Role of Asphalt and Aggregate in the Aging of Bituminous Mixtures

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The development of short- and long-term aging procedures has been ongoing at Oregon State University under Strategic Highway Research Program (SHRP) Project A-003A. In the first phase of this project several alternative methods for short- and long-term aging of asphalt-aggregate mixtures were examined. From these, one short-term method and two long-term procedures were chosen to be examined further in the second phase of the project. For short-term aging a procedure of curing the loose mix in a forced-draft oven at 135°C for 4 hr was chosen. Two procedures were used to evaluate the effects of long-term aging: low-pressure oxidation at 60° and 85°C for 5 days and long-term oven aging at 85°C for 5 days and 100°C for 2 days. The evaluation was done in an extensive testing program using eight asphalts and four aggregates. The results of the asphalt-aggregate mixture testing presented in this paper show that the aging of the mixture is dependent on both the asphalt and the aggregate. Also, it appears from the evaluation of data from other SHRP contractors that the aging and subsequent testing of asphalt alone are not good predictors of the effects of the asphalt-aggregate interaction on mixture behavior.

The development of laboratory aging procedures to simulate short- and long-term aging for asphalt-aggregate mixtures has been undertaken as part of Strategic Highway Research Program (SHRP) Project A-003A at Oregon State University. This work was described in an earlier paper by Bell et al. (*1*). The purpose of this paper is to report on an expanded testing program that has been conducted using these laboratory aging procedures.

The procedure developed for short-term aging involves heating the loose mix in a forced-draft oven for 4 hr at a temperature of 135°C. This simulates the aging of the mixture during the construction process while it is in an uncompacted condition.

Two alternative procedures have been developed for long-term aging of the compacted mixture. These are designed to simulate the aging of in-service pavements after several years. The following long-term approaches have been found to be appropriate:

1. Long-term oven aging (LTOA) of compacted specimens in a forced-draft oven and
2. Low-pressure oxidation (LPO) of compacted specimens in a triaxial cell by passing oxygen through the specimen.

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With these two methods of aging, alternative combinations of temperature and time have been evaluated and are reported here.

The effects of aging were evaluated by the resilient modulus at 25°C using both the diametral (indirect tension) and triaxial compression modes of testing. Tensile strength tests were also performed on the specimens once all other data had been collected. At the time of this writing (July 1992) the tensile strength tests had not been completed and will not be discussed here.

EXPERIMENTAL DESIGN

Variables

The experimental design included eight different asphalt types and four different aggregates. All specimens to be long-term aged were first short-term aged at 135°C for 4 hr before compaction. Four different long-term aging procedures were examined: LPO at 60° and 85°C and LTOA at 85°C, all for 5 days, and LTOA at 100°C for 2 days.

Materials

The materials used for this testing program were selected from those stored at the SHRP Materials Reference Library (MRL) in Austin, Texas. The aggregates used represent a broad range of aggregate characteristics, from those of a high-absorption crushed limestone to a those of a river run gravel. The asphalts used also cover a broad range of asphalt grades. Table 1 briefly describes the material properties.

AGING METHODS

No Aging

Three specimens were prepared at the time of mixing to represent the "unaged" condition. These specimens were prepared in the same manner as the others except that they were not cured for 4 hr at 135°C. As soon as mixing was complete, the specimens were placed in an oven and brought to the proper equiviscous temperature for that mix (665 ± 80 cSt). Once the proper temperature had been achieved, the specimens were compacted using a California kneading compactor.

TABLE 1 Materials Used

Aggregate		Asphalt	
Code	**Description**	**Code**	**Grade**
RC	Limestone (high absorption)	AAA-1	150/200
RD	Limestone (low absorption)	AAB-1	AC-10
RH	Greywacke	AAC-1	AC-8
RJ	Conglomerate	AAD-1	AR-4000
		AAF-1	AC-20
		AAG-1	AR-4000
		AAK-1	AC-30
		AAM-1	AC-20

Short-Term Aging

The short-term aging method used in this test program was developed at Oregon State University under the SHRP A-003A test development program (*1*). The method employed consisted of curing mixture samples in a forced-draft oven at 135°C for a period of 4 hr. During the curing period the mixture was placed in a pan at a spread rate of approximately 21 kg/m^2. The mix was also stirred and turned once an hour to ensure that the aging was uniform throughout the sample. After the curing period the samples were brought to an equiviscous temperature of 665 ± 80 cSt and compacted using a California kneading compactor.

LPO

LPO is an aging procedure to simulate the long-term aging that a pavement experiences in service. The procedure was carried out on compacted specimens after they had been short term aged. Before testing, the specimen was prepared by placing a 1-in.-wide band of silicone rubber and a rubber membrane around the specimen to ensure that the oxygen was flowing through the specimen rather than around the sides. After the silicone had been allowed to dry, the specimen was placed in the triaxial pressure cell and fitted with a rubber membrane to seal the specimen from the atmospheric gases. Next the specimen was loaded into the cell and a confining pressure was applied to keep the membrane tightly on the specimen. Once the confining pressure had been reached, typically 10 to 30 psi, oxygen flow was started though the specimen at a flow rate of 4 standard ft^3/hr (SCFH). When the oxygen rate had been adjusted, the cell was placed in a water bath that had been preheated to the conditioning temperature (60° or 85°C). The cell was left in the conditioning bath for a period of 5 days, at which time it was extracted from the bath and left to cool to room temperature. The specimens were then removed from the cell and allowed to stand for at least 24 hr before being tested for resilient modulus.

LTOA

LTOA is also a procedure to simulate long-term aging. The procedure was carried out on compacted specimens after they had been short term aged. The specimens were placed in a forced-draft oven preheated to 85°C and left for 5 days. Alternatively, a temperature of 100°C and a period of 2 days were used. After the aging period, the oven was turned off and left to cool to room temperature. The specimens were then removed from the oven and prepared to be tested at least 24 hr after removal from the oven.

EVALUATION METHODS

Resilient Modulus

The resilient modulus was determined at 25°C using the diametral (indirect tension) (ASTM D 4123) and triaxial compression modes of testing with a 0.1-sec loading time at a frequency of 1 Hz. A constant strain level of 100 strain was maintained throughout the test.

Dynamic Modulus

A selection of specimens was subjected to a thorough dynamic modulus evaluation at temperatures of 0°, 25°, and 40°C. Eleven frequencies ranging from 15 to 0.01 Hz were used in this test program. The testing system, developed at Oregon State University, used a haversine wave load pulse generated on a semi-closed-loop servohydraulic testing system. From load and deformation data collected by the testing system, loss and storage modulus along with the phase angle and loss tangent can be computed. Testing of this type takes approximately 8 hr per specimen because of the large temperature change. Therefore, it is not possible to test all the specimens with this procedure. The dynamic modulus data are presented in a companion paper in this Record by AbWahab et al.

Tensile Strength Test

The tensile strength test was performed when all modulus testing had been completed. A deformation rate of 50 mm (2 in.) per minute was used, with the load and deformation of the specimen monitored continuously until failure occurred. The strains at yield and failure were considered significant as well as the strength. The broken portions of the specimen may be used to obtain recovered asphalt for further testing. At the time of this writing (July 1992), this testing was not complete and will not be discussed here.

RESULTS

Resilient Modulus Data

The results of the resilient modulus data for both diametral and triaxial modes of testing are summarized by aggregate type in Tables 2 through 5. These data include moduli for unaged, short-term-aged and long-term-aged specimens.

Short-Term Aging

The modulus ratios, short-term-aged modulus divided by adjusted-unaged modulus, from the diametral testing are shown

TABLE 2 Modulus Values for Aggregate RC

			Modulus Values			
	Aging	% Air	Diametral		Triaxial	
Asphalt	Method	Voids	Before	After	Before	After
AAA	LPO 85	8.2	211	572	295	805
AAA	LPO 85	8.4	193	504	350	802
AAA	LPO 60	8.0	233	367	434	600
AAA	LPO 60	8.1	270	414	373	442
AAA	LTOA 85	9.5	225	405	357	780
AAA	LTOA 85	8.7	221	412	295	583
AAA	LTOA 100	9.0	219	475	270	570
AAA	LTOA 100	8.6	216	499	295	455
AAA	NONE	8.0	152	--	230	--
AAA	NONE	8.8	153	--	225	--
AAA	NONE	7.9	164	--	236	--
AAB	LPO 85	8.4	299	638	517	1041
AAB	LPO 85	9.2	317	438	419	635
AAB	LPO 60	8.3	364	525	420	621
AAB	LPO 60	8.3	300	644	379	1041
AAB	LTOA 85	8.9	305	606	395	875
AAB	LTOA 85	9.3	339	614	500	956
AAB	LTOA 100	8.3	378	694	426	698
AAB	LTOA 100	9.7	286	618	533	958
AAB	NONE	8.8	216	--	385	--
AAB	NONE	7.8	207	--	421	--
AAB	NONE	8.2	249	--	467	--
AAC	LPO 85	8.4	329	715	574	1052
AAC	LPO 85	9.4	398	750	440	844
AAC	LPO 60	9.3	348	520	579	879
AAC	LPO 60	10.2	339	460	384	667
AAC	LTOA 85	9.1	345	561	690	889
AAC	LTOA 85	9.3	377	600	407	787
AAC	LTOA 100	9.4	335	557	409	697
AAC	LTOA 100	8.9	343	623	435	643
AAC	NONE	9.1	236	--	325	--
AAC	NONE	9.3	235	--	277	--
AAC	NONE	8.2	249	--	315	--
AAD	LPO 85	9.3	286	645	274	970
AAD	LPO 85	8.8	293	694	380	950
AAD	LPO 60	9.6	321	450	399	850
AAD	LPO 60	9.0	257	394	432	711
AAD	LTOA 85	8.9	324	615	391	1101
AAD	LTOA 85	9.4	309	616	491	882
AAD	LTOA 100	9.3	225	611	379	775
AAD	LTOA 100	9.0	269	695	344	539
AAD	NONE	8.2	202	--	279	--
AAD	NONE	8.1	208	--	277	--
AAD	NONE	8.5	182	--	275	--
AAF	LPO 85	9.3	650	891	861	1384
AAF	LPO 85	8.8	687	996	864	1275
AAF	LPO 60	7.8	636	898	1113	1345
AAF	LPO 60	9.4	621	896	1323	1305
AAF	LTOA 85	9.0	612	943	980	1205
AAF	LTOA 85	9.0	701	842	1103	1573
AAF	LTOA 100	9.1	558	1004	823	1124
AAF	LTOA 100	9.7	590	1016	999	1357
AAF	NONE	9.0	507	--	779	--
AAF	NONE	9.9	428	--	550	--
AAF	NONE	9.1	458	--	851	--

TABLE 2 (*continued*)

			Modulus Values			
	Aging	% Air	Diametral		Triaxial	
Asphalt	Method	Voids	Before	After	Before	After
AAG	LPO 85	10.9	652	983	853	1262
AAG	LPO 85	10.6	606	1038	684	1141
AAG	LPO 60	10.2	682	840	701	1000
AAG	LPO 60	10.7	744	881	851	1134
AAG	LTOA 85	10.9	714	1004	928	1191
AAG	LTOA 85	11.2	656	819	1024	1520
AAG	LTOA 100	10.2	614	1030	918	1245
AAG	LTOA 100	10.9		939	921	1113
AAG	NONE	11.0	450	--	658	--
AAG	NONE	9.9	523	--	734	--
AAG	NONE	9.6	476	--	804	--
AAK	LPO 85	7.9	555	974	671	1430
AAK	LPO 85	8.5	572	1000	655	1740
AAK	LPO 60	9.2	497	644	644	992
AAK	LPO 60	9.3	427	577	574	866
AAK	LTOA 85	7.9	563	827	834	1367
AAK	LTOA 85	9.2	451	713	614	993
AAK	LTOA 100	9.6	544	1019	607	1068
AAK	LTOA 100	8.6	502	1049	662	1260
AAK	NONE	9.2	345	--	413	--
AAK	NONE	8.0	450	--	579	--
AAK	NONE	8.1	429	--	578	--
AAM	LPO 85	8.9	470	763	436	1006
AAM	LPO 85	8.1	445	840	641	1110
AAM	LPO 60	8.0	421	580	577	796
AAM	LPO 60	8.6	405	602	558	850
AAM	LTOA 85	8.5	446	796	510	897
AAM	LTOA 85	9.0	456	747	488	910
AAM	LTOA 100	9.2	404	750	552	816
AAM	LTOA 100	8.5	450	787	537	818
AAM	NONE	8.3	332	--	453	--
AAM	NONE	9.0	303	--	358	--
AAM	NONE	7.9	346	--	442	--

NOTE: All Modulus data reported in KSI
KEY :
NONE = No Aging.
LPO 60 = Low Pressure Oxidation 60°C / 5 days.
LPO 85 = Low Pressure Oxidation 85°C / 5 days.
LTOA 85 = Long-Term Oven Aging, 85°C / 5 days.
LTOA 100 = Long-Term Oven Aging, 100°C / 2 days.

TABLE 3 Modulus Values for Aggregate RD

			Modulus Values			
	Aging	% Air	Diametral		Triaxial	
Asphalt	Method	Voids	Before	After	Before	After
AAA	LPO 85	8.2	211	572	295	805
AAA	LPO 85	8.4	193	504	350	802
AAA	LPO 60	8	233	367	434	600
AAA	LPO 60	8.1	270	414	373	442
AAA	LTOA 85	9.5	225	405	357	780
AAA	LTOA 85	8.7	221	412	295	583
AAA	LTOA 100	9	219	475	270	570
AAA	LTOA 100	8.6	216	499	295	455
AAA	NONE	8	152	--	230	--
AAA	NONE	8.8	153	--	225	--
AAA	NONE	7.9	164	--	236	--
AAB	LPO 85	8.6	356	627	320	541
AAB	LPO 85	7.2	400	632	475	539
AAB	LPO 60	8.9	414	456	450	535
AAB	LPO 60	8.4	380	506	489	696
AAB	LTOA 85	8.7	390	502	465	755
AAB	LTOA 85	8.5	528	582	578	780
AAB	LTOA 100	7.4	509	603	589	631
AAB	LTOA 100	7.5	444	642	411	588
AAB	NONE	8.4	233	--	353	--
AAB	NONE	7.6	306	--	399	--
AAB	NONE	7.6	302	--	314	--
AAC	LPO 85	8.3	419	657	614	950
AAC	LPO 85	8.2	467	671	498	884
AAC	LPO 60	6.9	486	630	762	886
AAC	LPO 60	8.1	526	628	761	741

(*continued on next page*)

TABLE 3 *(continued)*

Asphalt	Aging Method	% Air Voids	Modulus Values Diametral Before	Diametral After	Triaxial Before	Triaxial After
AAC	LTOA 85	7.1	435	532	519	726
AAC	LTOA 85	7.4	456	600	644	782
AAC	LTOA 100	7.8	451	522	403	679
AAC	LTOA 100	7.3	496	658	647	732
AAC	NONE	7.9	304	--	506	--
AAC	NONE	7.1	291	--	464	--
AAC	NONE	7.5	319	--	505	--
AAD	LPO 85	8.6	321	584	383	893
AAD	LPO 85	8.2	334	633	432	966
AAD	LPO 60	8.5	325	463	425	845
AAD	LPO 60	8.2	362	450	352	698
AAD	LTOA 85	7.8	356	578	472	689
AAD	LTOA 85	8.4	393	611	410	679
AAD	LTOA 100	9.3	341	515	398	670
AAD	LTOA 100	9	395	544	438	441
AAD	NONE	8.1	250	--	227	--
AAD	NONE	6.9	253	--	298	--
AAD	NONE	7	262	--	286	--
AAF	LPO 85	8.9	795	1193	763	1393
AAF	LPO 85	8.9	857	1244	1009	1818
AAF	LPO 60	9	703	1034	998	1588
AAF	LPO 60	8.6	704	862	806	1359
AAF	LTOA 85	9.2	807	1072	1066	1342
AAF	LTOA 85	8.3	786	1068	1036	1538
AAF	LTOA 100	8.9	754	1100	871	919
AAF	LTOA 100	8.9	706	1119	1127	1796
AAF	NONE	9.6	493	--	609	--
AAF	NONE	8.9	526	--	700	--
AAF	NONE	8.8	564	--	850	--
AAG	LPO 85	8.6	991	1147	1194	1588
AAG	LPO 85	8.8	1101	1162	1380	2298
AAG	LPO 60	7.7	1002	1312	1178	1570
AAG	LPO 60	8.7	854	1201	1162	1598
AAG	LTOA 85	8.5	917	1108	1264	1617
AAG	LTOA 85	8.4	893	1161	1186	1277
AAG	LTOA 100	8.4	791	1015	1116	1266
AAG	LTOA 100	8.5	745	1105	1215	1272
AAG	NONE	8	608	--	1040	--
AAG	NONE	8.4	551	--	733	--
AAG	NONE	8	552	--	975	--
AAK	LPO 85	7.8	544	977	507	1039
AAK	LPO 85	8.2	545	782	672	1065
AAK	LPO 60	8	538	721	556	745
AAK	LPO 60	8	567	804	638	1104
AAK	LTOA 85	7.6	527	761	690	1062
AAK	LTOA 85	8.8	336	650	302	1120
AAK	LTOA 100	7.7	507	900	646	842
AAK	LTOA 100	7.2	516	890	723	1066
AAK	NONE	9.3	343	--	391	--
AAK	NONE	8.3	482	--	436	--
AAK	NONE	7.7	493	--	536	--
AAM	LPO 85	8.8	437	629	536	793
AAM	LPO 85	8.2	509	703	556	668
AAM	LPO 60	8.3	406	571	605	882
AAM	LPO 60	8.3	446	616	476	807
AAM	LTOA 85	7.3	458	638	510	807
AAM	LTOA 85	8	459	710	593	809
AAM	LTOA 100	8.2	410	648	546	696
AAM	LTOA 100	8.6	458	639	518	840
AAM	NONE	5.5	438	--	485	--
AAM	NONE	8.6	407	--	391	--
AAM	NONE	7.9	518	--	469	--

NOTE: All Modulus data reported in KSI

KEY :

NONE = No Aging.

LPO 60 = Low Pressure Oxidation 60°C / 5 days.

LPO 85 = Low Pressure Oxidation 85°C / 5 days.

LTOA 85 = Long-Term Oven Aging, 85°C / 5 days.

LTOA 100 = Long-Term Oven Aging, 100°C / 2 days.

TABLE 4 Modulus Values for Aggregate RH

Asphalt	Aging Method	% Air Voids	Modulus Values Diametral Before	Diametral After	Triaxial Before	Triaxial After
AAA	LPO 85	8.2	211	572	295	805
AAA	LPO 85	8.4	193	504	350	802
AAA	LPO 60	8	233	367	434	600
AAA	LPO 60	8.1	270	414	373	442
AAA	LTOA 85	9.5	225	405	357	780
AAA	LTOA 85	8.7	221	412	295	583
AAA	LTOA 100	9	219	475	270	570
AAA	LTOA 100	8.6	216	499	295	455
AAA	NONE	8	152	--	230	--
AAA	NONE	8.8	153	--	225	--
AAA	NONE	7.9	164	--	236	--
AAB	LPO 85	8.8	311	479	281	541
AAB	LPO 85	10.6	244	385	275	539
AAB	LPO 60	8.5	276	490	306	605
AAB	LPO 60	8.9	256	330	356	539
AAB	LTOA 85	8.8	313	419	351	567
AAB	LTOA 85	8.4	289	445	363	655
AAB	LTOA 100	7.6	360	454	564	562
AAB	LTOA 100	8	348	451	425	434
AAB	NONE	8.8	160	--	165	--
AAB	NONE	7.8	191	--	260	--
AAB	NONE	7.5	216	--	305	--
AAC	LPO 85	8.3	290	505	271	589
AAC	LPO 85	8.5	313	487	288	520
AAC	LPO 60	8.4	264	374	242	373
AAC	LPO 60	7.8	307	375	310	449
AAC	LTOA 85	8.8	286	403	319	507
AAC	LTOA 85	8.4	272	387	364	439
AAC	LTOA 100	6.8	419	453	493	521
AAC	LTOA 100	6.8	413	455	618	548
AAC	NONE	7.5	176	--	200	--
AAC	NONE	7.7	163	--	220	--
AAC	NONE	8	161	--	210	--
AAD	LPO 85	6.3	252	553	272	573
AAD	LPO 85	8.4	317	616	401	826
AAD	LPO 60	8.9	229	316	295	522
AAD	LPO 60	7.3	261	309	237	408
AAD	LTOA 85	8	227	385	317	613
AAD	LTOA 85	7.8	278	435	184	283
AAD	LTOA 100	6.6	256	348	307	513
AAD	LTOA 100	6.9	240	390	261	567
AAD	NONE	6.2	197	--	167	--
AAD	NONE	6.9	162	--	240	--
AAD	NONE	5.6	174	--	255	--
AAF	LPO 85	6.9	677	982	656	1206
AAF	LPO 85	8	864	1089	1158	1705
AAF	LPO 60	7.4	889	1041	874	896
AAF	LPO 60	8	816	903	790	986
AAF	LTOA 85	6.6	776	918	720	1128
AAF	LTOA 85	7.2	762	862	742	1260
AAF	LTOA 100	7.5	775	855	787	1004
AAF	LTOA 100	7.5	700	935	689	932
AAF	NONE	7.2	617	--	855	--
AAF	NONE	7.2	603	--	665	--
AAF	NONE	6.5	673	--	864	--
AAG	LPO 85	9.4	643	912	615	1133
AAG	LPO 85	10.3	610	886	627	1020
AAG	LPO 60	10.2	624	964	925	1102
AAG	LPO 60	10.1	617	837	967	1034
AAG	LTOA 85	8.9	858	1260	982	1303
AAG	LTOA 85	8.4	727	1001	1012	1246
AAG	LTOA 100	--	--	--	--	--
AAG	LTOA 100	--	--	--	--	--
AAG	NONE	8.9	483	--	641	--
AAG	NONE	8.5	511	--	709	--
AAG	NONE	8.6	602	--	663	--
AAK	LPO 85	8.5	506	735	593	904
AAK	LPO 85	8.2	430	700	594	904
AAK	LPO 60	8.8	453	592	607	845
AAK	LPO 60	8.1	400	543	453	710
AAK	LTOA 85	7.6	502	571	517	847
AAK	LTOA 85	8.3	421	453	453	764
AAK	LTOA 100	8	371	646	753	1018
AAK	LTOA 100	7.1	443	626	531	667
AAK	NONE	7.5	250	--	353	--
AAK	NONE	6.9	274	--	303	--
AAK	NONE	6.8	277	--	377	--

(continued on next page)

TABLE 4 *(continued)*

			Modulus Values			
			Diametral		Triaxial	
Asphalt	Aging Method	% Air Voids	Before	After	Before	After
AAM	LPO 85	6.8	432	563	430	747
AAM	LPO 85	7.4	382	606	583	818
AAM	LPO 60	7.1	408	521	537	721
AAM	LPO 60	7.2	365	467	530	620
AAM	LTOA 85	6.6	411	479	500	705
AAM	LTOA 85	6.5	411	545	485	779
AAM	LTOA 100	7.1	416	560	467	541
AAM	LTOA 100	7	429	576	517	546
AAM	NONE	5.8	319	--	478	--
AAM	NONE	5.1	349	--	624	--
AAM	NONE	4.6	338	--	666	--

NOTE: All Modulus data reported in KSI
KEY :
NONE = No Aging.
LPO 60 = Low Pressure Oxidation 60°C / 5 days.
LPO 85 = Low Pressure Oxidation 85°C / 5 days.
LTOA 85 = Long-Term Oven Aging, 85°C / 5 days.
LTOA 100 = Long-Term Oven Aging, 100°C / 2 days.

TABLE 5 Modulus Values for Aggregate RJ

			Modulus Values			
			Diametral		Triaxial	
Asphalt	Aging Method	% Air Voids	Before	After	Before	After
AAA	LPO 85	8.2	211	572	295	805
AAA	LPO 85	8.4	193	504	350	802
AAA	LPO 60	8	233	367	434	600
AAA	LPO 60	8.1	270	414	373	442
AAA	LTOA 85	9.5	225	405	357	780
AAA	LTOA 85	8.7	221	412	295	583
AAA	LTOA 100	9	219	475	270	570
AAA	LTOA 100	8.6	216	499	295	455
AAA	NONE	8	152	--	230	--
AAA	NONE	8.8	153	--	225	--
AAA	NONE	7.9	164	--	236	--
AAB	LPO 85	8.7	277	398	357	556
AAB	LPO 85	9	318	521	357	578
AAB	LPO 60	8.8	325	426	284	480
AAB	LPO 60	9.4	292	376	286	588
AAB	LTOA 85	8.6	293	431	344	536
AAB	LTOA 85	9.1	292	455	494	521
AAB	LTOA 100	8.2	335	451	324	536
AAB	LTOA 100	8.2	328	460	373	650
AAB	NONE	7.9	196	--	247	--
AAB	NONE	8.2	209	--	253	--
AAB	NONE	7.5	231	--	235	--
AAC	LPO 85	8.6	267	490	341	843
AAC	LPO 85	7.6	405	594	464	604
AAC	LPO 60	7.8	392	493	478	534
AAC	LPO 60	6.7	440	558	582	651
AAC	LTOA 85	7.2	405	480	439	595
AAC	LTOA 85	8	326	457	589	689
AAC	LTOA 100	8.2	350	431	379	585
AAC	LTOA 100	8.4	345	453	500	636
AAC	NONE	6.4	326	--	376	--
AAC	NONE	6.8	238	--	355	--
AAC	NONE	7	245	--	365	--
AAD	LPO 85	7.7	259	502	445	795
AAD	LPO 85	7.9	265	507	343	780
AAD	LPO 60	7.6	262	375	434	581
AAD	LPO 60	8	299	452	296	548
AAD	LTOA 85	8.4	271	491	420	708
AAD	LTOA 85	7.5	285	476	283	439
AAD	LTOA 100	8.6	317	496	308	651
AAD	LTOA 100	9.2	326	571	481	790
AAD	NONE	7.1	149	--	205	--
AAD	NONE	7.6	136	--	192	--
AAD	NONE	7.6	154	--	214	--
AAF	LPO 85	8.7	635	1001	802	1186
AAF	LPO 85	8.7	752	1062	798	1025
AAF	LPO 60	7.6	673	849	756	951
AAF	LPO 60	8.9	706	871	926	1117

TABLE 5 *(continued)*

			Modulus Values			
			Diametral		Triaxial	
Asphalt	Aging Method	% Air Voids	Before	After	Before	After
AAF	LTOA 85	8.3	677	884	988	1123
AAF	LTOA 85	8.4	779	1006	809	988
AAF	LTOA 100	8.4	681	961	711	1251
AAF	LTOA 100	9	712	1061	736	937
AAF	NONE	9	558	--	668	--
AAF	NONE	8.4	575	--	723	--
AAF	NONE	7.8	567	--	802	--
AAG	LPO 85	7.9	620	895	745	1465
AAG	LPO 85	8.1	735	1006	771	1341
AAG	LPO 60	8.1	812	914	853	1268
AAG	LPO 60	8.2	675	810	760	1030
AAG	LTOA 85	7.9	673	785	822	1324
AAG	LTOA 85	7.4	722	857	885	1349
AAG	LTOA 100	8.9	598	821	717	1010
AAG	LTOA 100	7.9	698	939	986	1116
AAG	NONE	7.5	527	--	657	--
AAG	NONE	7.1	535	--	563	--
AAG	NONE	7.2	581	--	640	--
AAK	LPO 85	9.1	403	660	674	1057
AAK	LPO 85	8.4	419	712	512	1066
AAK	LPO 60	9.2	408	574	499	824
AAK	LPO 60	8.5	463	665	460	656
AAK	LTOA 85	8.3	533	862	551	808
AAK	LTOA 85	9.3	562	928	771	1022
AAK	LTOA 100	9.7	354	586	520	808
AAK	LTOA 100	9	450	737	692	972
AAK	NONE	7.9	309	--	473	--
AAK	NONE	7.8	340	--	421	--
AAK	NONE	7.7	347	--	460	--
AAM	LPO 85	7.2	370	548	347	652
AAM	LPO 85	8.2	344	492	602	792
AAM	LPO 60	7.9	367	504	598	734
AAM	LPO 60	7.3	394	529	452	621
AAM	LTOA 85	8.1	437	558	604	813
AAM	LTOA 85	8.3	385	479	480	717
AAM	LTOA 100	7.6	410	442	510	492
AAM	LTOA 100	7.5	356	491	436	519
AAM	NONE	7.3	312	--	422	--
AAM	NONE	6.8	323	--	393	--
AAM	NONE	6.6	343	--	355	--

NOTE: All Modulus data reported in KSI
KEY :
NONE = No Aging.
LPO 60 = Low Pressure Oxidation 60°C / 5 days.
LPO 85 = Low Pressure Oxidation 85°C / 5 days.
LTOA 85 = Long-Term Oven Aging, 85°C / 5 days.
LTOA 100 = Long-Term Oven Aging, 100°C / 2 days.

in Figure 1 for each of the four aggregates, with the asphalts shown in rank order in each case. Only the diametral modulus data are presented in Figures 2 and 3. Less variability was experienced with the diametral modulus data—approximately ± 10 percent versus ± 15 percent with the triaxial modulus data. This difference was attributed to the relatively short specimen used (4 in.) in the triaxial mode. The asphalt showing the greatest aging (in terms of modulus change) has the highest ratio. The ratios were developed using a procedure to adjust the modulus values to correspond to the same air void content. The procedure is described later.

Long-Term Aging

The modulus ratios, long-term-aged modulus divided by adjusted-unaged modulus, from the diametral testing of the long-term-aged specimens are shown in Figures 2 and 3. These graphs are similar to those in Figure 1 with the rankings based

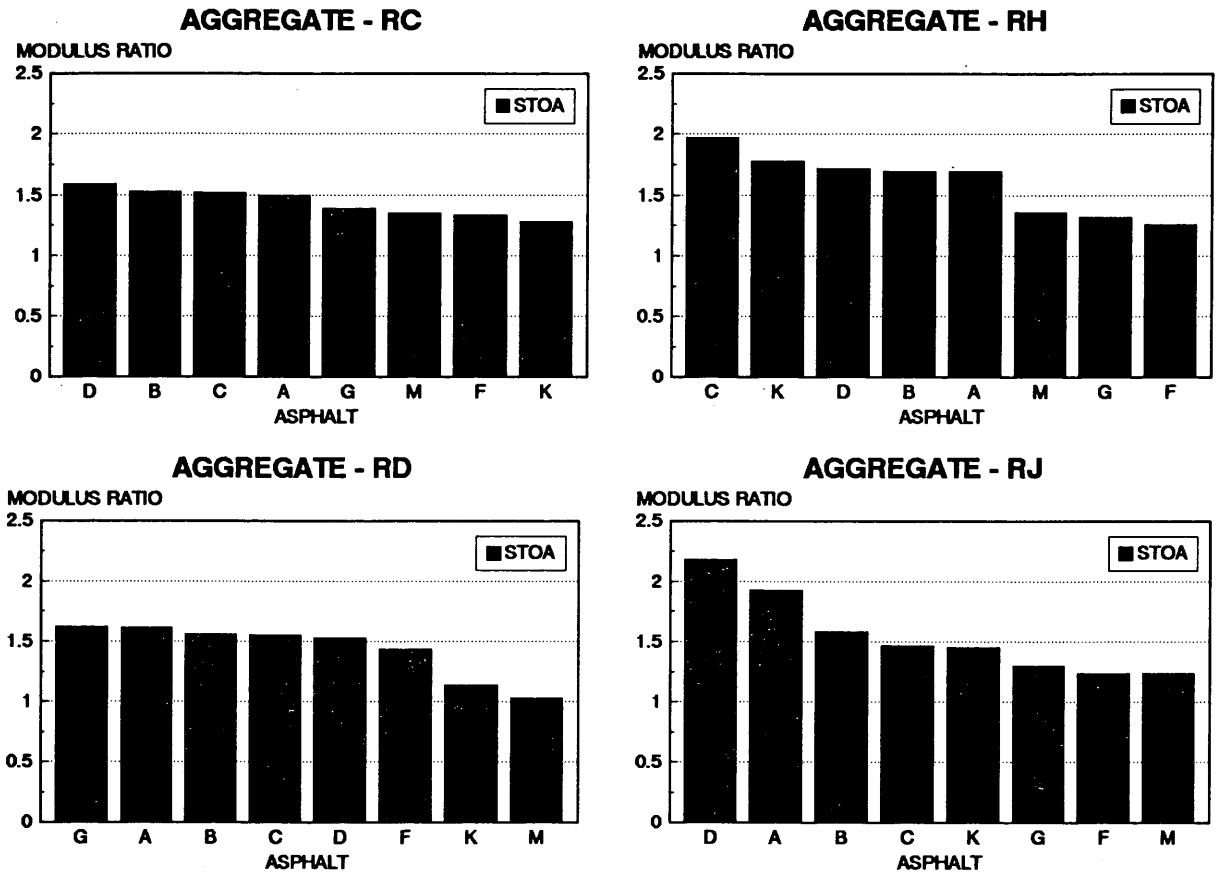

FIGURE 1 Diametral modulus ratio rankings for short-term oven aging.

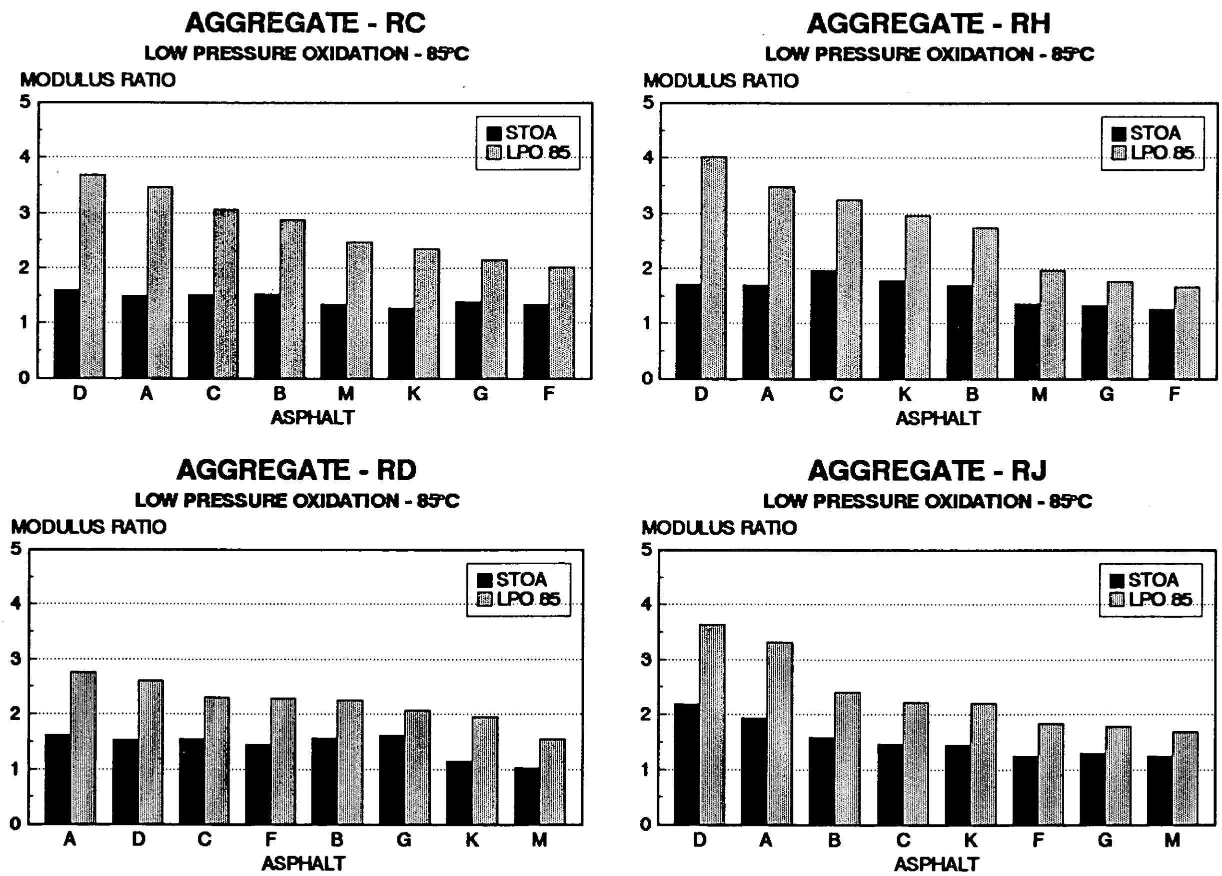

FIGURE 2 Diametral modulus ratio rankings for LPO at 85°C.

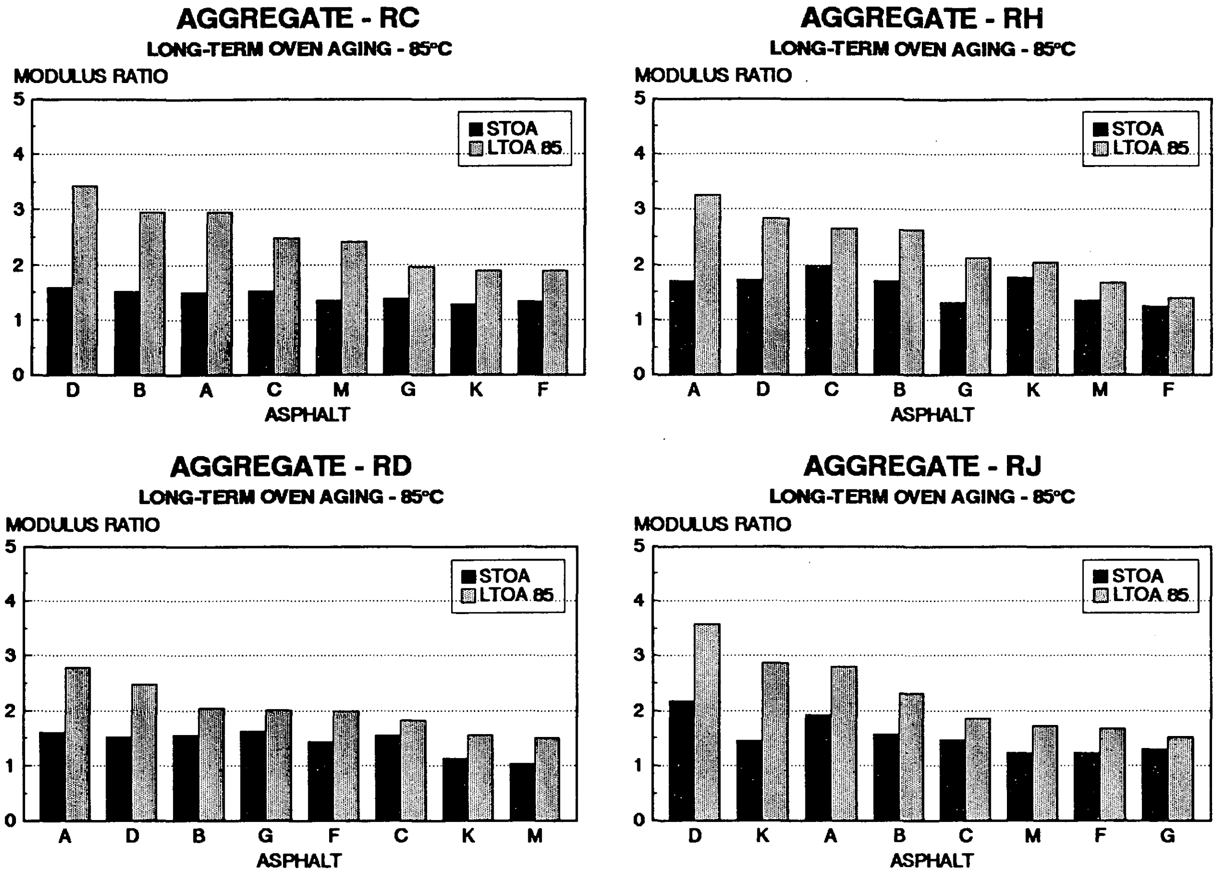

FIGURE 3 Diametral modulus ratio rankings for LTOA at 85°C.

on the ratio of long-term-aged modulus to unaged modulus. As with the results of the short-term aging, the modulus values were adjusted as described below.

Adjustment of Modulus Data

To analyze the effects of short- and long-term aging on asphalt-aggregate mixtures, a method of creating an aging ratio was needed. To create this ratio a measure of the unaged modulus was needed to compare with the aged specimens. At the time of mixing in the laboratory, three additional specimens besides those needed for long-term aging were prepared and compacted as soon as they could be brought to the proper compaction temperature. These specimens were said to be in an "unaged" condition and were tested for resilient modulus. In all but a few cases, the unaged specimens were found to have a different air void level than the short-term-aged specimens. This prompted a need to adjust the modulus values of the short-term-aged specimens to correspond to the same air void level as that of the unaged specimens.

To achieve this adjustment, an average slope was determined from the modulus versus air voids for the unaged specimens over the entire data set. With this slope and values for the average modulus and air void level for each combination of materials, an equation for the unaged modulus at any void level could be determined. From this equation an adjusted unaged modulus could be calculated for each short-term-aged specimen and used in calculating the short- and long-term aging ratios.

ANALYSIS OF RESULTS

Short-Term Aging of Asphalt-Aggregate Mixtures

The data presented in Figure 1 suggest that the aging susceptibility of a mixture is aggregate dependent. However, the effect of the asphalt is more significant. The rankings of the eight asphalts based on short-term aging (Figure 1) vary with aggregate type. In particular, asphalt AAK-1 moves around in the rankings, showing relatively little aging with basic aggregates (RC and RD) and relatively high aging with the acidic aggregates (RH and RJ).

The observed aging phenomenon appears to be related to the adhesion of the asphalt and aggregate. It is hypothesized that the greater the adhesion, the greater the mitigation of aging. It should be noted that there is no statistically significant difference between any of the asphalts; instead (for a particular aggregate) two or more asphalts show a similar degree of aging. This is shown in Table 6, which gives numerical rankings corresponding to the short-term aging rankings shown in Figure 1. The underlined areas identify groups of statistically similar aging ratios as determined by Waller groupings (*2*). When these groupings are examined, it can be

TABLE 6 Short-Term Rankings by Aggregate

Aggregate	Ranking														
RC	D	>	B	>	C	>	A	>	G	>	M	>	F	>	K
	1.59		1.53		1.52		1.58		1.39		1.35		1.34		1.28
RD	G	>	A	>	B	>	C	>	D	>	F	>	K	>	M
	1.62		1.61		1.56		1.55		1.53		1.44		1.14		1.03
RH	C	>	K	>	D	>	B	>	A	>	M	>	G	>	F
	1.97		1.78		1.72		1.70		1.70		1.36		1.32		1.26
RJ	D	>	A	>	B	>	C	>	K	>	G	>	F	>	M
	2.18		1.93		1.58		1.47		1.45		1.30		1.24		1.24

Note: Waller groupings of statistically similar behavior are underscored.

seen that only asphalt AAM-1 is consistently in the lowest group and asphalt AAD-1 consistently in the upper group.

Long-Term Aging of Asphalt-Aggregate Mixtures

The data for long-term aging (Figures 2 and 3) support those for short-term aging; that is, they also suggest that aging is aggregate dependent as well as asphalt dependent. Tables 7 and 8 present the rankings numerically and show where groups of asphalts are statistically similar, again using Waller groupings. Note that there appears to be more differentiation among asphalts following long-term aging than after short-term aging; this becomes more pronounced with the severity of the aging procedure.

TABLE 7 Long-Term Aging by LPO at 85°C: Rankings by Aggregate

Aggregate	Ranking														
RC	D	>	A	>	C	>	B	>	M	>	K	>	G	>	F
	3.69		3.47		3.07		2.88		2.47		2.36		2.15		2.01
RD	A	>	D	>	C	>	F	>	B	>	G	>	K	>	M
	2.76		2.61		2.30		2.29		2.26		2.07		1.96		1.55
RH	D	>	A	>	C	>	K	>	B	>	M	>	G	>	F
	4.03		3.49		3.24		2.97		2.75		1.97		1.77		1.67
RJ	D	>	A	>	B	>	C	>	K	>	F	>	G	>	M
	3.63		3.32		2.40		2.23		2.20		1.84		1.78		1.68

Note: Waller groupings of statistically similar behavior are underscored.

TABLE 8 LTOA at 85°C: Rankings by Aggregate

Aggregate	Ranking														
RC	D	>	B	>	A	>	C	>	M	>	G	>	K	>	F
	3.43		2.95		2.95		2.49		2.41		1.96		1.90		1.89
	———		———	———	———		———	———	———		———	———	———	———	———
RD	A	>	D	>	B	>	G	>	F	>	C	>	K	>	M
	2.78		2.48		2.04		2.01		2.00		1.83		1.56		1.51
	———	———	———		———	———	———	———	———	———	———		———	———	———
											———	———	———		
RH	A	>	D	>	C	>	B	>	G	>	K	>	M	>	F
	3.26		2.84		2.65		2.63		2.13		2.05		1.67		1.41
	———	———	———	———	———	———	———		———	———	———	———	———	———	———
			———	———	———	———	———	———	———						
					———	———	———	———	———	———	———				
RJ	D	>	K	>	A	>	B	>	C	>	M	>	F	>	G
	3.58		2.88		2.80		2.31		1.86		1.73		1.67		1.52
	———		———	———	———		———	———	———						
									———	———	———	———	———	———	———

Note: Waller groupings of statistically similar behavior are underscored.

Comparison of Mixture Aging by Short-Term and Long-Term Aging Methods

The numerical rankings of aging presented in Tables 6 through 8 are summarized in Table 9. Comparison of the rankings due to short-term aging with those due to long-term aging shows that small movements in the rankings are common. However, using the short-term ranking as a datum, only a few asphalts move more than two places in the rankings, as shown in Table 9. These comparisons imply that the LPO aging procedure relates more closely to the short-term aging rankings than to the LTOA procedure, possibly because of the greater potential for specimen damage in the LTOA procedure. This possibility of damage could be the cause of the greater variability in the LTOA specimens, particularly for the 100°C procedure. It should be noted that the short-term aging rankings are based on data from six specimens, whereas those for each set of long-term-aged specimens are based on data from only two specimens. Hence, more variability is expected for the long-term aging.

Comparison of Mixture Aging with Asphalt Aging

Aging of asphalt cement was carried out in SHRP Project A-002A. Data for original (tank), thin-film-oven (TFO) aged,

TABLE 9 Ranking of Asphalt for Each Aggregate Based on Diametral Modulus Ratios and Aging Method

	Short-Term Oven Aging Aggregate				Low Pressure Oxidation at 60°C				Low Pressure Oxidation at 85°C				Long-Term Oven Aging at 85°C				Long-Term Oven Aging at 100°C			
	RC	RD	RH	RJ	RC	RD	RH	RJ	RC	RD	RH	RJ	RC	RD	RH	RJ	RC	RD	RH	RJ
Worst	D	G	C	D	A	G	K	D	D	A	D	D	D	A	A↑4	D	D	A	A↑4	D
	B	A	K	A	D	C	C	A	A	D↑3	A↑3	A	B	D↑3	D	K↑3	A	D↑3	K	A
	C	B	D	B	B	A	D	B	C	C	C	B	A	B	C	A	B	B	C	B
	A	C	B	C	C	D	B	C	B	F	K	C	C	G↓3	B	B	K↑4	F	B	K
	G	D	A	K	F	B	A	K	M	B	B	K	M	F	G	C	C	K	D	C
	M	F	M	G	G	F	G	M	K	G↓5	M	F	G	C	K↓4	M	M	C	M	F
	F	K	G	F	M	K	M	G	G	K	G	G	K	K	M	F	F	G↓6	F	G
Best	K	M	F	M	K	M	F	F	F	M	F	M	F	M	F	G	G↓3	M		M

Key: A shaded block illustrates an asphalt that changes more than two rankings relative to the short-term aging rankings. The arrow and adjacent number indicate the number of places moved and the direction.

TABLE 10 Summary of Routine Test Data for Asphalt Alone

	Asphalt							
	AAA-1 (150/200)	AAB-1 (AC-10)	AAC-1 (AC-8)	AAD-1 (AR-4000)	AAF-1 (AC-20)	AAG-1 (AR-4000)	AAK-1 (AC-30)	AAM-1 (AC-20)
ORIGINAL ASPHALT								
Viscosity (60°C) (Poises)	900	1120	710	1140	1750	1950	3320	2040
AGED ASPHALT (THIN FILM OVEN TEST)								
Viscosity (60°C) (Poises)	2080	2620	1780	3690	4560	3490	10240	4490
Viscosity Ratio (60°C TFO Aged/Original)	2.31	2.34	2.51	3.24	2.61	1.79	3.08	2.20
LONG-TERM AGED (PAV)								
Viscosity (60°C) (Poises)	5380	7110	5170	12000	16250	8140	27300	17150
Viscosity Ratio (60°C, PAV Aged/Original)	5.98	6.35	7.28	10.53	9.29	4.17	8.22	8.41

and pressure-aging-vessel (PAV) aged asphalt have been presented in several A-002A reports. These routine data were summarized recently by Christensen and Anderson (*3*). As with mixture aging data, the asphalt aging data can be used to calculate an aging ratio based on the aged viscosity at 60°C compared with the original viscosity at 60°C. The asphalts can then be ranked in order of aging susceptibility. Table 10 shows the routine asphalt data and the calculated viscosity ratios.

Short-Term Aging

Table 11 shows rankings for mixtures based on short-term aging and the asphalt rankings based on TFO aging. It should be noted that TFO aging is analogous to short-term mixture aging and that (as with mixture rankings) the differences between some asphalts are not statistically significant. Nevertheless, it is clear that there is little relationship between the mixture rankings and the asphalt rankings. The major similarity is that asphalt AAM-1 is one of the two "best" asphalts in both the mixture and asphalt short-term aging. A major difference is that asphalt AAK-1 is ranked one of the two "worst" from asphalt TFO aging and among two of the "best" if short-term aging with aggregates RC and RD is considered.

Long-Term Aging

Table 12 shows the rankings for mixtures based on long-term aging by LPO at 85°C and rankings for asphalt developed from the data reported by Christensen and Anderson (*3*). Also summarized are rankings developed from data reported by Robertson et al. (*4*) for asphalt recovered from "mixtures" of single-size fine aggregate and asphalt subjected to pressure aging.

As with the short-term aging comparisons, there is little similarity between the rankings for long-term aging of asphalt mixtures and asphalt alone. In fact, there is even less similarity, because asphalt AAM-1 appears to have more susceptibility to long-term PAV aging than to TFO aging (relative to the other asphalts) and has moved in the rankings.

There is more similarity between the rankings based on mixture aging and those based on the data for fine aggregate mixtures developed by Project A-003A. However, the rankings are different, as indicated in Table 12.

TABLE 11 Comparison of Rankings for Short-Term Aging Mixtures and Asphalt Alone

	Ranking of Asphalt					
	A-003A[1]					A-002A[2]
	Aggregate RC	Aggregate RD	Aggregate RH	Aggregate RJ	Average of A-003A Rankings	No Aggregate
Worst	D	G	C	D	D	D
	B	A	K	A	A	K
	C	B	D	B	C	F
	A	C	B	C	B	C
	G	D	A	K	K	B
	M	F	M	G	G	A
	F	K	G	F	F	M
Best	K	M	F	M	M	G

[1] Based on short-term aging ratios from diametral modulus.
[2] Based on data reported by Christensen and Anderson *(3)*.

TABLE 12 Comparison of Rankings for Long-Term Aging of Mixtures and Asphalts

	Ranking of Asphalts								
	A-003A[1]				A-002A[2]	A-002A[3]		A-002A[4]	
	Aggregate RC	Aggregate RD	Aggregate RH	Aggregate RJ	No Aggregate	Aggregate RD	Aggregate RJ	Aggregated RD	Average of A-003A Rankings
Worst	D	A	D	D	D	F	D	F	D
	A	D	C	A	F	$M_{\uparrow}^{6}$	B	$M_{\uparrow}^{6}$	A
	C	C	A	B	M	D	$F_{\uparrow}^{3}$	C	C
	B	F	C	C	K	C	C	D	B
	M	B	K	K	C	$A_{3}^{\downarrow}$	$M_{\uparrow}^{3}$	G	K
	K	G	M	F	B	K	$A_{4}^{\downarrow}$	$A_{4}^{\downarrow}$	F
	G	K	G	G	A	G	K	$B_{3}^{\downarrow}$	G
Best	F	M	F	M	G	$B_{4}^{\downarrow}$	G	K	M

[1] Based on long-term aging ratios from diametral modulus for low pressure oxidation aging.
[2] Based on data reported by Christensen and Anderson *(3)* for TFO-PAV aging.
[3] Reported in 4th Quarterly Report, 1991, based on PAV aging at 60°C for 144 hours. Prior short-term aging.
[4] Reported in 4th Quarterly Report, 1991. Asphalt alone was subjected to TFO aging prior to mixing and PAV aging.

General Discussion

The difference in rankings between mixtures and asphalt, based on either short-term or long-term aging data, indicates the need for testing to evaluate the mixture's aging susceptibility. Clearly the aging of the asphalt alone or in a fine aggregate mixture is not an indicator of how a mixture will age. Aging is caused by the influence of the aggregate on the mixture, which appears to be related to the chemical interaction of the aggregate and the asphalt. This interaction may be related to adhesion; the greater the adhesion, the greater the mitigation of aging. The mixture aging rankings given in Tables 7 and 8 suggest this hypothesis, since the rankings are similar for the two "basic" aggregates (RC and RD) and for the two "acidic" aggregates (RH and RJ). Some of the asphalts rank similarly regardless of the aggregate type, whereas others (such as AAG-1 and AAK-1) behave very differently according to aggregate type. It is known that asphalt AAG-1 was lime treated in the refining process, and it is therefore reasonable that it would exhibit good adhesion and a reduced aging tendency with acidic aggregates (RH and RJ) as indicated by the short-term aging data. However, the rankings of asphalt AAG-1 for long-term aging do not appear to be influenced by aggregate type.

CONCLUSIONS

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

1. The aging of asphalt-aggregate mixtures is influenced by both the asphalt and the aggregate.
2. Aging of the asphalt alone and subsequent testing do not appear to be adequate for predicting mixture performance because of the apparent mitigating effect of some aggregates on aging.
3. The aging of certain asphalts is strongly mitigated by some aggregates but not by others. This appears to be related to the strength of the chemical bonding (adhesion) between the asphalt and the aggregate.
4. The short-term aging procedure produces a change in resilient modulus of up to a factor of 2. For a particular aggregate, there is no statistically significant difference in the aging of certain asphalts. The eight asphalts investigated typically fell into three groups—those with high, medium, or low aging susceptibility.
5. The four long-term aging methods produce somewhat different rankings of aging susceptibility compared with the short-term aging procedure and with each other. This is partially attributable to variability in the materials, aging process, and testing. However, it appears that the short-term aging procedure does not enable prediction of long-term aging.
6. The LPO long-term aging procedure causes the most aging and less variability in the rankings of aging susceptibility relative to the short-term aging rankings.

ACKNOWLEDGMENTS

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