*/sin δ) to find the most suitable method of predicting the rutting potential of asphalt mixtures. Rut depths obtained from the asphalt pavement analyzer (APA), and the final deformation from the repeated load creep (RLC) test together with the S_D were used as the mixture rutting properties for regression analyses with binder G*/sin δ values.

These regression analyses showed that the S_D and APA data had high correlations with G*/sin δ with R^2 approximately 0.90. Even though statistically no significant difference was found in the mean R^2 values between the two, the mean R^2 values of the two aggregates for the S_D were more consistent than for the APA. The correlation analysis of the S_D with the APA showed somewhat lower but still good R^2 values (i.e., 0.78).

This study indicates that the S_D obtained from the Kim Test has high correlations with the stiffness data of binders and the rutting data of the APA and RLC tests, all of which are known to be reliable rutting test procedures. Since, relatively high correlations were found in all regression analyses of the S_D with the data from those proven test procedures, the Kim Test can be considered a suitable test procedure for estimating the rutting potential of asphalt mixtures at high temperatures.

However, these results are from the laboratory phase of study only and further study is needed through long and short term field validation to prove that the S_D is reasonably reliable and repeatable for materials being used in the field before it is adapted as a standard procedure.

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