Evaluation of Laboratory Methods Simulating Aging Effects of Asphalt Binder

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The effects of short-term and long-term aging are important when evaluating the properties of asphalt binder. Thus, the properties of asphalts aged for the short term and the long term are considered in the Superpave binder specification. The most practical way of predicting the effects of aging within an asphalt binder is through laboratory simulation methods. For many years the thin film oven test (TFOT) method and the rolling thin film oven test (RTFOT) method have been used to simulate short-term aging. To simulate long-term aging the pressure aging vessel (PAV) method was developed within the Strategic Highway Research Program. However, the Superpave binder specification uses only the RTFOT method for short-term aging and uses RTFOT along with the PAV method for long-term aging. For a short period of time AASHTO considered the use of either the TFOT method or the RTFOT method and then the PAV long-term aging procedure for short-term aging. Unfortunately, few published data address this issue. The test data from a testing program conducted to evaluate these laboratory procedures for short-term and long-term aging with different asphalt binders are presented. The effects of aging are evaluated by dynamic shear stiffness ($G^*\sin\delta$), measured by using the dynamic shear rheometer at three intermediate temperatures. The data indicate that there are no significant differences at the 95 percent confidence interval between the properties of RTFOT-aged residues and those of TFOT-aged residues after exposure to the PAV procedure. The differences before aging by the PAV procedure, however, still exist. It is recommended that only one short-term aging procedure be used for the Superpave binder specification and that work be conducted to develop or improve the short-term aging procedure.

Aging of asphalt binder causes increased stiffness of the asphalt because of volatilization and oxidation when the thin film of the asphalt binder is subjected to high temperatures during construction. Additional aging will occur after construction, primarily because of oxidation. The extent of this long-term aging depends on the crude source, degree of compaction, and temperature. Although the increase in stiffness will increase the resistance to rutting, the increased stiffness and the increased brittleness reduce the resistance to cracking and raveling (*1*).

Because asphalt binders produced from different petroleum crudes and by different refinery techniques have different aging characteristics, it is necessary to specify or control the aging characteristics of the asphalt binders used for paving. The most practical way to estimate the aging characteristics of an asphalt binder is to simulate aging by laboratory methods. Since aging can take place during two stages in pavement life, these methods must consider both short-term and long-term aging. Short-term aging occurs during the manufacturing of asphalt paving mixtures and the subsequent laying down and compaction; long-term aging continues as a result of exposure to oxygen at moderate temperatures.

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For many years the thin film oven test (TFOT) method (ASTM D-1754, AASHTO-T179), the rolling thin film oven test (RTFOT) method (ASTM D-2872, AASHTO-T240), and variations of these procedures have been used to simulate short-term aging. In addition, a long-term aging procedure was developed in the late 1960s (*2,3*). By this long-term aging method the asphalt was subjected to an elevated temperature and pressure in the presence of oxygen. During development of the Superpave binder specification by the Strategic Highway Research Program (SHRP) it was decided to adopt one of the standard short-term aging procedures. Early in the program a decision was made to adopt and further develop and validate the long-term pressure aging procedure. Thus, the final specifications required the use of the RTFOT method for short-term aging and the pressure aging vessel (PAV) procedure for long-term aging.

With regard to the two short-term aging procedures, it is often assumed by many users that the two methods are interchangeable and, thus, that either could be used in the Superpave specification. For a short period of time, AASHTO considered the use of either the TFOT method or the RTFOT method for short-term aging, this was followed by the use of the PAV long-term aging procedure (*4, 5*). To date, unfortunately, little work has been conducted to evaluate whether Superpave binder properties are significantly different for short-term-aged asphalts by the RTFOT method or the TFOT method and the effect of each short-term aging procedure on the properties of the asphalt binder after long-term aging.

A rather extensive evaluation, however, was reported by Zupanick (*6*), who made conclusions based on each of four commonly used aging ratios: viscosity ratio at 60°C (140°F), viscosity ratio at 135°C (275°F), percent retained penetration at 25°C (77°F), and percent weight change. He found that the RTFOT test is somewhat more precise and severe than the TFOT test. He also confirmed that these two tests are not identical. In addition, because of skin formation in the TFOT test, he believed that the RTFOT test is the better of the two tests for simulating hot-mix plant aging.

The purpose of this paper is to report on a testing program conducted to evaluate these laboratory aging procedures for short-term and long-term aging by using different asphalt binders.

EXPERIMENT DESIGN

The experiment involved 10 asphalt binder types, two short-term aging methods, one long-term aging method, and three testing temperatures. Six of 10 asphalt binder types were unmodified asphalts, and 4 were modified asphalts.

The six asphalts used in the study were from the SHRP Material Reference Library and are described in Table 1. The aging index, which is the ratio of the viscosity at 60°C (140°F) after TFOT to that before TFOT, was used as the criterion of selection. Two asphalts

TABLE 1 Selective Asphalt Binders from SHRP Material Reference Library Used

Unmodified Asphalt	PG-grade	Source	Aging Sensitivity	Aging Index
AAD-1 (AR-4000)	58-28	California	HIGH	3.24
AAK-1 (AC-30)	64-22	Boscan	HIGH	2.98
AAB-1 (AC-10)	58-22	Wyoming	INTERMEDIATE	2.31
AAS-2 (AC-10)	58-28	Middle East (Arab)	INTERMEDIATE	2.25
AAG-1 (AR-4000)	58-10	California Valley	LOW	1.75
AAZ (AC-20)	58-16	West Texas	LOW	1.65

Modified Asphalt	Modifier type
AAG-1 + SBS	Styrene-Butadiene Styrene Block Copolymer
AAK-1 + SBS	Styrene-Butadiene Styrene Block Copolymer
AAG-1 + PE	Polyethylene
AAK-1 + PE	Polyethylene

had high aging indexes, two had low values, and two had intermediate values. In addition, two stiff (high-viscosity) asphalt cements from those selected were added to modifiers such as styrene-butadiene styrene block copolymer and polyethylene.

The short-term aging procedures used were the TFOT method and the RTFOT method. The long-term aging procedure used was the PAV method. All long-term-aged specimens were first short-term aged by the RTFOT method or the TFOT method. The effects of aging were evaluated in terms of dynamic shear stiffness, ($G^*\sin\delta$) where G^* is the complex shear modulus and δ is the phase angle), measured with a dynamic shear rheometer (DSR) at three intermediate temperatures (20°C, 25°C, and 30°C). $G^*\sin\delta$ is the parameter used in the new SHRP performance-based binder specification for controlling the properties of long-term-aged asphalt binder. Four replicates of each cell of testing (Table 2) were performed, and the averages and standard deviations were calculated. Residues aged over the short term by the RTFOT method and the TFOT method were tested and compared (Table 3). Residues aged over the long term by the RTFOT method and the TFOT method and then the PAV aging procedure were also tested (Table 4).

SHORT-TERM AGING

Both the TFOT method and the RTFOT method were used for short-term aging.

TFOT Method

The TFOT aging technique is conducted by placing a 50-g sample of asphalt binder in a cylindrical flat-bottom pan producing an approximate 3.2-mm (1/8-in.) asphalt binder layer. The pan containing the asphalt binder sample is transferred to a shelf in a ventilated oven maintained at 163°C (325°F). The shelf can carry four pans at a time and rotates at a rate of 5 to 6 rpm. The sample is kept in the oven for 5 hr. In the present study the samples either were tested with the DSR or were transferred to PAV pans for long-term aging.

RTFOT Method

The RTFOT aging technique involves placing 35 g of asphalt into a bottle, which is placed in a rack within an electrically heated convection oven. The oven contains a vertical circular carriage that contains holes to accommodate sample bottles. The carriage is mechanically driven and rotates about its center. The oven also contains an air jet that is positioned to blow air into each sample bottle at its lowest travel position. During the test the sample is required to remain in the oven at a temperature of 163°C (325°F) for 85 min. In the present study the aged samples either were tested with the DSR or were transferred to PAV pans for long-term aging.

LONG-TERM AGING

The pressure aging procedure, developed by SHRP from previous work (*2*), simulates the long-term aging that asphalt experiences in service. The apparatus consists of the PAV and a temperature chamber. Air pressure is provided by a cylinder of dry, clean compressed air with a pressure regulator, release valve, and a slow-release bleed valve.

The pressure vessel is fabricated from stainless steel and is designed to operate under the pressure (2070 kPa) and temperature (90°C, 100°C, or 110°C) of the test. The vessel can accommodate 10 stainless steel TFOT sample pans at one time. A forced draft oven is used as a temperature chamber. The oven must control temperature to within a 0.2°C range for 20 hr. A digital readout connected to a platinum-resistant thermometer is used to control the internal vessel temperature. During the test the pans loaded

TABLE 2 Experiment Design

TEST EQUIPMENT		DYNAMIC SHEAR RHEOMETER											
TEST TEMPERATURE		20 °C				25 °C				30 °C			
AGING METHOD / SAMPLE		TFOT	RTFOT	TFOT+ PAV	RTFOT+ PAV	TFOT	RTFOT	TFOT+ PAV	RTFOT+ PAV	TFOT	RTFOT	TFOT+ PAV	RTFOT+ PAV
UNMODIFIED	AAD-1	4	4	4	4	4	4	4	4	4	4	4	4
	AAK-1	4	4	4	4	4	4	4	4	4	4	4	4
	AAB-1	4	4	4	4	4	4	4	4	4	4	4	4
	AAS-2	4	4	4	4	4	4	4	4	4	4	4	4
	AAG-1	4	4	4	4	4	4	4	4	4	4	4	4
	AAZ	4	4	4	4	4	4	4	4	4	4	4	4
MODIFIED	AAG-1+SBS	4	4	4	4	4	4	4	4	4	4	4	4
	AAK-1+SBS	4	4	4	4	4	4	4	4	4	4	4	4
	AAG-1+PE	4	4	4	4	4	4	4	4	4	4	4	4
	AAK-1+PE	4	4	4	4	4	4	4	4	4	4	4	4
											TOTAL	=	480

with short-term-aged residue are placed in the vessel, and the vessel is then loaded into the temperature chamber to which the pressure hose and temperature transducer are attached. When the temperature is within 2°C of the test temperature, air pressure is slowly applied. When the air pressure and temperature reach 2070 kPa (300 lb/in.^{2}) and the designated temperature the test time begins.

After 20 hr the pressure is slowly released (8 to 10 min) by using the bleed valve to avoid excessive air bubbles in the sample. The pans are removed from the sample holder and are placed in an oven at 150°C for 30 min or less to remove entrapped air from the samples. The samples are then transferred to a single container that can be covered to avoid any contamination if tests to determine dynamic shear modulus are not performed immediately (*4*).

In the present study a temperature of 100°C was used, which is recommended for most of the United States.

DYNAMIC SHEAR STIFFNESS EVALUATION METHOD

The dynamic shear stiffness (G^* sin δ), which is used to control the properties of short-term- and long-term-aged asphalt binder in the Superpave binder specification, was used as an evaluation property in the present study. This value was determined at temperatures of 20°C, 25°C, and 30°C with the DSR (model CS of Bohlin) at a constant frequency of 10 rad/sec. A constant stress mode was used.

The testing system applies a selected constant oscillating stress (linear viscoelastic range) to a 2-mm asphalt disk sandwiched between the oscillating spindle 8 mm in diameter and the fixed base. The resulting strain is measured. From the shear stress and strain data obtained by the testing system, the complex shear modulus (G^*) and the phase angle (δ) can be estimated and the dynamic shear stiffness (G^*sin δ) can be calculated.

ANALYSIS OF RESULTS

The results of the dynamic shear stiffness evaluation, measured from both short-term-aged and long-term-aged specimens, are summarized in Tables 3 and 4, respectively.

Two statistical analyses were conducted to compare the test data for residues measured by the TFOT method before and after the PAV procedure and those measured by the RTFOT method before and after the PAV procedure. A paired *t*-test (*7*) was conducted to examine the differences between the two short-term aging methods both before and after long-term aging by the PAV procedure. The results of the analysis are given in Tables 5, 6, and 7. In addition, a *t*-test (*7,8*) was used to test hypotheses concerning whether there were significant differences between the properties for individual asphalt binders that were aged by the RTFOT method or the TFOT method and whether the two short-term aging procedures produced significant effects on the properties of the long-term-aged asphalt

TABLE 3 Comparison of Dynamic Shear Stiffness Data Between Two Short-Term Aging Methods

TEST TEMPERATURE		20 °C						25 °C						30 °C					
		TFOT		RTFOT		%		TFOT		RTFOT		%		TFOT		RTFOT		%	
	SAMPLE	G*sin delta (MPa)	RSD	G*sin delta (MPa)	RSD	Difference		G*sin delta (MPa)	RSD	G*sin delta (MPa)	RSD	Difference		G*sin delta (MPa)	RSD	G*sin delta (MPa)	RSD	Difference	
UNMODIFIED	AAD-1	1.04	3%	1.28	9%	23.60%	S	0.46	4%	0.58	9%	25.00%	S	0.21	2%	0.26	9%	22.90%	S
	AAK-1	2.39	4%	2.96	6%	24.10%	S	1.14	4%	1.45	7%	26.90%	S	0.54	4%	0.69	7%	27.30%	S
	AAB-1	1.72	4%	1.84	7%	7.00%	NS	0.86	5%	0.94	5%	8.40%	S	0.40	6%	0.44	5%	10.00%	NS
	AAS-2	0.90	8%	1.15	7%	28.50%	S	0.44	8%	0.57	9%	31.60%	S	0.20	6%	0.27	8%	33.30%	S
	AAG-1	7.18	7%	9.05	5%	26.00%	S	2.54	6%	3.48	6%	37.00%	S	0.85	6%	1.23	6%	44.00%	S
	AAZ	4.19	2%	5.32	5%	26.90%	S	1.76	3%	2.27	5%	29.00%	S	0.69	2%	0.90	5%	30.00%	S
MODIFIED	AAG-1+SBS	4.68	7%	5.18	7%	10.60%	NS	1.69	7%	1.94	7%	14.84%	S	0.61	6%	0.70	6%	15.20%	S
	AAK-1+SBS	1.72	6%	2.23	10%	29.70%	S	0.93	5%	1.28	11%	38.00%	S	0.50	6%	0.66	8%	33.80%	S
	AAG-1+PE	10.73	9%	12.85	4%	19.70%	S	4.71	6%	5.81	4%	23.40%	S	1.91	5%	2.39	5%	25.50%	S
	AAK-1+PE	3.55	7%	5.14	5%	44.55%	S	1.77	6%	2.70	5%	52.62%	S	0.85	5%	1.33	5%	57.69%	S

S means "There are significant differences between TFO method and RTFO method at 95% confidence interval"

NS means " There is no significant difference between TFO method and RTFO method at 95% confidence interval"

RSD means "The coefficient of variation (the ratio of standard deviation and mean)"

TABLE 4 Comparison of Dynamic Shear Stiffness Data Between Two Long-Term Aging Methods

TEST TEMPERATURE		20 °C						25 °C						30 °C					
	SAMPLE	TFOT+PAV		RTFOT+PAV		%		TFOT+PAV		RTFOT+PAV		%		TFOT+PAV		RTFOT+PAV		%	
		G*sin delta (MPa)	RSD	G*sin delta (MPa)	RSD	Difference		G*sin delta (MPa)	RSD	G*sin delta (MPa)	RSD	Difference		G*sin delta (MPa)	RSD	G*sin delta (MPa)	RSD	Difference	
UNMODIFIED	AAD-1	3.00	4%	2.85	3%	5.17%	NS	1.49	3%	1.53	5%	2.20%	NS	0.78	4%	0.84	9%	8.40%	NS
	AAK-1	4.72	1%	4.90	6%	3.80%	NS	2.44	3%	2.67	6%	9.60%	S	1.19	3%	1.36	6%	14.60%	S
	AAB-1	3.67	2%	3.62	7%	1.40%	NS	2.02	9%	1.91	10%	5.10%	NS	1.14	4%	1.12	9%	1.80%	NS
	AAS-2	2.64	1%	2.72	4%	3.30%	NS	1.43	1%	1.47	4%	2.80%	NS	0.74	1%	0.76	3%	2.70%	NS
	AAG-1	14.60	4%	14.56	13%	0.30%	NS	6.51	5%	6.74	15%	3.50%	NS	2.56	5%	2.64	17%	3.30%	NS
	AAZ	8.44	3%	8.45	3%	0.20%	NS	4.29	4%	4.40	3%	2.50%	NS	1.98	5%	2.02	3%	2.00%	NS
MODIFIED	AAG-1+SBS	9.23	6%	9.51	9%	3.00%	NS	4.01	6%	4.19	9%	4.60%	NS	1.58	6%	1.67	10%	5.70%	NS
	AAK-1+SBS	3.94	7%	3.86	6%	2.10%	NS	2.19	7%	2.16	7%	1.50%	NS	1.19	8%	1.15	6%	3.60%	NS
	AAG-1+PE	15.70	4%	18.89	8%	20.30%	S	8.31	5%	10.21	9%	22.90%	S	3.95	10%	4.79	9%	21.20%	S
	AAK-1+PE	6.30	7%	8.22	5%	30.58%	S	3.60	7%	4.92	4%	36.62%	S	1.93	6%	2.74	4%	42.15%	S

S means "There are significant differences between TFO method and RTFO method at 95% confidence interval"

NS means " There is no significant difference between TFO method and RTFO method at 95% confidence interval"

RSD means "The coefficient of variation (the ratio of standard deviation and mean)"

TABLE 5 Paired *t*-Test for Short- and Long-Term Aging Methods at 20°C

Value: G*sin delta (MPa) at 20°C

Short-term aging methods between TFOT and RTFOT

Sample	TFOT	RTFOT	Differences	
AAD-1	1.04	1.28	0.24	
AAK-1	2.39	2.96	0.57	
AAB-1	1.72	1.84	0.12	
AAS-2	0.90	1.15	0.25	
AAG-1	7.18	9.05	1.87	
AAZ	4.19	5.32	1.13	
AAG-1+SBS	4.68	5.18	0.50	
AAK-1+SBS	1.72	2.23	0.51	
AAG-1+PE	10.73	12.85	2.12	
AAK-1+PE	3.55	5.14	1.59	
		Mean =	**0.89**	
		Std. =	0.73	
		SQ(Std.) =	0.54	
		t-value =	**3.84**	significant at 95%
		t*(n-1=9) =	2.262	confidence interval

Long-term aging methods between TFOT+PAV and RTFOT+PAV

Sample	TFOT+PAV	RTFOT+PAV	Differences	
AAD-1	3.00	2.85	-0.15	
AAK-1	4.72	4.90	0.18	
AAB-1	3.67	3.62	-0.05	
AAS-2	2.64	2.72	0.08	
AAG-1	14.60	14.56	-0.04	
AAZ	8.44	8.45	0.01	
AAG-1+SBS	9.23	9.51	0.28	
AAK-1+SBS	3.94	3.86	-0.08	
AAG-1+PE	15.70	18.89	3.19	
AAK-1+PE	6.30	8.22	1.92	
		Mean =	**0.53**	
		Std. =	1.11	
		SQ(Std.) =	1.24	
		t-value =	**1.52**	Not significant at 95%
		t*(n-1=9) =	2.262	confidence interval

TABLE 6 Paired *t*-Test for Short- and Long-Term Aging Methods at 25°C

Value : G* sin delta (MPa) at 25 °C

Short-term aging methods between TFOT and RTFOT

Sample	TFOT	RTFOT	Differences	
AAD-1	0.46	0.58	0.12	
AAK-1	1.14	1.45	0.31	
AAB-1	0.86	0.94	0.08	
AAS-2	0.44	0.57	0.13	
AAG-1	2.54	3.48	0.94	
AAZ	1.76	2.27	0.51	
AAG-1+SBS	1.69	1.94	0.25	
AAK-1+SBS	0.93	1.28	0.35	
AAG-1+PE	4.71	5.81	1.10	
AAK-1+PE	1.77	2.70	0.93	
		Mean =	**0.47**	
		Std. =	0.38	
		SQ(Std.) =	0.15	
		t-value =	**3.91**	significant at 95%
		t*(n-1=9) =	2.262	confidence interval

Long-term aging methods between TFOT+PAV and RTFOT+PAV

Sample	TFOT+PAV	RTFOT+PAV	Differences	
AAD-1	1.49	1.53	0.04	
AAK-1	2.44	2.67	0.23	
AAB-1	2.02	1.91	-0.11	
AAS-2	1.43	1.47	0.04	
AAG-1	6.51	6.74	0.23	
AAZ	4.29	4.40	0.11	
AAG-1+SBS	4.01	4.19	0.18	
AAK-1+SBS	2.19	2.16	-0.03	
AAG-1+PE	8.31	10.21	1.90	
AAK-1+PE	3.60	4.92	1.32	
		Mean =	**0.39**	
		Std. =	0.67	
		SQ(Std.) =	0.44	
		t-value =	**1.86**	Not significant at 95%
		t*(n-1=9) =	2.262	confidence interval

binders. The results of this analysis are summarized in Tables 3 and 4. A significance level of 5 percent, or a 95 percent confidence interval, was used for all statistical analyses in the study.

Short-Term Aging

The data presented in Table 3 show that the RTFOT method is more severe in terms of aging than the TFOT method for all test specimens. Although the TFOT method might be expected to produce more variability in the test results because of skin formation of the asphalt binder (*6*), the data from the present study indicate that the coefficients of variation or the relative standard deviations (RSDs) for the TFOT method are equal to or less than those for the RTFOT method for most asphalt binders. The results of the paired *t*-test, presented in Tables 5, 6, and 7, confirmed that there were significant differences between the two short-term aging methods. In addition, a comparison of the individual asphalt binders indicated that significant differences between the properties of the TFOT-aged residues and the RTFOT-aged residues were found in 8 of 10 test binders at 20°C, 10 of 10 test binders at 25°C, and 9 of 10 test binders at 30°C (Table 3).

Long-Term Aging

The data presented in Table 4 and the graphs in Figures 1 through 3 indicate that the PAV long-term aging process reduced the differences in the properties produced by the TFOT and the RTFOT methods of short-term aging. The stiffness of long-term-aged residues obtained from two different short-term aging processes become very similar. Results of the paired *t*-test analyses presented in Tables 5, 6, and 7 indicated that there was no significant difference between the properties of RTFOT-aged residues and those of TFOT-aged residues after exposure to the PAV aging procedure. Nevertheless, the *t*-test analyses of the properties of the individual asphalt binders indicated that there were significant differences for 3 of the 10 test binders at 25°C and 30°C and 2 of the 10 test binders at 20°C (Table 4). It was also found that there was a significant effect for the polyethylene-modified asphalt binder. After exposure to the PAV aging procedure, this binder tended to separate and a skin was observed on the surface of the binder in the pan.

CONCLUSIONS

The following conclusions can be drawn from the results of the present study:

1. For short-term aging, the RTFOT method produced more severe aging than the TFOT method for both unmodified and modified asphalt binders. These differences in properties were significant at the 95 percent confidence interval.

TABLE 7 Paired *t*-Test for Short- and Long-Term Aging Methods at 30°C

Value : G* sin delta (MPa) at 30°C				
Short-term aging methods between TFOT and RTFOT				
Sample	TFOT	RTFOT	Differences	
AAD-1	0.21	0.26	0.05	
AAK-1	0.54	0.69	0.15	
AAB-1	0.40	0.44	0.04	
AAS-2	0.20	0.27	0.07	
AAG-1	0.85	1.23	0.38	
AAZ	0.69	0.90	0.21	
AAG-1+SBS	0.61	0.70	0.09	
AAK-1+SBS	0.50	0.66	0.16	
AAG-1+PE	1.91	2.39	0.48	
AAK-1+PE	0.85	1.33	0.48	
		Mean =	**0.21**	
		Std. =	0.17	
		SQ(Std.) =	0.03	
		t-value =	**3.86**	significant at 95%
		t*(n-1=9) =	2.262	confidence interval
Long-term aging methods between TFOT+PAV and RTFOT+PAV				
Sample	TFOT+PAV	RTFOT+PAV	Differences	
AAD-1	0.78	0.84	0.06	
AAK-1	1.19	1.36	0.17	
AAB-1	1.14	1.12	-0.02	
AAS-2	0.74	0.76	0.02	
AAG-1	2.56	2.64	0.08	
AAZ	1.98	2.02	0.04	
AAG-1+SBS	1.58	1.67	0.09	
AAK-1+SBS	1.19	1.15	-0.04	
AAG-1+PE	3.95	4.79	0.84	
AAK-1+PE	1.93	2.74	0.81	
		Mean =	**0.21**	
		Std. =	0.33	
		SQ(Std.) =	0.11	
		t-value =	**1.95**	Not significant at 95%
		t*(n-1=9) =	2.262	confidence interval

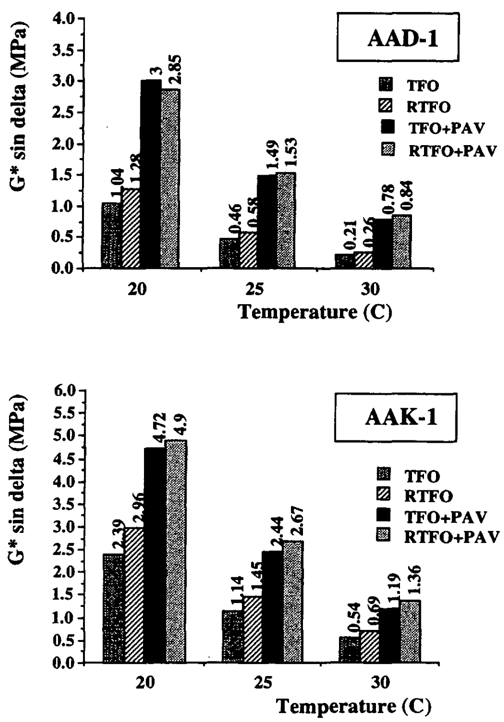

FIGURE 1 Dynamic shear stiffnesses of two high-aging-index asphalts after short- and long-term aging.

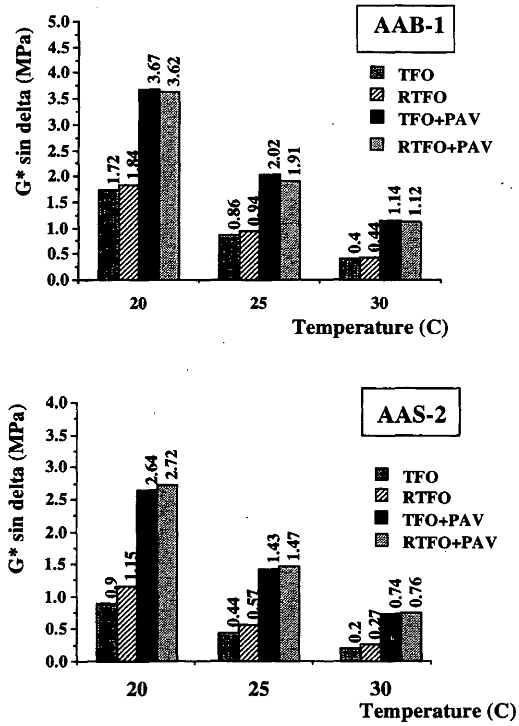

FIGURE 2 Dynamic shear stiffnesses of two intermediate-aging-index asphalts after short- and long-term aging.

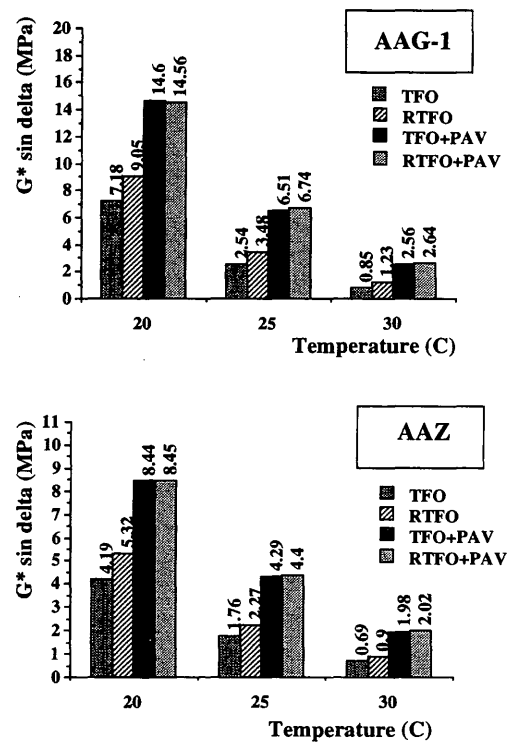

FIGURE 3 Dynamic shear stiffness of two low-aging-index asphalts after short- and long-term aging.

2. Based on the results of the study the TFOT and RTFOT methods should not be used interchangeably for short-term aging.

3. Long-term (PAV) aging reduced the differences in the properties of asphalts over the long term produced by the TFOT and the RTFOT methods of short-term aging. The differences were not significant at the 95 percent confidence interval.

4. There was a significant difference for the PAV-aged polyethylene-modified asphalt binders and for some of the asphalt binders.

5. The study showed that the TFOT method of short-term aging produces less variability than the RTFOT method in most asphalt binders both before and after long-term aging by the PAV procedure.

6. Because of differences or potential differences only one method of short-term aging should be used for the Superpave binder specification.

7. It is recommended that a new or modified short-term aging procedure be developed.

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