Investigation of Laboratory Aging Procedures for Asphalt-Aggregate Mixtures

C. A. BELL, Y. ABWAHAB, AND M. E. CRISTI

A Strategic Highway Research Program project—entitled Performance-Related Testing and Measuring of Asphalt-Aggregate Interactions and Mixtures—includes development of procedures to age mixtures in the laboratory. Two major effects dominate aging of asphalt-aggregated mixtures: (a) loss of volatile components and oxidation in the construction phase (short-term aging) and (b) progressive oxidation of the in-place mixture in the field (long-term aging). Other factors may contribute to aging. In particular, molecular structuring may occur over a long period of time, resulting in steric hardening. Actinic light, primarily in the ultraviolet range, also has an effect, particularly in desert-like climates. Aging may result in hardening (stiffening) of the mixture, which alters the performance of the mixture. This may be beneficial, because a stiffer mixture will have improved load-distribution properties and will be more resistant to permanent deformation. However, aging may also result in embrittlement (increased tendency to crack and ravel) and loss of durability in terms of wear resistance and moisture susceptibility. Preliminary tests to evaluate aging methods for asphalt-aggregate mixtures have been conducted. Short-term methods include oven aging and extended mixing; long-term methods include oven aging and oxygen enrichment. The effects of temperature level and duration of aging are noted. Test specimens were fabricated from two asphalts and two aggregates, representing extreme property levels. The four mixture combinations were prepared at two levels of permeability representing good and moderate compaction conditions. The effects of aging were determined using the diametral resilient modulus test.

With regard to asphalt mixtures, aging is associated with the phenomenon of hardening. Other terms also commonly used include age hardening or embrittlement. The aging process occurs in two stages: short term and long term. The first stage occurs during the construction phase and is primarily attributable to the loss of volatile components and oxidation while the mix is hot. Long-term hardening is primarily attributable to the progressive oxidation of the mixture while in service.

The majority of previous work has investigated the aging effects of asphalt cements rather than the mixture (*1*), and to date no standard procedure exists for aging mixtures. A major objective of this study is to develop standard laboratory procedures simulating field aging conditions.

A preliminary study of laboratory aging procedures for asphalt-aggregate mixtures has been conducted. The study is not yet complete, but a substantial amount of data can be presented. An overview of the aging methods is given together with an outline of test procedures used to evaluate the effect of alternate aging methods. Summary tables of data are presented for those readers interested in specific property levels measured. The authors have not yet completed a detailed statistical evaluation of the data, and therefore this evaluation is based on general trends presented in a series of figures.

Department of Civil Engineering, Oregon State University, Corvallis, Oreg. 97331-4304.

TEST PROGRAM

A detailed laboratory test program has been presented in a separate document for the Strategic Highway Research Program (SHRP) Project A-003A (*2*). A major objective of the study reported here is to evaluate the most promising aging method(s) to simulate short- and long-term aging effects. Three phases are being undertaken: (a) preliminary test program, (b) expanded test program, and (c) field validation. Only the preliminary program is outlined here. This program involves a limited number of material and test variables. The expanded test program and field validation phases will consider more material and test variables and will be used to develop further those methods appearing to be most appropriate in the preliminary program.

Aging Methods

The preliminary program involves two groups of aging procedures falling into short- and long-term categories:

Short-Term	*Long-Term*
Forced-draft oven aging	Forced-draft oven aging
Extended mixing	Pressure oxidation
	Triaxial cell aging

The short-term methods involve conditioning loose mixtures, whereas the long-term methods involve conditioning compacted samples. More details are given for each method in a subsequent section.

Evaluation Methods

The tests being used to evaluate the effect of each aging method include the following:

Mixture Tests	*Asphalt Tests*
Resilient modulus	Rheology tests
Dynamic modulus	
Tensile test	

Other tests may be used, such as infrared spectroscopy and size-exclusion chromatography on recovered asphalt. More details are given for each group of tests in a subsequent section.

Variables Used for Oven Aging and Extended Mixing

The same variables were selected for each of the three short-term aging methods and for the long-term oven aging as shown in Table 1. All mixtures were prepared using the mix design asphalt content and gradations and standard compaction procedures for the California kneading compactor. The program is a 3/4 fraction of the complete factorial with no replicate tests. For each aging method, 36 specimens were prepared and tested according to the combinations of variables shown in Table 1. Two asphalts with substantially different properties and designated with SHRP codes AAK-1 and AAG-1 were used. Similarly, two distinctly different aggregates with SHRP codes RB and RL were used. As shown in Table 1, the two asphalts and two aggregates enabled a total of four mixtures to be tested.

TABLE 1 VARIABLES USED IN OVEN AGING AND EXTENDED MIXING PROGRAMS

Asphalt and Aggregate Combinations	LOW AIR VOIDS (~4%)						MEDIUM AIR VOIDS (~8%)					
	Temperature						Temperature					
	Level 1			Level 2			Level 1			Level 2		
	Time Period						Time Period					
	a	b	c	a	b	c	a	b	c	a	b	c
RL + AAK-1	X	X	X				X	X	X	X	X	X
RL + AAG-1	X	X	X	X	X	X				X	X	X
RB + AAK-1	X	X	X	X	X	X				X	X	X
RB + AAG-1	X	X	X				X	X	X	X	X	X

Variables Used for Pressure Oxidation

For the pressure oxidation tests, both oxygen and compressed air were used at pressures of 100 and 300 psi to provide oxygen enrichment. Therefore, a 1/4 factorial experiment was designed requiring 48 specimens as shown in Table 2.

Variables Used for Triaxial Cell Aging

This approach, which was initiated in June 1990, consisted of forcing either oxygen or air to flow through a mixture specimen, thus providing oxygen enrichment. A 1/2 fraction of the complete factorial requiring 48 specimens with no replicate tests is being used, as shown in Table 3.

TABLE 2 VARIABLES USED IN PRESSURE OXIDATION PROGRAM

Asphalt and Aggregate Combinations	ATMOSPHERE															
	Oxygen								Air							
	Low Pressure				High Pressure				Low Pressure				High Pressure			
	Low Voids		High Voids		Low Voids		High Voids		Low Voids		High Voids		Low Voids		High Voids	
	Temperature (°C)				Temperature (°C)				Temperature (°C)				Temperature (°C)			
	60		25		60		25		60		25		60		25	
	Time Period				Time Period				Time Period				Time Period			
	abc	abc	abc	abc	abc	abc	abc	abc	abc	abc	abc	abc	abc	abc	abc	abc
RL + AAK-1	X--	-X-	--X	---	--X	---	X--	-X-	-X-	X--	---	--X	---	--X	-X-	X--
RL + AAG-1	---	--X	-X-	X--	-X-	X--	---	--X	--X	---	X--	-X-	X--	-X-	--X	---
RB + AAK-1	---	--X	-X-	X--	-X-	X--	---	--X	--X	---	X--	-X-	X--	-X-	--X	---
RB + AAG-1	X--	-X-	--X	---	--X	---	X--	-X-	-X-	X--	---	--X	---	--X	-X-	X--

TABLE 3 VARIABLES USED IN TRIAXIAL CELL AGING PROGRAM

Asphalt and Aggregate Combinations	ATMOSPHERE							
	OXYGEN				AIR			
	Air Voids Low		Air Voids Medium		Air Voids Low		Air Voids Medium	
	Temperature (°C)		Temperature (°C)		Temperature (°C)		Temperature (°C)	
	25	60	25	60	25	60	25	60
	Time Period		Time Period		Time Period		Time Period	
	a b c	a b c	a b c	a b c	a b c	a b c	a b c	a b c
RL + AAK-1	X X X			X X X		X X X	X X X	
RL + AAG-1		X X X	X X X		X X X			X X X
RB + AAK-1		X X X	X X X		X X X			X X X
RB + AAG-1	X X X			X X X		X X X	X X X	

SAMPLING PREPARATION, AGING, AND TEST PROCEDURES

Preparation

The preliminary test program used two asphalts with extreme characteristics (AAG-1 and AAK-1). The aggregates (RB and RL) are a crushed granite and a chert gravel. Mixing and compaction followed a protocol established by the study team for SHRP A-003A; they are based on the method used to prepare Hveem samples (ASTM D1560-81a and D1561-81a). The physical properties determined on the mixture samples include bulk specific gravity, maximum theoretical specific gravity, and permeability. The modulus and tensile properties were also determined; they will be described more fully, along with an outline of tests for the recovered asphalt. The tensile strain at yield and tensile strength are determined in an indirect tensile test. The properties of the original and recovered asphalt are being determined using a steady-state rotational viscometer at this stage in the study. However, a dynamic mode of testing is planned for the expanded test program.

Short-Term Aging Procedures

The short-term aging portion of this investigation involved aging mixtures in their uncompacted state to simulate the precompaction phase of the construction process. Short-term oven aging used a forced-draft oven for either 0, 6, or 15 hr at 135°C or 163°C. The aged mix was then compacted at either 250 or 500 psi compactive effort using a kneading compactor to attain target void levels of approximately 8 and 4 percent, respectively. The actual levels of voids obtained depended on the asphalt-aggregate combination used and vary from the target levels. The bulk specific gravity, permeability, resilient modulus, and tensile properties were determined for all samples.

The extended mixing program involved using a modified rolling thin film oven (RTFO) test. An attachment to the RTFO drum enabled loose mixture to be rolled, thus extending the mixing time. Samples were mixed using the standard procedure and then subjected to 0, 10, 120, or 360 min mixing at 135°C or 163°C. The aged mix was compacted at 250 or 500 psi to attain two void levels. The bulk specific gravity, permeability, resilient modulus, and tensile properties were determined for all samples.

Long-Term Aging Procedures

The oven aging method used forced-draft ovens, ensuring that the temperature was constant everywhere in the oven as compared to a regular convection oven. The method used is essentially the same as that used in the asphalt-aggregate mixture analysis system study (*3*). Compacted samples were preconditioned for 2 days at 40°C or 60°C. The preconditioning was a measure to ensure the stability of the sample. The specimens were then exposed to conditions of either 0, 2, or 7 days at 107°C. The before-aging and after-aging characteristics were determined.

The pressure oxidation vessel utilized both oxygen and compressed air. The compacted samples were exposed to either environment for 0, 2, or 7 days at 100 or 300 psi at either 25°C or 60°C. The preconditioning step performed with the oven aging method was not required in this procedure. As with other aging methods, tests were performed on the unaged and aged samples to determine effects of aging.

The triaxial cell aging approach involves conditioning a sample while it is positioned in a triaxial test cell as illustrated in Figure 1. For this stage of the study, conventional kneading compactor samples were used (i.e., 4 in. diameter by 2½ in. high). Oxygen or air was passed through the sample and the resilient modulus determined at any time during the conditioning process. A flow rate of 4 ft^3/hr was used, which required a pressure of about 50 psi. Tests were run at 25°C and 60°C.

Test Procedures

The resilient modulus is usually determined using an indirect tensile mode of testing. A triaxial mode of testing is also used where convenient, as in the case of the triaxial aging approach. The dynamic modulus will be determined in the expanded test program with a modified triaxial mode of testing, in which the frequency of loading is varied and the phase lag between the applied load pulse and the strain response is determined. The tangent and loss modulus are obtained at different frequencies to give a thorough characterization of mixture samples. This approach is analogous to the dynamic mechanical analysis of asphalt cement samples.

The modulus tests are nondestructive and yield information on the elasticity (and plasticity, in the case of the dynamic test) of the mixture sample. The tensile test is destructive and, therefore, is not done until all the modulus data have been collected. The test is done at a deformation rate of 2 in./min,

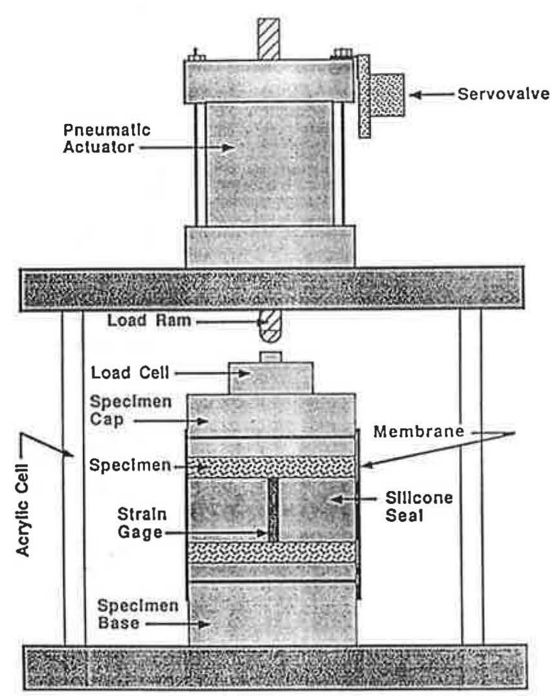

FIGURE 1 Triaxial aging process.

and the load and deformation of the sample are monitored, enabling the strength and the strain at yield to be determined. These data indicate the brittleness of the sample. Von Quintus et al. (*3*) suggested that the strain at yield was an indicator of the aging achieved in a mixture sample. Following the tensile test, the mixture portions may be used to obtain recovered asphalt samples.

Only limited tests on the recovered asphalt are being done in the preliminary test program, and the data obtained will not be reported or discussed here because testing is not yet complete. The tests being done include size-exclusion chromatography, infrared spectroscopy, and rheological tests. The rheology is being defined with a plate-to-plate rotational viscometer. This is being used in a steady-state mode during the preliminary test program, but it will be upgraded to enable dynamic measurements to be made in the expanded test program.

RESULTS

Tables 4–8 show the complete set of data collected for the short-term oven aging, extended mixing, long-term oven aging, pressure oxidation, and triaxial aging respectively. The footnotes to each table explain the code used to identify samples. For the purposes of this paper only, the first three characters are significant, representing the asphalt, aggregate, and air void content of the samples.

The majority of the figures presented herein show resilient modulus ratio versus time plots. This modulus ratio is determined as follows:

$$\frac{\text{resilient modulus after aging}}{\text{resilient modulus before aging}}$$

To date, the majority of the evaluation of the procedures used has been based on the modulus ratios determined. Other data

TABLE 4 SUMMARY OF SHORT-TERM OVEN AGING DATA

SAMPLE ID	AGING CONDITION PERIOD (hours)	TEMP. (°C)	VOIDS	ACTUAL VOIDS (%)	MODULUS (ksi) BEFORE AGING	AFTER AGING	RATIO	PERMEABILITY (E-9cm/sec)	TENSILE STRESS (psi)	STRAIN μ-strain
KBLS000	0	LOW	LOW	4.4	304	304	1.0	LOW	127	7930
KBLS100	6	LOW	LOW	4.9	304	582	1.9	LOW	205	7621
KBLS200	15	LOW	LOW	6.2	304	736	2.4	LOW	244	7122
KBLS010	0	HIGH	LOW	2.6	341	341	1.0	LOW	173	7959
KBLS110	6	HIGH	LOW	7.0	341	807	2.4	LOW	232	5214
KBLS210	15	HIGH	LOW	14.6	341	258	0.8	LOW	90	6324
KBMS010	0	HIGH	HIGH	7.1	407	407	1.0	LOW	135	10106
KBMS110	6	HIGH	HIGH	11.7	407	656	1.6	6.04	150	2991
KBMS210	15	HIGH	HIGH	17.8	407	228	0.6	4.66	61	4499
GBLS000	0	LOW	LOW	4.6	455	455	1.0	LOW	257	6927
GBLS100	6	LOW	LOW	4.2	455	896	2.0	LOW	274	9278
GBLS200	15	LOW	LOW	3.9	455	1224	2.7	LOW	373	3838
GBMS000	0	LOW	HIGH	7.2	364	364	1.0	LOW	195	7638
GBMS100	6	LOW	HIGH	7.0	364	870	2.4	3.59	244	4779
GBMS200	15	LOW	HIGH	7.2	364	1206	3.3	4.68	294	9885
GBMS010	0	HIGH	HIGH	6.1	368	368	1.0	1.96	205	8306
GBMS110	6	HIGH	HIGH	7.2	368	1445	3.9	4.34	319	2312
GBMS210	15	HIGH	HIGH	13.6	368	1179	3.2	6.48	190	2471
GLLS000	0	LOW	LOW	6.6	193	193	1.0	2.3	223	8123
GLLS100	4	LOW	LOW	6.7	193	651	3.4	2.1	295	8751
GLLS200	8	LOW	LOW	6.9	193	702	3.6	4.8	288	7392
GLMS000	0	LOW	HIGH	9.4	124	124	1.0	13.3	171	11779
GLMS100	4	LOW	HIGH	8.6	124	411	3.3	19.2	243	9249
GLMS200	8	LOW	HIGH	8.5	124	624	5.0	14.2	277	5595
GLMS010	0	HIGH	HIGH	8.2	141	141	1.0	12.0	191	11768
GLMS110	4	HIGH	HIGH	9.4	141	720	5.1	18.8	298	3717
GLMS210	8	HIGH	HIGH	12.8	141	797	5.7	70.0	193	1879
KLLS000	0	LOW	LOW	5.4	236	236	1.0	0.7	162	7464
KLLS100	4	LOW	LOW	6.5	236	394	1.7	0.7	200	5977
KLLS200	8	LOW	LOW	6.4	236	514	2.2	1.3	244	9044
KLLS010	0	HIGH	LOW	5.2	202	202	1.0	1.0	173	12863
KLLS110	4	HIGH	LOW	8.1	202	721	3.6	7.2	223	8749
KLLS210	8	HIGH	LOW	11.2	202	479	2.4	2.8	149	6433
KLMS010	0	HIGH	HIGH	6.2	208	208	1.0	0.5	177	6440
KLMS110	4	HIGH	HIGH	12.7	208	520	2.5	34.3	163	7617
KLMS210	8	HIGH	HIGH	15.2	208	300	1.4	34.9	78	6168

KEY FOR SAMPLE IDENTIFICATION:

K	ASPHALT	K=AAK-1	G=AAG-1
L	AGGREGATE	L=RL	B=RB
L	VOIDS	L=LOW	M=MEDIUM
S	SHORT TERM	S=SHORT TERM	
0	AGING PERIOD	0=6/4 HOURS	1=15/8 HOURS
0	AGING TEMP.	0=LOW(135°C)	1=HIGH(163°C)
O	AGING TYPE	O=SHORT TERM OVEN AGING	

TABLE 5 SUMMARY OF EXTENDED MIXING DATA

SAMPLE ID	AGING TIME (minutes)	TEMPER-ATURE	VOIDS	ACTUAL VOIDS (%)	MODULUS (ksi) BEFORE	AFTER	RATIO	PERMEA-BILITY (E-9cm/sec)	TENSILE STRESS	STRAIN
KBLS00E	10	LOW	LOW	3.1	333	333	1.00	LOW	158.1	6892.0
KBLS10E	120	LOW	LOW	2.3	333	398	1.20	LOW	209.9	6464.0
KBLS20E	360	LOW	LOW	1.8	333	777	2.33	LOW	271.1	4545.0
KBLS01E	10	HIGH	LOW	5.0	301	301	1.00	LOW	158.4	8031.0
KBLS11E	120	HIGH	LOW	4.2	301	818	2.72	LOW	247.8	5159.9
KBLS21E	360	HIGH	LOW	8.3	301	839	2.79	14.9	205.9	4838.7
KBMS01E	10	HIGH	HIGH	7.7	279	279	1.00	2.5	135.8	7691.4
KBMS11E	120	HIGH	HIGH	11.0	279	558	2.00	HIGH	154.2	3960.7
KBMS21E	360	HIGH	HIGH	7.8	279	630	2.26	15.7	220.3	3724.9
GBLS00E	10	LOW	LOW	4.1	491	491	1.00	LOW	218.2	6407.0
GBLS10E	120	LOW	LOW	3.7	491	827	1.68	LOW	342.5	6801.6
GBLS20E	360	LOW	LOW	0.8	491	810	1.65	LOW	380.0	5150.8
GBMS00E	10	LOW	HIGH	6.1	345	345	1.00	1.1	207.8	10846.9
GBMS10E	120	LOW	HIGH	4.5	345	557	1.61	LOW	256.0	6039.2
GBMS20E	360	LOW	HIGH	5.9	345	681	1.97	LOW	315.4	5320.7
GBMS01E	10	HIGH	HIGH	7.5	324	324	1.00	LOW	179.2	5499.5
GBMS11E	120	HIGH	HIGH	6.5	324	888	2.74	3.6	293.6	3903.2
GBMS21E	360	HIGH	HIGH	3.8	324	1713	5.29	LOW	457.6	3696.7
GLLS00E	10	LOW	LOW	6.5	228	228	1.00	2.1	153.3	9293.7
GLLS10E	120	LOW	LOW	6.3	228	447	1.96	2.9	208.2	9321.7
GLLS20E	360	LOW	LOW	8.0	228	699	3.07	HIGH	213.3	7603.7
GLMS00E	10	LOW	HIGH	8.6	140	140	1.00	13.2	122.7	10160.1
GLMS10E	120	LOW	HIGH	10.5	140	327	2.34	HIGH	141.3	9243.7
GLMS20E	360	LOW	HIGH	10.2	140	657	4.69	HIGH	179.9	3390.3
GLMS01E	10	HIGH	HIGH	9.3	163	163	1.00	21.7	113.9	17009.4
GLMS11E	120	HIGH	HIGH	11.1	163	522	3.20	HIGH	155.1	3867.3
GLMS21E	360	HIGH	HIGH	15.5	163	459	2.82	HIGH	93.3	4642.5
KLLS00E	10	LOW	LOW	0.6	291	291	1.00	LOW	154.7	8906.5
KLLS10E	120	LOW	LOW	4.6	291	436	1.50	HIGH	178.4	7220.0
KLLS20E	360	LOW	LOW	6.0	291	804	2.76	HIGH	233.1	5760.9
KLLS01E	10	HIGH	LOW	0.6	273	273	1.00	LOW	154.6	8647.9
KLLS11E	120	HIGH	LOW	7.8	273	523	1.92	HIGH	158.7	7767.3
KLLS21E	360	HIGH	LOW	8.7	273	662	2.42	HIGH	180.7	4446.1
KLMS01E	10	HIGH	HIGH	2.2	215	215	1.00	4.3	126.9	7325.6
KLMS11E	120	HIGH	HIGH	8.8	215	660	3.07	HIGH	169.6	6024.4
KLMS21E	360	HIGH	HIGH	4.6	215	710	3.30	HIGH	178.2	3050.2

KEY FOR SAMPLE IDENTIFICATION:

K	ASPHALT	K=AAK-1 G=AAG-1
L	AGGREGATE	L=RL B=RB
L	VOIDS	L=LOW M=MEDIUM
S	SHORT TERM	S=SHORT TERM
0	AGING PERIOD	0=10 MIN. 1=120 MIN. 2=360 MIN.
0	AGING TEMP.	0=LOW(135°C) 1=HIGH(163°C)
E	AGING TYPE	E=EXTENDED MIXING

TABLE 6 SUMMARY OF LONG-TERM OVEN AGING DATA

SAMPLE ID	AGING TIME (days)	TEMPER-ATURE (°C)	TARGET VOIDS	ACTUAL VOIDS (%)	MODULUS (ksi) BEFORE AGING	MODULUS (ksi) AFTER AGING	MODULUS RATIO	PERM (E-9c/s) BEFORE AGING	PERM (E-9c/s) AFTER AGING	TENSILE STRESS (psi)	TENSILE STRAIN μ-strain
GLLL00O	0	40	LOW	7.38	249	294	1.18	-	2.92	138	(2)
GLLL10O	2	40	LOW	7.99	340	928	2.73	-	3.29	(1) 150	(2)
GLLL20O	7	40	LOW	7.42	401	1547	3.86	-	-	231	(2)
GLLL01O	0	60	LOW	7.91	351	367	1.05	-	-	161	(2)
GLLL11O	2	60	LOW	7.87	290	865	2.98	-	-	204	(2)
GLLL21O	7	60	LOW	7.54	329	1587	4.82	2.12	3.00	241	(2)
GLML01O	0	60	HIGH	10.00	234	348	1.49	3.71	3.89	144	(2)
GLML11O	2	60	HIGH	9.30	240	679	2.83	3.50	3.97	170	(2)
GLML21O	7	60	HIGH	10.00	258	1136	4.40	3.56	2.97	170	(2)
KLLL00O	0	40	LOW	6.69	295	328	1.11	1.37	1.59	137	(2)
KLLL10O	2	40	LOW	7.55	308	507	1.65	2.43	2.74	156	(2)
KLLL20O	7	40	LOW	7.23	355	1593	4.49	1.81	2.86	177	(2)
KLML00O	0	40	HIGH	9.20	198	240	1.21	3.55	-	91	(2)
KLML10O	2	40	HIGH	9.50	185	629	3.40	3.48	-	132	(2)
KLML20O	7	40	HIGH	9.10	208	1285	6.18	3.34	3.70	192	(2)
KLML01O	0	60	HIGH	9.00	203	344	1.69	3.62	3.36	116	(2)
KLML11O	2	60	HIGH	9.40	190	537	2.83	3.63	3.36	128	(2)
KLML21O	7	60	HIGH	8.90	208	1318	6.34	3.71	4.10	188	(2)
KBLL01O	0	60	LOW	6.57	303	376	1.24	-	-	141	(2)
KBLL11O	2	60	LOW	6.11	351	563	1.60	1.41	-	178	(2)
KBLL21O	7	60	LOW	6.42	288	894	3.10	LOW	-	(1) 171	(2)
KBLL00O	0	40	LOW	6.50	314	358	1.14	1.26	1.14	133	(2)
KBLL10O	2	40	LOW	6.82	345	565	1.64	0.56	1.06	166	(2)
KBLL20O	7	40	LOW	7.83	357	894	2.50	1.76	1.88	207	(2)
KBML01O	0	60	HIGH	9.03	296	344	1.16	3.65	3.23	115	(2)
KBML11O	2	60	HIGH	8.74	273	519	1.90	2.63	3.56	144	(2)
KBML21O	7	60	HIGH	8.64	257	994	3.87	2.57	2.66	261	(2)
GBLL00O	0	40	LOW	3.53	530	509	0.96	LOW	LOW	181	(2)
GBLL10O	2	40	LOW	2.42	511	562	1.10	LOW	LOW	235	(2)
GBLL20O	7	40	LOW	2.94	578	509	0.88	2.87	-	139	(2)
GBML00O	0	40	HIGH	8.00	312	328	1.05	2.11	2.40	138	(2)
GBML10O	2	40	HIGH	8.20	298	548	1.84	1.33	2.42	168	(2)
GBML20O	7	40	HIGH	8.90	264	1334	5.05	3.45	2.18	214	(2)
GBML01O	0	60	HIGH	8.40	329	376	1.14	2.86	3.75	121	(2)
GBML11O	2	60	HIGH	9.20	279	529	1.90	2.52	3.16	127	(2)
GBML21O	7	60	HIGH	8.20	346	1121	3.24	3.14	2.48	184	(2)

NOTES:

(1) Power shut off. Second stress was applied.

(2) No data recorded.

\- No data recorded due to either operator or equipment error.

KEY FOR SAMPLE IDENTIFICATION:

K	ASPHALT	K=AAK-1 G=AAG-1	
L	AGGREGATE	L=RL B=RB	
L	VOIDS	L=LOW M=MEDIUM	
L	LONG TERM	L=LONG TERM	
0	AGING PERIOD	0=0 DAYS 1=2 DAYS 2=7 DAYS	DAYS AT 107°C
0	CONDITION'G TEMP.	0=LOW(40°C) 1=HIGH(60°C)	TEMP. USED FOR 2 DAYS BEFORE USING 107°C
O	AGING TYPE	O=LONG TERM OVEN AGING	

TABLE 7 SUMMARY OF PRESSURE OXIDATION DATA

(a) PRESSURIZED WITH OXYGEN

SAMPLE ID *	AGING CONDITION PERIOD (days)	TEMP. (°C)	PRESSURE (psi)	ACTUAL VOIDS (%)	MODULUS (ksi) BEFORE AGING	AFTER AGING	Mr RATIO	PERMEABILITY (E-9c/s) BEFORE AGING	AFTER AGING	TENSILE TEST STRESS (psi)	STRAIN μ-strain
GLLL013P	0	60	300	7.96	272	249	0.92	2.06	1.81	162.9	9250
GLLL103P	2	25	300	8.08	272	257	0.94	1.40	2.23	135.8	8175
GLLL211P	7	60	100	7.15	300	387	1.29	LOW	1.39	100.5	11407
GLML011P	0	60	100	9.50	222	279	1.26	4.95	5.49	132.4	1187
GLML101P	2	25	100	9.20	211	337	1.60	4.21	4.69	129.8	12585
GLML213P	7	60	300	9.40	176	128	0.73	4.60	HIGH	67.4	25449
KLLL001P	0	25	100	7.30	224	194	0.87	2.07	1.91	110.0	9266
KLLL111P	2	60	100	7.70	294	274	0.93	3.13	HIGH	116.8	7010
KLLL203P	7	25	300	7.10	237	165	0.70	0.86	1.97	124.9	8249
KLML003P	0	25	300	8.80	283	216	0.76	2.68	3.99	6.4	3247
KLML113P	2	60	300	8.40	334	133	0.40	1.90	HIGH	93.0	11331
KLML201P	7	25	100	8.60	242	219	0.90	2.94	1.39	104.7	7164
KBLL013P	0	60	300	4.60	455	427	0.94	LOW	LOW	183.3	4206
KBLL103P	2	25	300	4.60	420	180	0.43	LOW	LOW	142.5	9962
KBLL211P	7	60	100	5.00	488	164	0.34	LOW	LOW	130.4	9782
KBML001P	0	25	100	8.00	326	239	0.73	1.70	2.00	133.9	5617
KBML101P	2	25	100	8.90	259	180	0.69	4.28	4.42	104.9	9494
KBML213P	7	60	300	8.10	292	73	0.25	3.05	HIGH	71.3	28887
GBLL001P	0	25	100	7.00	476	418	0.88	1.76	0.74	219.1	7523
GBLL111P	2	60	100	7.40	458	419	0.91	0.21	LOW	221.1	9878
GBLL203P	7	25	300	7.70	450	228	0.51	0.54	2.14	228.2	8279
GBML003P	0	25	300	9.10	409	420	1.03	3.02	2.35	210.7	7145
GBML113P	2	60	300	8.10	486	167	0.34	3.37	6.31	130.2	26118
GBML201P	7	25	100	8.10	499	387	0.78	3.14	8.69	216.0	4448

(b) PRESSURIZED WITH AIR

SAMPLE ID *	AGING CONDITION PERIOD (day)	TEMP. (°C)	PRESSURE (psi)	ACTUAL VOIDS (%)	MODULUS (ksi) BEFORE AGING	AFTER AGING	Mr RATIO	PERMEABILITY (E-9c/s) BEFORE AGING	AFTER AGING	TENSILE TEST STRESS (psi)	STRAIN μ-strain
GLLL003P	0	25	300	6.99	366	413	1.13	0.99	1.17	251.9	3441
GLLL113P	2	60	300	8.57	488	101	0.21	3.63	4.45	117.6	15739
GLLL201P	7	25	100	7.68	347	281	0.81	1.99	3.05	182.5	7058
GLML001P	0	25	100	9.06	228	199	0.87	4.10	3.98	167.7	10570
GLML111P	2	60	100	9.35	210	175	0.83	4.05	4.49	164.7	13317
GLML203P	7	25	300	9.08	216	88	0.41	3.74	cracked	83.7	33872
KLLL011P	0	60	100	6.50	263	328	1.25	1.96	1.87	124.9	7074
KLLL101P	2	25	100	6.70	411	262	0.64	1.50	1.83	133.4	5957
KLLL213P	7	60	300	6.70	340	66	0.19	2.68	4.34	78.1	13264
KLML013P	0	60	300	10.20	217	148	0.68	3.58	5.53	88.4	2921
KLML103P	2	25	300	9.10	211	70	0.33	3.58	4.87	70.8	19234
KLML211P	7	60	100	8.30	289	138	0.48	2.53	3.82	94.5	13333
KBLL003P	0	25	300	4.90	455	414	0.91	LOW	LOW	170.9	2142
KBLL113P	2	60	300	5.40	387	56	0.14	LOW	1.78	68.5	27902
KBLL201P	7	25	100	4.80	325	125	0.38	LOW	LOW	109.7	16228
KBML001P	0	25	100	9.00	345	279	0.81	2.61	3.51	123.8	6091
KBML111P	2	60	100	8.00	383	92	0.24	1.78	2.12	92.1	21194
KBML203P	7	25	300	8.90	265	91	0.34	2.40	3.3	79.9	16244
GBLL010P	0	60	100	4.20	596	430	0.72	LOW	LOW	249.9	5007
GBLL101P	2	25	100	5.40	601	300	0.50	0.84	3.73	207.5	10998
GBLL213P	7	60	300	5.00	817	126	0.15	0.46	2.72	143.8	22602
GBML013P	0	60	300	9.50	332	320	0.96	7.75	5.23	162.6	12450
GBML103P	2	25	300	7.80	531	101	0.19	4.70	4.26	192.7	10474
GBML211P	7	60	100	8.80	642	249	0.39	6.36	4.26	184.5	12058

KEY FOR SAMPLE IDENTIFICATION:

K	ASPHALT	K=AAK-1 G=AAG-1
L	AGGREGATE	L=RL B=RB
L	VOIDS	L=LOW M=MEDIUM
L	LONG TERM	L=LONG TERM
0	AGING PERIOD	0=0 DAYS 1=2 DAYS 2=7 DAYS
0	AGING TEMP.	0=LOW(25°C) 1=HIGH(60°C)
0	AGING PRESSURE	0=ROOM PRESSURE 1=100 PSI 3=300 PSI
P	AGING TYPE	P=PRESSURE OXIDATION AGING

TABLE 8 SUMMARY OF TRIAXIAL AGING DATA

(a) USING OXYGEN

SAMPLE ID	AGING COND'N PERIOD (day)	AGING COND'N TEMP. (°C)	ACTUAL VOIDS (%)	MODULUS (ksi) BEFORE AGING	MODULUS (ksi) AFTER AGING	MODULUS RATIO	PERM (E-9c/s) BEFORE AGING	PERM (E-9c/s) AFTER AGING	TENSILE STRESS (psi)	TENSILE STRAIN μ-strain
KLLL00TO	0	25	4.9	387	387	1.00	0.47	0.45	188	6398
KLLL10TO	1	25	5.0	416	500	1.20	0.03	0.09	204	5725
KLLL20TO	3	25	5.3	489	550	1.12	0.38	0.67	205	4912
KLML01TO	0	60	7.3	407	407	1.00	2.08	2.60	*	*
KLML11TO	1	60	7.0	412	396	0.96	3.75	3.38	181	6358
KLML21TO	3	60	7.9	336	430	1.28	5.87	4.86	194	6122
KLML31TO	7	60	7.4	317	478	1.51	3.04	3.60	198	5382
GLLL01TO	0	60	6.3	421	421	1.00	0.54	0.48	237	5906
GLLL11TO	1	60	5.5	457	549	1.20	LOW	0.57	254	6279
GLLL21TO	3	60	6.1	460	593	1.29	1.07	3.67	*	*
GLML00TO	0	25	7.1	422	422	1.00	0.84	1.26	200	7292
GLML10TO	1	25	8.3	308	390	1.27	5.01	3.69	160	7933
GLML20TO	3	25	8.1	404	487	1.21	1.23	2.52	223	5760
GLML31TO	7	60	7.8	448	747	1.67	3.65	3.80	298	4270
KBLL01TO	0	60	5.3	334	334	1.00	LOW	LOW	*	*
KBLL11TO	1	60	5.2	350	465	1.33	LOW	0.36	214	6222
KBLL21TO	3	60	4.8	338	500	1.48	LOW	0.10	230	5549
KBML00TO	0	25	7.8	289	289	1.00	0.78	1.43	*	*
KBML10TO	1	25	6.6	280	267	0.95	LOW	1.01	169	6735
KBML20TO	3	25	7.4	295	320	1.08	0.07	1.48	173	5772
KBML31TO	7	60	6.7	284	496	1.76	0.71	0.09	182	7093
GBLL00TO	0	25	4.8	508	508	1.00	0.03	0.04	286	6589
GBLL10TO	1	25	4.8	499	581	1.16	LOW	0.14	301	6762
GBLL20TO	3	25	5.1	480	637	1.33	0.07	0.13	277	7681
GBML01TO	0	60	7.1	396	513	1.30	0.33	0.53	248	9415
GBML11TO	1	60	7.3	437	529	1.21	0.80	1.82	258	6920
GBML21TO	3	60	7.0	503	763	1.52	0.49	1.16	248	7175
GBML31TO	7	60	7.4	449	744	1.66	0.71	2.49	327	4818

(b) USING AIR

SAMPLE ID	AGING COND'N PERIOD (days)	AGING COND'N TEMP. (°C)	ACTUAL VOIDS (%)	MODULUS (ksi) BEFORE AGING	MODULUS (ksi) AFTER AGING	MODULUS RATIO	PERM (E-9cm/s) BEFORE AGING	PERM (E-9cm/s) AFTER AGING	TENSILE STRESS (psi)	TENSILE STRAIN μ-strain
KLLL00TA	0	25	4.6	390	390	1.00	0.63	0.43	178.8	6474.0
KLLL10TA	1	25	5.0	333	393	1.18	0.14	0.15	183.4	6890.5
KLLL20TA	3	25	5.4	355	403	1.14	LOW	0.14	168.7	7239.3
KLML01TA	0	60	7.0	365	365	1.00	0.51	0.71	173.5	6384.2
KLML11TA	1	60	6.2	334	388	1.16	0.27	2.07	152.8	6190.1
KLML21TA	3	60	7.2	299	411	1.37	1.68	3.30	161.2	4525.6
GLLL01TA	0	60	5.3	596	596	1.00	0.16	0.17	*	*
GLLL11TA	1	60	5.7	594	571	0.96	0.43	1.56	293.7	5485.1
GLLL21TA	3	60	6.2	520	566	1.09	4.17	4.29	324.1	4361.8
GLML00TA	0	25	8.2	471	473	1.00	1.60	4.13	219.3	7042.4
GLML10TA	1	25	7.3	465	461	0.99	1.90	2.95	252.6	4513.1
GLML20TA	3	25	7.5	451	397	0.88	0.95	3.87	252.1	5646.3
KBLL01TA	0	60	5.0	353	353	1.00	LOW	LOW	186.5	4231.2
KBLL11TA	1	60	4.7	339	376	1.11	LOW	LOW	214.4	6241.5
KBLL21TA	3	60	3.8	364	382	1.05	LOW	LOW	227.9	6095.2
KBML00TA	0	25	7.1	347	347	1.00	LOW	0.36	*	*
KBML10TA	1	25	7.4	332	317	0.95	0.76	1.15	171.7	7853.2
KBML20TA	3	25	8.1	305	314	1.03	3.10	3.32	158.2	7013.0
GBLL00TA	0	25	4.8	479	500	1.04	0.23	0.50	297.4	6168.9
GBLL10TA	1	25	4.8	538	516	0.96	0.26	0.52	291.7	5768.8
GBLL20TA	3	25	5.1	631	519	0.82	LOW	LOW	331.7	5711.5
GBML01TA	0	60	7.1	449	449	1.00	0.71	2.49	*	*
GBML11TA	1	60	7.3	525	463	0.88	2.11	2.79	253.8	5036.8
GBML21TA	3	60	7.0	570	569	1.00	3.73	2.83	324.4	3716.7

NOTES AND KEY FOR SAMPLE IDENTIFICATION:

* Due to an operator error this data was lost.

K	ASPHALT	K=AAK-1	G=AAG-1
L	AGGREGATE	L=RL	B=RB
L	VOIDS	L=LOW	M=MEDIUM
L	LONG TERM	L=LONG TERM AGING	
0	AGING PERIOD	0=O DAY	1=1 DAY 2=3 DAYS
0	AGING TEMP.	0=LOW(25°C)	1=HIGH(60°C)
TO or TA	AGING TYPE	TO=OXYGEN	TA=AIR

evaluation has not been done completely and, in the interest of space, will not be attempted here.

The resilient modulus data for the short-term oven aging are shown in Figures 2–5; resilient modulus data for extended mixing test programs are shown in Figures 6–9. In all the figures presented, the key uses a three-character code (similar to those used in Tables 4–8) to indicate the asphalt-aggregate combination used, for example, KBO represents asphalt AAK-1 with aggregate RB prepared at low air voids level (0), and KB1 represents a higher air void level (1).

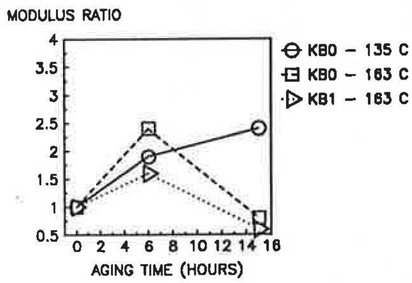

FIGURE 2 Short-term oven aging results, AAK-1 and RB.

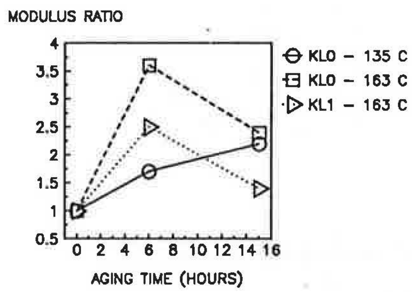

FIGURE 3 Short-term oven aging results, AAK-1 and RL.

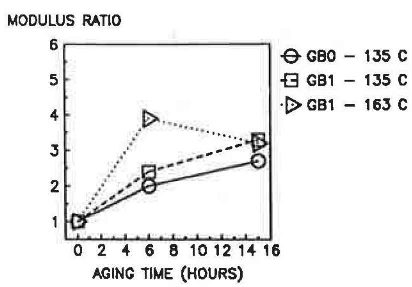

FIGURE 4 Short-term oven aging results, AAG-1 and RB.

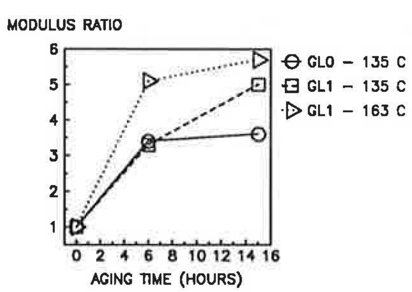

FIGURE 5 Short-term oven aging results, AAG-1 and RL.

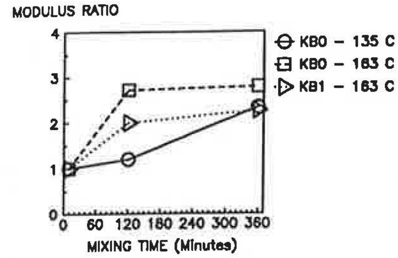

FIGURE 6 Extended mixing results, AAK-1 and RB.

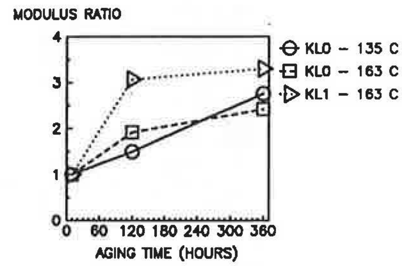

FIGURE 7 Extended mixing results, AAK-1 and RL.

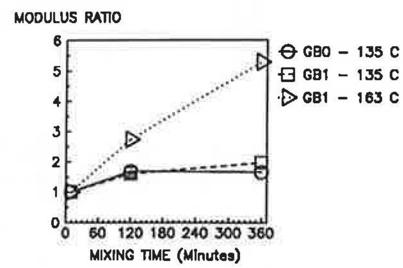

FIGURE 8 Extended mixing results, AAG-1 and RB.

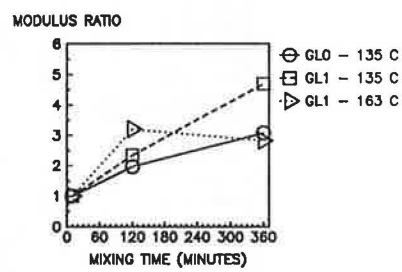

FIGURE 9 Extended mixing results, AAG-1 and RL.

Figures 10 and 11 show resilient modulus data for the long-term oven aging tests. Note that the modulus ratios shown for 0 days aging are greater than 1 because these samples have undergone conditioning at 40°C or 60°C, which increases their modulus slightly. Figures 12–15 show resilient modulus data for the pressure oxidation tests with oxygen, and Figures 16–19 show similar data for the tests with compressed air.

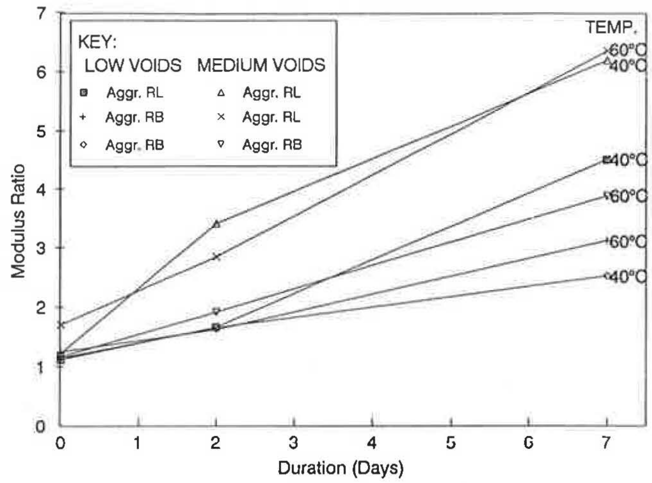

FIGURE 10 Long-term oven aging results for AAK-1.

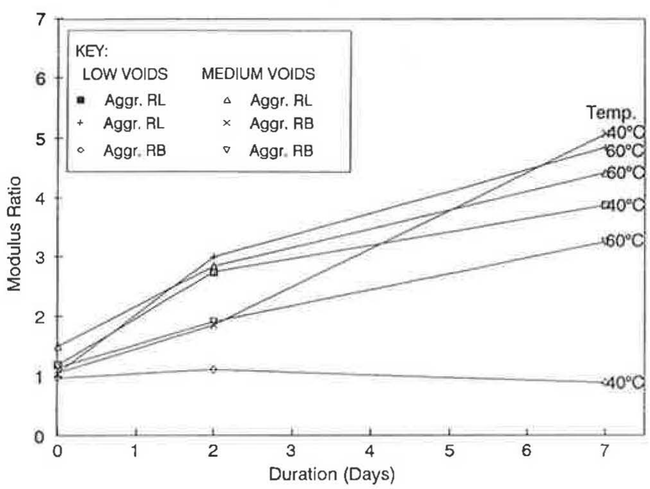

FIGURE 11 Long-term oven aging results for AAG-1.

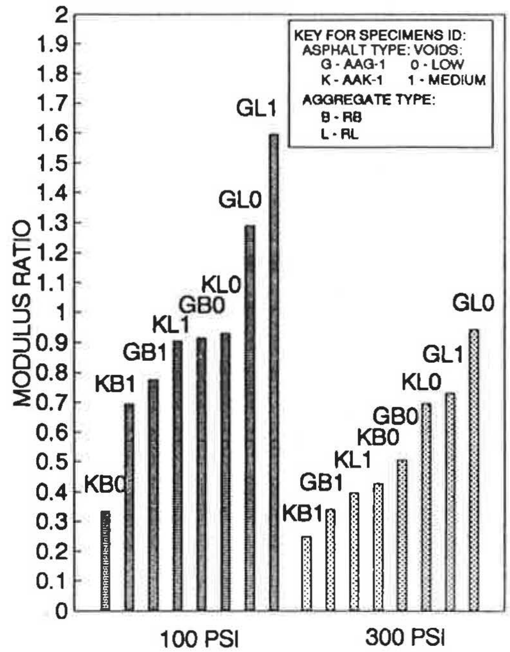

FIGURE 12 Effect of pressure, pressure oxidation with oxygen.

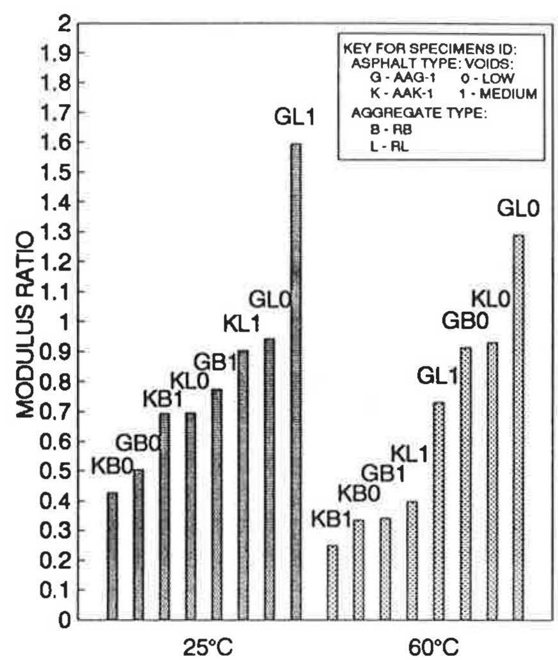

FIGURE 13 Effect of temperature, pressure oxidation with oxygen.

Tensile test data are available for all the short- and long-term tests done to date and tend to follow the resilient modulus data in terms of ranking aging procedures. Figures 20 and 21 show sample tensile test data for the pressure oxidation with oxygen tests. These figures show the effect of pressure on tensile strength and strain at yield, respectively.

The test program for the triaxial cell approach was completed recently. Figure 22 shows modulus ratios using oxygen at low pressure. Only the data for the medium air void samples conditioned with oxygen at 60°C are shown. All other samples showed a very low and sporadic increase in modulus.

DISCUSSION OF RESULTS

Short-Term Oven Aging

The data from these tests (Figures 2–5) show that significant aging occurs as indicated by an increase in modulus with aging time. In cases in which a temperature of 163°C was used, the modulus ratio for samples aged for 15 hr is lower than for those aged 6 hr. This was attributed to severe aging of the asphalt film in the coated mixture and inability to compact these samples adequately after aging. Table 4 shows that the air voids of these samples were much higher than unaged samples and much higher than with samples aged at 135°C. Compaction of all samples was done at 120°C, as with unaged samples. It may be more appropriate to use an equiviscous compaction temperature in future studies with this approach. Also, subsequent short-term oven aging will be done for shorter periods of time at a temperature of 135°C with a maximum

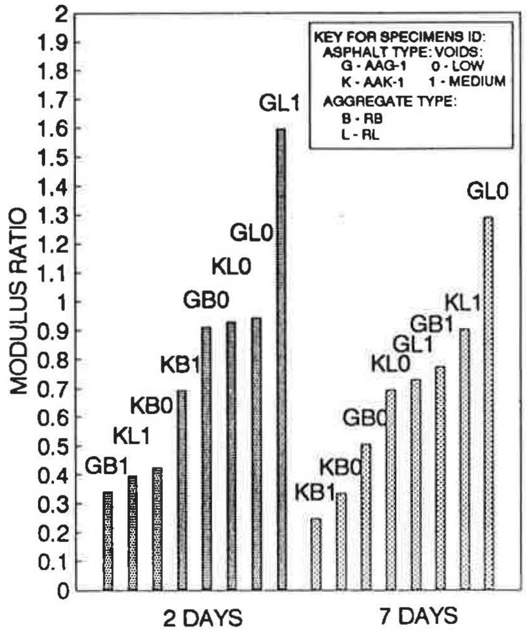

FIGURE 14 Effect of aging period, pressure oxidation with oxygen.

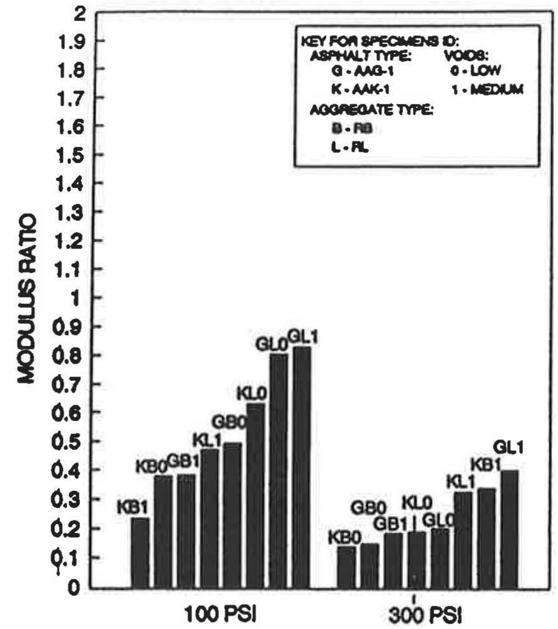

FIGURE 16 Effect of pressure, pressure oxidation with compressed air.

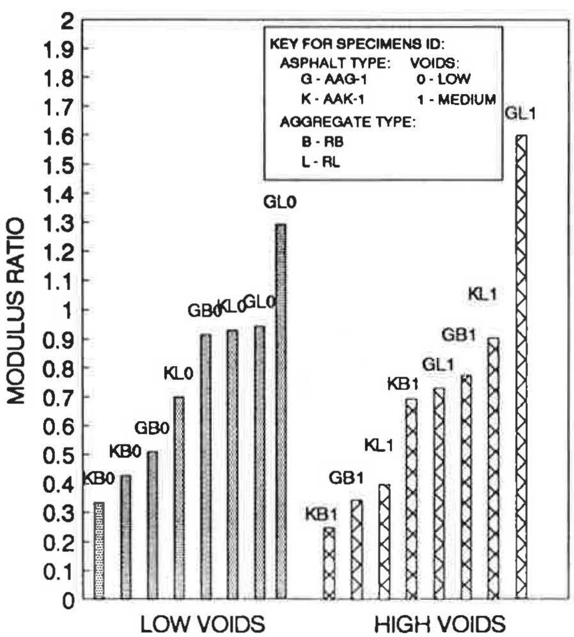

FIGURE 15 Effect of voids, pressure oxidation with oxygen.

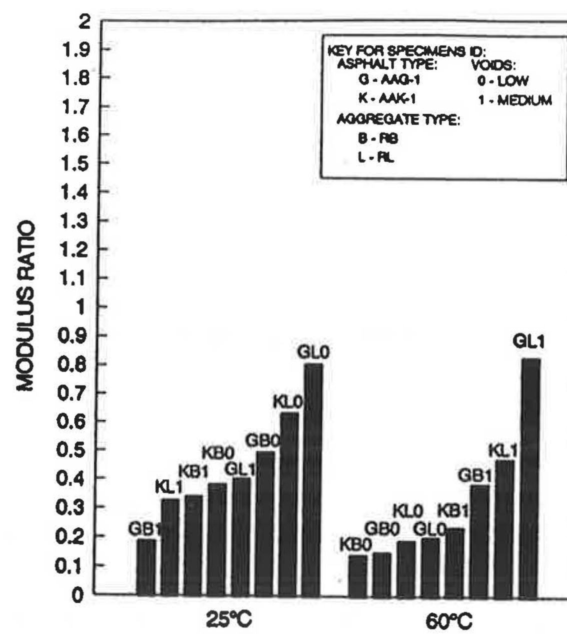

FIGURE 17 Effect of temperature, pressure oxidation with compressed air.

time of around 10 hr. An advantage of this approach is that several trays of material can be aged at the same time.

Extended Mixing

The data from these tests (Figures 6–9) show that aging increases with aging time, as indicated by increasing modulus ratio. Similar levels of modulus ratio increase were achieved in these tests and the oven aging tests. Although these tests were successful in achieving significant aging, to be viable for production testing, several ovens or significant modification to the RTFO would be needed.

Long-Term Oven Aging

The oven aging method generally produced an increase in the physical characteristics of the asphalt mixtures. Figures 10 and 11 show that modulus ratio increased as the duration of the

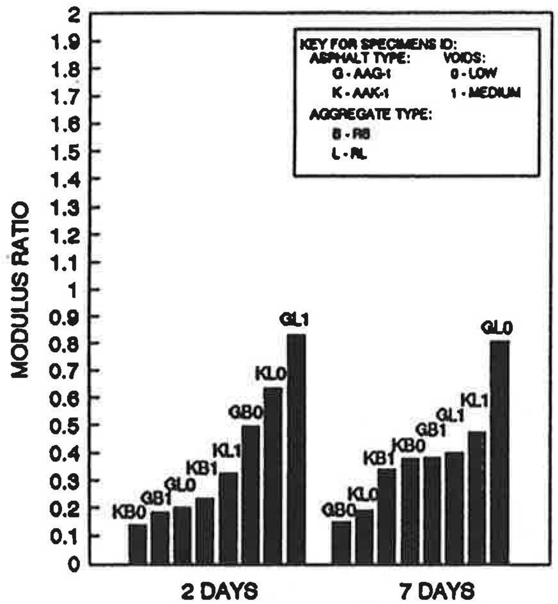

FIGURE 18 Effect of aging period, pressure oxidation with compressed air.

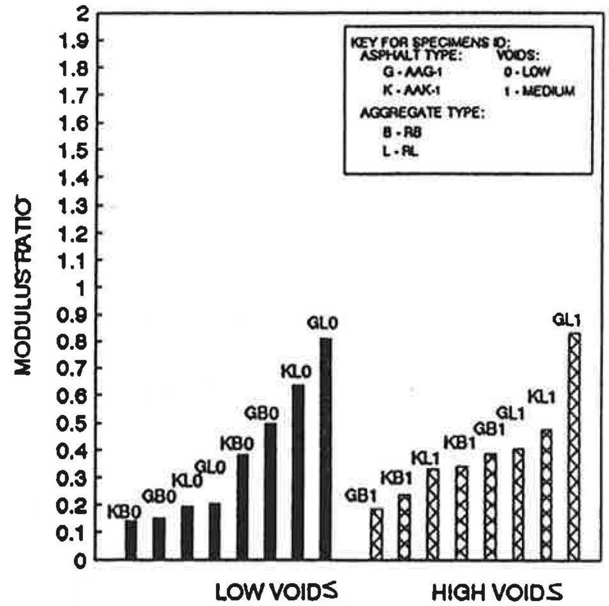

FIGURE 19 Effect of voids, pressure oxidation with compressed air.

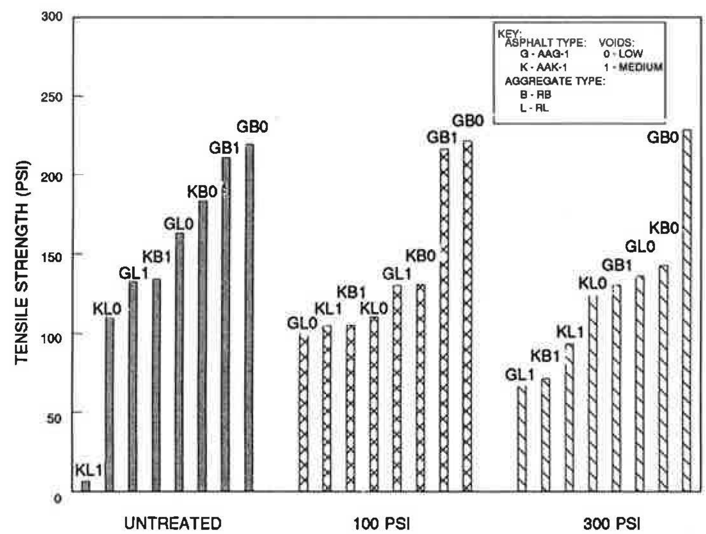

FIGURE 20 Effect of oxygen pressure on tensile strength.

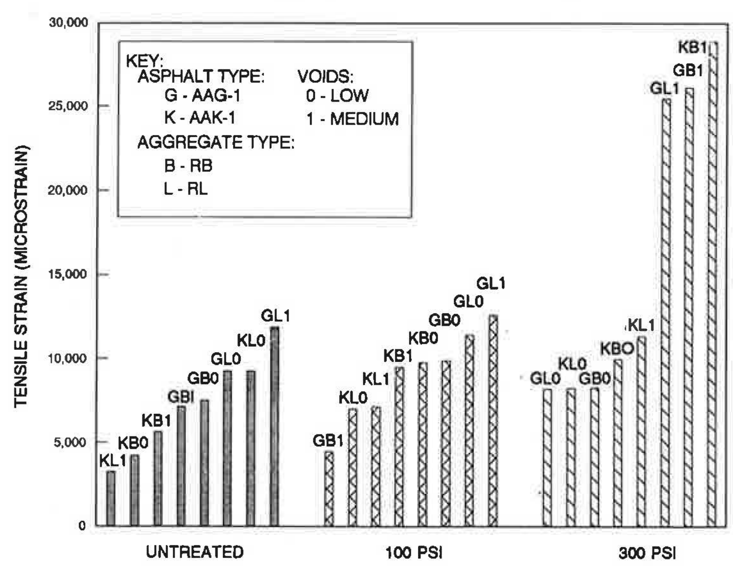

FIGURE 21 Effect of oxygen pressure on tensile strain.

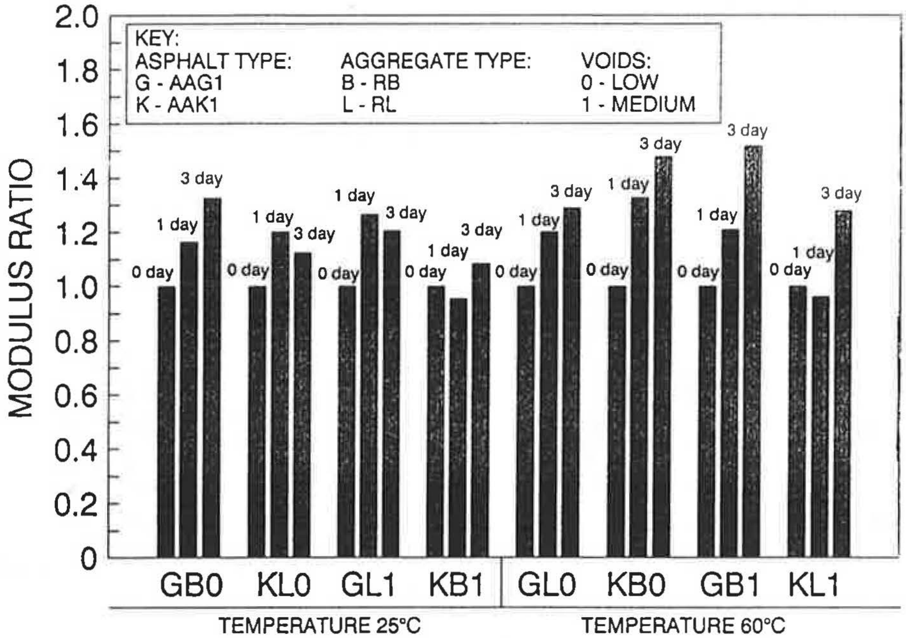

FIGURE 22 Modulus ratios for low-pressure oxidation with oxygen.

aging increased. It is apparent that the samples with the higher air voids attained a higher modulus ratio. The two asphalts produced mixes with different aging susceptibility with the AAK-1 mixes exhibiting somewhat greater increase in modulus. Also, aggregate RL tended to produce a higher level of aging than aggregate RB. The exposure temperature also affected the samples. In addition, the permeability tended to increase, although this behavior did not occur for all the samples. The tensile strengths increased as the aging duration increased (Table 6), and the strain at break decreased.

This approach is similar to that recommended by Von Quintus et al. (*3*). It is simple to apply and produces a rapid change in the mixtures within a few days. However, the use of temperatures above 100°C is not representative of the conditions occurring in the field and produces moduli greater than 1,500,000 psi in some mixtures. This is about 50 percent higher than moduli of cores recovered from the field (*4*) or of samples aged in the field (*5*). There is some evidence to suggest that the mechanism of oxidation at high temperatures is different than that at low temperature (*6*), and therefore, a long-term aging method using a lower temperature would be preferable.

Pressure Oxidation Vessel Using Oxygen

The pressure oxidation vessel using oxygen produced unexpected results. In particular, the modulus ratios decreased with aging treatment, with the effect of pressure being most dramatic. The investigators observed a noticeable change in diameter and thickness for samples exposed to this environment for 7 days at 300 psi at 60°C. Because of this difference, a change in procedure may be necessary to ensure the stability of the samples. Preconditioning similar to that done with oven aging may be an appropriate additional step. The results shown in Figures 12–15 show that pressure was the most significant variable. As the pressure increased from 100 to 300 psi (Figure 12), the modulus ratio tends to decrease. As the temperature (Figure 13) and aging period (Figure 14) or void content (Figure 15) increased, the modulus ratio also tends to decrease. At the extreme conditions of 7 days, 300 psi, and 60°C, the specimens deteriorated most rapidly. Figures 20 and 21 show that the tensile strength deteriorated with level of pressure and the strain at break increased. Again, these trends are contrary to what is expected as samples age. Other data from the tensile tests were similar to those shown in Figures 20 and 21.

More investigation is necessary to understand the effect of oxygen on the asphalt-aggregate mixtures. However, it seems likely that subjecting the samples to a gas at higher pressure disrupts the integrity of the sample, thus reducing the modulus. The disruption probably occurs when pressure is released at the end of the test. An approach using low pressure and/or that confines the sample would be preferable.

Pressure Oxidation Vessel Using Compressed Air

The pressure oxidation vessel using compressed air produced similar results to the those for pressure oxidation with oxygen. The results for modulus changes are shown in Figures 16–19. Samples subjected to the most extreme conditions of 60°C at 300 psi for 7 days experienced greater deterioration in terms of their physical properties.

Triaxial Aging

The data shown in Figure 22 indicate that moderate increases in aging manifested by increasing resilient modulus ratio are achieved. It was anticipated that considerably more aging would occur after 7 days with this approach. However, it appears that this method is most viable, perhaps at slightly higher temperatures, for realistic long-term oxidative aging. It is also a much safer approach than the pressure oxidation approach, because the pressure required is much lower.

COMPARISON WITH PREVIOUS RESEARCH

Few data are available from previous studies. However, the data obtained from the long-term oven aging tests exhibit similar trends to those reported by Von Quintus et al. (*3*) as shown in Table 9. The results obtained in the pressure oxidation tests by Von Quintus et al. were variable, and some showed a decrease in modulus with aging treatment similar to that observed in this study. Previous work by Kim et al. (*7*) using 60°C and 100 psi oxygen pressure is shown in Figures 23 and 24 and also produced variable results. The general trend was for modulus to increase, although it did decrease in one case for low air-void samples. It appears that higher air-void samples are able to dissipate the pressure.

CONCLUSIONS

On the basis of the work done to date in this study, the following conclusions can be made:

1. Both short-term oven aging and extended mixing procedures for loose mixtures can cause a fourfold increase in resilient modulus in some mixtures.
2. Extended mixing appears to produce more uniform aging in the mix than oven aging of loose mixtures. However, oven aging is more viable where productivity is of concern, because several samples can be treated in one oven.
3. Subsequent development of the short-term oven aging approach will include adjustment to the maximum exposure

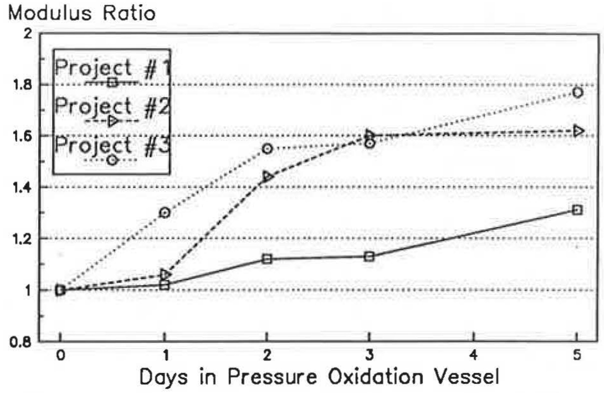

FIGURE 23 Aging modulus ratios for three asphalt mixtures at 88 percent compaction level (*7*).

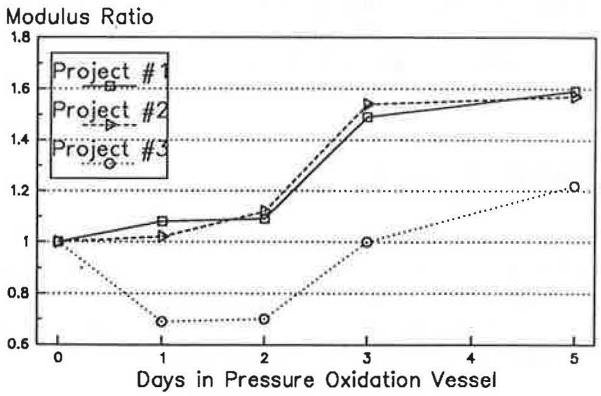

FIGURE 24 Aging modulus ratios for three asphalt mixtures at 94 percent compaction level (*7*).

TABLE 9 SUMMARY DATA FOR SPECIMENS CONDITIONED USING DIFFERENT ACCELERATED HARDENING TECHNIQUES (*3*)

State / Project	Accelerated Aging Method	No. of Days	Penetration (77°F)	Viscosity (140°F)	Indirect Tensile Strength psi	Strain @ Failure mils/in.	Resilient Modulus ksi
Michigan MI-0021	Unaged	0	60	2144	84	14.56	482
	Oxygen Bomb	5	63	3844	111	14.04	480
		10	43	7542	123	12.13	582
	Forced Draft Oven	2	76	2512	120	9.88	—
		7	49	5897	139	6.59	—
Texas TX-0021	Unaged	0	30	4388	129	9.01	601
	Oxygen Bomb	5	55	3488	151	8.84	738
		10	64	2822	167	5.98	683
	Forced Draft Oven	2	37	5654	200	5.11	—
		7	30	9904	241	2.69	—
Virginia VA-0621	Unaged	0	37	6000	114	7.97	758
	Oxygen Bomb	5	32	28021	128	10.23	569
		10	35	25021	121	10.66	431
	Forced Draft Oven	2	47	4401	146	5.37	—
		7	27	7910	177	2.69	—

time used and possibly adoption of an equiviscous temperature for compaction.

4. Long-term oven aging of compacted mixture samples can cause a sixfold increase in resilient modulus in some mixtures. This increase is regarded as too high, and this approach will only be adopted as a fallback position at a lower temperature than the 107°C used in this study. A temperature of 85°C is probably more appropriate.

5. The results from the pressure oxidation test program for either oxygen or compressed air show a general trend of decreasing modulus with the severity of treatment. This is a trend contrary to that anticipated and is attributed to disruption of the sample when the gas pressure is relieved. Modifications to the test procedure may improve this situation, but a low-pressure technique would be preferable.

6. The triaxial cell aging approach is an alternate method of oxygen enrichment to the pressure oxidation technique. To date, increases of 50 to 100 percent in resilient modulus have been observed with this approach. This is the most likely technique to carry forward for further development. A temperature higher than 60°C will be investigated in the future test program. A temperature of 85°C seems appropriate at this time.

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