Investigation of Laboratory Aging Processes of Asphalt Binders Used in Florida

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A laboratory investigation was performed to evaluate a variety of aging processes used for simulating the long-term aging of asphalt binders. Four promising methods investigated in this study include an extended thin film oven test (TFOT), an ultraviolet (UV) chamber, the California tilt oven (CTO), and the pressure aging vessel (PAV). A few conventional asphalts commonly used in Florida and a few modified binders were subjected to these aging processes, and their aged residues were tested for comparison of aging severity. Because of the insensitivity of consistency measurements at lower temperatures, the most sensitive parameter for differentiating the aging severity was found to be the aging index at 60°C, which is the ratio of absolute viscosities at 60°C. On the basis of this parameter, the relative aging severities of aging processes were established. Various asphalts were found to exhibit different aging severities when subjected to different aging processes. Asphalts from different sources exhibit differentiable degrees of volatile loss when subjected to the extended TFOT. The UV chamber was found to be effective only in aging the surfaces of the binder samples. Low-viscosity asphalts were found to age more in the CTO process. Whereas low-volatile-loss asphalts show less aging in most aging processes, some high-volatile-loss asphalts could age less in the PAV process.

Asphalts undergo two substantially different aging processes in their service life. They are subjected to high temperatures and a high degree of air exposure during their relatively short production time (short-term aging) and then to the environment at a relatively lower temperature and air void content for a long duration (long-term aging). A variety of methods have been proposed and investigated to simulate the aging effects on asphalt during mixing as well as field service. The purpose of this study was to conduct a laboratory evaluation of different aging processes on typical asphalt binders commonly used in Florida. The aging effects of the conventional aging processes were compared with the newly proposed pressure aging vessel (PAV) process. The effects of a few modifiers on the aging characteristics of the asphalts were also evaluated.

The most important mechanism of age hardening is the change in the chemical composition of asphalt molecules from reaction with atmospheric oxygen. As in most chemical reactions, the contact surface area and temperature dominate the oxidation rate of asphalt. First, substantial oxidation and loss of volatiles occur during mixing. The aging process continues, although at a much slower rate, while the asphalt concrete is processed through a surge or storage silo, transported to the paving site, laid, and compacted. After the asphalt pavement has cooled and been opened to traffic, the age hardening process continues at a significantly slower rate, depending on the air void content and pavement temperature. Corbett and Merz (*1*) showed that the amount of the saturate fraction, which is the potentially volatile component, remained virtually constant during 18 years of service in the well-known Michigan Road Test.

A tabulated review of the laboratory simulation of asphalt aging has been made by Welborn (*2*). Ideally, asphalts hardened by a laboratory aging method should be similar to those aged in actual service environments. Furthermore, the method should be reasonably simple to be used as a routine control test. The sample size of aged residue should be reasonable to allow for necessary tests.

The most successful simulation methods are the thin film oven test (TFOT) and rolling thin film oven test (RTFOT). These two methods are recognized to give the same aging effect and can be used to predict the degree of age hardening of an asphalt cement during conventional hot mixing at 150°C, as indicated by penetration or viscosity measurements. It is believed that some asphalts, especially those refined from heavy crudes, were affected more by mixing than in situ aging, whereas the opposite is true for some other asphalts. Therefore Santucci and Schmidt (*3*) suggested that it might be unreliable to predict long-term durability from short-term hardening characteristics.

In a study by Kemp and Predoehl (*4*), the RTFOT test was modified to heat asphalt at a lower temperature (111°C) for 168 hr with the oven slightly tilted to prevent asphalt buildup. Penetration at 25°C, absolute viscosity at 60°C, and ductility at 25°C were measured on the aged residues as indicators of the durability characteristics of the asphalts after 2 years of exposure to a hot desert environment. Higher-viscosity asphalts tend to roll less during the rolling process in the RTFOT, which might result in a lower oxidation rate. This is one of the possible drawbacks of the California tilt oven (CTO).

Durability studies at the University of Florida showed that it is possible to simulate the effects of aging during service and the hot mixing process by using the TFOT or RTFOT at a higher temperature (*5,6*). The potential advantages of using the TFOT at higher temperatures as compared with other long-term aging tests are that existing standardized equipment could be conveniently used and that the test would require much less time to complete. To determine the aging characteristics of asphalts at a lower temperature, an ultraviolet (UV) chamber, which is maintained at a temperature of 60°C, was used to simulate the effects of heat, UV light, and air on asphalt mixtures.

The PAV has been proposed by SHRP researchers to simulate long-term aging of asphalt binders. By applying a higher oxygen content through increasing air pressure, oxidation of asphalt can be accelerated at a lower temperature, which is closer to the real

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exposure temperature. These proposed methods need to be evaluated and compared with one another before being introduced into the asphalt specifications.

TESTING PROGRAM

Laboratory Aging Processes Used

As indicated in Table 1, four promising laboratory aging methods, including an extended TFOT, UV chamber, CTO, and PAV, were selected for simulating the effect of long-term asphalt aging.

Extended TFOT

The TFOT (ASTM D1754) was extended by using different process temperatures, durations, and film thicknesses, as indicated in Table 1, to obtain eight levels of age hardening.

UV Chamber

A UV chamber, which was built at the University of Florida (*6*), was used in this study. The chamber was made from 3/8-in. plywood in the shape of a trapezoidal box with a rectangular base 4 ft 2 in. × 3 ft 9-1/2in. and a height of 1 ft 10 in. The two sides of the chamber were hinged to permit access into the chamber, and the interiors of these two hinged sides were used to mount four lamp assemblies, each assembly carrying two lamps. The roof of the chamber was used to mount one more lamp assembly carrying two lamps. Ten 40-W fluorescent UV-B lamps (UVB-313) were used in the chamber. Temperature in the chamber was maintained at 60°C through the use of a thermostat, infrared heat lamps, and a circulation fan on the vertical end sides of the chamber. The residues from the conventional TFOT process were reduced to 25-g samples and placed in the same TFOT plates. The TFOT plates containing 25-g residues were then placed in the 60°C UV chamber for durations of 7, 14, and 28 days.

CTO

The rolling thin film oven (ASTM D2872) was positioned so that the horizontal axes of the glass containers are tilted by 1 degree higher in the front of the oven. The RTFOT bottles with 35-g samples were heated at 111°C for 24, 72, and 168 hr. After the process, the RTFOT bottles were put into a 160°C oven for 20 min to obtain sufficient fluidity to pour the aged residues out of the bottles.

PAV

The SHRP-proposed PAV was investigated in this study. In consideration of the convenience of the testing procedure, it was decided to perform the PAV test on TFOT residues (50-g samples transferred directly from TFOT oven) rather than on RTFOT residues. The PAV process was performed under 300 psi for 20 hr at three temperatures (90°C, 100°C, and 110°C).

Asphalt Binders and Evaluation Parameters Used

Five conventional asphalts commonly used in Florida were subjected to the 17 artificial aging processes, and their aged residues were evaluated. Five modifiers, which include fine ground tire rubber (GTR), carbon black (CB), styrene ethylene butylene styrene (SEBS), ethylene vinyl acetate (EVA), and styrene butadiene rubber (SBR), were blended at adequate dosage levels with an AC-30 to produce five blends of modified AC-30 asphalts. The modified asphalts were subjected to the CTO and PAV aging processes, and their aged residues were tested for the effects of modifiers on the aging characteristics of the asphalt binder.

The following tests were performed on both the unaged and aged samples:

1. Penetration at 25°C (ASTM D5),
2. Absolute viscosity at 60°C (ASTM D2171),
3. Schweyer rheometer tests at 25°C and 5°C, and
4. Infrared absorption spectral analysis.

The percent penetration retained, aging indices based on the ratios of viscosity at three temperatures, and carbonyl ratio index, which is the ratio of carbonyl ratio of the aged residue to the carbonyl ratio of original asphalt, were used to measure the severity of age hardening of the various aging processes.

The major concern in evaluating the aging characteristic of an asphalt binder is the potential of thermal cracking of the aged asphalt binder. Stiffness limit temperature concept has been proposed from the study of low-temperature cracking in the field (*7*). A stiffness limit of 300 MPa for a loading time of 2 hr has been used in the recent SHRP specification. Experiences in Florida (*6*) have shown that low-temperature cracking occurs when the constant power viscosity of the binder exceeds 2.6×10^{10} poise. Davis (*8*) suggested a maximum viscosity of 2.1×10^{10} poise for the control of asphalt. The constant stress (1-MPa) viscosity used in this study as described in the following section is smaller than its corresponding constant power (100-W/m^3) viscosity due to the pseudoplastic nature of asphalt at low temperature. A constant stress viscosity limit of 2×10^{10} poise was considered to be adequate and used in this study.

Schweyer Rheometer Tests

A Cannon Schweyer Constant Stress Rheometer was used to characterize low-temperature rheology of the binders in this study. A comprehensive review of the theoretical background of the Schweyer constant stress rheometer and the application of rheological concepts proposed by H. E. Schweyer has been presented by Tia and Ruth (*9*). The rheometer consists of a gas-operated pneumatic cylinder that applied a specified force to the plunger in the sample tube. An LVDT measured the movement of the plunger, and the output voltage was digitized and acquired by a data acquisition and analysis system, which was operated on an IBM PC-compatible computer.

On the basis of the steady-state laminar flow of power law fluid in the capillary tube, the shear stress and shear rate under the applied pressure can be obtained from the movement of the plunger and dimensions of the tube. Tests are usually conducted at a minimum of five stress levels. The shear susceptibility is computed and used to calculate the constant power viscosity at

TABLE 1 Asphalt Binders and Laboratory Aging Processes Investigated

Unmodified Binders		
Refinery Source	Grade	Abbreviation
Coastal	AC-30	CT30
Amoco	AC-30	AM30
Amoco	AC-20	AM20
Mariani	AC-30	MA30
Mariani	AC-20	MA20
Modified Binders (use Coastal AC-30 as base asphalt)		
Modifier	Dosage (%)	Abbreviation
#80 fine ground tire rubber	5	GTR
carbon black	10	CB
styrene ethylene butylene styrene	5	SEBS
ethylene vinyl acetate	5	EVA
styrene butadiene rubber	3.5	SBR
Extended TFOT		Abbreviation
TFOT, 50 g, 140 °C, 5 hours		TL
TFOT, 50 g, 163 °C, 5 hours		TS
TFOT, 50 g, 185 °C, 5 hours		TH
TFOT, 50 g, 163 °C, 10 hours		TF10
TFOT, 50 g, 163 °C, 15 hours		TF15
TFOT, 25 g, 140 °C, 5 hours		TLM
TFOT, 25 g, 163 °C, 5 hours		TSM
TFOT, 25 g, 185 °C, 5 hours		THM
UV Chamber		Abbreviation
reduce TS-residues to 25 g, 60 °C UV, 7 days		UV7
reduce TS-residues to 25 g, 60 °C UV, 14 days		UV14
reduce TS-residues to 25 g, 60 °C UV, 28 days		UV28
California Tilt Oven		Abbreviation
111 °C for 24 hours		C24
111 °C for 72 hours		C72
111 °C for 168 hours		C168
Pressure Aging Vessel		Abbreviation
TS + PAV, 300 psi, 90 °C for 20 hours		P90
TS + PAV, 300 psi, 100 °C for 20 hours		P100
TS + PAV, 300 psi, 110 °C for 20 hours		P110

100 W/m^3. This is the viscosity when the shear stress times the shear rate equals 100 W/m^3. When performed on highly aged residues at 5°C, it was found that the 100-W/m^3 constant power viscosity has to be extrapolated far from the observed data points. To avoid the extrapolating error, an apparent viscosity at a shear stress of 1 MPa (constant stress viscosity), which is close to the average shear stress used in performing the test at 5°C, was used instead. This is the viscosity when the shear stress is at 1 MPa.

Infrared Absorption Spectral Analysis

Infrared spectroscopic technique was used to measure changes in molecular structures of the binders due to aging in terms of the changes in the amount of certain functional groups in them. The infrared absorption spectrum between 1600 and 1900 cm^{-1} is of particular interest, since it contains the absorption bands for the functional groups of carboxylic acids, ketones, and anhydrides (*10*). In previous research by Tia et al. (*5,6*), it was concluded that the carbonyl ratio, which is a ratio of infrared absorbance at 1700 cm^{-1} and 1600 cm^{-1}, can be used to express the level of oxidation in an asphalt binder.

Statistical Model

In the comparison of aging processes, the test results were analyzed as a factorial experiment comprising 5 asphalts (ASPHALT) and 17 aging methods (METHOD). The concern is the specified aging processes and asphalts. Therefore, ASPHALT and METHOD are regarded as fixed effects. The following linear model is assumed for any single parameter in the experiment:

$$Y_{ijk} = \mu + \text{ASPHALT}_i + \text{METHOD}_j + \text{INTERACTION}_{ij} + \epsilon_{ijk} \quad (1)$$

where

Y_{ijk} = response of *k*th replicate, *j*th aging method, and *i*th asphalt;
μ = overall mean;

ASPHALT_i = main effect of ith asphalt;
METHOD_j = main effect of jth aging method;
INTERACTION_{ij} = interaction effect;
ϵ_{ijk} = experimental error;
i = 1 to 5 for the five asphalts;
j = 1 to 17 for the 17 aging methods; and
k = 1 to 2 for two replicates.

The SAS/STAT computer software was used for the statistical analysis.

It is well known that the variation of viscosity measurements is a function of viscosity value. The higher the viscosity, the larger the variation will be. Therefore, the aging index used as the response in the preceding statistical model could not satisfy the constant variance assumption. To solve this problem, a data transformation technique is suggested by most statisticians. The logarithm of the aging index was used as the response variable in the statistical model.

TEST RESULTS

Investigation of Aging Processes

The five conventional asphalts show substantially different weight changes in the extended TFOT process. The weight changes are differentiable by the refinery source of asphalt, as shown in Figure 1. CT asphalt shows the highest weight loss, and AM asphalts show higher weight loss than MA asphalts. Among the 17 aging processes, the high-temperature TFOT (using 50- or 25-g samples) produced large amounts of weight loss. On the other hand, the SHRP-proposed PAV processes produce large amounts of weight gain as shown in Figure 1. However, the PAV-aged residues are not differentiable by refinery source. The difference in the effect of refinery source appears to be enlarged by using a higher exposure temperature in the TFOT and PAV processes.

The results of the absolute viscosity test and the corresponding aging indices at 60°C are given in Table 2. The results of the Schweyer rheometer test at 5°C are given in Table 3. These data are the average values from two replicates. The analysis of variance (ANOVA) was performed according to the two-factor factorial model as described. The results of ANOVA and Duncan's multiple range test at α = 0.05 on the five aging severity parameters are summarized in Table 4.

Because of the insensitivity of the consistency measurements at lower temperatures, it was found that the aging index at 60°C is the most sensitive parameter in detecting differences in aging severity. The interaction of asphalt and aging method is seen to have a significant effect on the aging index at 60°C. This means that different aging methods are very likely to produce different aging severities on different asphalts. As an example, in the ranking of aging severity by the CTO process for 168 hr, CT30 is a severely aged asphalt as indicated by its high aging index at 60°C, given in Table 2. However, in the PAV method, it is the least severely aged asphalt no matter what process temperature is used. On the basis of the aging index at 60°C, the AM asphalts show higher aging potential than the MA asphalts in all 17 aging processes.

As seen in Figure 1 and Table 2, asphalts with low volatile loss during the TFOT processes exhibit a lower aging index, particularly at higher process temperatures. This trend is also observed in the TFOT processes using 25-g samples or longer exposure periods.

A close examination of the aging indices at 60°C of different asphalts in the processes of the UV chamber (Table 2) indicates that there was no significant additional hardening of the asphalt residues from 7 to 28 days' exposure in the UV chamber. This might be due to the formation of a thin skin on the surface of the

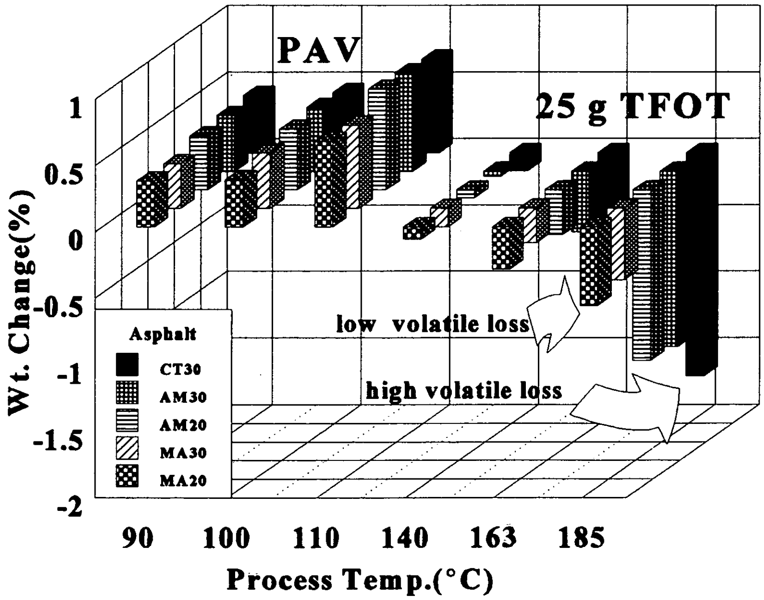

FIGURE 1 Weight change of various asphalts in the processes of PAV and 25-g TFOT at different process temperatures.

TABLE 2 Results of Absolute Viscosity Tests at 60°C and Corresponding Aging Indexes

Laboratory Aging Process	Asphalt Type				
	CT30	AM30	AM20	MA30	MA20
Original	2883	3146	2246	3108	2248
TL	4422*(1.53**)	5034(1.60)	3486(1.55)	4560(1.47)	3142(1.40)
TS	6064(2.10)	7454(2.37)	5266(2.34)	5988(1.93)	4943(2.20)
TH	13390(4.64)	17204(5.47)	11222(5.00)	11434(3.68)	8537(3.80)
TLM	6208(2.15)	7826(2.49)	5312(2.37)	6988(2.25)	4785(2.13)
TSM	11834(4.10)	17457(5.55)	11441(5.09)	13306(4.28)	9314(4.14)
THM	74405(25.81)	141495(44.98)	88590(39.44)	54798(17.63)	31327(13.94)
TF10	13311(4.62)	15600(4.96)	13239(5.89)	13715(4.41)	10235(4.55)
TF15	23450(8.13)	54878(17.44)	23276(10.36)	24578(7.91)	15920(7.08)
UV7	9672(3.35)	14784(4.70)	12754(5.68)	17167(5.52)	9646(4.29)
UV14	11730(4.07)	11558(3.67)	16088(7.16)	15622(5.03)	11412(5.08)
UV28	10344(3.59)	13770(4.38)	11756(5.23)	14790(4.76)	10208(4.54)
C24	12194(4.23)	12872(4.09)	10674(4.75)	15120(4.86)	11230(5.00)
C72	47250(16.39)	45904(14.59)	43014(19.15)	43863(14.11)	38749(17.24)
C168	127756(44.31)	111090(35.31)	103595(46.12)	82702(26.61)	95092(42.30)
P90	18698(6.49)	27166(8.64)	17750(7.90)	23922(7.70)	15500(6.90)
P100	18320(6.35)	34997(11.12)	31358(13.96)	30699(9.88)	20088(8.94)
P110	53796(18.66)	125046(39.75)	82366(36.67)	62216(20.02)	45057(20.04)

Note :

See Table 1 for the meaning of codes.
*: Absolute viscosity in Poises.
**: Aging index.

TABLE 3 Constant Stress Viscosities at 5°C as Measured by Schweyer Rheometer (10^9 poise)

Laboratory Aging Process	Asphalt Type				
	CT30	AM30	AM20	MA30	MA20
Original	1.22	0.88	0.70	0.66	0.40
TL	1.66	0.93	0.77	0.90	0.66
TS	2.68	1.52	1.07	0.97	0.88
TH	6.07	3.00	1.99	2.19	1.60
TLM	2.57	1.64	1.07	1.48	0.79
TSM	5.70	3.65	1.95	2.58	2.59
THM	13.40	6.70	5.08	5.25	3.18
TF10	5.53	2.13	1.85	2.22	1.21
TF15	8.06	2.35	2.37	3.00	1.70
UV7	5.55	2.79	2.26	3.26	1.75
UV14	4.63	2.86	1.91	4.32	1.58
UV28	4.96	2.96	1.72	3.78	1.86
C24	6.56	3.91	2.10	3.36	1.82
C72	24.40	8.33	6.14	8.58	3.32
C168	43.20	28.80	31.80	11.50	14.30
P90	9.77	6.82	3.93	3.61	1.34
P100	13.33	6.74	5.33	5.16	2.17
P110	25.70	26.90	12.18	7.68	3.72

Note:

See Table 1 for the meaning of codes.

TABLE 4 Results of Statistical Analysis in Comparison of Laboratory Aging Processes

Item		Penetration Retained (%)	Carbonyl Ratio Index	Aging Index at60 °C	Aging Index at25 °C	Aging Index at5 °C
RESULTS of ANOVA	Source	Significance	Significance	Significance	Significance	Significance
	A^*	Yes	Yes	Yes	Yes	Yes
	M^*	Yes	Yes	Yes	Yes	Yes
	I^*	No	No	Yes	No	No
Duncan's Grouping on ASPHALT		Grouping ASPHALT	Grouping ASPHALT	Grouping ASPHALT	Grouping ASPHALT	Grouping ASPHALT
		A MA30	A AM30	A AM20	A AM30	A CT30
		B A AM30	A MA20	A AM30	A CT30	B A MA30
		B A CT30	B AM20	B MA30	B AM20	B AM30
		B C MA20	B MA30	B MA20	B MA30	B MA20
		C AM20	B CT30	B CT30	B MA20	B AM20
Duncan's Grouping on METHOD		Grouping METHOD	Grouping METHOD	Grouping METHOD	Grouping METHOD	Grouping METHOD
		A TL	A P110	A C168	A C168	A C168
		B TS	B A C168	B THM	B P110	B P110
		B TLM	B C THM	B P110	C B C72	C B C72
		C THM	D C P100	C C72	C D THM	C D THM
		D C UV7	D C E C72	D P100	E D P100	C D P100
		D C UV14	D C E TF15	D TF15	E F P90	E D P90
		D C C24	D F E UV7	E P90	G F TF15	E F C24
		D C TF10	D F E UV28	F TF10	G F UV28	E F TSM
		D C TSM	G F E P90	F UV14	G C24	E F TF15
		D E UV28	G F E TF10	F TSM	G UV14	E F UV28
		F E TF15	G F UV14	F C24	G TSM	E F UV7
		F P90	G F C24	F UV7	G UV7	E F UV14
		G P100	G F TSM	F UV28	G TH	E F TH
		H C72	G TH	F TH	G TF10	F TF10
		H THM	H TS	G TLM	H TLM	G TLM
		H P110	H TLM	G TS	H TS	G TS
		I C168	H TL	H TL	I TL	G TL

Note: See Table 1 for the meaning of codes.
For Duncan's groupings, those with same letter are not significantly different at $\alpha = 0.05$.
*: A= ASPHALT; M= METHOD; I= INTERACTION

asphalt residue during early UV exposure, which might seal the rest of the asphalt residue from further oxidation.

In the CTO processes, AC-20 shows a higher aging index than AC-30. This might be due to the higher mobility of the less viscous AC-20, resulting in a larger exposure surface during the rolling process.

In the PAV processes, CT30, which exhibits high volatile loss in the extended TFOT and CTO tests, shows a low aging index at all three process temperatures. The high pressure and relatively lower temperature limit the volatile loss. However, the asphalts (MA) with low volatile loss show lower aging indexes than those (AM) with relatively higher volatile loss.

The 17 aging processes can be grouped as indicated in Table 4 from most severe aging to minor aging as follows:

1. CTO for 168 hr, with an average aging index of 38;
2. PAV at 110°C and high-temperature (185°C) TFOT using 25-g samples, with an average aging index of 25;
3. CTO for 72 hr, with an average aging index of 16;
4. PAV at 100°C and TFOT for 15 hr, with an average aging index of 9.5;
5. PAV at 90°C, with an average aging index of 7.5;
6. TFOT for 10 hr, using 25-g samples, high-temperature (185°C) TFOT, UV chamber for 7, 14, and 28 days, and CTO for 24 hr, with an average aging index of 4.5;
7. Standard TFOT and low-temperature (140°C) TFOT using 25-g samples, with an average aging index of 2; and
8. Low-temperature TFOT, with an average aging index of 1.5.

The aging severity order on the basis of percent penetration retained is similar to that on the basis of the aging index at 60°C. Because of the lower sensitivity of the penetration test on harder asphalts, low penetration asphalts (AC-30) show a higher percentage of penetration retained than high penetration asphalts (AC-20) as indicated in Table 4. The order of severity among the 17 aging processes as ranked on the basis of carbonyl ratio index, aging index at 25°C, and aging index at 5°C is in general agreement with that ranked by aging index at 60°C. However, the ranking of aging severity could be different if different parameters were used. The high-temperature TFOT process on 25-g samples produces aging severity similar to that of the PAV process at 110°C in terms of aging index at 60°C. In terms of carbonyl ratio index, the PAV process at 110°C produces higher oxidation than the high-temperature TFOT process on 25-g samples.

The temperature susceptibility of the tested binders was evaluated by two parameters, PVN′(25-60) and VTS(60-5), which are defined as follows:

$$\mathrm{PVN}'(25\text{-}60) = \frac{-1.5[(6.4890 - 1.59\log(p25) - \log(V60)]}{1.05 - 0.2234\log(p25)} \qquad (2)$$

$$\mathrm{VTS}(T_1 - T_2) = \frac{\log[\log(V_2)] - \log[\log(V_1)]}{\log(T_1) - \log(T_2)} \qquad (3)$$

where

V60 = viscosity (poise) at 60°C,
p25 = penetration in 0.1 mm at 25°C,
T_1, T_2 = temperature (degrees Kelvin), and
V_1, V_2 = viscosity (centipoise) at T_1 and T_2.

Both PVN′(25-60) and VTS(60-5) were found to be substantially reduced by the 17 aging processes as indicated in Table 5. The higher the degree of aging, the lower the temperature susceptibility would become. CT30 is the most temperature susceptible asphalt among the five asphalts used in this study, before or after any of the 17 aging processes.

The major concern with aged asphalt is its low temperature property. The viscosity at 5°C, which was obtained from the Schweyer rheometer test, is given in Table 3. The empirical viscosity limit in avoiding thermal cracking problem is the critical viscosity value of 2×10^{10} poise. As indicated in Table 3, six residues exhibit a viscosity value exceeding this limit at 5°C.

Investigation of Aging Characteristics of Modified Asphalts

The results of tests on modified asphalts that were aged by the CTO and PAV processes are given in Tables 6 and 7, respectively. These two aging processes were performed at similar temperatures. The CTO process provides longer reaction time, and the PAV process provides higher oxygen content through pressurized air. Because different asphalts produce different aging severity in different aging processes, the CTO and PAV data were analyzed separately.

The effects of different modifiers on the aging index at 60°C in the CTO processes are shown in Figure 2. The SBR modified asphalt was not investigated in the CTO process. The same statistical model described earlier was used to analyze the aging indices at 60°C. Because of the significant effect of interaction of

TABLE 5 Temperature Susceptibility Parameters of Unmodified Asphalts and Their Aged Residues

Parameter	PVN'(25-60)					VTS(60-5)				
Method	CT30	AM30	AM20	MA30	MA20	CT30	AM30	AM20	MA30	MA20
Original	-0.57	-0.40	-0.50	-0.52	-0.52	3.92	3.81	3.91	3.76	3.79
TL	-0.41	-0.32	-0.43	-0.38	-0.43	3.80	3.62	3.74	3.66	3.75
TS	-0.38	-0.15	-0.27	-0.32	-0.40	3.77	3.57	3.64	3.56	3.62
TH	-0.18	0.34	0.08	-0.08	-0.10	3.62	3.38	3.46	3.47	3.52
TF10	-0.08	0.20	0.14	-0.01	-0.09	3.61	3.35	3.38	3.40	3.39
TF15	0.27	1.02	0.52	0.36	0.13	3.46	2.90	3.21	3.24	3.29
TLM	-0.32	-0.03	-0.23	-0.29	-0.46	3.75	3.56	3.63	3.59	3.61
TSM	-0.29	0.26	0.09	-0.13	-0.22	3.66	3.41	3.45	3.45	3.59
THM	0.74	1.44	1.04	0.63	0.52	3.15	2.79	2.89	3.07	3.17
UV7	-0.23	0.11	0.07	0.04	-0.11	3.73	3.42	3.44	3.40	3.49
UV14	-0.06	-0.11	0.19	-0.04	-0.08	3.62	3.53	3.31	3.49	3.40
UV28	-0.22	0.04	-0.01	-0.04	-0.14	3.68	3.46	3.41	3.49	3.48
C24	-0.11	0.03	0.03	0.03	-0.05	3.68	3.55	3.49	3.45	3.44
C72	0.43	0.61	0.62	0.51	0.53	3.43	3.22	3.18	3.25	3.10
C168	0.83	1.08	1.02	0.83	0.95	3.19	3.16	3.20	3.08	3.07
P90	-0.05	0.40	0.23	0.17	0.06	3.63	3.44	3.44	3.33	3.24
P100	-0.12	0.50	0.47	0.27	0.13	3.60	3.33	3.39	3.30	3.30
P110	0.54	1.18	1.12	0.66	0.53	3.45	3.30	3.24	3.15	3.1

Note:

PVN'(25-60) calculated by Equation 2 and VTS(T_1-T_2) calculated by Equation 3.
See Table 1 for the meaning of codes.

TABLE 6 Results of Tests on CTO Residues of Modified Asphalts

Process Time	Asphalt Type				
	AC-30	GTR	CB	SEBS	EVA
Penetration at 25 °C (0.01 mm)					
0 hour	56	46	48	24	40
24 hours	30	28	27	21	22
72 hours	19	19	18	16	17
168 hours	14	17	14	14	11
Absolute viscosity at 60 °C (poise)					
0 hour	2883	5922	4600	24944	4880
24 hours	12194	23772	13512	58784	20757
72 hours	47250	53950	36584	83776	92725
168 hours	127756	122240	97678	145675	1909352
Viscosity at 25 °C (10^6 poise)					
0 hour	3.58	1.84	2.39	22.15	6.38
24 hours	16.10	28.45	17.65	44.70	10.15
72 hours	53.80	38.65	45.10	84.10	24.15
168 hours	178.00	92.35	89.55	154.00	70.50
Viscosity at 5 °C (10^9 poise)					
0 hour	1.22	1.00	0.87	5.30	5.56
24 hours	6.56	6.54	4.18	6.21	8.37
72 hours	24.40	9.29	15.65	13.00	9.90
168 hours	43.20	15.05	39.45	71.45	39.75
Carbonyl Ratio					
0 hour	0.3083	0.3214	-	0.3044	0.3874
24 hours	0.4350	0.4185	-	0.3015	0.4484
72 hours	0.4805	0.5380	-	0.3877	0.5968
168 hours	0.5662	0.5676	-	0.4427	0.7116

Note: See Table 1 for the meaning of codes.

-: Data not available caused by too many peaks in the spectrum.

the two main factors, the Duncan's multiple range test was performed at separate aging levels. The results of statistical analysis are given in Table 8. As indicated in Figure 2 and Table 8, the EVA-modified asphalt showed a high aging index, particularly when the process time is long, as in the 168-hr CTO process.

On the basis of the results of tests on the CTO residues, all three modified asphalts, with the exception of the EVA-modified asphalt, show lower aging severity in terms of lower aging indices at 60°C. Carbon black and fine ground tire rubber used in this study exhibit similar aging indices. The SEBS-modified asphalt exhibits a very low aging index, which might be attributed to the slower movement of the binders in the flasks during the rolling process of the CTO due to its high initial viscosity. This does not necessarily mean that the SEBS-modified asphalt will have a lower thermal cracking potential than the EVA-modified asphalt or the control AC-30. As long as the aged residues have low enough viscosity to prevent the buildup of high thermal stresses, an asphalt with low initial viscosity could be allowed to age to a high degree. As indicated in Table 6, after a 72-hr exposure in the CTO process, all four modified asphalts show lower viscosity at 5°C compared with their base AC-30. However, after a 168-hr exposure in the CTO, only the fine ground tire rubber–modified asphalt shows a significantly lower viscosity at 5°C.

The effects of modifiers on the aging index at 60°C in the PAV processes are plotted in Figure 3. In the PAV process at 90°C, only the SBR- and SEBS-modified asphalts show significantly less severe aging in terms of aging index at 60°C, as indicated in Figure 3 and Table 8. After the PAV process at 100°C, the carbon black- and EVA-modified asphalt show more severe aging than the control AC-30. Although SBR- and SEBS-modified asphalts show less aging after the PAV process at 100°C, the difference is not significant. After the PAV process at 110°C, EVA-, carbon

TABLE 7 Results of Tests on PAV Residues of Modified Asphalts

Process Temperature	Asphalt Type					
	AC-30	GTR	CB	SEBS	EVA	SBR
Penetration at 25 °C (0.01 mm)						
Original	56	46	48	24	40	-
90 °C	24	24	22	24	44	41
100 °C	23	22	20	21	22	42
110 °C	19	18	16	18	20	37
Absolute viscosity at 60 °C (poise)						
Original	2883	5922	4600	24944	4880	7404
90 °C	18699	34476	27540	100950	38392	26411
100 °C	18321	45204	40827	139257	58999	38861
110 °C	53796	88388	87361	278471	195354	56813
Viscosity at 25 ° C (10^6 poise)						
Original	3.58	3.52	2.39	22.15	6.38	1.02
90 °C	21.20	35.05	30.70	115.00	23.00	2.56
100 °C	25.90	40.15	49.60	160.00	19.80	6.32
110 °C	71.30	77.80	84.55	198.00	72.40	10.60
Viscosity at 5 °C (10^9 poise)						
Original	1.22	1.00	0.87	5.30	5.56	3.12
90 °C	9.77	8.74	11.80	17.92	10.63	2.52
100 °C	13.33	16.20	17.85	28.63	11.17	7.85
110 °C	25.70	22.90	32.60	34.71	21.21	11.26
Carbonyl Ratio						
Original	0.3083	0.3214	-	0.3044	0.3874	0.2209
90 °C	0.4502	0.4431	-	0.4120	0.5442	0.3840
100 °C	0.4896	0.4582	-	0.4354	0.5229	0.4678
110 °C	0.5759	0.5437	-	0.4958	0.5828	0.5129

Note: See Table 1 for the meaning of codes.

**: Missing Data. -: Data not available caused by too many peaks in the spectrum.

black-, and ground tire rubber-modified asphalts show a higher aging index at 60°C than the control AC-30. On the other hand, SBR- and SEBS-modified asphalts exhibit a lower aging index at 60°C than their base AC-30. The SBR-modified asphalt exhibits a substantially lower viscosity at 5°C, and the SEBS-modified asphalt shows a substantially higher viscosity at 5°C as indicated in Table 7. If the PAV processes could simulate long-term aging in the field, these results would indicate that the SBR-modified asphalt would probably have a lower thermal cracking potential, whereas the SEBS-modified asphalt would have a higher thermal cracking potential than that of the base asphalt. This observation may not be conclusive since there was great variability in the results of the Schweyer rheometer tests on the SBR-modified asphalts. The great variability of the test results might be due to the high compressibility of the SBR-modified asphalts, which makes the basic assumptions of the Schweyer rheometer test invalid.

SUMMARY

The major findings from this study are as follows:

1. A reasonable laboratory aging process and an adequate evaluation parameter are required in the durability study of asphalt binders. Different asphalts could age differently in different aging processes. The ranking of aging severity for different asphalts could depend on the parameters chosen.
2. Because of the insensitivity of consistency measurements at lower temperatures, the most sensitive parameter for characterizing the aging severity of asphalt binders was found to be the aging index at 60°C, which is the ratio of absolute viscosities at 60°C.
3. For conventional asphalts used in Florida, high-temperature TFOT processes produce higher weight loss and PAV processes produce weight gain. The weight loss in high-temperature TFOT

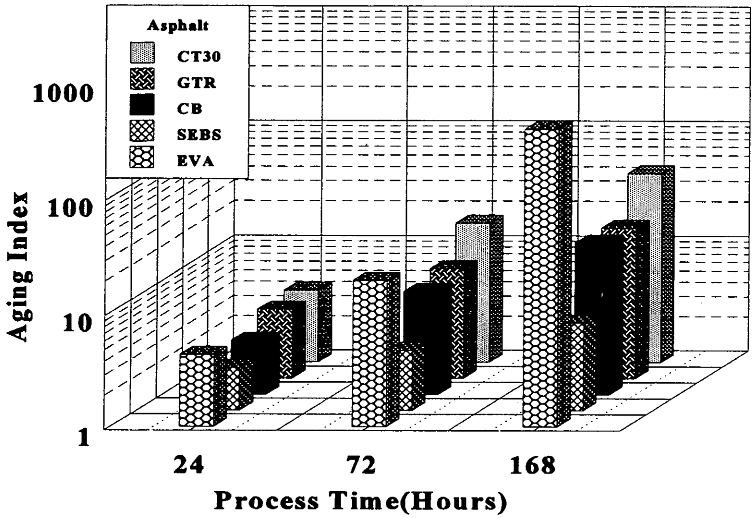

FIGURE 2 Effects of various modifiers on aging index at 60°C in CTO processes.

TABLE 8 Results of ANOVA and Duncan's Grouping on Aging Index at 60°C of CTO and PAV Residues

Item	CTO Process		PAV Process	
Results of ANOVA	Source	Significance	Source	Significance
	ASPHALT	Yes	ASPHALT	Yes
	METHOD	Yes	METHOD	Yes
	INTERACTION	Yes	INTERACTION	Yes
Duncan's Grouping on ASPHALT	Grouping at METHOD=C24 Grouping Mean N ASPHALT A 4.27 2 EVA A 4.23 2 AC-30 A 4.02 2 GTR A 3.01 2 CB A 2.56 2 SEBS		Grouping at METHOD=P90 Grouping Mean N ASPHALT A 7.87 2 EVA B A 6.48 2 AC-30 B 5.99 2 CB B 5.82 2 GTR C 4.05 2 SEBS C 3.57 2 SBR	
	Grouping at METHOD=C72 Grouping Mean N ASPHALT A 19.30 2 EVA A 16.39 2 AC-30 B 9.10 2 GTR B 8.14 2 CB C 3.65 2 SEBS		Grouping at METHOD=P100 Grouping Mean N ASPHALT A 12.09 2 EVA B 8.88 2 CB C B 7.63 2 GTR C D 6.35 2 AC-30 D 5.58 2 SEBS D 5.25 2 SBR	
	Grouping at METHOD=C168 Grouping Mean N ASPHALT A 380.19 2 EVA B 44.36 2 AC-30 C 21.28 2 GTR C 20.65 2 CB D 6.11 2 SEBS		Grouping at METHOD=P110 Grouping Mean N ASPHALT A 40.03 2 EVA B 18.99 2 CB B 18.65 2 GTR C 14.93 2 AC-30 D 11.16 2 SEBS D 7.67 2 SBR	

Note: See Table 1 for the meaning of codes.
For Duncan's groupings, those with same letter are not significantly different at $\alpha = 0.05$.

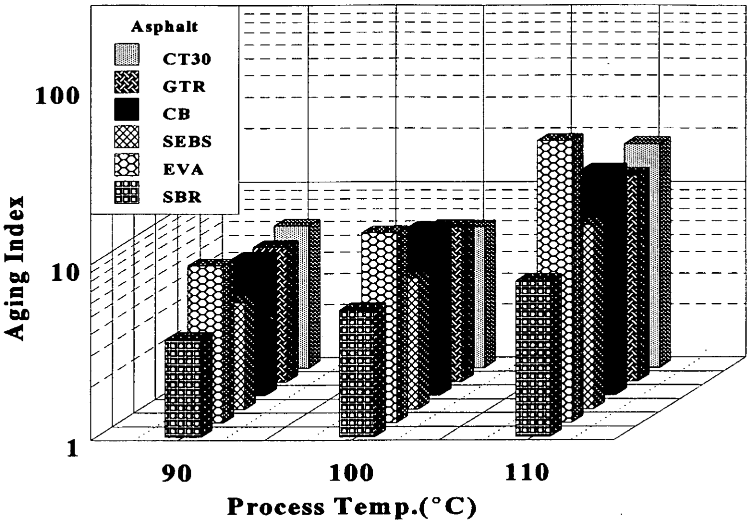

FIGURE 3 Aging index of modified asphalts in PAV processes at 60°C.

is differentiable by refinery source of the asphalt. Whereas asphalts with a low volatile loss show less aging in most aging processes, an asphalt with a high volatile loss could age less in the PAV process.

4. Only the surface of the asphalt samples was aged by the UV light in the UV chamber. Low-viscosity asphalts were found to age more in the CTO process because of a larger contact surface caused by higher mobility in the rolling process.

5. Most of the modified asphalts, except EVA-modified asphalt, show less aging in the CTO process than the control asphalt in terms of aging index at 60°C. All of the modified asphalts show lower viscosity at 5°C than the control asphalt after a 72-hr CTO exposure. However, after a 168-hr CTO exposure, only the ground tire rubber-modified asphalt exhibits a lower viscosity at 5°C than the control asphalt.

6. In terms of the aging index at 60°C, the effect of modifiers on reducing the aging severity of asphalts in the PAV process is different at different process temperatures. At 90°C, SEBS- and SBR-modified asphalts exhibit a lower aging index at 60°C than the control asphalt. When the process temperature was increased to 100°C, no substantial reduction of aging index was found for any of the five modified asphalts compared with the control asphalt. The fine ground tire rubber–, SEBS-, and SBR-modified asphalts exhibit lower aging indexes than the control asphalt at the process temperature of 110°C.

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