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Aging: Binder Validation

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Abstract

This research was conducted as part of the Strategic Highway Research Program (SHRP) A-003A contract at Oregon State University to validate the findings of SHRP contracts A-002A and A-003B with regard to aging. One short-term and four long-term aging methods were used to simulate aging of asphalt-aggregate mixes in the field. Four aggregates and eight asphalts for a total of 32 different material combinations were tested using the different aging methods. Results of the aging studies are compared with the A-002A and A-003B studies of asphalt binder or asphalt mixed with fine aggregate. This research concludes that aging of asphalt mixes cannot be predicted by tests on asphalt binder alone since results show that aggregates have considerable influence on aging.

Executive Summary

The development of laboratory aging procedures for asphalt-aggregate mixes as a part of project A-003A of the Strategic Highway Research Program (SHRP) has been described previously by Bell et al. (1992). The validation of these procedures is described in another report by Bell, Wieder, and Fellin (1992).

The procedure developed for short-term aging involves heating loose asphalt-aggregate mixes for four hours at 135°C (275°F) in a forced-draft oven prior to compacting the laboratory specimens. This procedure simulates the aging of mixes in the field during the construction process while they are uncompacted.

The following two alternate procedures have been developed to simulate long-term aging of asphalt-aggregate mixes:

1. Long-term oven aging (LTOA) of compacted specimens in a forced-draft oven.

2. Low-pressure oxidation (LPO) of compacted specimens in a modified triaxial cell by passing oxygen through the specimen.

Various combinations of temperature and time have been evaluated for these aging procedures, which simulate aging for periods of several years.

The effects of aging were evaluated by resilient modulus testing at 25°C (77°F) using diametral (indirect tension) and triaxial compression. Tensile strength tests were performed once all other data had been collected. Several specimens were subjected to dynamic mechanical analysis (DMA) frequency sweep testing. The DMA test was run at various frequencies and temperatures to gain a thorough characterization of mix properties.

The SHRP contractors who performed projects A-002A and A-003B were asked to rank asphalts in order of expected performance based on the chemical or physical properties of the asphalt binders. The A-002A study ranked the asphalt binders according to expected performance in the categories of permanent deformation, fatigue, thermal cracking, water sensitivity, and short-term and long-term aging. These rankings were validated by A-003A research on asphalt-aggregate mixes that were conditioned using short-term and long-term accelerated aging tests to evaluate the performance of the asphalt binder and asphalt-aggregate mixes.

The testing program included combinations of 4 aggregates and 8 asphalts for a total of 32 combinations. The properties of the aggregates used represent a broad range of characteristics, from a high-adsorptive crushed limestone to a river-run gravel. Similarly, the asphalts used span a broad range of asphalt grades.

Eleven specimens were prepared for each material combination. Eight of these were subjected to the short-term oven-aging procedure and then compacted. The other three specimens were compacted as soon as the compaction temperature could be achieved and are termed "unaged" specimens. After being compacted, the specimens were tested for volumetric properties and resilient modulus. Both diametral (indirect tension) and triaxial (axial compression) modes of modulus testing were employed.

After the specimens were tested for modulus, they were subjected to one of the four long-term aging procedures: LTOA at 85°C (185°F) for five days, LTOA at 100°C (212°F) for 2 days, or LPO at 60°C or 85°C (140°F or 185°F) for five days. After aging, resilient modulus testing was again performed.

Aging effects were measured by means of a modulus ratio. This ratio was developed by dividing the modulus of the specimen after short-term or long-term aging by a value for the unaged modulus. Once the ratios were determined for each group, the aging susceptibility of the asphalts was ranked for each aging method within each aggregate group.

A similar sort of aging ratio was calculated using data from the A-002A project. The reported values for after-aging viscosity were divided by the original values of viscosity to obtain an aging ratio. These values are compared with the A-003A data in this study.

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

- The aging of asphalt-aggregate mixes is influenced by both the asphalt and aggregate.

- Testing of aged asphalt alone does not appear to predict adequately mix performance because of the apparent mitigating effect that aggregate has on aging.

- The aging of certain asphalts is strongly mitigated by some aggregates but not by others. This variability appears related to the strength of the chemical bonding (adhesion) between the asphalt and aggregate.

- The short-term aging procedure produces a change in the resilient modulus of up to a factor of two. For a particular aggregate, there is not a 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.

- The three long-term aging methods produce somewhat different rankings of aging susceptibility when compared with the short-term aging procedure and with each other. This outcome is partially due to variability in the materials, aging process, and testing. However, the short-term aging procedure does not enable prediction of long-term aging.

- The low-pressure oxidation method of long-term oven aging causes the most aging and least variability in aging susceptibility rankings relative to short-term aging.

The following recommendations are made based on the results of this study and the companion test selection and field validation studies:

- Oven aging of loose mixes at 135°C (275°F) is recommended for short-term aging. An aging period of four hours appears to be appropriate.

- Oven aging of compacted mixes should be adopted for long-term aging of dense mixes. An aging temperature of 85°C (185°F) for five days is most appropriate for the procedure. It may be possible to use a temperature of 100°C (212°F) for two days, but such a high temperature may damage the specimens.

- A low-pressure oxidation (triaxial cell) technique is recommended for long-term aging of open-graded mixes or dense-graded mixes using soft grades of asphalt. A temperature of 85°C (185°F) for five days is recommended for this procedure. It may be possible to use a temperature of 100°C (212°F) for two days, but such a high temperature may damage the specimens.

1

Introduction

1.1 Background

The development of laboratory aging procedures for asphalt-aggregate mixes as part of project A-003A of the Strategic Highway Research Program (SHRP) has been described previously by Bell et al. (1992). The validation of these procedures is described in another report by Bell, Wieder, and Fellin (1992).

The procedure developed for short-term aging involves heating the loose mix for four hours at 135°C (275°F) in a forced-draft oven prior to compacting of laboratory specimens. This procedure simulates the aging of mixes in the field during the construction process while they are uncompacted.

Alternate procedures have been developed for long-term aging of mixes. These procedures simulate the aging of compacted mix for service periods of several years. The following approaches have been found to be appropriate:

1. Long-term oven aging (LTOA) of compacted specimens in a forced-draft oven.

2. Low-pressure oxidation (LPO) of compacted specimens in a triaxial cell by passing oxygen through the specimens.

Various combinations of temperature and time have been evaluated (Bell et al. 1992).

The effects of aging are evaluated by resilient modulus at 25°C (77°F) using diametral (indirect tension) and triaxial compression modes of testing. Tensile strength tests are performed on specimens once all other data have been collected. A selection of specimens was subjected to dynamic mechanical analysis (DMA) at different temperatures and loading frequencies.

1.2 Purpose

This report describes a laboratory study designed to compare the results of efforts to age asphalt (performed in the SHRP A-002A project) with the results of efforts to age asphalt-aggregate mixes (performed in the A-003A project).

1.3 Scope

Following a description of the hypothesis for aging of asphalts (developed in the A-002A project), the experiment design for the laboratory test program is presented. The results of the test program and their analysis, including comparison with A-002A results, are presented prior to the conclusions that arose from this study.

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Hypothesis for Aging of Asphalt

The asphalt contractors for the A-002A and A-003B projects were asked to rank the Strategic Highway Research Program (SHRP) asphalts in terms of expected performance based on chemical or physical properties of the asphalt cements. Both Western Research Institute (WRI) and Pennsylvania State University (PSU) provided this information for 16 SHRP asphalts. These rankings, together with similar ones provided for water sensitivity in the A-003B project, were to be validated by the A-003A study using simulative tests. This chapter summarizes the rankings put forth by the A-002A and A-003B contractors.

Since aging plays a role in the permanent deformation, fatigue, and thermal cracking of mixes, a summary of the hypothesis for each of these performance characteristics, as well as for aging and water sensitivity, is presented below.

2.1 Chemical Properties—Western Research Institute

The following discussion ranks the expected performance of SHRP asphalts in terms of their chemical properties (Petersen et al. 1994, forthcoming). (Similar information is provided in Robertson et al. 1994.) WRI has emphasized that the structural characteristics are primarily related to physical (viscoelastic) properties and that any given set of physical properties may be achieved by using substantially different chemical compositions. Rankings by distress type are discussed, and a schematic illustrating the relationship among chemical and physical properties and pavement performance is shown in figure 2.1.

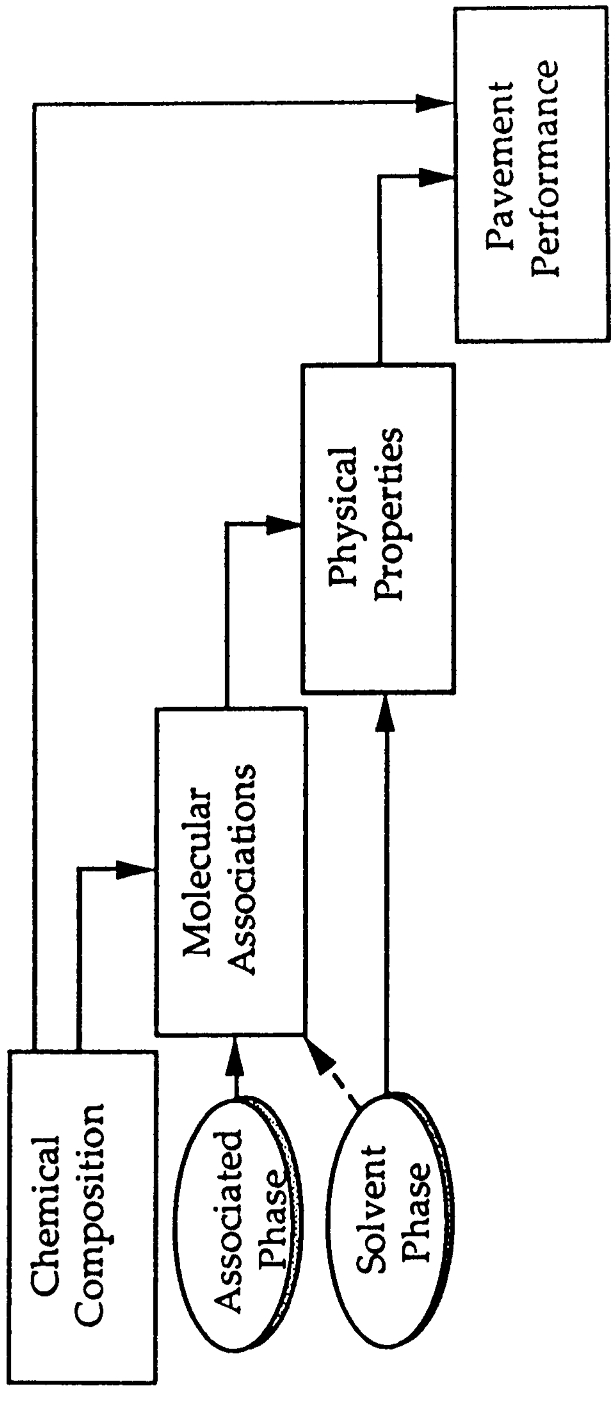

Figure 2.1. Chemistry–physical property–performance relationships

2.1.1 Permanent Deformation

Permanent deformation of asphalt-aggregate mixes can be affected by asphalt type or by aggregate type and mix characteristics. It generally occurs at high temperatures because of shear stresses in the upper part of the pavement surface.

Size exclusion chromatography (SEC) fraction I/fraction II ratios have been found to be strongly related to permanent deformation. These ratios are evaluated on asphalts that have not experienced any long-term aging. The SEC ratio is the ratio of the weight of nonfluorescent components (I) that appear to assemble into an elastic matrix to the weight of fluorescent materials (II) that form the dispersing phase.

See figure 2.2 for a plot of the SEC II fraction versus tan delta at 25°C (77°F). See table 2.1 for a ranking of the SHRP asphalts in terms of their resistance to permanent deformation.

Table 2.1. Ranking of high-temperature permanent deformation and rutting by SEC-tan delta

Asphalt Type	Expected Performance
AAM-1	Excellent resistance
AAK-1	"
AAE	"
AAS-1	Very good resistance
AAH	"
AAD-1	"
AAB-1	"
AAW	"
AAJ	"
AAA-1	Good resistance
AAN	"
AAX	Fair resistance
AAF-1	"
AAC-1	"
AAZ	Poor resistance
AAV	"
AAG-1	Little or no resistance
ABD	"

2.1.2 Low-Temperature Cracking

Thermal cracking in asphalt concrete requires two obvious situations: (1) contraction (shrinkage) of some or all components of the concrete, and (2) stiffening of the mix to a

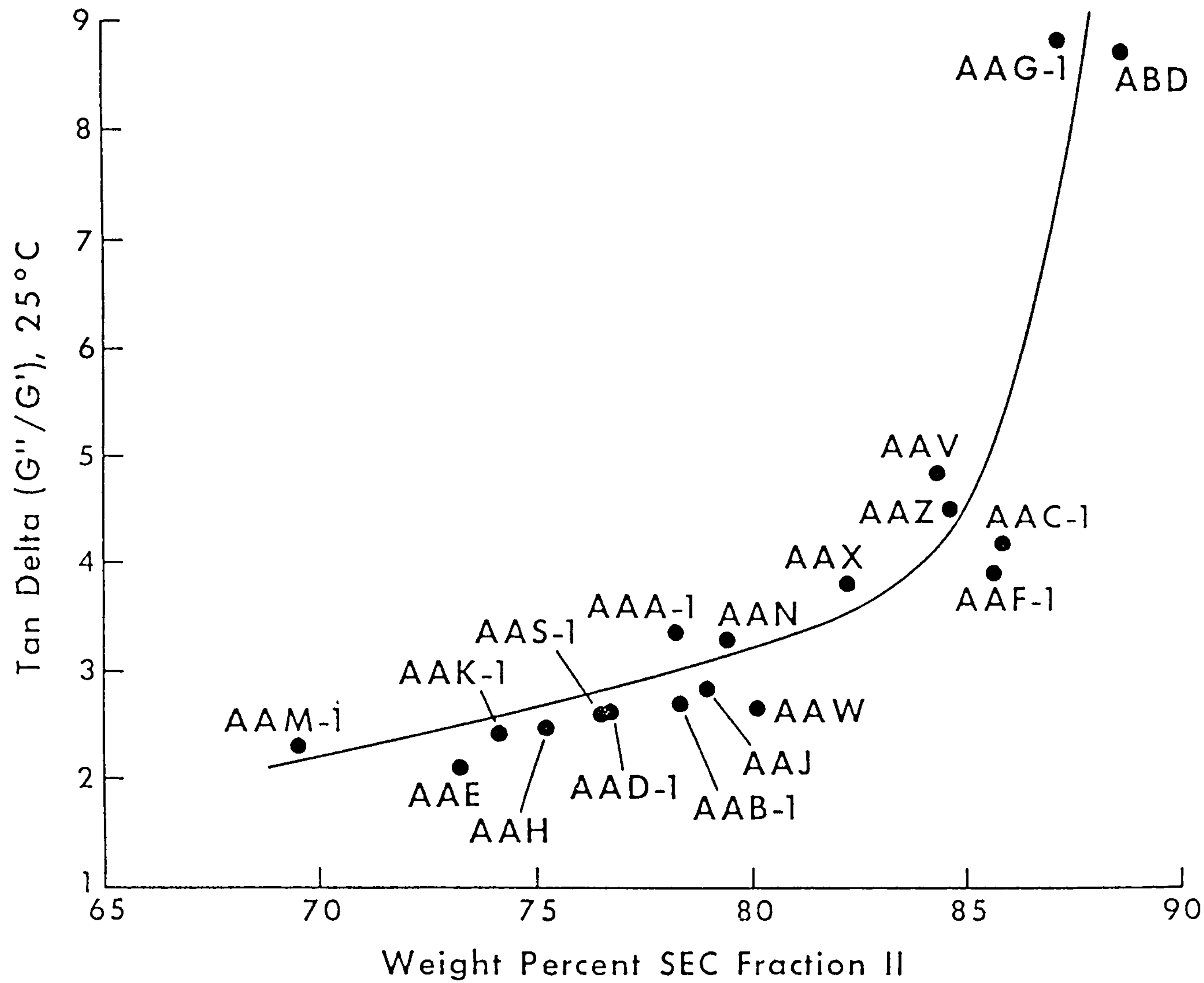

Figure 2.2. Relationship between weight percent SEC fraction II and trans delta of SHRP asphalts

point at which viscous flow cannot occur at a rate high enough to relieve the strain caused by the contraction. Since the aggregate effectively has no viscous flow (at any service temperature), the ability to flow and hence avoid cracking must be totally within the viscoelastic binder. However, aggregates may have various coefficients of thermal expansion and thus contribute differentially to pavement contraction. So, variations in aggregate may have an effect on the overall problem of thermal cracking. If the binder is presumed totally responsible for the creep properties, then some chemical property or set of properties of the binder is responsible for the variation in flow properties among different asphalts.

Viscous flow implies that the elastic matrix is not involved in thermal cracking, especially when the small amount of change involved is considered. For example, a 1-in. (2.54 cm) crack every 50 ft (15.25 m) amounts to a 0.17 percent contraction. Elasticity should accommodate this amount of volume change. Further, thermodynamic data suggest that most organization of the polar matrix has been achieved at moderate and higher temperatures. Transition of the neutral materials to a glass with an accompanying contraction, similar to crystallization of nonpolar materials, is a more likely cause of cracking. The stiffness, or rigidity, of homologous pseudocrystalline materials generally increases with molecular weight. The relative amounts may also have an effect, but ion exchange chromatography (IEC) experiments for the core asphalts show a neutral range of 51 to 60 percent—relatively similar amounts. The supercritical fluid chromatography (SFC) profiles for the IEC neutrals of core asphalts are significantly different and show that the molecular weight profiles of the neutral components differ substantially. Chemical structural variations among neutrals may affect rigidity of a pseudocrystalline phase also, but no such detailed information on neutral components has been acquired systematically. An indication of structural effects is being sought at present using Fourier transformation infrared (FTIR) radiation.

The ranking of six of the eight core asphalts in table 2.2 is based on the molecular weight average by SEC. Although not shown in table 2.2, asphalt AAM-1 has a maximum at 68 carbons, but it is an odd case with a very uniform and broad molecular weight range. Typically, such broad molecular weight mixes (for pseudocrystalline phases) do not harden disproportionately, as the carbon number might indicate. The presumption, based on the unique profile of AAM-1 neutral, is that the asphalt would show intermediate low-temperature cracking properties.

2.1.3 Fatigue Cracking

Fatigue cracking is typically associated with aged pavement, although it can occur in relatively new pavements. Fatigue cracking that occurs in relatively new pavement should be somewhat the opposite of rutting. Asphalts that have the smallest amounts of SEC II should have the greatest propensity to crack under stress of traffic. The matrix developed by a large SEC I would be expected to be too rigid. This hypothesis is highly speculative, and the best ranking available is the reverse order of the early rutting list (table 2.3).

Table 2.2. Ranking of SHRP asphalts in terms of their resistance to low-temperature cracking

Asphalt	Carbon Number at the Max of SEC Peak	Ranking
AAA-1	32	Least likely to crack at low temperatures
AAD-1	32	"
AAK-1	32	"
AAG	42	Moderate probability to crack at low temperatures
AAB	43	"
AAF	48	Most likely to crack at low temperatures

Fatigue cracking in aged asphalts is more likely caused by cracking in unaged binders. Based on figure 2.2, rankings were developed for three temperature regimes for the eight core asphalts shown in table 2.3. Each ranking also has a qualitative descriptor.

2.1.4 Aging

Aging of asphalt results from a complicated set of events involving oxidation at the molecular level and structuring at the intermolecular level. The primary chemical species formed are ketones and sulfoxides. More severe oxidation produces carboxylic anhydrides and small amounts of other highly oxidized species. Structuring appears to quench further oxidative aging. The rate of aging decreases with time at any given temperature. As temperature increases, the amount of structuring decreases and reactivity increases. The resulting oxidation rate increases and the level of quenching decreases. At very extended times (severe oxidation aging), at least one of the core asphalts (AAK-1) showed extreme hardening, but it is not clear whether this result is within normal road service conditions. It is speculated that the unique behavior of AAK-1 results from its extraordinary vanadium content. Vanadium may be a viable catalyst to oxidize asphalts rapidly and, hence, provide a usable test method that is much faster than TFO-PAV for evaluating oxidative aging.

In figure 2.3, the aging index (AI) profiles for the eight core asphalts are shown as a function of temperature between 60°C and 80°C (140°F and 176°F). Note that the oxidative age hardening spreads dramatically over this 20°C (36°F) range. Note, too, that 176°F (80°C) was chosen as an upper limit. (Perhaps this limit should be 185°F [85°C]). At 140°F (60°C), the aging rates for all asphalts have diminished very significantly, suggesting that, below 55°C to 60°C (131°F to 140°F), oxidative aging may be relatively insignificant.

Table 2.3. Resistance of aged asphalts to fatigue cracking

Moderate and Cool Climate (140°F and below surface temperatures)		Intermediate Climate (155°F-165°F surface temperatures)		Hot Climate (175°F higher than surface temperatures)	
AAA-1	Very resistant to fatigue cracking	AAG-1	Very resistant	AAG-1	Resistant to fatigue cracking
AAB-1	"			AAC-1	"
AAG-1	"	AAC-1	Resistant		
		AAB-1	"	AAB-1	Moderate susceptibility
AAK-1	Resistant to fatigue cracking	AAA-1	"	AAA-1	"
AAF-1	"	AAK-1	"		
AAC-1	"	AAF-1	"	AAF-1	Significant susceptibility
AAM-1	"			AAK-1	"
		AAM	Moderate susceptibility to fatigue cracking	AAM-1	"
AAD-1	Fair resistance to fatigue cracking				
		AAD	"	AAD-1	Very susceptible to fatigue cracking

°C = (°F − 32) ÷ 1.8

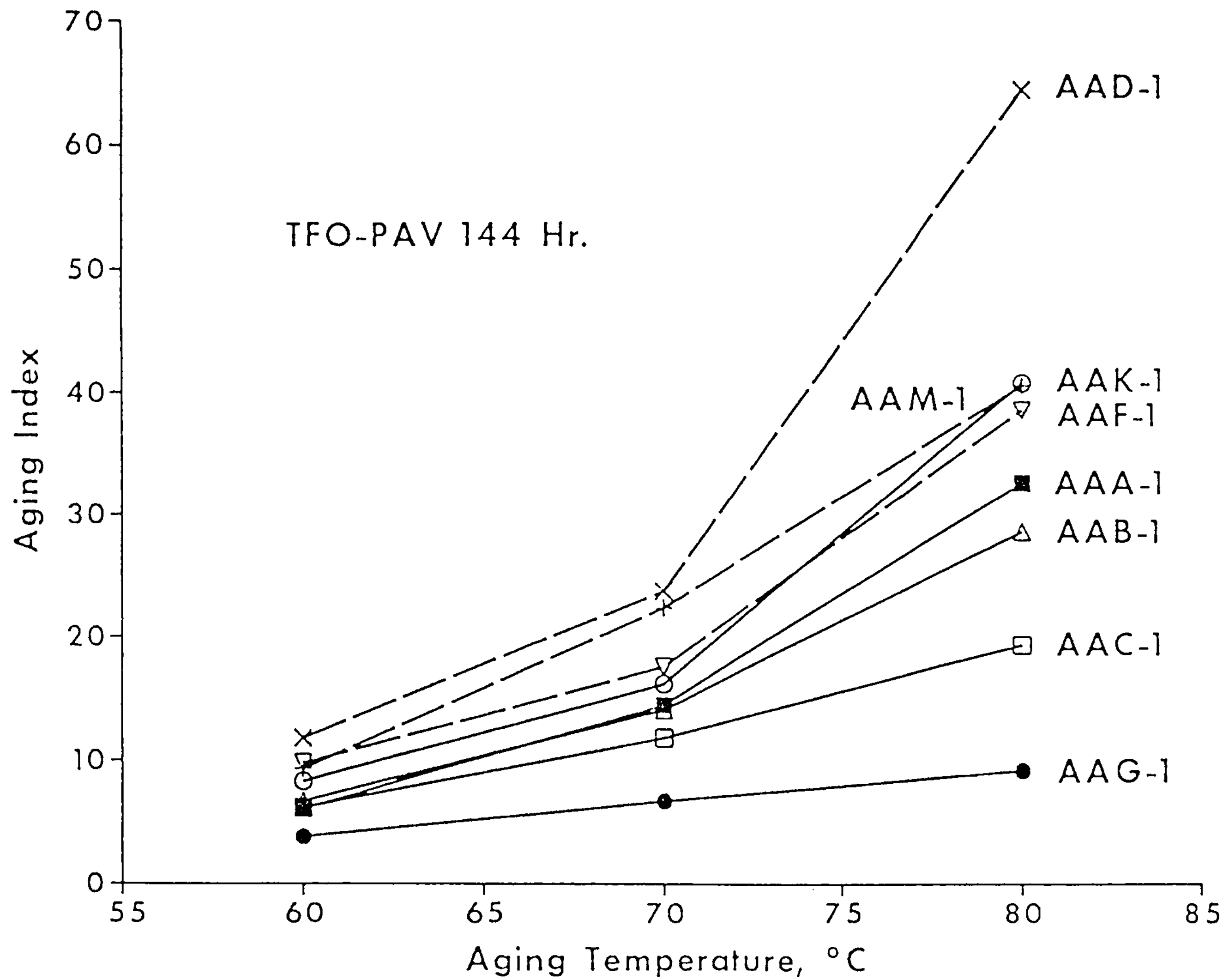

Figure 2.3. Aging indices at three temperatures of SHRP core asphalts

Thus far, TFO-PAV is the chosen method to develop into a specification method for oxidative aging.

2.1.5 Moisture Damage (Loss of Adhesion)

Numerous studies (A-003B in particular) have demonstrated that moisture damage that causes loss of adhesion is primarily associated with aggregate. Classifying moisture damage susceptibility from the chemistry of only the binder is probably a minor effect. Nonetheless, a highly speculative classification is shown in table 2.4 based on the carbonyl content, with emphasis on the free acid content, as determined by FTIR. Note that aging affects the eight core asphalts differently.

Table 2.4. Ranking of moisture damage resistance by infrared radiation of functional group analysis (limited to asphalt; aggregate not considered)

New Material		Aged Material	
AAF-1	Good (no order established)	AAB-1	Good (in order as shown)
AAB-1	"	AAM-1	"
AAM-1	"	AAC-1	"
AAA-1	"	AAF-1	"
AAD-1	Intermediate - Good	AAD-1	Intermediate—Good
AAK-1	"		
		AAA-1	Intermediate
AAG-1	Fair - Poor	AAG-1	Poor
ABD	Poor	ABD	Poor

2.2 Physical Properties—Pennsylvania State University

The Penn State rankings (see Robertson et al. 1994) consider three distress modes: (1) low-temperature thermal shrinkage cracking, (2) load-associated fatigue, and (3) rutting caused by plastic deformation in the upper layers of the hot-mix asphalt concrete. In some instances in which multiple parameters were selected for the ranking, better understanding of the failure mechanisms and better models were developed by other SHRP research programs.

For the performance parameters given in the attached tables, a score has been assigned to each asphalt. This score is a value from 1 to 8 and is based on the parameter value for the selected asphalt and the observed range for that parameter. When more than one parameter has been given, an average score has been calculated for that test or failure mode. The total score is based on this average and has also been calculated on a scale of 1 to 8. In all cases, a lower score is associated with better performance in the test or failure mode under consideration. The tables also include a rating (G—good, M—moderate, or P—poor) that was assigned based on the total score. Total scores below 2.5 were rated G; total scores above 6.5 were rated P. All intermediate scores were rated M. These ratings are designed to help identify asphalts that showed extreme behavior in the various tests and failure modes.

2.2.1 Load-Associated Fatigue Cracking

The mechanism responsible for fatigue cracking is not clear. At temperatures somewhat above 0°C (32°F), asphalt cement behaves in a ductile manner, and cracks do not propagate in a brittle manner. At lower temperatures, asphalt behaves in a brittle manner. Thus, the mechanism must be different in the region of ductile and brittle failure, and the binder properties that correlate with field behavior are probably different in the different flow regimes.

It is not clear at which temperature fatigue occurs in the field. If cumulative damage (in terms of a reduced modulus, etc.) is the criterion, then failure more inclusive than pure fatigue is implied. Thus, performance may be a function of multiple mechanisms and the ranking may not depend on a single parameter. To further complicate the matter, the ranking criterion in the brittle or viscoelastic response region must be different for controlled stress and controlled strain. Both modes of testing are included in the validation program used in this study:

1. Laboratory—bending beam fatigue, 20°C (68°F). At this temperature, it was assumed that viscous deformation in the asphalt is responsible for crack formation and propagation. If this is the case, the viscous component of the modulus (G_v) at 20°C (68°F) should correlate with the laboratory fatigue test; fatigue performance should improve with increasing values of the viscous modulus. See table 2.5 for the ranking.

   The ranking should probably be defined by controlled stress, controlled strain, or controlled energy. These distinctions were not made.

2. Laboratory—bending beam fatigue, 0°C (32°F). At this temperature, the asphalt can crack in a brittle manner with a brittle or viscoelastic response. Therefore, classic fatigue parameters for the asphalt cements should be related to the bending-beam fatigue tests conducted on the mixes. Asphalt cement fatigue parameters (N_f) and a measure of the stiffness at 0°C (32°F) are included in the ranking:

   a. N_f—number of cycles to failure in bending beam test
   b. C^*—complex modulus @ 0°C (32°F).

   See table 2.6 for the ranking.

Table 2.5. Ranking of asphalts in load-associated fatigue bending beam at 20°C (68°F)

Asphalt	Log G_v at 20°C (68°F) Pa	Score	Rating
AAA-1	6.37	8.0	P
AAB-1	6.99	4.5	M
AAC-1	6.99	4.5	M
AAD-1	6.66	6.4	M
AAF-1	7.44	2.1	G
AAG-1	6.98	4.6	M
AAK-1	7.26	3.1	M
AAM-1	7.63	1.0	G

Table 2.6. Ranking of asphalts in load-associated fatigue bending beam at 0°C (32°F)

Asphalt	N_f @ 0°C (32°F) Cycles	Score	Log C* @ 0°C (32°F) Pa	Score	Average Score	Total Score	Rating
AAA-1	15,064	8.0	7.403	1.0	4.5	4.0	M
AAB-1	22,879	4.4	7.640	2.8	3.6	2.4	G
AAC-1	20,147	5.6	7.934	5.1	5.4	5.5	M
AAD-1	23,630	4.0	7.474	1.6	2.8	1.0	G
AAF-1	30,115	1.0	8.047	6.0	3.5	2.2	G
AAG-1	20,088	5.7	8.304	8.0	6.8	8.0	P
AAK-1	18,537	6.4	7.749	3.7	5.0	4.9	M
AAM-1	26,358	2.7	7.910	4.9	3.8	2.8	M

Table 2.7. Ranking of asphalts in load-associated fatigue wheel tracking test at 20°C (68°F)

Asphalt	G_v @ 20°(68°F) Pa	Score	Rating
AAA-1	6.37	8.0	P
AAB-1	6.99	4.5	M
AAC-1	6.99	4.5	M
AAD-1	6.66	6.4	M
AAF-1	7.44	2.1	G
AAG-1	6.98	4.6	M
AAK-1	7.26	3.1	M
AAM-1	7.63	1.0	G

3. Laboratory—slab on elastic foundation, 20°C (68°F). In this test, the passing wheel probably creates shear stresses in the slab that are the primary cause of rutting and crack formation. At this temperature, plastic deformation in the mix is the primary cause of both the cracks and the ruts. Therefore, the viscous modulus (G_v—viscous modulus @ 20°C [68°F]) has been used in the ranking. See table 2.7.

4. Field—classic fatigue failure. As discussed above, this fatigue will only occur when the asphalt cement within a paving mix behaves in a brittle or highly viscoelastic manner. The gel point temperature, at a frequency of 10 rad/s, has been chosen as an estimate of the brittle-ductile transition temperature under traffic-loading conditions. The higher this temperature, the greater the potential for fatigue in the field. The width (standard deviation) of the relaxation spectrum is related to the fracture toughness of the asphalt; toughness and fatigue performance should generally increase with increasing spectrum width.

   a. T_{gp}—temperature @ gel point
   b. S(tau)—width of relaxation spectrum.

   See table 2.8 for a ranking of the asphalts.

Table 2.8. Ranking of asphalts in load-associated fatigue field

Asphalt	T_{gp} (C°)	Score	N_f @ 0°C Cycles	Score	Average Score	Total Score	Rating
AAA-1	1	1.0	15064	8.0	4.5	5.2	M
AAB-1	7	4.5	22879	4.4	4.4	5.0	M
AAC-1	8	5.1	20147	5.6	5.4	7.3	P
AAD-1	2	1.6	23630	4.0	2.8	1.0	G
AAF-1	11	6.8	30115	1.0	3.9	3.7	K
AAG-1	9	5.7	20088	5.7	5.7	8.0	P
AAK-1	5	3.3	18537	6.4	4.9	6.0	M
AAM-1	13	8.0	26350	2.7	5.4	7.3	P

2.2.2 Rutting in Upper Layers of Hot-Mix Asphalt

Rutting is the result of accumulated permanent deformation in the mix, which is related to the viscous deformation within the binder. Rutting also depends on the temperatures to which the paving mix is subjected. For the purpose of testing, 45°C (113°F) was selected as a representative critical temperature for permanent deformation in the field. The viscous modulus (G_v) at the test temperature was used to rank the asphalts' resistance to rutting in both the wheel tracking test and in the field (table 2.9).

Table 2.9. Ranking of asphalts in rutting in hot-mix asphalt wheel tracking test at 45°C (113°F)

Asphalt	Log G_v @ 20°C (68°F) Pa	Score	Rating
AAA-1	6.37	8.0	P
AAB-1	6.99	4.5	M
AAC-1	6.99	4.5	M
AAD-1	6.66	6.4	M
AAG-1	7.44	2.1	G
AAG-1	6.98	4.6	M
AAK-1	7.26	3.1	M
AAM-1	7.63	1.0	G

Table 2.10. Ranking of SHRP tank asphalts for resistance to low-temperature cracking, as indicated by A-002A

Asphalt Type	Temperature @ S(t) = 200 MPa @ 2 h, °C	Ultimate Strain @ -26°C, 2 h, %	Overall Rank 1 = Best
AAA-1	-31	3.1	1
AAB-1	-28	1.7	12
AAC-1	-25	1.5	15
AAE-1	-29	2.1	8
AAF-1	-21	1.2	20
AAG-1	-18	0.8	25
AAH-1	-32	2.1	6
AAJ-1	-25	1.5	15
AAK-1	-27	1.7	12
AAL-1	-30	2.8	3
AAM-1	-24	1.5	16
AAN-1	-24	1.5	15
AAO-1	-28	2.1	9
AAP-1	-27	2.2	9
AAQ-1	-24	1.1	18
AAR-1	-26	1.7	13
AAS-1	-27	2.0	11
AAT-1	-23	1.6	16
AAU-1	-23	1.7	16
AAV-1	-25	1.2	17
AAW-1	-22	1.6	17
AAX-1	-20	1.1	21
AAY-1	-28	1.8	11
AAZ-1	-20	1.2	21
ABA-1	-29	2.4	7
ABC-1	-30	2.2	8
ABD-1	-15	0.5	28

2.2.3 Low-Temperature Thermal Shrinkage Cracking

The selected parameters for predicting thermal shrinkage cracking are the same for both the restrained tensile strength test and field conditions. The glass transition temperature has been selected as an indicator of the temperature at which stresses within the asphalt will begin to accumulate and the strain capacity will decrease during cooling. The energy to failure at 1 percent strain has been included in these rankings as an indicator of the fracture toughness of the asphalt cement. The third parameter used in the rankings is the ratio of flexural stiffness at -15°C (5°F) and at 2 minutes after 96 hours of conditioning at the test temperature, to the value found after only 2 hours of conditioning. This parameter was chosen as an indicator of the potential for physical hardening. The ranking of the asphalts (table 2.10) based on the following properties:

1. T_g—glass transition temperature.
2. Energy to failure at 1 percent strain.
3. Physical hardening at -15°C (5°F).

2.2.4 Moisture Damage

Physical property tests are not available for ranking asphalts' moisture sensitivity.

2.2.5 Aging

According to the Pennsylvania State University (A-002A) researchers, ranking of performance after aging is best measured by testing the asphalt cement and mixes for the specific performance-related parameters. Thus, they recommend that tests for fatigue and other performance indicators be conducted on aged mixes. Correlations with a single point measurement of stiffness are not expected.

2.3 Auburn University—A003B

The following paragraphs are extracted from the A-003B executive summary to the project's final report (Curtis, Ensley, and Epps, 1991).

> An important element of the SHRP A-003B research was to investigate the chemical and physical processes that govern adhesion and absorption. Many different investigations were undertaken to achieve that goal. Some of them were exploratory in nature while others were much more extensive. These studies laid the groundwork for the two major products from this contract: the adhesion and stripping models and the net adsorption test.
>
> The initial asphalt-aggregate model that was proposed postulated the adherence of asphalt at the asphalt-aggregate interface, followed by the

development of a structured interphase region. Beyond the interphase was the bulk asphalt. A new understanding of asphalt-aggregate interactions has emerged from the work of SHRP A-003B in conjunction with research results from other SHRP contractors. During hot-mix processing, asphalt components contact and adhere to the interfacial surface of the aggregate with the more polar constituents, those compounds containing heteroatoms of sulfur, nitrogen or oxygen, being most competitive for the active sites on the surface. Several different methods of measuring the energy of adsorption indicate that physisorption rather than chemisorption is occurring. This interaction can result from electrostatic, dipole-dipole, or Van der Waals interactions. Asphalt once contacted to the aggregate remains stationary; no net migration of polar constituents to the surface from the bulk asphalt is apparent. Some surface diffusion may occur, though, as the mix softens on a hot summer day.

2.3.1 Adhesion

Effect of Chemistry. Aggregate chemistry plays a key role in adhesion. Each aggregate of a given mineralogical type with a specific history has a unique surface chemistry. The electrokinetic properties as well as the electron donating and accepting abilities of the aggregate vary according to the active metal species on the aggregate surface. The active sites on the aggregate surface that have been postulated from observed behavior have been confirmed by autoradiography. These active sites promote adsorption of asphaltic components. The covering of those active sites by nonpolar hydrocarbons completely masks their activity. Dust coatings that naturally occur on aggregate surfaces can change the chemistry of adhesion and result in weak bonding between the dust and aggregate surface, leading to attrition of the bonding forces that help maintain the pavement.

Evaluation of asphalt-aggregate interactions shows that the aggregate chemistry is much more influential than the asphalt composition for both adhesion and sensitivity to water. Large differences were observed in the amount of asphalt adsorbed and the amount of asphalt retained after exposure to water with both siliceous and calcareous aggregates. Although the asphalt compositional factors have a smaller effect, some differences in the amounts adsorbed and retained on a specific aggregate were observed.

No chemical or thermodynamic evidence has been found in this study for the development of a structured interphasal region. Aging experiments that determined the oxidatively aged products in asphalt at the interface and in the 125μm region beyond the interface showed no differentiation in type or concentration of asphalt oxidative products. Heats of interaction only showed an initial release of energy corresponding to the heat released upon initial contact between asphalt and aggregate. No long-term energy release was observed, indicating the lack of structuring. Autoradiography also showed no evidence of structuring.

The asphalt-aggregate mix can be visualized as a system in which large, small and fine aggregate particles are coated with asphalt. The active sites on the particle attract the most polar and bondable asphaltic species upon initial contact, with little or no diffusion of asphaltic species after the mix is cooled. Each asphalt molecule comes in contact with an aggregate or an aggregate surface. The fines that compose 5 to 8 percent of the aggregate are interspersed with the asphalt to form a mastic, a medium in which it is difficult to distinguish between asphalt and aggregate.

Aging. The aging of asphalt in road pavement occurs in the presence of aggregate, so it is natural to evaluate the aging process with aggregate present. SHRP A-003B evaluated the chemistry of the aging process in terms of the production of carbonyls (including ketones and carboxylic acids) and sulfoxides. Sulfoxide production largely depends on the amount of sulfur present in the asphalt. The aggregate chemistry of a granite and a limestone had no effect on the production of these particular functional groups. However, other changes that may have occurred in the asphalt were not measured. In road pavements the ostensible measure of aging is viscosity. Recent research in SHRP contracts A-002A and A-003A suggests that the presence of aggregate decreases the viscosity of asphalt compared with bulk asphalt for equivalent aging times. This difference in viscosity may be caused by the aggregate particles binding some of the oxidative functional groups formed and thereby preventing the formation of viscosity-building species.

Water Sensitivity. Stripping of asphalt from aggregate stems from the intrusion of water into the asphalt-aggregate system. The modes of failure are many and dependent upon the character of the system. The most important modes of failure are:

- diffusion of water through the asphalt film;
- entry of water through cracks in the asphalt film;
- separation of the bond at the interface;
- failure within the asphalt where soluble components are removed; and
- cohesive failure within the aggregate.

If the water-proofing layer of asphalt surrounding an aggregate particle is continuous, then water can penetrate the system by diffusing through the asphalt film, removing along the way those asphaltic components that are solubilized. If cracks occur in the film, then water can intrude to the asphalt-aggregate interface, causing failure at or near the interface. The failure can be interfacial or cohesive either in the asphalt or in the aggregate. Reduction in water damage can be attained by modifying the aggregate surface through silylation or the addition of antistripping agents. However, complete covering of the particle by an asphalt film should decrease the quantity of water reaching the aggregate and reduce the deleterious effect of water on the aggregate. Building of roads with low air voids or good drainage may be most influential in reducing water damage by limiting the exposure of the asphalt-aggregate bond to water.

Resilience of Asphalt-Aggregate Bonds. Adhesion between an asphalt-aggregate pair can be promoted or inhibited by processing and environmental factors. Researchers in SHRP

A-003B evaluated the effect of pH on the asphalt-aggregate bond. High pH which resulted in a very basic medium was detrimental to most asphalt-aggregate bonds; however, treatment at somewhat lower but still basic pH did not affect the bond substantially. Curing at elevated temperatures after mixing promoted adhesion in some asphalt-aggregate pairs. A test involving the factors of increased pH and curing, incorporated into the modified Lottman (AASHTO-283) test, has been suggested as a means of differentiating among asphalt-aggregate combinations. Those particular asphalt-aggregate combinations that do not perform well under chemical preconditioning (high pH) or curing can be treated with additives, either liquid antistripping agents or lime, to improve their performance. Retesting the treated mix under the stringent pH conditions offers a means of determining the effectiveness of the treatment.

2.3.2 Products from the A-003B Research

Two major products were produced from SHRP A-003B: the adhesion and stripping models and the net adsorption test.

The net adsorption test provides a method to determine the affinity of an asphalt-aggregate pair and its sensitivity to water. This test provides a method for selecting asphalt-aggregate pairs and determining their compatibility. The test is composed of two steps. First, asphalt is adsorbed onto aggregate from toluene solution, the amount of asphalt remaining in solution is measured, and the amount of asphalt adsorbed to the aggregate is determined. Second, water is introduced into the system, asphalt is desorbed from the aggregate surface, the asphalt present in the solution is measured, and the amount remaining on the aggregate surface is calculated. The amount of asphalt remaining on the surface after the desorption step is termed "net adsorption." The net adsorption offers a direct means to compare the affinity of different asphalt-aggregate pairs. The test is relatively fast, reliable and readily performed. The net adsorption test predicts the behavior of the SHRP aggregates quite well when using the reputation of the aggregate within its state as the criterion.

For this study, the 11 MRL aggregates were tested with three different aged asphalts: AAD-1, AAK-1, and AAM-1. Although the asphalts differed quite substantially in their chemical composition and characteristics, for a given aggregate the differences in the asphalts' initial adsorption behavior were quite small. Based on the amount adsorbed, the asphalts ranked AAD-1 $\geq$ AAK-1 > AAM-1 for most aggregates, with AAD-1 and AAK-1 occasionally changing positions.

The adsorption behavior of the siliceous aggregates before and after water desorption varied considerably. Two aggregates, RA-granite and RJ-gravel, showed consistently low adsorption and were quite sensitive to water, regardless of the asphalt used. Aggregates RB-granite, RE-gravel, and RG-sandstone, showed similar behavior in their initial asphalt adsorption for the three asphalts; however, RE-gravel tended to show a higher sensitivity to water and an increased amount of asphalt desorbed compared to the other aggregates. The two siliceous aggregates that gave the largest amounts of asphalt adsorption, regardless of asphalt, were RH-greywacke and RK-basalt. Both of these aggregates also had low sensitivity to water.

The MRL limestones used in this study included RC, a highly absorptive limestone, RD, a nonabsorptive limestone, and RF, a calcareous sandstone, a limestone with other types of minerals present. The initial adsorption behavior of the three asphalts was similar on the three limestones and ranked the aggregates RC > RF > RD. However, the moisture sensitivities of these limestones seemed somewhat asphalt dependent, with AAM-1 showing more sensitivity to water than either AAD-1 or AAK-1. RF-limestone yielded a considerably higher amount of desorbed asphalt than did either RC or RD-limestones. Even though the amount of adsorption and desorption for a given aggregate varied somewhat from asphalt to asphalt, the net adsorption, defined as the amount of asphalt remaining on the aggregate, was similar as shown in figure 2.4. The net adsorption ranking of the siliceous aggregates for all three asphalts was RK-basalt > RH-greywacke ≈ RL-gravel > RB-granite > RE-gravel > RG-sandstone > RJ-gravel > RA-granite. The net adsorption of the limestone aggregates ranked as RC > RD ≈ RF.

Additional limestone samples were obtained by SHRP and used in the net adsorption test. See figure 2.4 for the net adsorption for the limestones. The net adsorption ranking of the limestones for all three asphalts was R7 > R3 ≥ R8 > R6 > R1 > R5 > R2. The average net adsorption ranged from a high of 1.27 mg/g on R7 to a low of 0.34 mg/g on R2.

State highway officials from the respective states from which the limestones were obtained provided a classification of the limestones as stripping or nonstripping according to their observed behavior. The behavior of R1, R2 and R7 limestones in the net adsorption test did not agree with that indicated by state highway officials. The reasons for these discrepancies are not known; however, some obvious possibilities include the fact that only a very small fraction of the aggregate was used and because the aggregate was prewashed.

The aggregate properties predominated in the net adsorption test, showing a stronger influence than the asphalt on the initial amount of asphalt adsorbed, the amount of asphalt desorbed by water, and the amount of asphalt remaining, the net adsorption.

The net adsorption test presents an effective means of evaluating the affinity and water sensitivity of an asphalt-aggregate pair and enables prediction of those aggregate materials that will achieve a substantial asphalt coating and maintain that coating in the presence of water. The test also provides a means of predicting which asphalts would be susceptible to water. For the net adsorption test to represent most accurately the aggregates used in road paving, the recommended sample is a minus No. 4 fraction of unwashed aggregate.

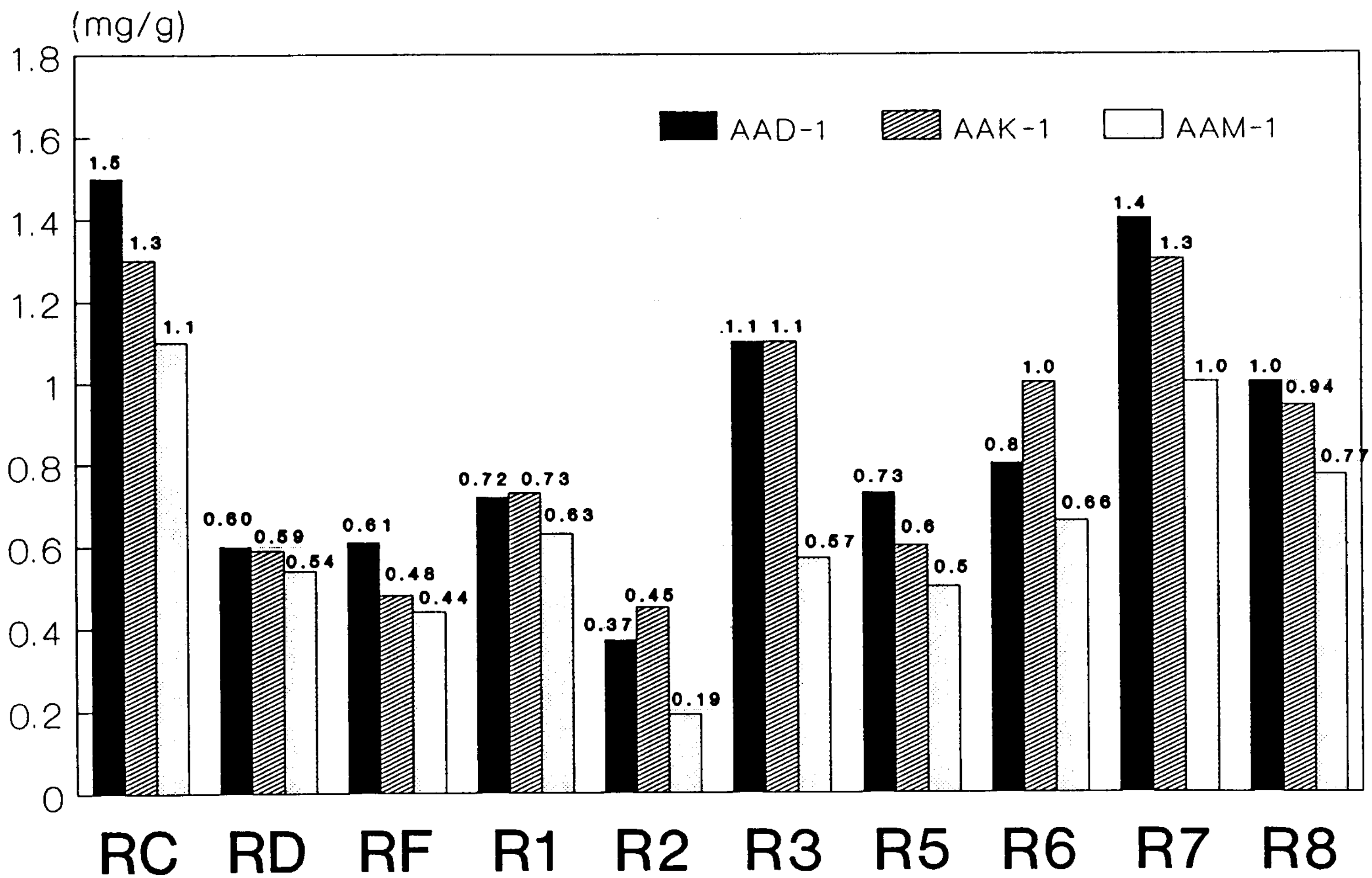

Figure 2.4. Net adsorption of asphalts on various limestones

3

Experiment Design

3.1 Variables

As mentioned earlier, the experiment 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 (275°F) for four hours before compaction. Four different long-term aging processes were examined: low-pressure oxidation (LPO) at 60°C and 85°C (140°F and 185°F), long-term oven aging (LTOA) at 85°C (185°F) for five days, and LTOA at 100°C (212°F) for two days. See table 3.1 for the LPO variables and table 3.2 for the LTOA variables.

3.2 Materials

The materials used for this testing program were selected from materials stored at the Materials Reference Library (MRL).

The aggregates used represent a broad range of aggregate characteristics, from a high-absorption crushed limestone to a river-run gravel. Similarly, the asphalts span a broad range of asphalt grades. See table 3.3 for a brief description of the materials.

3.3 Aging Methods

3.3.1 No Aging

Three specimens were prepared at the time of mixing to represent an "unaged" condition. Their preparation was the same as for other specimens except that they were not cured for

Table 3.1. Low-pressure aging experiment design

No. of asphalts		8
No. of aggregates		4
No. of asphalt contents		1
No. of air voids		1
Test Conditions		
Temperature:	Short term	1 at 135°C (275°F)
	Long term	2 at 60°C and 85°C (140°F and 185°F)
Aging periods		
	None (datum)	1
	Short term and long term	1
Total Tests		
	No aging (unaged)	32
	Short term and long term	64
Replication of unaged		32
Replication of short term and long term		64
TOTAL		192

Table 3.2. Long-term oven-aging experiment design

No. of asphalts		8
No. of aggregates		4
No. of asphalt contents		1
No. of void contents		1
Test Conditions		
Temperature:	Short term	1 at 135°C (275°F)
	Long term	2 at 85°C and 100°C (185°F and 212°F)
Aging Periods		
	None (datum)	1
	Short term and long term	1
Total Tests		
	No aging	32
	Short term and long term	64
Replication of short term and long term		64
TOTAL		160

Table 3.3. 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

four hours at 135°C (275°F). As soon as mixing was complete, the specimens were placed in an oven and brought to the proper equiviscous temperature (665 ± 80 cSt). The specimens were then compacted using a California Kneading Compactor.

3.3.2 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. The procedure is described in detail in Harrigan et al. 1994. The method consists of curing mix samples in a forced-draft oven at 135°C (275°F) for four hours prior to compaction. After curing, the samples are brought to an equiviscous temperature and compacted using a California Kneading Compactor.

3.3.3 Low-Pressure Oxidation

Low-pressure oxidation is a procedure used to simulate long-term aging. It is carried out on compacted specimens after they have been short-term aged. After the specimen is loaded into the cell, a confining pressure is applied to keep the membrane tight around the specimen. Once the confining pressure is achieved, oxygen flow is started through the specimen at a rate of 4 standard cubic feet per hour (scfh) (0.113 cu m/h [m^3/h]). When the oxygen rate has been adjusted, the cell is placed in a water bath that has been preheated to the conditioning temperature, 60°C or 85°C (140°F or 185°F). The cell is left in the conditioning bath for five days, then removed and left to cool to room temperature. The specimens are extracted from the cell and allowed to stand for at least another 24 hours before testing.

3.3.4 Long-Term Oven Aging

Long-term oven aging is also used to simulate long-term aging. The procedure (described in detail in Harrigan et al. 1994) is carried out on compacted specimens after they have been short-term aged. The specimens are placed in a forced-draft oven, pre-heated to 85°C (185°F), and left for five days. Alternately, a temperature of 100°C (212°F) and a period of 2 days is used. After the aging period, the oven is turned off and left to cool to room temperature. The specimens are then removed from the oven and are tested no less than 24 hours later.

3.4 Evaluation Methods

3.4.1 Resilient Modulus

The resilient modulus is determined at 25°C (77°F) using diametral (indirect tension) (American Society for Testing and Materials D4123) and triaxial compression modes of testing with a 0.1-second loading time at a frequency of 1.0 Hz. A constant strain level of 100 microstrain is maintained throughout the test.

3.4.2 Dynamic Modulus

Several specimens were subjected to a thorough dynamic modulus evaluation at temperatures of 0°C (32°F), 25°C (77°F), and 40°C (140°F). Loading frequencies ranging from 15 Hz to 0.01 Hz in 11 steps were used. This testing, called dynamic mechanic analysis (DMA), takes approximately eight hours per specimen; therefore, it was not possible to test all specimens with this procedure. Typical test results are presented in appendix B.

3.4.3 Tensile Strength Test

The tensile strength test is performed after all modulus testing has been completed. A deformation rate of 2 in. (50 mm) per minute is used, with the load and deformation of the specimen monitored continuously until failure occurs. The strains at yield and failure are considered significant, as is the specimen's strength. Broken portions of specimens may be used to obtain recovered asphalt. Appendix A contains tensile strength test data from a small sample of specimens.

4

Results

4.1 Resilient Modulus Data

The results of the resilient modulus test for both diametral and triaxial compression are summarized in tables 4.1 through 4.4 for each aggregate type.

4.1.1 Short-Term Aging Results

See figure 4.1 for the modulus ratios from diametral testing of short-term aged specimens for each of the four aggregates. The asphalts are shown in rank order in each case. (See tables 4.1 through 4.4 for the data used to generate these figures.) The asphalt showing the greatest aging (in terms of modulus change) has the highest ratio in each case. The ratios have been developed by adjusting the modulus values to correspond to the same air void content. This procedure is described in section 4.1.3.

4.1.2 Long-Term Aging Results

See figures 4.2 through 4.5 for the modulus ratios from diametral testing of the long-term aged specimens. These ratios are shown in a format similar to figure 4.1, with rankings based on the ratio of long-term aged modulus to unaged modulus. As with the short-term results, the modulus values were adjusted as described in section 4.1.3. (The data used to generate these tables are also presented in tables 4.1 through 4.4.)

4.1.3 Adjustment of Modulus Data

To analyze the effects of short-term and long-term aging on asphalt-aggregate mixes, 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, 3 specimens, in addition to 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 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 with 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, which could then be used in calculating the short-term and long-term aging ratios.

Table 4.1. Modulus data 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	--

°F = 1.8(°C) + 32

Note: All modulus data are 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 4.1 (continued). Modulus data for aggregate RC

Asphalt	Aging Method	% Air Voids	Modulus Values Diametral Before	After	Triaxial Before	After
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	--
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	587	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	--

°F = 1.8(°C) + 32
Note: All modulus data are 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 4.2. Modulus data for aggregate RD

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	8.6	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
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	--

°F = 1.8(°C) + 32

Note: All modulus data are 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 4.2 (continued). **Modulus data for aggregate RD**

Asphalt	Aging Method	% Air Voids	Modulus Values: Diametral Before	Diametral After	Triaxial Before	Triaxial After
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	--

°F = 1.8(°C) + 32
Note: All modulus data are 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 4.3. Modulus data 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	--

°F = 1.8(°C) + 32
Note: All modulus data are 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 4.3 (continued). Modulus data for aggregate RH

			Modulus Values			
	Aging	% Air	Diametral		Triaxial	
Asphalt	Method	Voids	Before	After	Before	After
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	--
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	--

°F = 1.8(°C) + 32

Note: All modulus data are 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 4.4. Modulus data for aggregate RJ

			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	8.7	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	--

°F = 1.8(°C) + 32

Note: All modulus data are 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 4.4 (continued). **Modulus data for aggregate RJ**

Asphalt	Aging Method	% Air Voids	Modulus Values: Diametral Before	Diametral After	Triaxial Before	Triaxial After
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
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	--

°F = 1.8(°C) + 32

Note: All modulus data are 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.

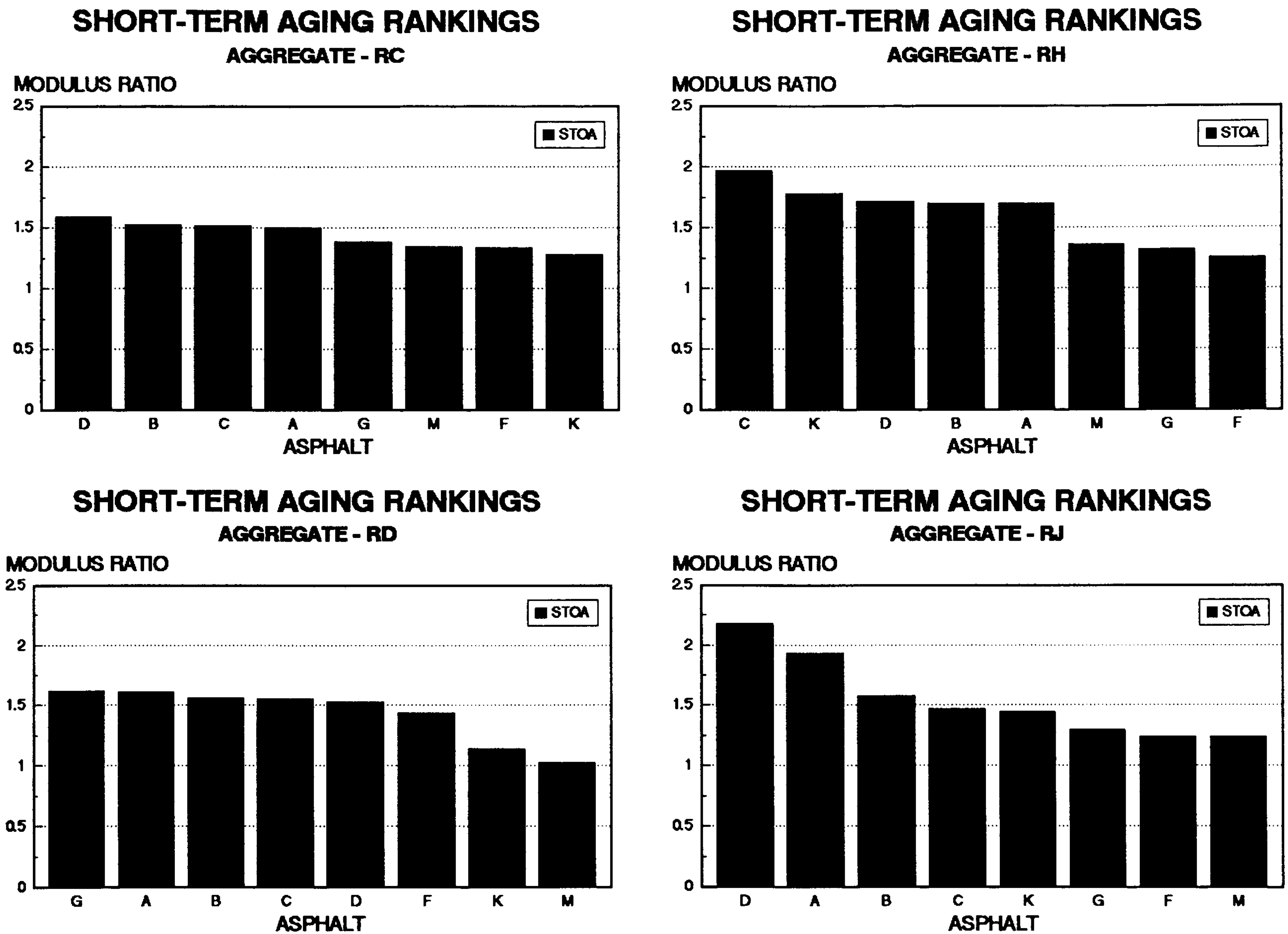

Figure 4.1. Short-term aging: rankings based on diametral modulus

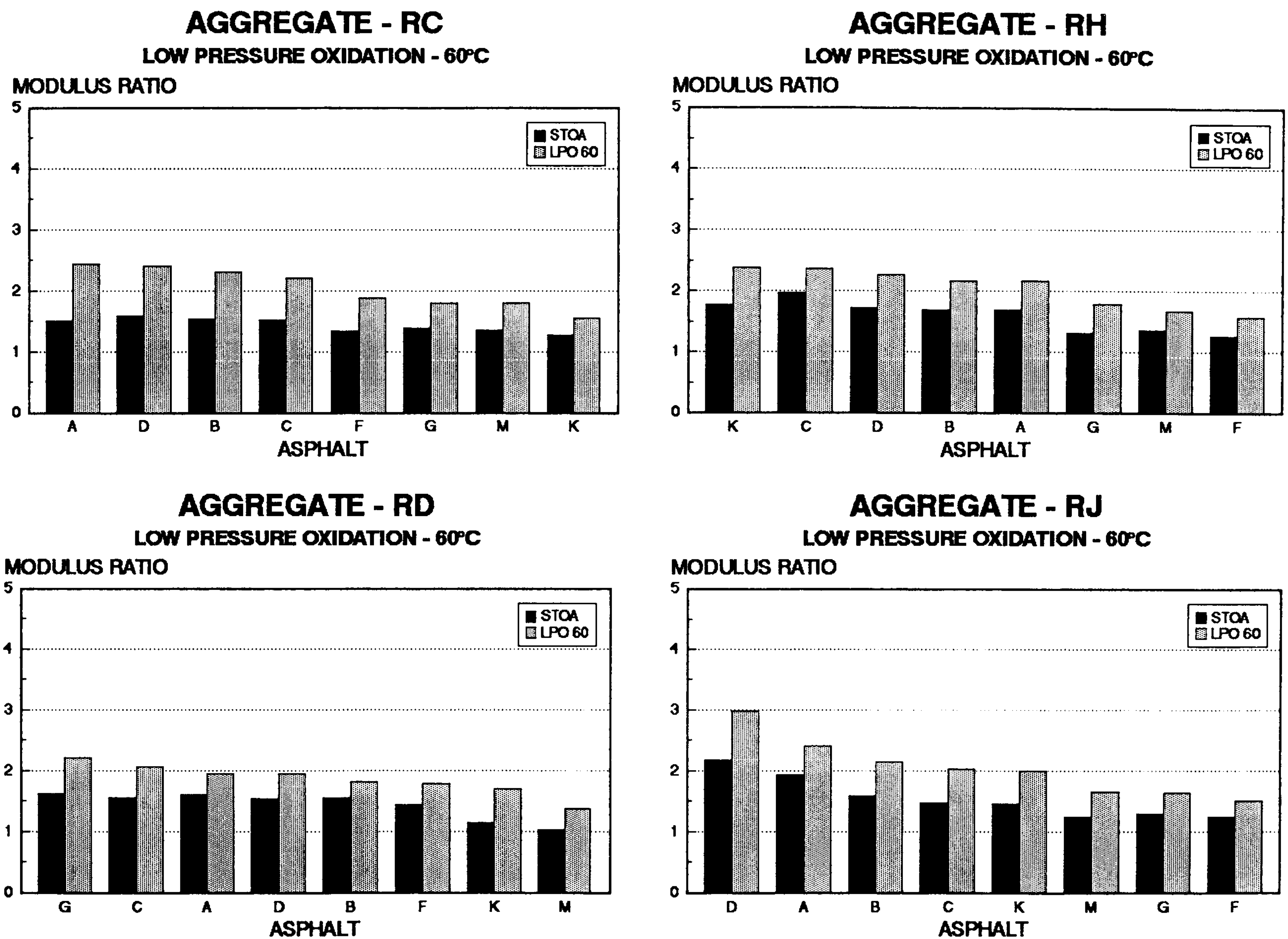

Figure 4.2. Long-term aging by low-pressure oxidation at 60°C: rankings based on diametral modulus

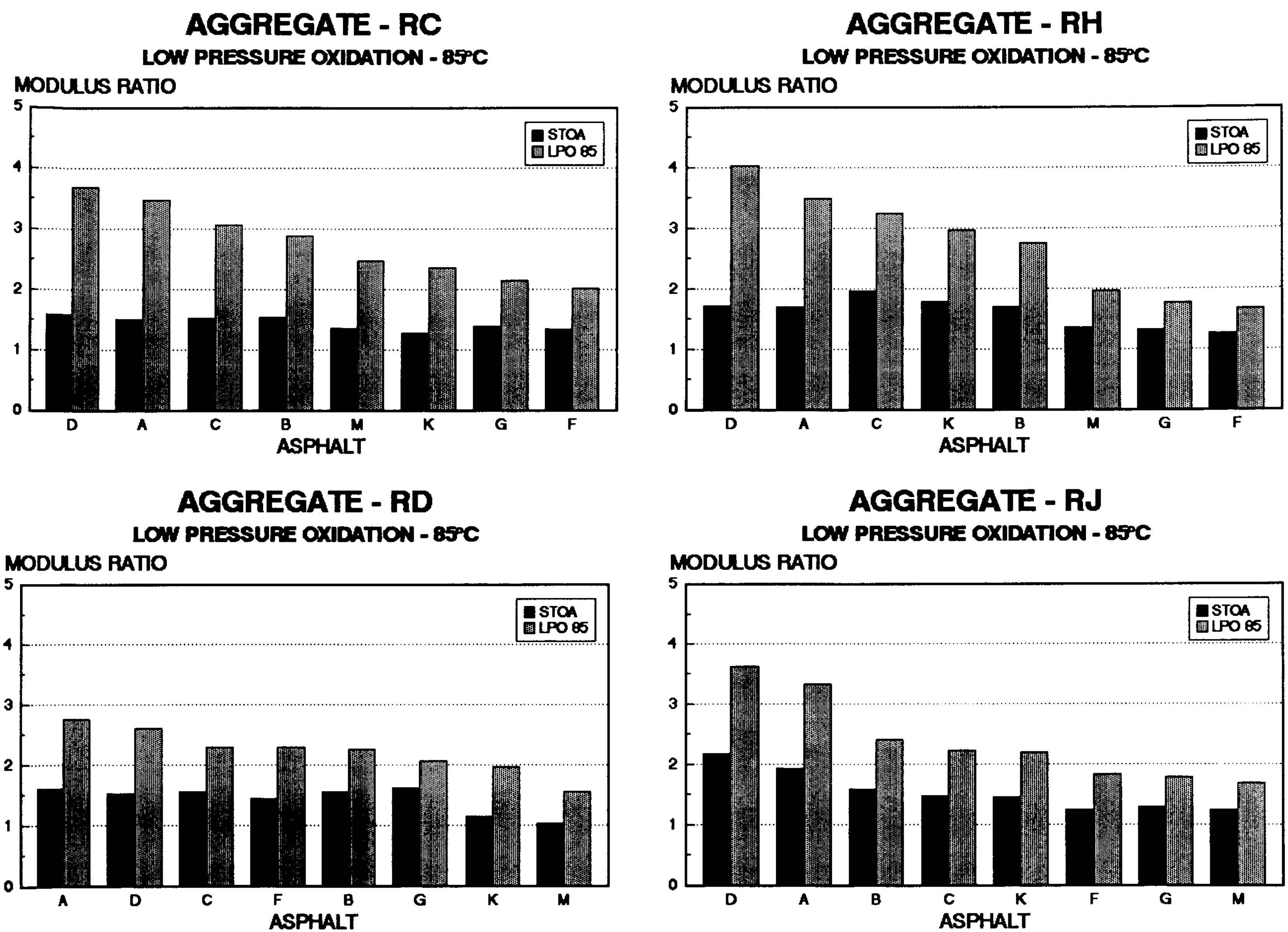

Figure 4.3. Long-term aging by low-pressure oxidation at 85°C: rankings based on diametral modulus

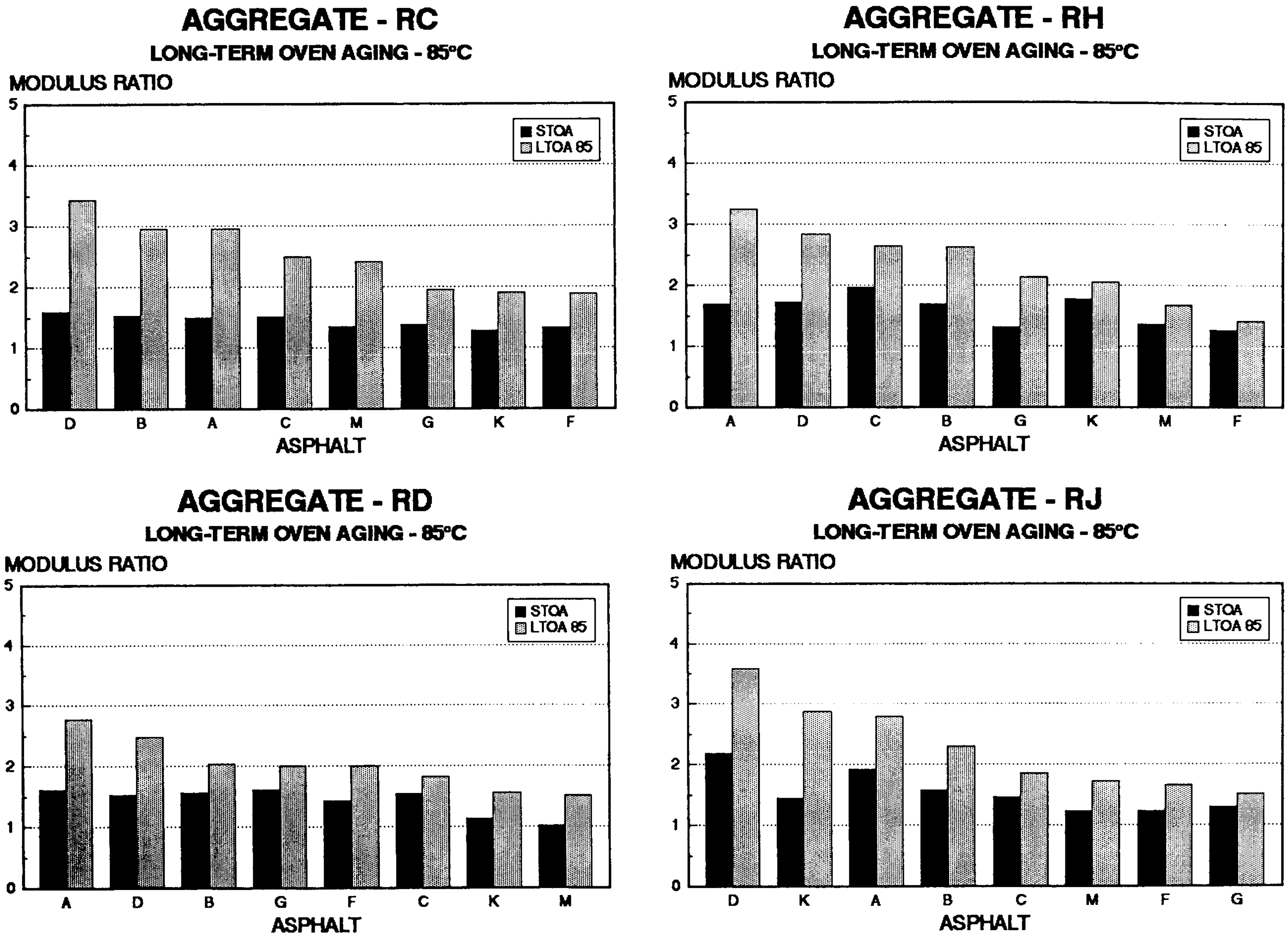

Figure 4.4. Long-term aging by long-term oven aging at 85°C: based on diametral modulus

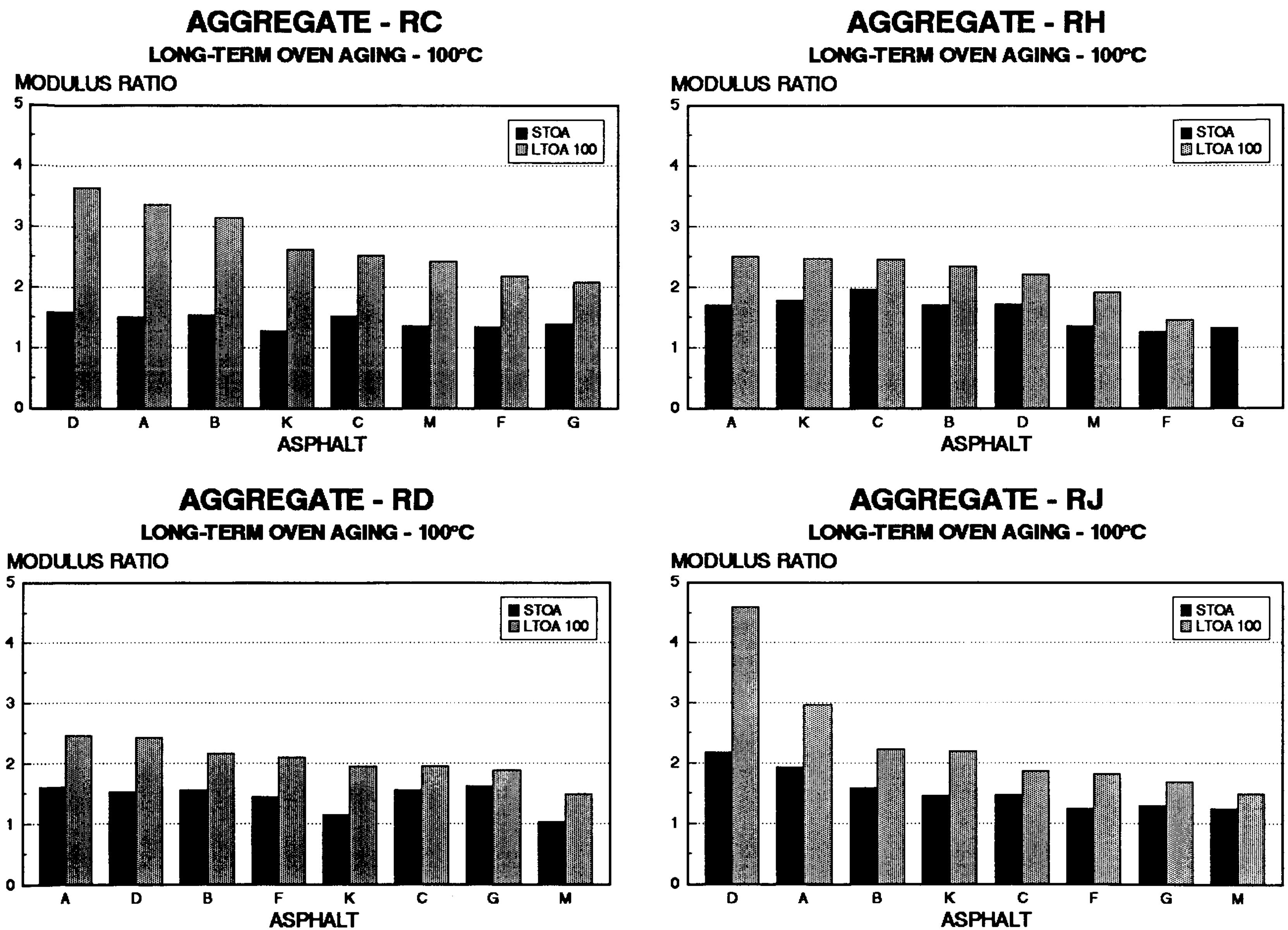

Figure 4.5. Long-term aging by long-term oven aging at 100°C: based on diametral modulus

5

Analysis of Results

5.1 Statistical Analysis

Statistical analysis of the short-term and long-term aging data was completed using the General Linear Model (GLM) procedure in the SAS/STAT software package produced by the SAS Institute, Inc. (1988). Specifically, GLM was used to run analysis of variance (ANOVA) and to rank the asphalts in terms of their aging susceptibility using the Waller-Duncan ranking method.

5.1.1 Data Description

The data were analyzed by aggregate group. The asphalt was the only source variable. Prior to statistical analysis, all of the data were normalized to the same air void content to eliminate the influence of air voids.

The dependent variable in the data analysis was either the short-term or long-term aging ratio. The short-term ratio is defined as the resilient modulus determined after the short-term aging process divided by the adjusted baseline modulus for that particular specimen. The long-term ratio is the resilient modulus value taken after a particular long-term aging procedure divided by the adjusted baseline modulus for that specimen.

5.1.2 Waller-Duncan Groupings

The ANOVA F statistic reveals that there are statistically significant differences in the means, although it does not tell us which ones are different. This information is determined using the Waller-Duncan method. The Waller-Duncan method uses a different set of assumptions than most other methods that rank groups by multiple comparison.

Waller-Duncan minimizes the Bayes risk under additive loss rather than control the type I error rates as do most of the other methods. The Waller-Duncan method is less conservative in grouping means together than most other methods and thus allows more distinct groups to be formed within the analysis.

5.2 Short-Term Aging of Asphalt-Aggregate Mixes

The data presented in figure 4.1 suggest that aging susceptibility of mixes is aggregate dependent. However, the effect of asphalt is more significant. The rankings of the eight asphalts based on short-term aging 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 acidic aggregates (RH and RJ). The observed aging phenomenon appears related to adhesion of the asphalt and aggregate. A hypothesis is that the greater the adhesion, the greater the mitigation of aging. It should be noted that there is not a statistically significant difference among all asphalts. Rather, for a particular aggregate, two or more asphalts show a similar degree of aging. See table 5.1 for an illustration of this fact. The numerical rankings correspond to the short-term aging rankings shown in figure 4.1. The asphalts within the bracketed areas are groups of statistically similar aging ratios as determined by Waller-Duncan groupings. Examination of the groupings reveals that only asphalt AAM-1 is consistently in the lowest group and only asphalt AAD-1 is consistently in the upper group.

5.3 Long-Term Aging of Asphalt-Aggregate Mixes

The data for long-term aging (figures 4.2 through 4.5) support those for short-term aging; that is, they suggest that aging is aggregate dependent as well as asphalt dependent. See tables 5.2 through 5.5 for numerical rankings of the data. The rankings reveal which groups of asphalt are statistically similar, again using Waller-Duncan groupings. Note that there appears to be greater differentiation among asphalts following long-term aging as opposed to short-term aging, and that this differentiation becomes more pronounced with the severity of the aging procedure.

5.4 Comparison of Mix Aging by Short-Term and Long-Term Aging Methods

The numerical rankings of aging presented in tables 5.1 through 5.5 are summarized in table 5.6. Comparison of the short-term and long-term aging rankings shows that small movements in the rankings are common. However, when the short-term rankings are used as a datum, only a few asphalts move more than two places. These comparisons imply that the low-pressure oxidation technique relates more closely to short-term oven aging rankings than does the long-term oven aging procedure. This situation may be due to the greater potential for specimen damage in long-term oven aging, which causes greater variability in the long-term oven-aged specimens. Remember that the short-term aging rankings are

Table 5.1. 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-Duncan groupings of statistically similar behavior are identified with floating lines.

Table 5.2. Long-term aging by low-pressure oxidation at 60°C (140°F): rankings by aggregate

Aggregate	Ranking														
RC	A	>	D	>	B	>	C	>	F	>	G	>	M	>	K
	2.44		2.40		2.31		2.21		1.88		1.80		1.80		1.56
RD	G	>	C	>	A	>	D	>	B	>	F	>	K	>	M
	2.21		2.07		1.95		1.95		1.82		1.78		1.70		1.37
RH	K	>	C	>	D	>	B	>	A	>	G	>	M	>	F
	2.38		2.36		2.26		2.17		2.17		1.79		1.67		1.58
RJ	D	>	A	>	B	>	C	>	K	>	M	>	G	>	F
	2.99		2.40		2.14		2.03		1.99		1.66		1.63		1.51

Note: Waller-Duncan groupings of statistically similar behavior are identified with floating lines.

Table 5.3. Long-term aging by low-pressure oxidation at 85°C (185°F): 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-Duncan groupings of statistically similar behavior are identified with floating lines.

Table 5.4. Long-term oven aging at 85°C (185°F): 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-Duncan groupings of statistically similar behavior are identified with floating lines.

Table 5.5. Long-term oven aging at 100°C (212°F): rankings by aggregate

Aggregate	Ranking														
RC	D	>	A	>	B	>	K	>	C	>	M	>	F	>	G
	3.63		3.36		3.14		2.62		2.52		2.42		2.18		2.07
RD		>	D	>	B	>	F	>	K	>	C	>	G	>	M
	2.46		2.42		2.16		2.09		1.95		1.95		1.88		1.49
RH	A	>	K	>	C	>	B	>	D	>	M	>	F		G
	2.51		2.48		2.45		2.34		2.21		1.91		1.45		
RJ	D	>	A	>	B	>	K	>	C	>	F	>	G	>	M
	4.59		2.97		2.22		2.19		1.86		1.81		1.68		1.49

Note: Waller-Duncan groupings of statistically similar behavior are identified with floating lines.

Table 5.6. 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 (140°F)				Low-Pressure Oxidation at 85°C (185°F)				Long-Term Oven Aging at 85°C (185°F)				Long-Term Oven Aging at 100°C (212°F)			
	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	$\underline{A_{\uparrow}^{4}}$	D	D	A	$\underline{A_{\uparrow}^{4}}$	D
	B	A	K	A	D	C	C	A	A	$\underline{D_{\uparrow}^{3}}$	$\underline{A_{\uparrow}^{3}}$	A	B	$\underline{D_{\uparrow}^{3}}$	D	$\underline{K_{\uparrow}^{3}}$	A	$\underline{D_{\uparrow}^{3}}$	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	$\underline{G_{3}^{\downarrow}}$	B	B	$\underline{K_{\uparrow}^{4}}$	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	$\underline{G_{5}^{\downarrow}}$	M	F	G	C	$\underline{K_{4}^{\downarrow}}$	M	M	C	M	F
	F	K	G	F	M	K	M	G	G	K	G	G	K	K	M	F	F	$\underline{G_{6}^{\downarrow}}$	F	G
Best	K	M	F	M	K	M	F	F	F	M	F	M	F	M	F	G	$\underline{G_{3}^{\downarrow}}$	M		M

Note: An underlined cell indicates 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.

based on data from eight specimens, while those for long-term aging are based on data from only two specimens. Hence, greater variability in the data is expected for long-term aging.

5.5 Comparison of Mix Aging with Asphalt Aging

Aging of asphalt cement has been carried under the Strategic Highway Research Program (SHRP) A-002A contract. Data for original (tank), thin-film oven (TFO) aged, and pressure-aging vessel (PAV) aged asphalt have been presented in several A-002A reports and have been summarized by Christensen and Anderson (1992). As with the mix-aging data, the asphalt-aging data can be used to calculate an aging ratio based on the aged viscosity at 60°C (140°F) compared with the original viscosity at 60°C (140°F). The asphalts can then be ranked in order of aging susceptibility. See table 5.7 for the routine asphalt data and the calculated viscosity ratios.

5.5.1 Short-Term Aging

See table 5.8 for rankings of mixes based on short-term aging and of asphalts based on TFO aging. Note that TFO aging is analogous to short-term mix aging and that (as with mix rankings) the differences among some asphalts are not statistically significant. Nevertheless, there is little relationship between the mix rankings and the asphalt rankings with the following exceptions. Asphalt AAM-1 is one of the two "best" asphalts in both mix and asphalt short-term aging; asphalt AAK-1 is one of the two "worst" from asphalt TFO aging and one of the two "best" if short-term oven aging with aggregates RC and RD is considered.

5.5.2 Long-Term Aging

See table 5.9 for rankings of mixes based on long-term aging by low-pressure oxidation at 85°C (185°F) and rankings of asphalt developed from the data reported by Christensen and Anderson (1992). Also summarized are rankings developed from data reported by Petersen et al. (1994, forthcoming) for asphalt recovered from mixes of single-size fine aggregate and from asphalt subjected to pressure aging.

As with the short-term aging comparisons, there is little similarity between the rankings for long-term aging of mixes and those for asphalt alone. In fact, there is even less similarity, since asphalt AAM-1 appears to have more susceptibility to long-term aging in the PAV than it does in the TFO (relative to the other asphalts), as shown by its movement in the rankings.

There is greater similarity between the rankings based on mix aging and those based on data for fine-aggregate mixes developed under SHRP project A-003A.

Table 5.7. 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

Table 5.8. Comparison of rankings for short-term aging mixes and asphalt alone

	Ranking of Asphalt					
	A-003A[a]					A-002A[b]
	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

[a]Based on short-term aging ratios from diametral modulus.
[b]Based on data reported by Christensen and Anderson (1992).

Table 5.9. Comparison of rankings for long-term aging of mixes and asphalts

	Ranking of Asphalts								
	A-003A[a]				A-002A[b]	A-002A[c]		A-002A[d]	
	Aggregate RC	Aggregate RD	Aggregate RH	Aggregate RJ	No Aggregate	Aggregate RD	Aggregate RJ	Aggregate RD	Average of A-003A Rankings
Worst	D	A	D	D	D	F	D	F	D
	A	D	C	A	F	$M^{6}_{\uparrow}$	B	$M^{6}_{\uparrow}$	A
	C	C	A	B	M	D	$F^{3}_{\uparrow}$	C	C
	B	F	C	C	K	C	C	D	B
	M	B	K	K	C	$A^{\downarrow}_{3}$	$M^{3}_{\uparrow}$	G	K
	K	G	M	F	B	K	$A^{\downarrow}_{4}$	$A^{\downarrow}_{4}$	F
	G	K	G	G	A	G	K	$B^{\downarrow}_{3}$	G
Best	F	M	F	M	G	$B^{\downarrow}_{4}$	G	K	M

[a]Based on long-term aging ratios from diametral modulus for low-pressure oxidation aging.
[b]Based on data reported by Christensen and Anderson (1992) for TFO-PAV aging.
[c]Based on data reported by Petersen et al. (1994, forthcoming).
[d]Based on data reported by Petersen et al. (1994, forthcoming). Asphalt *alone* was subjected to TFO aging prior to mixing and PAV aging. PAV aging at 60°C (140°F) for 144 hours. Prior short-term aging.

5.6 General Discussion

The differences in rankings between mixes and asphalt based on either short-term or long-term aging data indicate the need for testing to evaluate the aging susceptibility of a mix. Clearly, the aging of asphalt alone or in a fine-aggregate mix does not indicate how a mix will age. Testing is needed to determine the influence of the aggregate on mix aging. This influence appears to be related to the chemical interaction of the aggregate and the asphalt, which may be related to adhesion: the greater the adhesion, the greater the mitigation of aging. The mix-aging rankings in tables 5.7 and 5.8 suggest this hypothesis, since the rankings are similar for two basic aggregates (RC and RD) and for the two acidic aggregates (RH and RJ). Some asphalts rank similarly regardless of the aggregate type, while others (such as AAG-1 and AAK-1) behave very differently, depending on the aggregate type. Asphalt AAG-1 for example was lime treated in the refining process and thus exhibited good adhesion and a reduced aging tendency with the acidic aggregates (RH and RJ), as the short-term aging data indicate (table 5.7). However, the rankings of asphalt AAG-1 for long-term aging do not appear to be influenced by aggregate type. Asphalt AAK-1 is unusually chemically active. Thus, its high aging tendency when subjected to TFO aging is due to its reactivity. This reactivity appears to mitigate its tendency to age when in a mix, particularly with basic aggregates.

Tensile test data and dynamic modulus data using frequency sweep testing (dynamic mechanical analysis, DMA) for a subset of the 32 mixes used are presented in appendixes A and B, respectively. As mentioned in the appendixes, both the tensile strength test and the DMA procedure differentiate among the aging methods and different mixes. The tensile strength test is not as sensitive to aging changes as the resilient modulus test. DMA data are much more difficult to interpret than the resilient modulus data. For these reasons, resilient modulus was the measurement tool used most extensively in this analysis.

A major drawback to the comparison included here is the use of resilient modulus values that were determined at one loading time and at one temperature to generate rankings of aging susceptibility. The use of DMA parameters, which describe behavior over a wide range of conditions, is much more desirable. Similarly, the use of viscosity at 60°C (140°F) to generate rankings of asphalt aging susceptibility is much less desirable than considering asphalt DMA parameters such as those developed for the A-002A project. Time constraints did not permit comparisons of mix and asphalt DMA parameters.

Another problem with the comparisons made herein is the difference in the definition of an "unaged" condition for mixes and asphalt. The unaged condition for mixes can only be defined by tests on laboratory specimens that are compacted immediately after mixing. Inevitably, the mixing process ages asphalt, perhaps by a substantial amount. This situation contrasts with the unaged condition of asphalt, which is defined by tests on the original asphalts and represents a true unaged condition.

6

Conclusions and Recommendations

6.1 Conclusions

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

1. The aging of asphalt-aggregate mixes is influenced by both the asphalt and the aggregate.

2. Aging of the asphalt alone and subsequent testing does not appear to predict adequately mix performance because of the apparent mitigating effect that aggregate has on aging.

3. The aging of certain asphalts is strongly mitigated by some aggregates but not by others. This variability appears related to the strength of the chemical bonding (adhesion) between the asphalt and aggregate.

4. The short-term aging procedure produces a change in resilient modulus of up to a factor of two. For a particular aggregate, there is not a 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 three long-term aging methods produced somewhat different rankings of aging susceptibility when compared with the short-term aging procedure and with each other. This outcome is partially due to variability in the materials, aging processes, and testing. However, the short-term aging procedure does not appear to enable prediction of long-term aging.

6. The low-pressure oxidation method of long-term aging causes the most aging and least variability in aging susceptibility rankings relative to the short-term aging rankings.

6.2 Recommendations

Based on the results of this study and the companion test selection and field validation test program, the following recommendation are made:

1. Oven aging of loose mix at 135°C (275°F) is recommended for short-term aging. An aging period of 4 hours appears to be appropriate.

2. Oven aging of compacted mixes should be adopted for long-term aging of dense mixes. A temperature of 85°C (185°F) for five days is most appropriate for the procedure. It may be possible to use a temperature of 100°C (212°F) for two days, but such a high temperature may damage the specimens.

3. A low-pressure oxidation (triaxial cell) technique is recommended for long-term aging of open-graded mixes or densely graded mixes using soft grades of asphalt. A temperature of 85°C (185°F) for five days is most appropriate for this procedure. It may be possible to use a temperature of 100°C (212°F) for two days, but such a high temperature may damage the specimens.

7

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Appendix A

Tensile Strength Test Results

Test Procedure

Table A.1. Tensile strength test results for aggregate RC

Aging	Binder	Tensile Strength (psi)	Final Modulus (ksi)	Strain at Yield (μ-strain)
LPO 85	AAD	196	645	2085
LPO 60	AAD	135.5	450	2073
LTOA 85	AAD	181	615	1926
LTOA 100	AAD	156.5	611	2147
BASE	AAD	87.9	182	3067
LPO 85	AAF	259.4	891	1141
LPO 60	AAF	264	898	1423
LTOA 85	AAF	233.4	943	2208
LTOA 100	AAF	220.1	1004	810
BASE	AAF	185.5	458	1914
LPO 85	AAM	163.6	763	1298
LPO 60	AAM	157.8	580	1055
LTOA 85	AAM	156.4	796	1704
LTOA 100	AAM	140.9	750	1177
BASE	AAM	120.4	346	2624

Table A.2. Tensile strength test results for aggregate RH

Aging	Binder	Tensile Strength (psi)	Final Modulus (ksi)	Strain at Yield (μ-strain)
LPO 85	AAD	185.1	553	2564
LPO 60	AAD	127.1	316	3853
LTOA 85	AAD	138.5	385	4638
LTOA 100	AAD	131.1	348	2539
BASE	AAD	100.8	174	5521
LPO 85	AAF	288.8	982	1937
LPO 60	AAF	264.9	1014	1802
LTOA 85	AAF	259.7	918	1975
LTOA 100	AAF	230	855	1377
BASE	AAF	215	673	3299
LPO 85	AAM	169.8	563	1890
LPO 60	AAM	149.5	521	2810
LTOA 85	AAM	154.6	479	2932
LTOA 100	AAM	146.5	560	2847
BASE	AAM	140.4	338	4675

Table A.3. Rankings for LPO, 85°C (185°F)

Specimen	Tensile Strength Ratio	Rank	Strain @ Yeild	Rank	Diametral Modulus Ratio	Rank	DMA Ratio	Rank
DC	2.23	1	0.68	1	3.7	1	4.3	1
FC	1.39	2	0.60	2	1.9	3	2.6	2
MC	1.37	3	0.40	3	2.4	2	2.2	3
DH	1.85	1	0.47	2	3.1	1	2.3	2
FH	1.34	2	0.59	1	1.6	3	1.8	3
MH	1.21	3	0.40	3	1.9	2	2.6	1

Table A.4. Rankings for LTOA, 85°C (185°F)

Specimen	Tensile Strength Ratio	Rank	Strain @ Yeild	Rank	Diametral Modulus Ratio	Rank	DMA Ratio	Rank
DC	2.06	1	0.625	3	3.3	1	3.6	1
FC	1.25	3	1.16	1	2.0	3	2.0	2
MC	1.30	2	0.65	2	2.4	2	1.6	3
DH	1.39	1	0.47	2	2.7	1	1.8	1
FH	1.20	2	0.59	1	1.4	3	1.5	3
MH	1.10	3	0.40	3	1.6	2	2.6	2

Table A.5. Rankings for LTOA, 100°C (212°F)

Specimen	Tensile Strength Ratio	Rank	Strain @ Yeild	Rank	Diametral Modulus Ratio	Rank	DMA Ratio	Rank
DC	1.78	1	0.70	1	3.5	1	2.4	1
FC	1.18	2	0.423	3	2.1	3	1.8	2
MC	1.04	3	0.45	2	2.4	2	1.3	3
DH	1.31	1	0.46	2	2.0	1	2.7	1
FH	1.07	2	0.42	3	1.4	3	1.4	3
MH	1.04	3	0.61	1	1.9	2	2.0	2

Appendix B

Dynamic Mechanical Analysis

Test Method

Table B.1. Percent air voids for each asphalt-aggregate combination

Aggregate	Asphalt	Specimen #		Percent Void	
RH	AAD-1	1	7	6.3	6.6
		2	8	8.4	6.9
		3	9	8.9	6.2
		4	10	7.3	6.9
		5	11	8.0	5.6
		6		7.8	
RH	AAF-1	1	7	6.9	7.5
		2	8	8.0	7.5
		3	9	7.4	7.2
		4	10	8.0	7.2
		5	11	6.6	6.5
		6		7.2	
RH	AAM-1	1	7	6.8	7.1
		2	8	7.4	7.0
		3	9	7.1	5.8
		4	10	7.2	5.1
		5	11	6.6	4.6
		6		6.5	
RC	AAD-1	1	7	9.3	9.3
		2	8	8.8	9.0
		3	9	9.6	8.2
		4	10	9.0	8.1
		5	11	8.9	8.5
		6		9.4	
RC	AAF-1	1	7	9.3	9.1
		2	8	8.8	9.7
		3	9	7.8	9.0
		4	10	9.4	9.9
		5	11	9.0	9.1
		6		9.0	
RC	AAM-1	1	7	8.9	9.2
		2	8	8.1	8.5
		3	9	8.0	8.3
		4	10	8.6	9.0
		5	11	8.5	7.9
		6		9.0	

Table B.2. Resilient modulus ratio for short-term and long-term oven aging

Aggregate	Asphalt	Aging Ratio			
		Short-Term Oven	Long-Term Oven @ 100°C (212°F)	Long-Term Oven @ 85°C (185°F)	Low-Pressure Oxidation @ 85°C (185°F)
RC	AAD-1	1.59	3.69	3.43	3.63
	AAF-1	1.34	2.01	1.90	2.18
	AAM-1	1.35	2.47	2.41	2.42
RH	AAD-1	1.72	4.03	2.84	2.21
	AAF-1	1.26	1.67	1.41	1.45
	AAM-1	1.36	1.97	1.67	1.91

Table B.3. Complex modulus (ksi) data selected at frequencies of 0.001, 1, and 1,000 Hz

Aggregate	Asphalt	Frequency	Complex Modulus (ksi)				
			Unaged	Short-Term Oven @ 135°C	Long-Term Oven @ 100°C	Long-Term Oven @ 85°C	Low Pressure Oxidation @ 85°C
RC	AAD-1	0.001	42	50	105	155	195
		1	280	330	670	1020	1190
		1000	1400	1620	2180	2900	3300
	AAF-1	0.001	69	100	180	210	330
		1	710	890	1250	1450	1850
		1000	2320	2650	3050	3300	4000
	AAM-1	0.001	50	85	160	130	215
		1	470	610	960	800	1200
		1000	1450	1950	2350	2100	2700
RH	AAD-1	0.001	35	42	65	48	55
		1	190	280	520	340	430
		1000	1680	2000	2420	2050	2150
	AAF-1	0.001	60	70	120	140	170
		1	740	890	1000	1100	1300
		1000	2750	3000	3100	3200	3400
	AAM-1	0.001	50	68	70	79	125
		1	495	550	650	770	1080
		1000	1950	2200	2350	2500	3050

Table B.4. Complex modulus ratio selected at frequencies of 0.001, 1, and 1,000 Hz

Aggregate	Asphalt	Frequency	Complex Modulus Ratio[a]				
			Unaged	Short-Term Oven @ 135°C	Long-Term Oven @ 100°C	Long-Term Oven @ 85°C	Low-Pressure Oxidation @ 85°C
RC	AAD-1	0.001	1.0	1.2	2.5	3.7	4.6
		1	1.0	1.2	2.4	3.6	4.3
		1000	1.0	1.2	1.6	2.1	2.4
	AAF-1	0.001	1.0	1.4	2.6	3.0	4.8
		1	1.0	1.3	1.8	2.0	2.6
		1000	1.0	1.1	1.3	1.4	1.7
	AAM-1	0.001	1.0	1.4	1.4	1.6	2.5
		1	1.0	1.1	1.3	1.6	2.2
		1000	1.0	1.1	1.2	1.3	1.6
RH	AAD-1	0.001	1.0	1.2	1.9	1.4	1.6
		1	1.0	1.5	2.7	1.8	2.3
		1000	1.0	1.2	1.4	1.2	1.3
	AAF-1	0.001	1.0	1.2	2.0	2.3	2.8
		1	1.0	1.2	1.4	1.5	1.8
		1000	1.0	1.1	1.1	1.2	1.2
	AAM-1	0.001	1.0	1.7	3.2	2.6	4.3
		1	1.0	1.3	2.0	1.7	2.6
		1000	1.0	1.3	1.6	1.4	1.9

[a]Ratio calculated by dividing with unaged complex modulus.

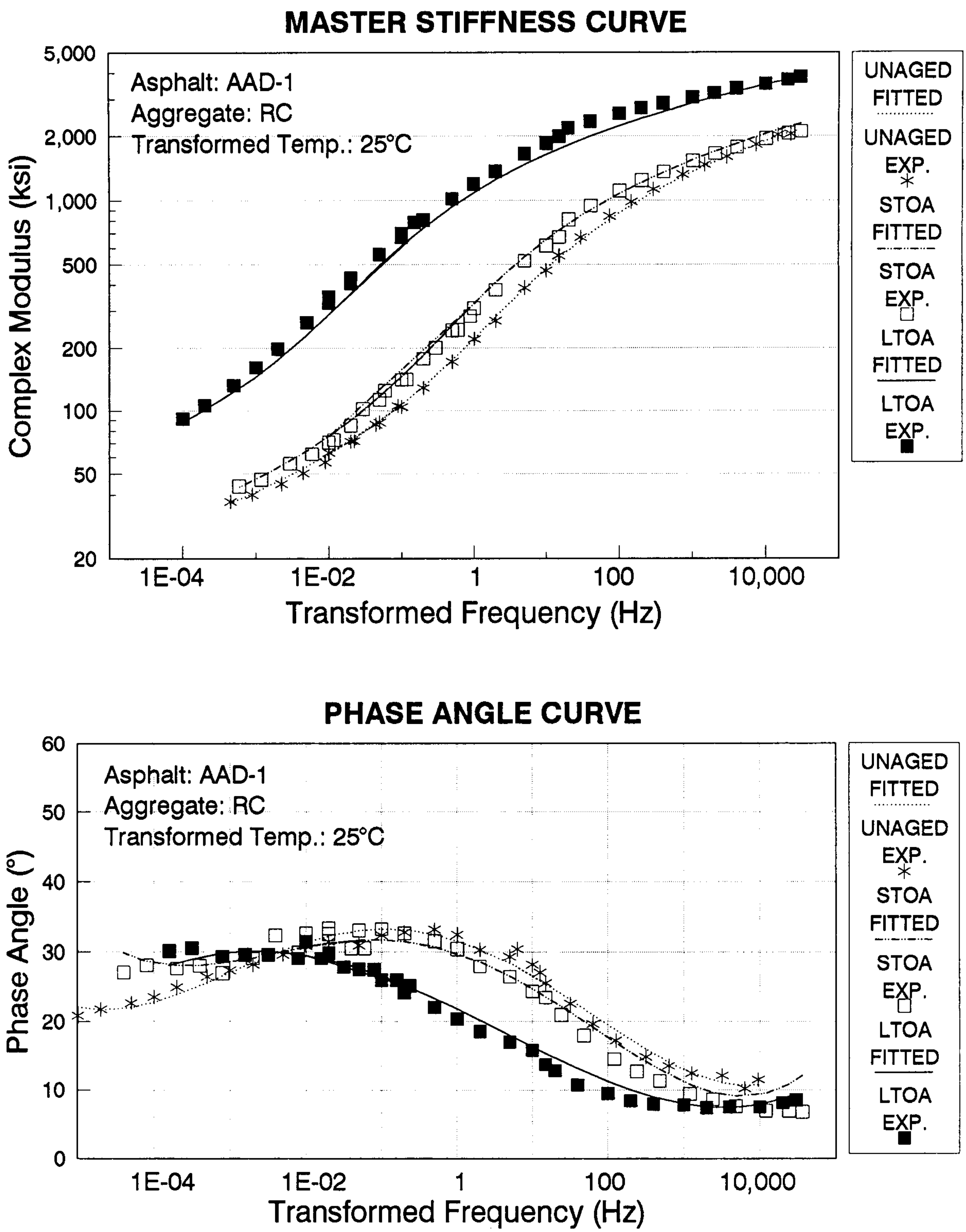
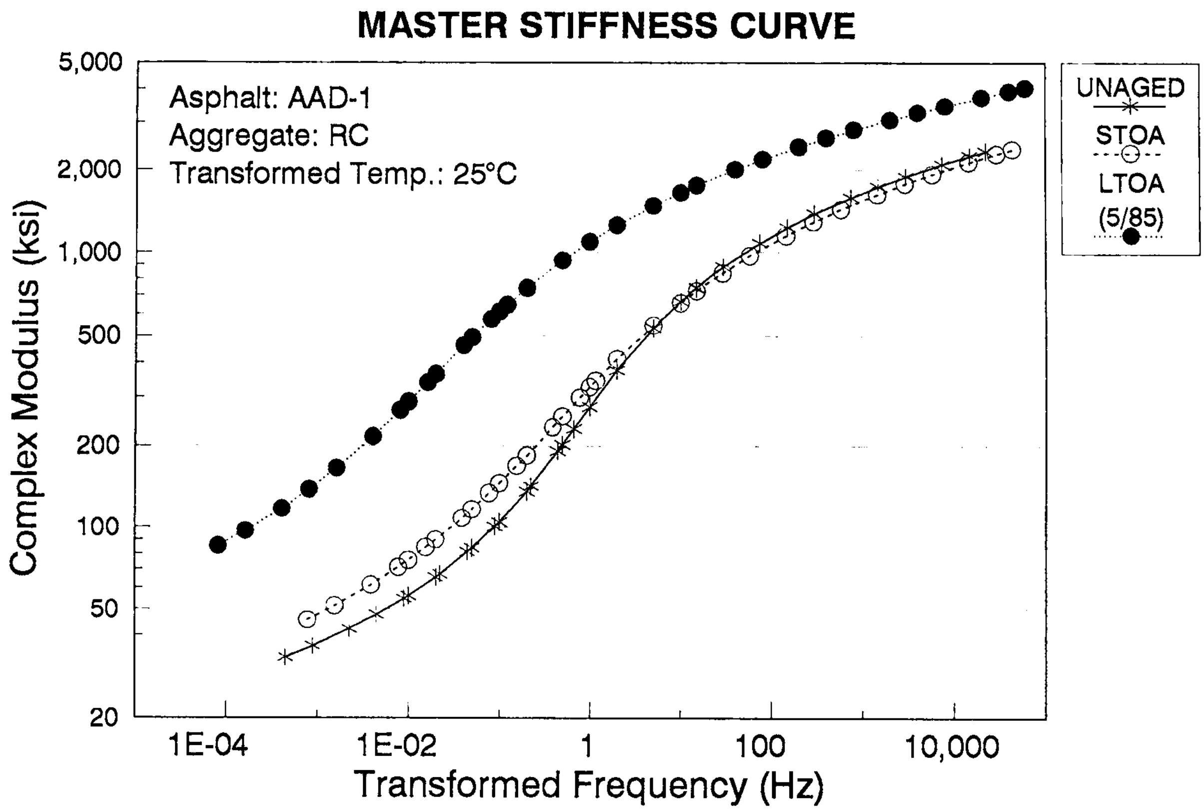


Figure B.1. Experimental data and regression data for master curve and phase angle curve



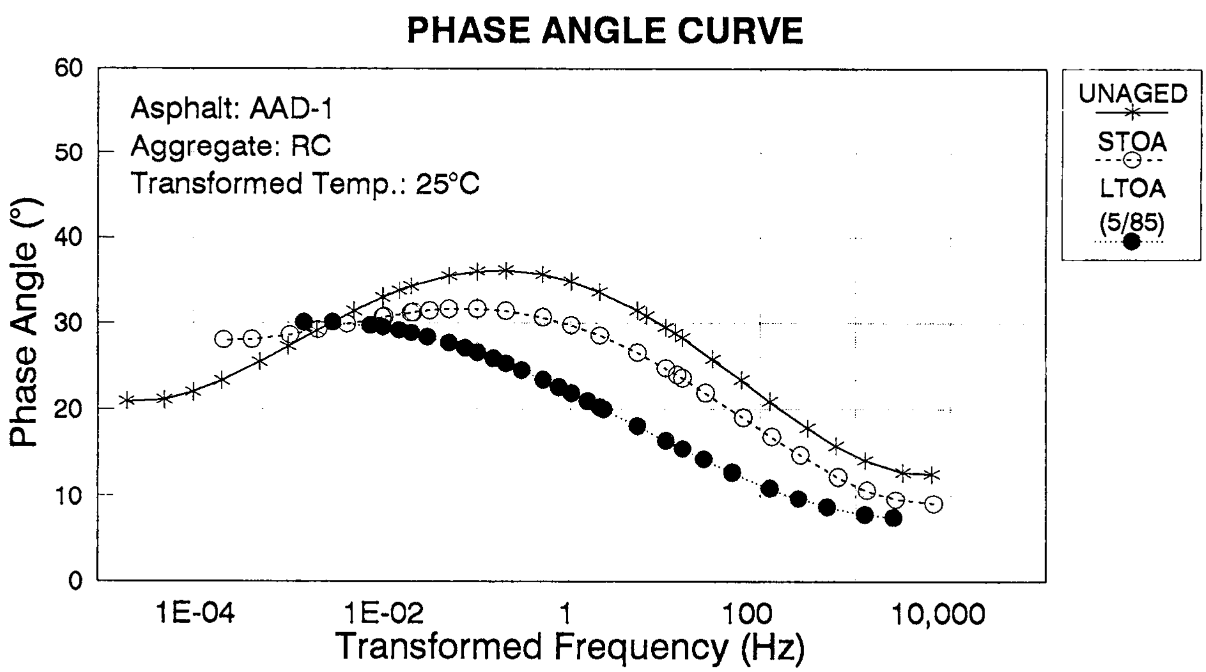
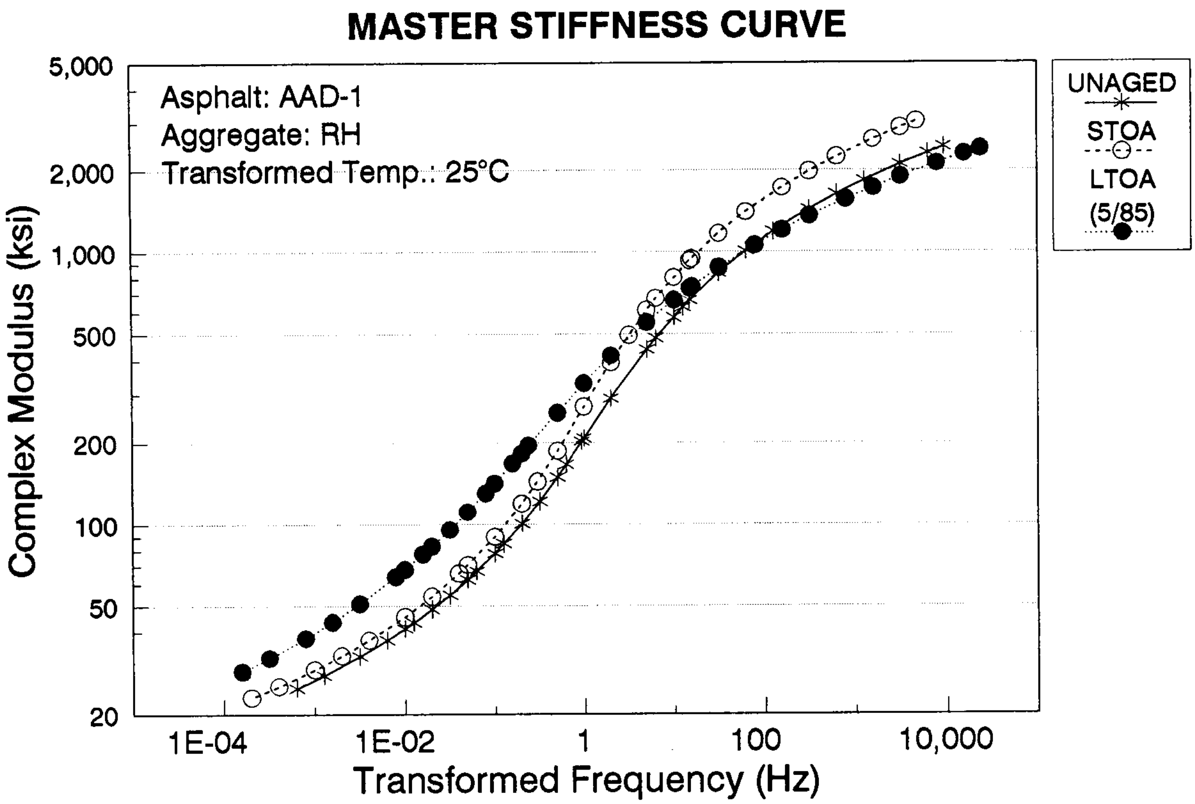


Figure B.2. Master curve and phase angle curve for asphalt AAD-1 and aggregate RC



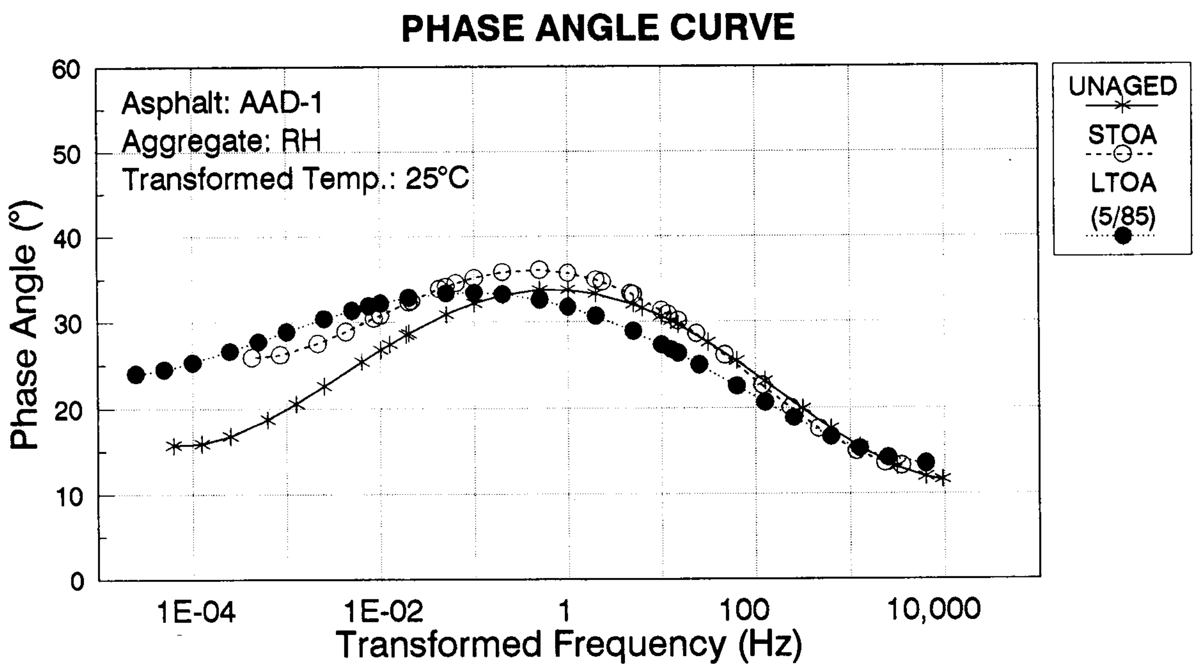
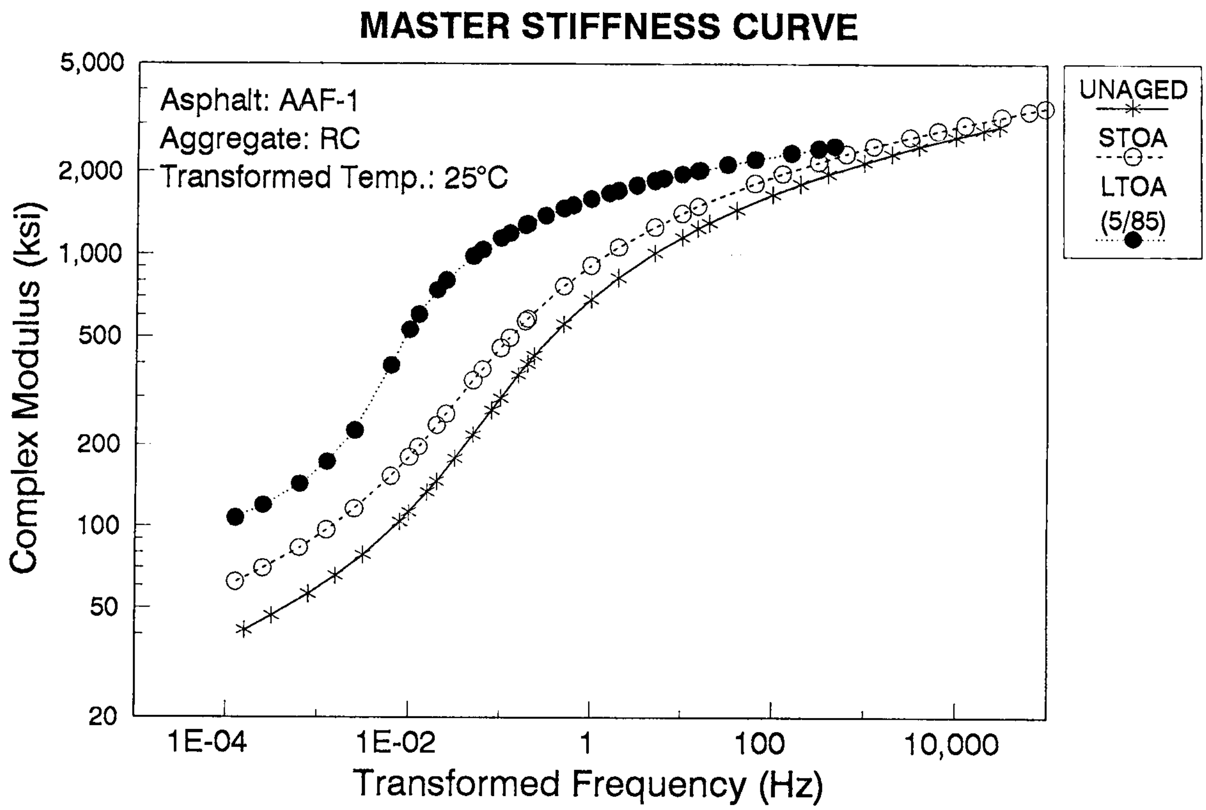


Figure B.3. Master curve and phase angle curve for asphalt AAD-1 and aggregate RH



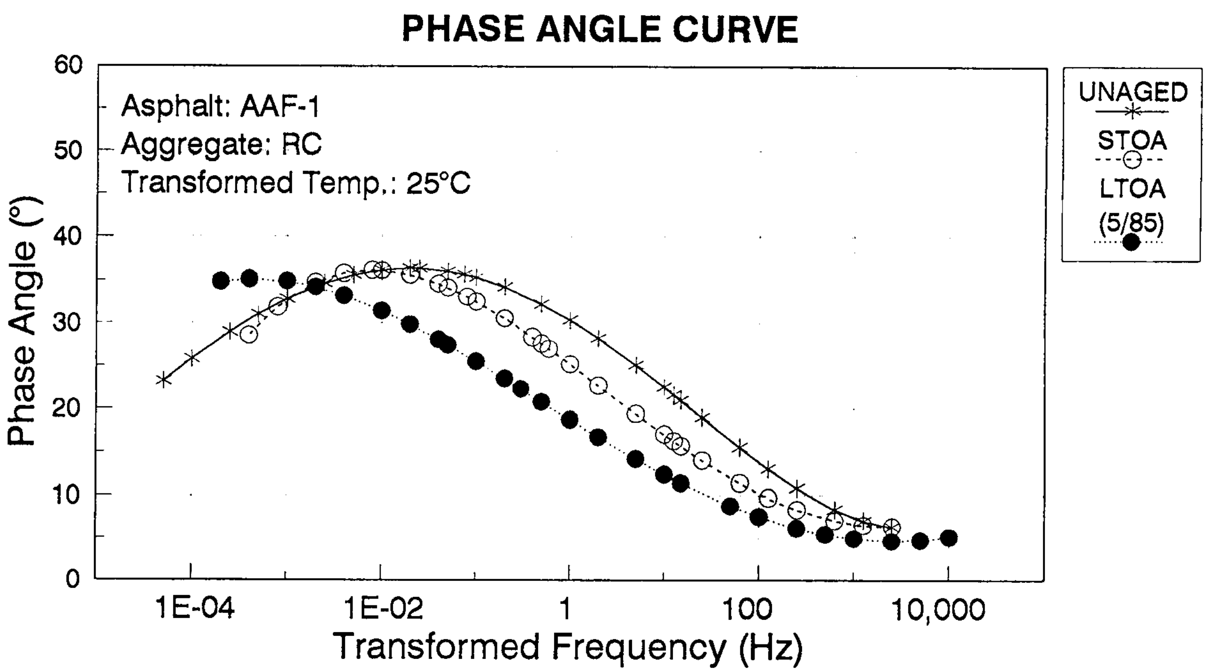
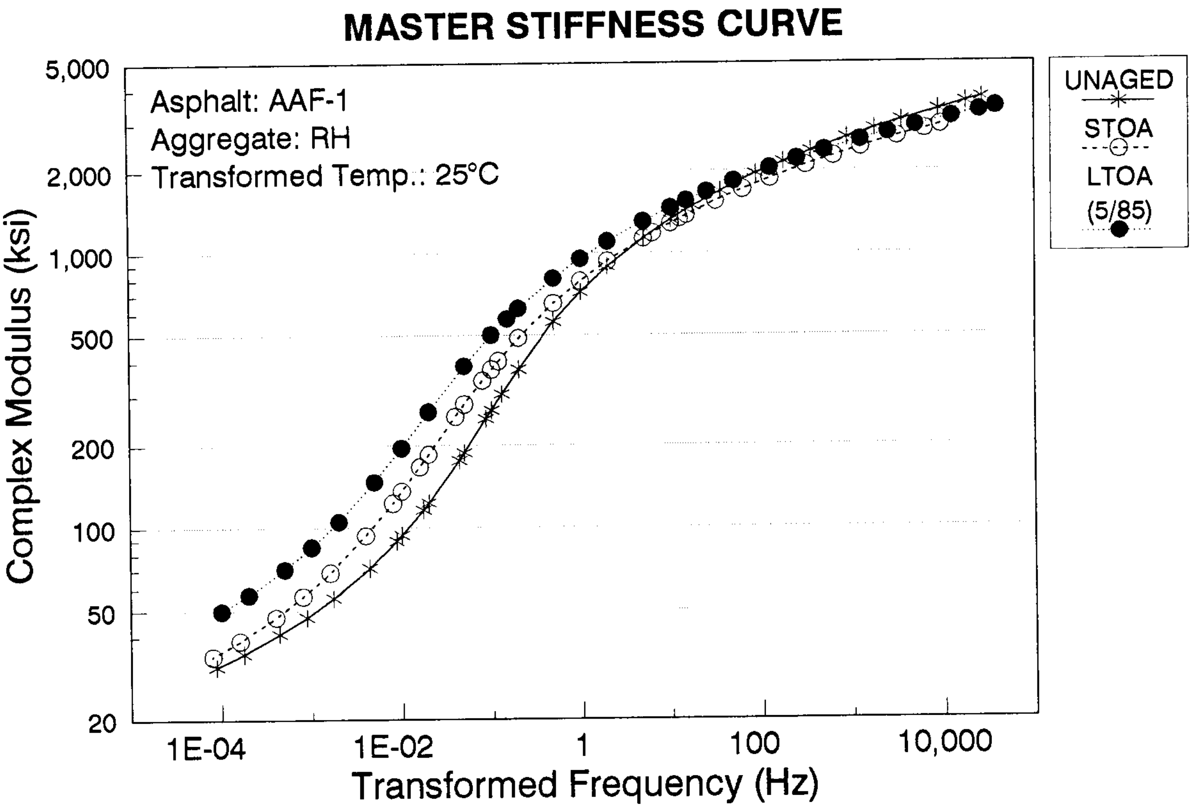


Figure B.4. Master curve and phase angle curve for asphalt AAF-1 and aggregate RC



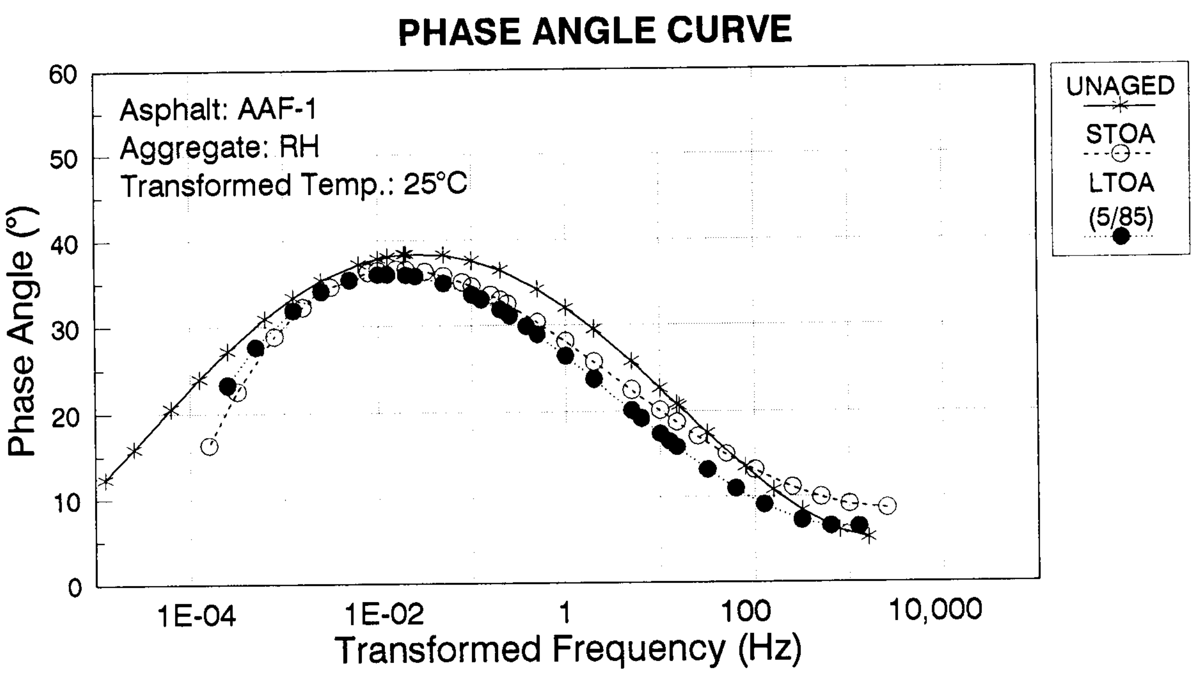


Figure B.5. Master curve and phase angle curve for asphalt AAF-1 and aggregate RH

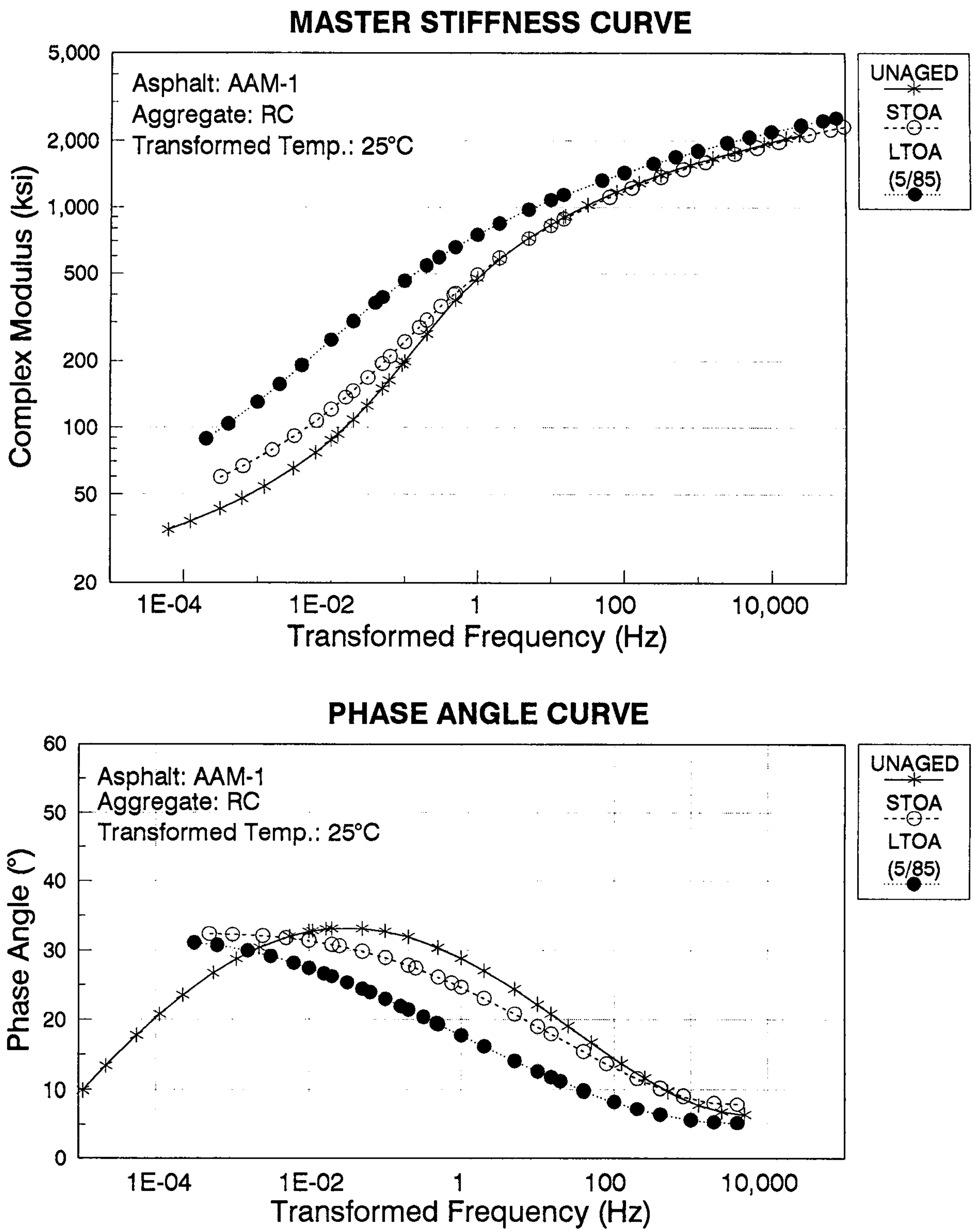
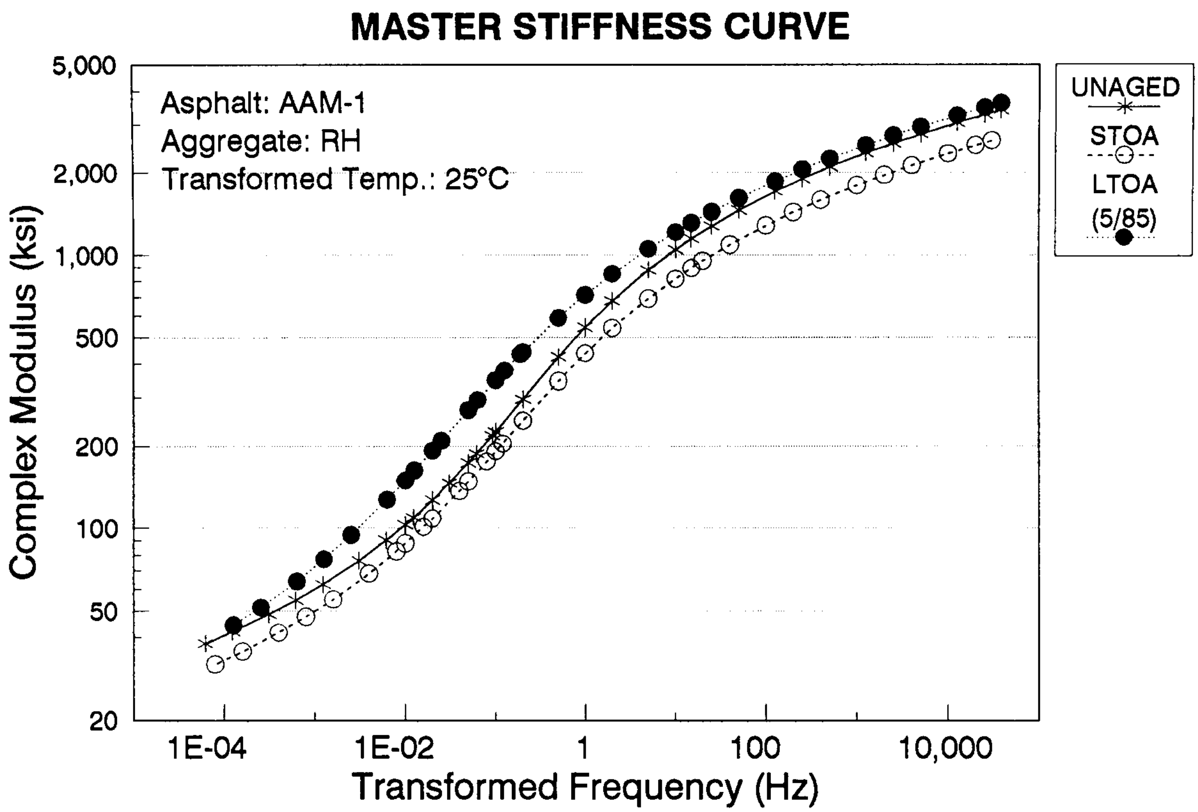


Figure B.6. Master curve and phase angle curve for asphalt AAM-1 and aggregate RC



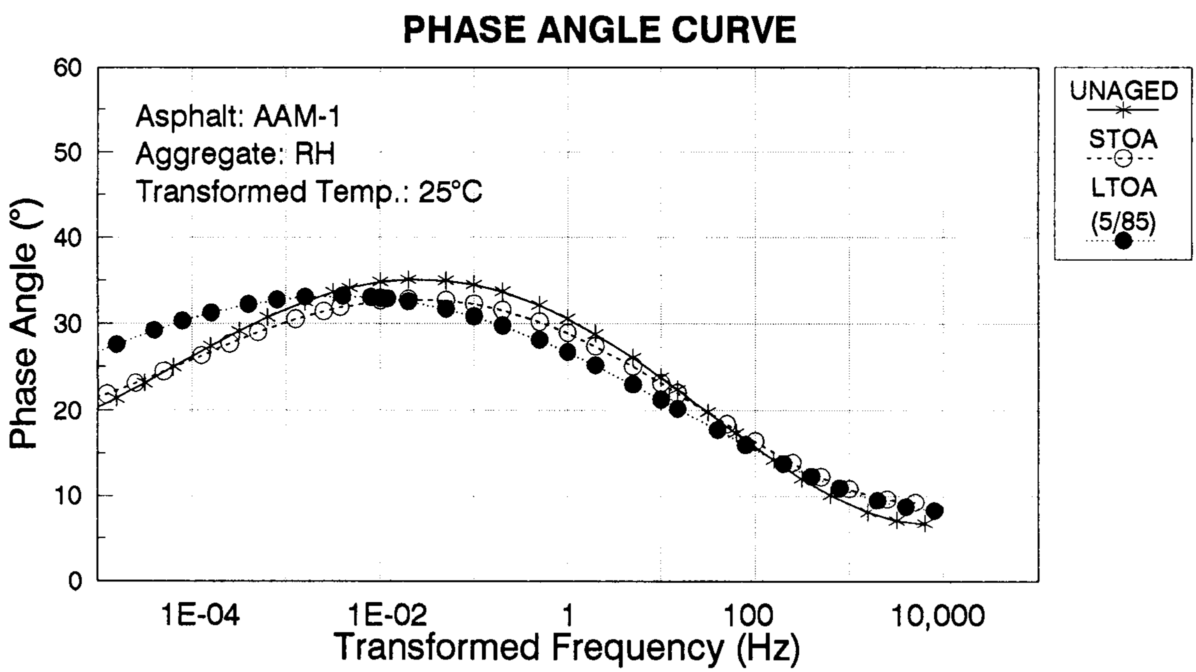


Figure B.7. Master curve and phase angle curve for asphalt AAM-1 and aggregate RH