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Performance Evaluation of Sulfur-Extended Asphalt Pavements--Laboratory Evaluation

Office of Research and Development
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6300 Georgetown Pike
McLean, Virginia 22101-2296

FOREWORD

In 1985 through 1987 the Federal Highway Administration (FHWA) performed a field study of sulfur-extended asphalt (SEA) pavements. These pavements and their asphalt control sections were examined for performance. The study documented in this report complements the field study. Pavement cores were obtained from many of the projects and tested in the laboratory for their properties. This report will be of interest to individuals concerned with the use of sulfur in asphalt paving mixtures and also with testing and evaluating bituminous paving mixtures in general. Many of the findings may be of use to agencies which use asphalt additives. One finding will be of interest to agencies which recycle asphalt pavements.

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16. Abstract

In 1987 the Federal Highway Administration (FHWA) completed a field study to compare the performance of sulfur-extended asphalt (SEA) pavements to conventional asphalt control (AC) pavements. A representative set of pavements was chosen to provide a comprehensive evaluation of the effects of sulfur on pavement performance. The primary conclusion was that there was no difference in overall performance between the SEA and AC sections. This field study is documented in FHWA Report DP54-01, Federal Highway Administration, Washington DC, 1987. It is entitled "Performance Evaluation of Sulfur-Extended Asphalt Pavements - Field Survey and Assessment."

The laboratory study documented in the accompanying report complements the field study. Cores were obtained from many of the pavements and tested (1) to verify that the SEA and AC sections were similar in thickness and mixture composition, except for sulfur content, (2) to predict whether the pavement performances of the SEA and AC sections will remain similar, and (3) to investigate individual pavements where the performances of the two sections were not equal. In general, the laboratory test results supported the results of the field study. Overall, sulfur did not increase or decrease most test properties, and often it had no effect on a given test property of a mixture. Sulfur did decrease the resistance to moisture susceptibility in the laboratory. There were also minor trends indicating that with some mixtures, sulfur may reduce the susceptibility to rutting and increased the susceptibility to fatigue cracking. This report also presents the results of several tasks where SEA binders and mixtures prepared in the laboratory were evaluated.

17. Key Words
Sulfur extended asphalt, SEA, Creep test, Resilient modulus, Moisture susceptibility, Asphalt mixtures, Steric hardening, Asphalt modifiers, Aggregate specific gravity

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

LENGTH

Symbol	When You Know	Multiply By	To Find	Symbol
in	inches	25.4	millimetres	mm
ft	feet	0.305	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km

AREA

Symbol	When You Know	Multiply By	To Find	Symbol
in^2	square inches	645.2	millimetres squared	mm^2
ft^2	square feet	0.093	metres squared	m^2
yd^2	square yards	0.836	metres squared	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	kilometres squared	km^2

VOLUME

Symbol	When You Know	Multiply By	To Find	Symbol
fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	litres	L
ft^3	cubic feet	0.028	metres cubed	m^3
yd^3	cubic yards	0.765	metres cubed	m^3

NOTE: Volumes greater than 1000 L shall be shown in m^3.

MASS

Symbol	When You Know	Multiply By	To Find	Symbol
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg

TEMPERATURE (exact)

Symbol	When You Know	Multiply By	To Find	Symbol
°F	Fahrenheit temperature	5(F-32)/9	Celcius temperature	°C

APPROXIMATE CONVERSIONS FROM SI UNITS

LENGTH

Symbol	When You Know	Multiply By	To Find	Symbol
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi

AREA

Symbol	When You Know	Multiply By	To Find	Symbol
mm^2	millimetres squared	0.0016	square inches	in^2
m^2	metres squared	10.764	square feet	ft^2
ha	hectares	2.47	acres	ac
km^2	kilometres squared	0.386	square miles	mi^2

VOLUME

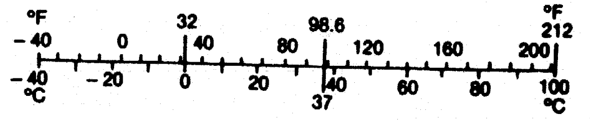
Symbol	When You Know	Multiply By	To Find	Symbol
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m^3	metres cubed	35.315	cubic feet	ft^3
m^3	metres cubed	1.308	cubic yards	yd^3

MASS

Symbol	When You Know	Multiply By	To Find	Symbol
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	short tons (2000 lb)	T

TEMPERATURE (exact)

Symbol	When You Know	Multiply By	To Find	Symbol
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F



* SI is the symbol for the International System of Measurement

(Revised April 1989)

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

LIST OF FIGURES

LIST OF TABLES

LIST OF TABLES (Continued)

LIST OF TABLES (Continued)

CHAPTER 1: INTRODUCTION

1. Background and Objectives

In 1985 the Federal Highway Administration (FHWA) initiated a field study to compare the performances of sulfur-extended asphalt (SEA) pavements to conventional asphalt control (AC) pavements. A representative set of pavements from 18 States was chosen to provide a comprehensive evaluation of the effects of sulfur on pavement performance when used as an extender. The term "extender" denotes that a significant quantity of sulfur is used to replace asphalt cement in a mixture and thereby reduce the amount of asphalt needed. Usually, 20 percent sulfur by total binder weight, or greater, is used. The field study was completed in 1987, and the findings have been documented.(1,2) The primary conclusion of the study was that there was no difference in overall performance between the SEA and AC sections. The types of distress recorded on each project, for example, rutting and total cracking, also tended to be the same in both sections.

The laboratory study documented in this report complements the field study. Core specimens were obtained from many, but not all, of the pavements and tested (1) to verify that the SEA and AC sections were similar in thickness and mixture composition, except for sulfur content, (2) to predict whether the pavement performances of the SEA and AC sections will remain similar, and (3) to investigate individual pavements where the performances of the two sections were not equal. Fifteen cores were obtained from each SEA and AC section: 12 cores from "in the wheelpath" and three "out of the wheelpath." The majority of the cores were obtained "in the wheelpath" so that performance as measured by the laboratory tests could be determined where the traffic loads are highest. The additional three cores were obtained to investigate differences between these two areas of the pavement. The pavements were from 3 to 8 years old when cored. This laboratory study started in 1987.

2. Pavements Evaluated

Table 1 shows the locations of the pavements where cores were taken and the two-letter designations used in this report. The FHWA review number was used to identify pavements in the field study. The Kansas (KS) pavement was not part

Table 1. Projects evaluated.

FHWA Review Number	Two Letter Designation	Location	Age in years	Blending Method[1]	Additional Information on Location
860602	CA	California-Anaheim	4.3	C	Lincoln Ave., East Section
850601	CB	California-Baker	3.2	B	Barstow/Baker, I-15
851001	DE	Delaware	6.4	B,C	Greenwood, Route 13
861301	GA	Georgia	4.6	C	Bainbridge Bypass, U.S. 84
851601	ID	Idaho	4.0	B	Elk City, State Route 14
000000	KS	Kansas	5.0	C	Johnson Co, 151st Street
862201	LA	Louisiana[2]	6.0/7.2	B	LA 22, Gulf Process Section
852301	MB	Maine-Benton	4.1	C	Kennebec County, I-95
852302	MC	Maine-Crystal	6.2	C	Aroostock County, U.S. 2
862701	MN	Minnesota	7.0	C	Rochester/Zumbro Falls,TH-63
862801	MS	Mississippi	4.4	C	S of Phila.,NeshobaCo, Rt.15
853801	ND	North Dakota	5.2	B	NW of Minot, U.S. 2
853501	NM	New Mexico	3.7	B	Carlsbad, U.S. 62/180
854802	TC	Texas-College Station	7.4	A	Brazos County, MH 153
854801	TP	Texas-Pecos	4.2	B	Bakersfield/Ft.Stockton,I-10
854803	TX	Texas-Nocogdoches	5.2	C	Loop 495
865501	WI	Wisconsin	3.6	B	Wittenberg-Tilleda, SH 29
865601	WY	Wyoming	3.7	C	West of Cheyenne, SR 225

[1] A = Colloid mill preblending
B = In-line blending (liquid)
C = Direct feed (liquid)

[2] The AC section was 6.0 years old and the SEA section was 7.2 years old.

of the field study and thus does not have a number. Table 2 shows the Present Condition Index (PCI) for each pavement and deduct values. The PCI is an overall rating for the pavement with "100" indicating no damage. The deduct values are shown for the major distresses encountered in the field study. The deduct values indicate the degree of damage associated with a particular type of distress, with "0" indicating no damage. These values are used to compute the PCI. The field survey was performed according to the method given in FHWA/RD-81/080 entitled, "A Pavement Moisture Accelerated Distress (MAD) Identification System."(3) Additional information is contained in the two field study reports.(1,2)

The PCI and deduct values shown in table 2 match the areas of the pavements where the cores were taken. In the field study, many of the pavements were divided into subsections (called "samples" in the field study) in order to reduce the length of pavement being evaluated at a time. For some pavements, cores were only taken from one subsection, so the PCI and deduct values for this subsection are given. For other pavements, the cores were taken from more than one subsection, so average PCI and deduct values for these subsections are given. Table 2 indicates that the ratings for most sections were high, and therefore most of the pavements were in good condition. Both the SEA and AC sections of the Kansas (KS) project failed and were rehabilitated, so PCI of "0" were assigned to these sections. All cores were taken no later than six months after the field survey.

With some pavements, the effects of various percentages of sulfur were evaluated, while others considered various thickness designs. These variations within a project are called "design sections" in the field study report. As shown by table 2, cores from different design sections were obtained from four projects: CB, ID, MB, and ND. The MB (10/90) design section was not included in the field study, so no performance data were available. (The ratio 10/90 denotes a binder containing 10 percent sulfur and 90 percent asphalt by weight.) With some pavements, SEA was used in more than one layer.

Table 1 shows that the asphalt control section of the LA project was 6.0 years old while the SEA section was 7.2 years old. Thus the asphalt control section was not a true control section. However, this project was not eliminated from this research study. It was found by the end of this study that the air voids and most mechanical test properties for the two sections were similar, and there was no difference in aggregate type and gradation or the percent binder content

Table 2. Present Condition Indices (PCI) and deduct values.

Project	PCI		DEDUCT VALUES							
			Rutting		Combined Cracking		Bleeding		Pothole	
	AC	SEA	AC	SEA	AC	SEA	AC	SEA	AC	SEA
CA	100	100	0	0	0	0	0	0	0	0
CB (loc.#1)	100	100	0	0	0	0	0	0	0	0
CB (loc.#2)	100	100	0	0	0	0	0	0	0	0
DE	90	85	0	0	29	47	0	0	0	0
GA	87	90	0	0	16	10	0	0	0	4
ID (loc.#1)	100	100	0	0	0	0	0	0	0	0
ID (loc.#2)	95	100	5	0	0	0	0	0	0	0
KS	0	0	--	--	--	--	--	--	--	--
LA	90	87	0	0	5	11	0	0	0	12
MB (10/90)	--	--	--	--	--	--	--	--	--	--
MB (20/80)	87	92	0	0	47	28	0	0	0	0
MB (30/70)	87	84	0	0	47	44	0	0	0	0
MC	88	80	11	37	8	0	0	0	0	0
MN	49	79	0	0	51	61	72	0	0	26
MS	100	100	0	0	0	0	0	0	0	0
ND (loc.#1)	82	80	20	14	6	4	0	0	0	0
ND (loc.#2)	85	83	4	19	11	8	0	0	0	0
NM	95	100	0	0	6	0	0	0	0	0
TC	57	80	31	9	58	24	0	0	37	16
TP	100	100	0	0	0	0	0	0	0	0
TX	80	85	0	0	13	24	24	0	0	0
WI	47	83	48	17	5	0	0	0	0	0
WY	82	80	15	0	44	49	0	0	0	0

by volume. The LA project did contain SEA sections that were built at the same time as the AC section, but cores from these SEA sections were not received.

3. Testing Program

To accomplish the objectives, the following testing program was performed:

- Initial evaluation.
  - Visual evaluation.
  - Density.
- Modulus and deformation tests to determine differences in the susceptibility to rutting and cracking.
  - Diametral resilient modulus (Mr) at 41, 77, and 104 °F (5, 25, 40 °C) with the total deformation measured in the horizontal, tensile direction.
  - Diametral incremental creep test at 41, 77, and 104 °F (5, 25, 40 °C) to measure the creep modulus (Mc) and total, resilient, viscoelastic, and permanent deformations in the vertical, compressive direction.
- Moisture susceptibility.
  - Wet and dry diametral (indirect) tensile strengths and retained ratios.
  - Wet and dry diametral (indirect) tensile strains at failure.
  - Wet and dry diametral resilient moduli and retained ratios.
  - Percent visual stripping.
- Marshall stability and flow.
- Fatigue cycles to failure (controlled stress mode) to determine the susceptibility to cracking.
- Mixture composition.
  - Voids analysis.
  - Aggregate gradation.
  - Percent binder.
  - Percent sulfur.
  - Binder properties.

4. Analysis of Data

The "pooled formula" and "paired" statistical t-tests were used to determine whether there were significant differences between the AC and SEA sections.(4) The pooled formula t-test compares two averages using the specimen-to-specimen variations of the two data sets. It was used to compare the data of an AC section of a project to the data of the corresponding SEA section. The paired t-test is used when each variate of a data set can be paired with a particular variate of another data set. This analysis was performed when the data from many projects were grouped together to determine the influence of some factor such as pavement age. Average values for each AC and SEA section contained in a group of projects were first computed. Pairs of average values formed by the AC sections and their corresponding SEA sections were then analyzed to determine the overall effect of sulfur for the group of projects. Because this analysis does not account for the specimen-to-specimen variation within an AC or SEA section, it only gives trends in the data.

Both t-tests provide a probability value labeled "p" in this report. This value is dependent on the "degrees of freedom," which are the total number of variates minus the number of independent relationships. For the pooled formula t-test, the degrees of freedom are the total number of data values minus two. For the paired t-test, the degrees of freedom are the number of pairs minus one. A probability "p" computed from the test data which is greater than 0.05 indicates no significant difference between two data sets at a 95 percent confidence level. A value less than or equal to 0.05 indicates there is a difference between the data sets. In all tables showing the effects of sulfur on a property, "I" indicates sulfur increased the property, "D" indicates sulfur decreased the property, and "NS" indicates there was no significant difference between the properties and thus sulfur had no effect.

The statistical analyses evaluated the effects of sulfur on a given property for (1) all projects grouped together, (2) projects grouped according to pavement age ("less than 5 years" versus "more than 5 years"), (3) projects grouped according to the method of incorporating the sulfur into the mixture ("in-line blending" versus "direct feed"), (4) projects grouped according to the stiffnesses of the mixtures, and (5) on a project-by-project basis. The paired t-test was used for the first four analyses while the pooled formula t-test was used for all project-by-project analyses. Each design section for a pavement and each layer evaluated was treated individually or considered a separate "project" in these analyses. The number of projects for each of the above groups, or number of possible comparisons between SEA and AC sections, are given in table 3. For

Table 3. Number of comparisons between SEA and AC sections for each group.

	All Projects	Pavement Age Less than 5 years old	Pavement Age Greater than 5 years old	Blending Method In-line	Blending Method Direct	Mixture Stiffness Soft	Mixture Stiffness Hard
Density	29	17	12	11	16	15	13
Mechanical Tests	22	14	8	11	9	11	11

States in each Climatic Zone

Wet Freeze	Dry Freeze	Wet No-Freeze	Dry No-Freeze
MB	ID	DE	CB
MC	ND	LA	TC
MN	KS	MS	TP
WI			TX
			NM

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some mechanical tests, the number of comparisons was less than in the table because of an insufficient number of specimens.

In the "in-line blending" method, liquid sulfur and asphalt are combined and blended before being introduced into the plant. In the "direct feed" method, liquid sulfur is directly metered into the weigh bucket of the batch plant or into the drum of the drum mixer plant. Blending the sulfur with the asphalt using a colloidal mill was only used on one project in this study, and thus was not included in the analyses.

The stiffness of a mixture was based on the resilient modulus (Mr) at 77 °F (25 °C). Mixtures with moduli less than 600,000 lbf/in^2 (4137 MPa) were defined as "soft", while the others were defined as "stiff." This modulus was chosen simply because it divided the projects into two approximately equal groups. Why each mixture was either soft or stiff was unknown. A difference in stiffness could be related to the binder, aggregate shape and gradation, air void level, or a combination of these factors.

Analyses to determine the effect of the percent sulfur added to the binder on the test properties could not be justified and were not performed. The number of possible comparisons between the SEA and AC sections was originally 32. Approximately 30 percent sulfur by total binder weight was the target amount in 23 out of these 32 SEA sections. Six projects had a target of 10 or 20 percent sulfur, although four of these were variations of one pavement at the MB site. Only three sections had a target of 40 percent sulfur. There were not enough sections with other than 30 percent sulfur to warrant an analysis. The level of sulfur had no significant effect in the field study.(1)

At the end of this research study, the percent sulfur for each AC and SEA section was obtained. Conventional asphalt cements can contain up to approximately 6 percent sulfur by weight. The average amount of sulfur added to the sections was 23.2 percent by total binder weight with a range of 10.9 to 33.2 percent. As discussed later in chapter 7, it was decided not to determine the effect of the measured percent sulfur on the test properties.

Based on the sulfur contents determined at the end of the study, it was found that three projects had to be eliminated: CA, GA, and WY. All of the test data on these projects had already been measured and are included in the data tables of this report. However, the data were not included in any analysis. Both sets of cores from the CA project contained a high amount of sulfur, and it is probable that some of the AC cores were taken from the SEA section. Both sets of cores from the GA project had very little sulfur, and it appeared that both sets came from the AC section. Both sets of cores from the WY project contained sulfur, and it appeared that both sets came from the SEA section. Thus the number of possible comparisons between the SEA and AC sections, as shown in table 3, was 29 instead of 32.

Climatic zones, as shown in table 3, were established. However, it was found that the effects of the climatic zones were confounded by other factors. For example, as could be expected, the wet and dry freeze zones contained most of the soft mixtures. Stiffness was already being evaluated. Therefore, the analyses based on climatic zone were eliminated.

Adequate groups for analyzing the data according to the type of layer (surface, binder, or base) could not be established. The different layers were simply treated as different mixtures. The effect of traffic level and layer thickness also could not be considered. Interpretations of these analyses would be hindered by the variety of pavement designs and the lack of data for the pavement layers not tested. The TX project was the only project where an open-graded mixture was used. No mechanical tests were performed on this mixture. The majority of the cores were from the surface layers of low volume roads.

For most pavements, mixture designs were only performed for the AC sections. The SEA binder was simply substituted for the asphalt binder and the mixture was not redesigned. Because the specific gravity of the SEA binder would be greater than the specific gravity of the asphalt binder, the substitution should be on an equal volume basis rather than an equal weight basis. However, SEA binder properties, including specific gravity, were generally not measured when the projects were built and little data on these projects were available. The method of substitution, either by volume or by weight, was not determined during the FHWA field study, and for some projects, the information was not available. For cases where the method of substitution was known, one method did not prevail over the other. The effects of this variable on the test properties of this study were not determined, although binder contents were measured and reviewed at the end of the study. The effects would also be confounded with any changes in the rheological properties of the binder due to the sulfur. Rheological properties of the SEA binders were generally not measured when the projects were built, nor could they be determined in this study.

There are other analyses that could be performed. For example, the data from the various SEA sections of the MB project could be compared to each other. Likewise, the data for the two locations of the ID project could be compared. These types of analyses may be of interest to the individual highway agencies, but they were considered beyond the scope of this study and were not performed.

CHAPTER 2: INITIAL EVALUATION

1. Visual Examination of Field Cores

Table 4 shows the results of an examination of the field cores. This examination was performed to verify that each corresponding SEA and AC section had similar structures because unequal structures could affect pavement performance. Layers containing the SEA binders are designated in the table. When the thickness of a layer varied from core to core by more than 0.25 in (0.64 cm), a range in thickness was established. Layers designated as "original" are those which were overlaid. All others were newly constructed. The cores were also examined for visual differences between the SEA and AC sections. Full-depth cores were generally not received from the State highway agencies.

Excluding the evidence of crystalline sulfur, the only major differences between the SEA and AC sections were as follows:

- KS - The base layers in both sections showed moisture damage in the form of stripping, but the damage in the AC section was more severe. The base layers of both sections were sawed into two parts because the bottom parts were more damaged than the top parts.

- NM - The open-graded overlay in the AC section (PCI = 95) was thinner than the open-graded overlay in the SEA section (PCI = 100). The slight amount of cracking which was observed in the AC section but not in the SEA section during the field study could be related to this difference in thickness.

- TC - The surface overlay in the SEA section (PCI = 80) was more variable in thickness and often thinner than the AC section (PCI = 57). These differences in thicknesses did not correlate to the pavement ratings. The base layer was placed in three lifts. The top 1.5 in (3.8 cm) lift of the AC base cores was different in color compared to the two lower lifts. This lift was sawed off and tested separately. The three SEA base lifts were homogeneous in appearance. During this study, the top and bottom portions were found to have slightly dissimilar properties. However, the properties of the SEA base cores were only compared to those of the bottom portion of the AC base cores. The conclusions regarding the effect of sulfur on the mixture were generally the

Table 4. Examination of field cores (thicknesses are in inches).

	Layer	Asphalt Control Section	SEA Section
1. CA	Surface	1.25 to 1.75 (SEA)	1.25 to 1.75 (SEA)
	Base (original)[1]	5 to 8	3 to 5
2. CB	Surface	2.5	2.5 (SEA)
3. DE	Surface	1	1 (SEA)
4. GA	Surface[2]	0.62 to 2	0.62 to 2
	Binder (original)	1.5	1.5
	Base (original)	2 to 3	2 to 3
5. ID	Surface treatment	0.25	0.25
	Surface (2 lifts)[3]	2.5 to 3.5	2.5 to 3.5 (SEA)
	Leveling	0 to 1.5	0 to 1.5
	Overlay or patch (original)	--	--
	Stabilized base (original)	--	--
6. KS	Surface[4]	1	1 (SEA)
	Base[5]	8	8 (SEA)
7. LA	Surface[6]	1.75 to 2.25	2 (SEA)
	Base (2 lifts)[6]	4.5 to 5.5 (SEA)	4.5 to 5.5 (SEA)
8. MB	Surface	1.25	1.25 (SEA)
	Binder	1.75 to 3	1.75 to 3 (SEA)
	Stone chip	0.25	0.25
	Leveling	0.75	0.75
9. MC	Surface	1.25	1.25 (SEA)
	Binder	2.25 to 3.25	2.25 to 3.25 (SEA)
	Base	1 to 2	1 to 2 (SEA)
10. MN	Surface	1.5	1.5 (SEA)
	Leveling	1.5 to 2.25	1.38 to 2.75
11. MS	Surface	1.12 to 2.12	1.12 to 2.12 (SEA)
	Binder	1.5	1.5 (SEA)
	Base (2nd lift)	2.25 to 3	2.25 to 3 (SEA)
	Base (1st lift)	2 to 4	2 to 4 (SEA)
	Granular base	--	--

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[1] Base layer was broken or cracked in both sections.
[2] Surface layer was milled in both sections.
[3] Surface layer showed some segregation in both sections.
[4] Surface layer showed cracking and raveling in both sections.
[5] Base layer showed moisture damage in both sections.
[6] Both layers showed moisture damage in both sections.

Table 4. Examination of field cores (thicknesses are in inches) (continued).

	Layer	Asphalt Control Section	SEA Section
12. ND	Surface treatment	0.38	0.38
	Overlay or patch	0 to 1.5	0 to 1.5
	Surface	3 to 4	2.75 to 3.5 (SEA)
13. NM	Open-graded friction	0.25	0.38 to 0.75
	Surface	2 to 3	1.88 (SEA)
	Base (2nd lift)	2.5	1.25 to 3 (SEA)
	Base (1st lift)	2.75	2.75 (SEA)
	Granular base	--	--
14. TC	Surface	0.88	0.25 to 1
	Base (3 lifts)	5.38 to 6.12	5.5 to 6 (SEA)
15. TP	Surface treatment	0.62	0.62
	Surface	1.25	1.25 (SEA)
	Binder	2	2 (SEA)
16. TX	Open-graded friction	0.62	1 (SEA)
	Surface treatment (original)[7]	0.19	0.19
	Surface (original)	1	1.5
	Surface treatment (original)	0.19	0.19
	Surface (original)	1.25	2.25
	Surface treatment (original)	0.19	
	Surface (original)	0.62	
17. WI	Surface	4 to 6	5 to 6 (SEA)
18. WY	Surface treatment	0.38	0.38
	Surface	2 (SEA)	2 (SEA)

[7] Cores were broken or cracked in both sections under the open-graded friction course.

NOTE: Projects CA, GA, and WY were eliminated from the analyses. Both sets of cores from the CA project contained sulfur; both sets of cores from the GA project contained only asphalt, and both sets of cores from the WY project contained sulfur.

same regardless of which portion of the AC core was used. Secondary analyses comparing the top and bottom portions to each other and the top portions to the SEA cores are not presented in this report. In the data tables of this report the two portions of the AC base cores are referred to as the top and bottom halves.

- TX - The open-graded AC section (PCI = 80) was thinner than the open-graded SEA section (PCI = 85). The AC section had bled and lost most of its open-graded texture.

Table 4 also shows that the AC and SEA surface layers of the LA project were both placed on a newly constructed SEA base layer. Densities at 77 °F (25 °C) and resilient moduli at 41, 77, and 104 °F (5, 25, and 40 °C) were measured for this layer. These properties were the same in both sections.

All projects used the same grade of asphalt in the SEA section as in the AC control, except for the MC project which used an AC-10 in the AC section and an AC-5 in the SEA section. However, this project was not eliminated from the data analysis. Two asphalt control sections were used in the CB project. One contained an AR-2000 asphalt and the other an AR-4000 asphalt. Both SEA sections contained the AR-2000 asphalt. Thus the AR-2000 was chosen as the control. Both the SEA (20/80) section and the SEA (40/60) section were compared to this AR-2000 section.

An examination of the GA cores indicated that the surface layer was milled. It was then learned that this layer had been milled in both the AC and SEA sections prior to the field study. Rutting had occurred in both sections. Thus the PCI and deduct values in table 2 are misleading. This did not pose a problem for this laboratory study, because this project, along with CA and WY, had to be eliminated from the data analyses because proper cores were not obtained. It was decided not to remove the results of the examination of the field cores for these three projects from table 4.

One unusual observation was the high degree of visual stripping around the LA cores compared to the high pavement ratings (AC PCI = 90; SEA PCI = 87). Additional observations applicable to both the AC and SEA sections are included in table 4.

Each SEA and corresponding AC layer, as shown in table 4, was sawed from the cores for testing. The only layers which could not be evaluated were the MC base layer, because the bottoms of the cores were severely damaged during coring, and the TP surface layer, which was highly contaminated by the surface treatment materials. Over 1000 sawed specimens were evaluated.

2. Density

The bulk specific gravity and density of each specimen was obtained in accordance with AASHTO T 166 with the specimen being air dried to constant weight before and after testing.(5) Table 5 shows the average calculated density and standard deviation for each project. Table 6 shows the effect of sulfur on density for all projects and projects grouped according to pavement age, blending method, and the stiffness of the mixture. Because the specific gravity of sulfur is about twice that of asphalt, it could be expected that the density of an SEA section would be slightly higher than the density of the corresponding AC control at equal void levels. However, because of construction variability, this slight difference would not be measurable, and any effects of sulfur on density would be caused by differences in properties which affect compaction, such as the stiffness or temperature susceptibility of the mixture.

As shown by table 6, the densities of the groups were not statistically different. Assuming both groups are from the same population and are normally distributed, the table also indicates, as expected, that soft mixtures are easier to compact than stiff mixtures. However, the difference between the average densities of the stiff and soft mixtures was 8.0 lbm/ft^3 (128 kg/m^3) for the AC sections and 9.3 lbm/ft^3 (149 kg/m^3) for the SEA sections. These are very high and thus it appears that each group is not representative of the population of either soft or stiff mixtures. A difference closer to 4.0 lbm/ft^3 (64 kg/m^3) would be expected.

As shown by table 7, the effect of sulfur varied on a project-by-project basis, and no trends were evident. Tables 6 and 7 both show that there was no overall trend indicating that sulfur affects density. The effect of sulfur on the variability of the density data, and "in the wheelpath" versus "out of the wheelpath" comparisons are discussed in chapter 3 with the resilient moduli data.

Table 5. Averages and standard deviations for densities.

Project	Pavement Layer	Material	Density Average (lbm/ft^3)	Standard Deviation
CA	Surface	SEA (30/70)	136.1	1.9
		SEA (30/70)	139.2	2.5
CB	Surface[1] Location #1	AR-2000	140.3	0.3
		SEA (20/80)	136.9	0.1
	Surface[1] Location #2	AR-4000	138.9	0.3
		SEA (40/60)	143.0	0.4
DE	Surface	AC-20	149.7	2.1
		SEA (30/70)	150.4	3.1
GA	Surface	AC-20	148.2	1.3
		AC-20	147.8	2.2
ID	Surface Location #1	AR-4000	148.9	1.3
		SEA (30/70)	149.8	2.0
	Surface Location #2	AR-4000	148.8	2.3
		SEA (30/70)	148.3	3.7
KS	Surface	AC-20	139.2	3.4
		SEA (30/70)	136.7	2.6
	Base, top half	AC-20	140.0	2.3
		SEA (30/70)	139.2	2.6
	Base, bottom half	AC-20	139.5	1.8
		SEA (30/70)	140.3	2.0
LA	Surface	AC-30	145.1	2.6
		SEA (40/60)	143.6	3.3
	Base under AC surface	SEA (40/60)	132.1	1.7
	Base under SEA surface	SEA (40/60)	133.0	1.8
MB	Surface	AC-10	151.8	0.5
		SEA (10/90)	152.4	0.4
		SEA (20/80)	153.2	0.4
		SEA (30/70)	152.7	0.4
	Binder	AC-10	152.5	2.2
		SEA (10/90)	154.7	1.4
		SEA (20/80)	154.4	0.7
		SEA (30/70)	154.6	1.4
MC	Surface[2]	AC-10	150.6	0.8
		SEA (30/70)	152.9	1.0
	Binder[2]	AC-10	152.3	1.1
		SEA (30/70)	153.8	0.3

[1] AR-2000 was used in SEA section.
[2] AC-5 was used in SEA section.

$(lbm/ft^3)(16.02)=(kg/m^3)$

Table 5. Averages and standard deviations for densities (continued).

Project	Pavement Layer		Material	Density Average (lbm/ft^3)	Density Standard Deviation
MN	Surface		AC 200-300	148.1	1.3
			SEA (40/60)	146.0	0.6
MS	Surface		AC-20	140.0	2.1
			SEA (30/70)	139.2	1.5
	Binder		AC-40	138.1	2.2
			SEA (30/70)	136.4	2.6
	Base		AC-40	135.5	2.3
			SEA (30/70)	138.5	2.7
ND	Surface	Location #1	AC 120-150	148.1	0.9
			SEA (30/70)	143.0	1.3
	Surface	Location #2	AC 120-150	147.9	1.2
			SEA (25/75)	148.2	1.8
NM	Surface		AC-10	150.0	1.4
			SEA (30/70)	147.4	3.0
	Base		AC-10	149.5	2.7
			SEA (30/70)	147.4	2.2
TC	Base, top half		AC-20	147.7	1.2
	Base, bottom half		AC-20	146.4	0.9
			SEA (30/70)	142.0	1.2
TP	Binder		AC-20	140.0	1.6
			SEA (30/70)	134.9	1.3
TX	Surface		AC-20	125.8	2.3
			SEA (35/65)	117.9	3.6
WI	Surface		AC 120-150	147.8	0.9
			SEA (30/70)	149.4	0.9
WY	Surface		SEA (20/80)	144.7	1.1
			SEA (20/80)	148.0	0.8

$(lbm/ft^3)(16.02)=(kg/m^3)$

Table 6. Effect of sulfur on density for all projects, and projects by pavement age, blending method, and the stiffness of the mixture.

	Average AC Density (lbm/ft^3)	Average SEA Density (lbm/ft^3)	Degrees of Freedom	p
All projects	145.7	145.1	28	0.240 NS
Projects less than 5 years	146.6	146.6	16	0.911 NS
Projects more than 5 years	144.4	142.8	11	0.102 NS
In-Line Blending	146.1	144.7	10	0.118 NS
Direct Feed	145.1	145.2	15	0.935 NS
Soft Mixtures	150.1	150.4	14	0.696 NS
Stiff Mixtures	142.1	141.1	12	0.140 NS

(lbm/ft^3)(16.02)=(kg/m^3)

Table 7. Effect of sulfur on density for each project.

Project	Pavement Layer	Material	Effect on Density
CB	Surface	SEA (20/80)	D
	Surface	SEA (40/60)	I
DE	Surface	SEA (30/70)	NS
ID	Surface Location #1	SEA (30/70)	NS
	Surface Location #2	SEA (30/70)	NS
KS	Surface	SEA (30/70)	NS
	Base, top half	SEA (30/70)	NS
	Base, bottom half	SEA (30/70)	NS
LA	Surface	SEA (40/60)	NS
MB	Surface	SEA (10/90)	I
		SEA (20/80)	I
		SEA (30/70)	I
	Binder	SEA (10/90)	I
		SEA (20/80)	I
		SEA (30/70)	I
MC	Surface	SEA (30/70)	I
	Binder	SEA (30/70)	I
MN	Surface	SEA (40/60)	D
MS	Surface	SEA (30/70)	NS
	Binder	SEA (30/70)	NS
	Base	SEA (30/70)	I
ND	Surface Location #1	SEA (30/70)	D
	Surface Location #2	SEA (25/75)	NS
NM	Surface	SEA (30/70)	D
	Base	SEA (30/70)	D
TC	Base	SEA (30/70)	D
TP	Binder	SEA (30/70)	D
TX	Surface	SEA (35/65)	D
WI	Surface	SEA (30/70)	I

CHAPTER 3: MODULUS AND DEFORMATION

1. Diametral Resilient Modulus

a. General

Resilient moduli (Mr) were determined using the Mark V Mr diametral (indirect) tensile apparatus manufactured by the Retsina Company. This device applies repeated loads pneumatically. Loads are measured using a 1000-lbf (4450-N) load cell while horizontal tensile deformations are measured by two Gould-Statham UTC3 transducers which have a range of 1 to 2000 microinches (2.5 to 5080 E-06 cm) and an error of 2 microinches (5.1 E-06 cm). As shown in figures 1 and 2, the loads were applied through 0.5-in (1.3-cm) loading strips curved to meet a 4-in (10.2-cm) diameter specimen, and the transducer holder is attached to the specimen. A ball is placed between the upper loading strip and the load cell to allow the loading strip to swivel. The curved sides of the cores were lightly ground to remove irregularities caused by the coring operations.

The resilient modulus was measured within the first 25 repetitions without preconditioning. The modulus is generally repeatable from repetition to repetition at low deformation levels within this range of repetitions. Tests were performed on two perpendicular axes and an average modulus was calculated.

Moduli obtained with this device are termed resilient moduli. Experiments at the FHWA have indicated that the device measures the total modulus which includes elastic, viscoelastic, and permanent deformations. A resilient modulus is a modulus based only on either the instantaneous resilient deformation (elastic) or the total resilient deformation (elastic plus recoverable viscoelastic). Typical load and deformation plots for two cycles are shown in figure 3. Deformations are recorded at 0.1 second after the start of each load pulse. The equation used to compute the modulus was as follows:

$$Mr = \frac{L\,(u + 0.2734)}{(t)(H_t)} \qquad (1)$$

where

Mr = resilient modulus, lbf/in^2;

L = load, lbf;

u = Poisson's ratio; assumed as 0.35;

t = specimen thickness, in; and

H_t = total horizontal deformation, in.

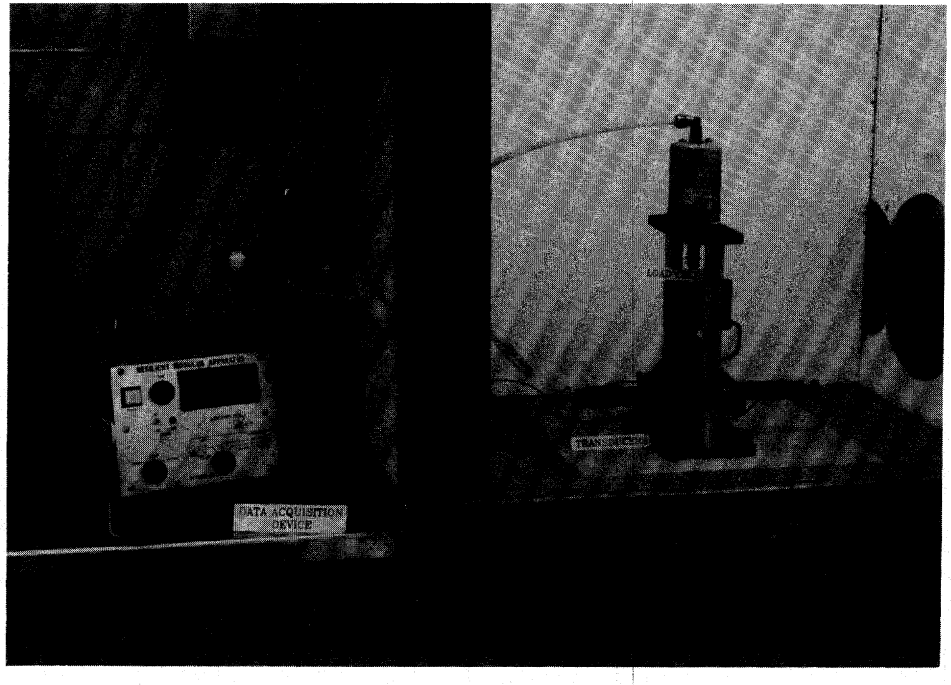


Figure 1. Retsina Mark V diametral resilient modulus apparatus.

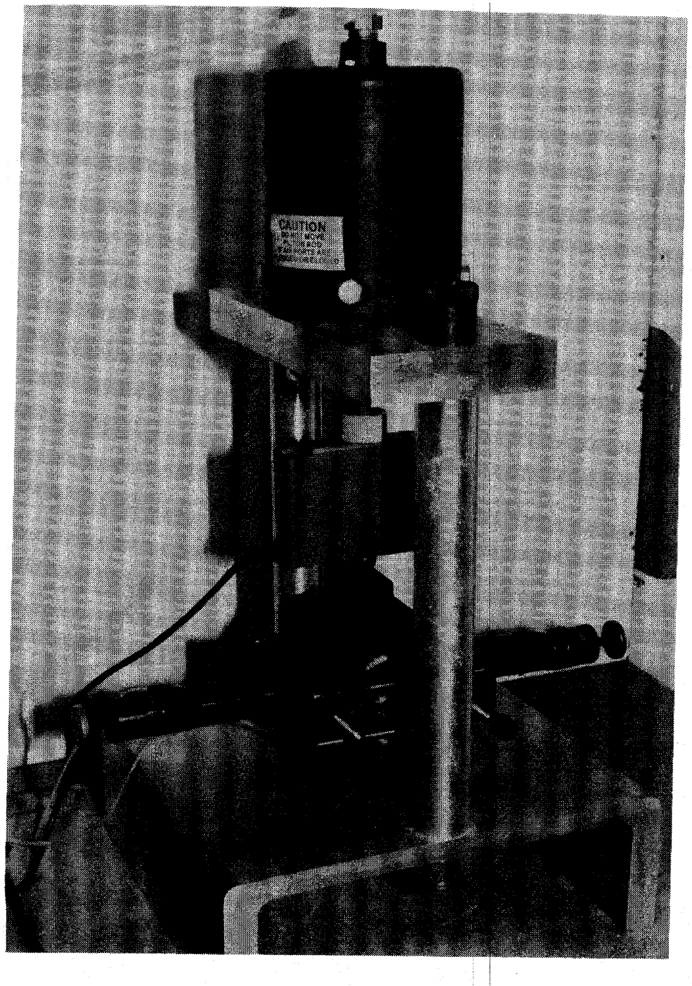


Figure 2. Loading configuration for the resilient modulus apparatus.

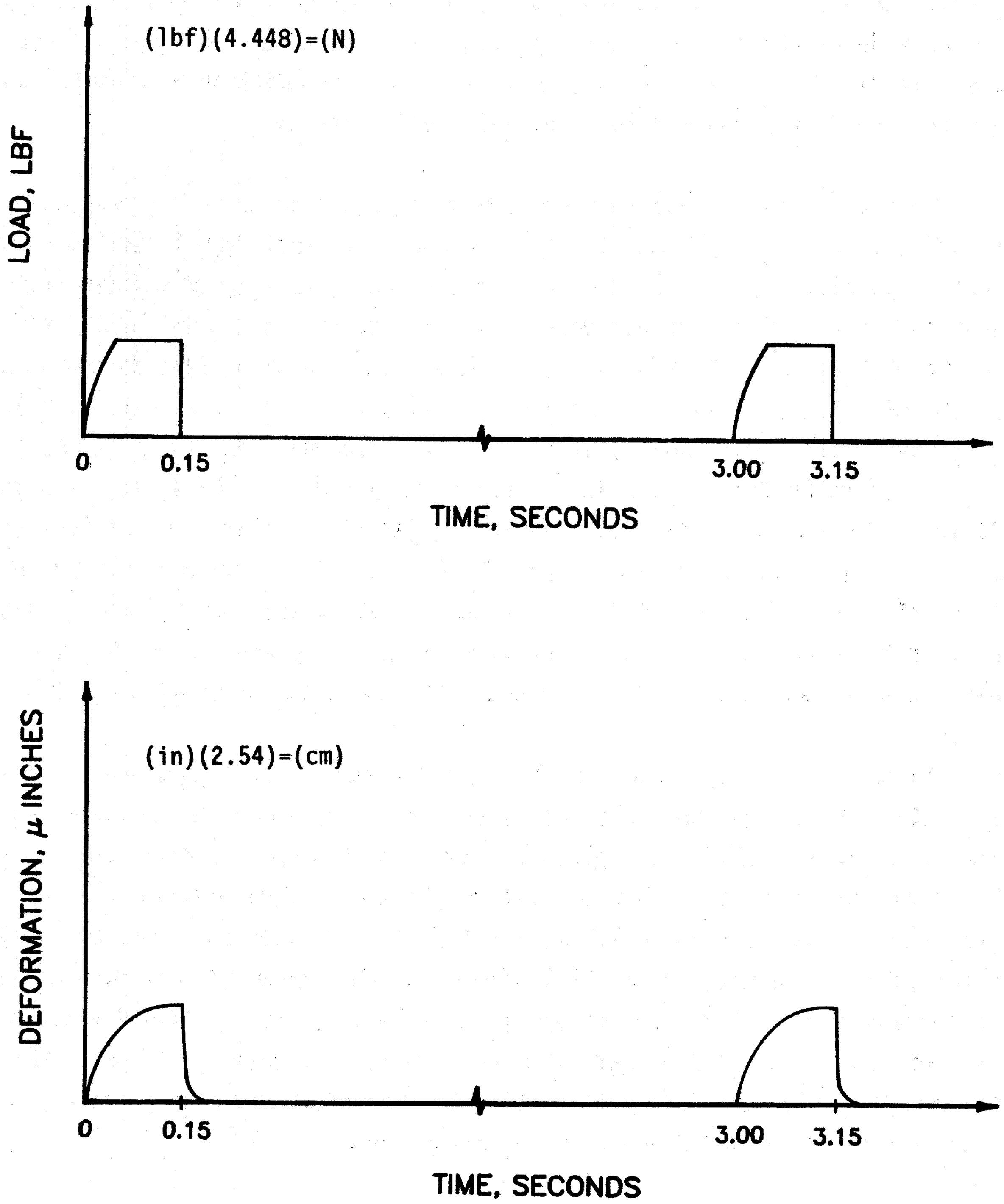


Figure 3. Typical load and deformation graphs for the resilient modulus apparatus.

The level of deformation was used to control the load (or stress) level. The load was adjusted in order to keep the deformations for all specimens within a 20 to 80-microinch (51 to 200 E-6 cm) range. Maintaining this range provides a linear viscoelastic modulus and assures that a specimen undergoes virtually no permanent deformation. In the linear viscoelastic range, the modulus does not vary with the load level. Equation 1 is also only applicable to this range. Poisson's ratio was assumed to be 0.35 for all mixtures.

The loads also had to be adjusted to account for specimen thickness, which varied from 0.75 to 2.5 in (1.9 to 6.4 cm). A single load level was used whenever possible to simplify the testing procedure, as long as the deformations remained between 20 and 80 microinches (51 to 200 E-6 cm). The loads averaged 200 lbf (890 N) at 41 °F (5 °C), with loads as low as 100 lbf (440 N) and as high as 300 lbf (1330 N). They averaged 75 lbf (330 N) at 77 °F (25 °C), with loads as low as 15 lbf (70 N) and as high as 150 lbf (670 N). At 104 °F (40 °C), the loads averaged 20 lbf (90 N), with loads as low as 10 lbf (40 N) and as high as 100 lbf (440 N). In a few cases at 104 °F (40 °C), the recorded deformations were slightly above the 80-microinch (200 E-6 cm) limit because the equipment could not provide low enough loads. Loads below 10 lbf (40 N) were needed to maintain this limit. This testing approach was developed under another FHWA research study which is still in progress.(6) It is based on ASTM D 4123.(8)

The Mr at 0.1 second for each AC and SEA section was determined. Tests at 77 °F (25 °C) were performed on all specimens. In order to minimize testing time, two smaller groups of specimens for each pavement section were used to obtain the Mr at 41 °F (5 °C) and 104 °F (40 °C). Specimens were sorted into these two groups based on the test results at 77 °F (25 °C). The two smaller groups had equal average Mr at 77 °F (25 °C). This average Mr was also equal to the average Mr obtained from testing all specimens. The standard deviations of the two groups were also approximately equal, but generally less than the standard deviation obtained from testing all specimens, because specimens whose Mr were outliers were not used in the two groups.

More than a month was needed to obtain the Mr data. The effects of any changes in properties due to laboratory aging, if any, could not be considered in this or any other test. However, each set of AC specimens and their corresponding SEA specimens were tested at the same time.

b. Statistical Analyses

The average resilient moduli of the specimens, determined at temperatures of 41, 77, and 104 °F (5, 25, and 40 °C), are shown in table 8. Missing data indicate that the specimens were either too thin (less than 0.75 in (1.9 cm)) after sawing to be tested, or were not tested for reasons given in chapter 2.

Table 9 shows the effect of sulfur on the moduli for all projects and projects grouped according to pavement age, blending method, and the stiffness of the mixture. The Mr of the SEA sections were greater in older projects at a temperature of 104 °F (40 °C). An examination of the data indicated that out of the eight projects in this group, the largest increases were in four projects which contained soft mixtures. Thus, the sulfur mainly stiffened the mixtures of older projects where softer mixtures were used, even though the analyses according to stiffness showed no significant differences.

Table 9 also shows that AC and SEA projects older than 5 years had lower average moduli compared to projects less than 5 years. Moduli should increase with age unless there is a high amount of damage such as cracking or stripping. Because there was very little damage on these projects, the data are not properly grouped for valid statistical comparisons concerning pavement age alone. Age is confounded by the change from using softer to stiffer mixtures over time. As shown by table 10, the effect of sulfur varied with the project. The effects were not found to be related to the testing temperature.

Figure 4 graphically shows the resilient moduli and indicates that the effect of temperature on the data was much greater than the effect of sulfur. By visually comparing the graphs, it can also be seen that the overall mixture composition had a greater effect than the presence of sulfur. These figures present a slightly different view of the data in some cases compared to the t-tests because they do not include the effects of specimen-to-specimen variability. However, no trends concerning the effects of sulfur were evident. Slopes from regression analyses for the graphs, which indicate temperature susceptibility, and coefficients of determination, or r^2, are shown in table 11. A table showing the effects of sulfur on the slopes was not generated because sulfur had no significant effect on any slope and there were no overall trends.

Table 8. Resilient moduli (Mr) at 41, 77, and 104 °F.

Project	Pavement Layer	Material	Resilient Modulus, ksi		
			41 °F	77 °F	104 °F
CA	Surface	SEA (30/70)	2787	1685	611
		SEA (30/70)	3283	1414	392
CB	Surface[1] Location #1	AR-2000	2870	696	168
		SEA (20/80)	2669	1024	321
	Surface[1] Location #2	AR-4000	3008	1016	273
		SEA (40/60)	3160	874	183
DE	Surface	AC-20	2419	761	255
		SEA (30/70)	2414	861	305
GA	Surface	AC-20	1277	216	57
		AC-20	1475	241	66
ID	Surface Location #1	AR-4000	2007	316	107
		SEA (30/70)	2154	324	99
	Surface Location #2	AR-4000	1929	294	103
		SEA (30/70)	2006	318	110
KS	Surface	AC-20	--	--	--
		SEA (30/70)	--	--	--
	Base, top half	AC-20	2378	721	313
		SEA (30/70)	2354	814	309
	Base, bottom half	AC-20	1420	288	91
		SEA (30/70)	1955	652	219
LA	Surface	AC-30	3481	1001	255
		SEA (40/60)	2511	987	351
	Base under AC surface	SEA (40/60)	1439	403	145
	Base under SEA surface	SEA (40/60)	1608	471	158
MB	Surface	AC-10	--	--	--
		SEA (10/90)	--	--	--
		SEA (20/80)	--	--	--
		SEA (30/70)	--	--	--
	Binder	AC-10	1113	110	39
		SEA (10/90)	1490	91	28
		SEA (20/80)	1400	105	30
		SEA (30/70)	1167	148	46
MC	Surface[2]	AC-10	--	--	--
		SEA (30/70)	--	--	--
	Binder[2]	AC-10	1738	302	60
		SEA (30/70)	1406	247	45

[1] AR-2000 was used in SEA section.
[2] AC-5 was used in SEA section.

(ksi)(6895)=(KPa)
((°F)-32)/1.8=(°C)

Table 8. Resilient moduli (Mr) at 41, 77, and 104 °F (continued).

			Resilient Modulus, ksi		
Project	Pavement Layer	Material	41 °F	77 °F	104 °F
MN	Surface	AC 200-300	785	72	23
		SEA (40/60)	1675	199	43
MS	Surface	AC-20	2080	639	194
		SEA (30/70)	2534	674	200
	Binder	AC-40	2383	910	406
		SEA (30/70)	2332	862	347
	Base	AC-40	2912	1420	695
		SEA (30/70)	3116	1321	565
ND	Surface Location #1	AC 120-150	1457	169	42
		SEA (30/70)	1587	334	104
	Surface Location #2	AC 120-150	1923	254	48
		SEA (25/75)	1936	332	85
NM	Surface	AC-10	3572	949	269
		SEA (30/70)	2858	526	119
	Base	AC-10	3300	813	294
		SEA (30/70)	2466	586	162
TC	Base, top half	AC-20	2967	573	89
	Base, bottom half	AC-20	3250	335	57
		SEA (30/70)	3364	806	179
TP	Binder	AC-20	2650	958	344
		SEA (30/70)	2072	1193	583
TX	Surface	AC-20	--	--	--
		SEA (35/65)	--	--	--
WI	Surface	AC 120-150	1099	54	16
		SEA (30/70)	1757	142	31
WY	Surface	SEA (20/80)	2095	381	98
		SEA (20/80)	1933	234	59

(ksi)(6895)=(KPa)
((°F)-32)/1.8=(°C)

Table 9. Effect of sulfur on resilient modulus (Mr) for all projects, and projects by pavement age, blending method, and the stiffness of the mixture.

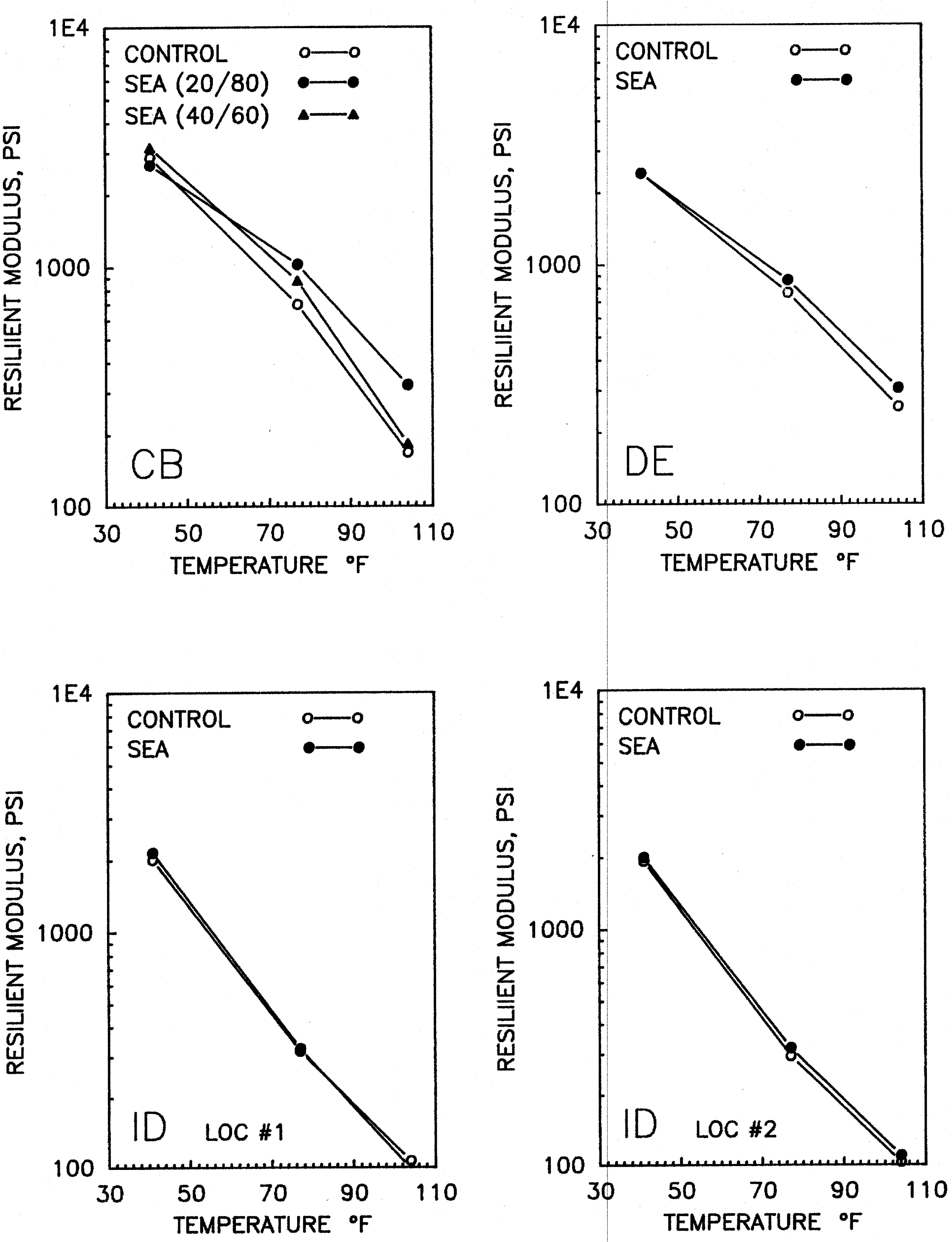
	Average AC Mr, ksi	Average SEA Mr, ksi	Degrees of Freedom	p
Test Temperature = 41 °F				
All projects	2202	2201	23	0.995 NS
Projects less than 5 years	2215	2227	13	0.921 NS
Projects more than 5 years	2179	2156	7	0.903 NS
In-Line Blending	2469	2289	10	0.279 NS
Direct Feed	1735	1942	8	0.117 NS
Soft Mixtures	1593	1813	10	0.052 NS
Stiff Mixtures	2810	2590	10	0.159 NS
Test Temperature = 77 °F				
All projects	531	580	23	0.218 NS
Projects less than 5 years	596	585	13	0.817 NS
Projects more than 5 years	452	573	7	0.069 NS
In-Line Blending	564	604	10	0.545 NS
Direct Feed	488	496	8	0.767 NS
Soft Mixtures	193	277	10	0.083 NS
Stiff Mixtures	869	884	10	0.828 NS
Test Temperature = 104 °F				
All projects	179	193	23	0.469 NS
Projects less than 5 years	206	202	13	0.886 NS
Projects more than 5 years	132	178	7	0.028 I
In-Line Blending	165	195	10	0.390 NS
Direct Feed	201	179	8	0.197 NS
Soft Mixtures	52	73	10	0.124 NS
Stiff Mixtures	306	313	10	0.842 NS

(ksi)(6895)=(KPa)
((°F)-32)/1.8=(°C)

Table 10. Effect of sulfur on resilient modulus (Mr) for each project.

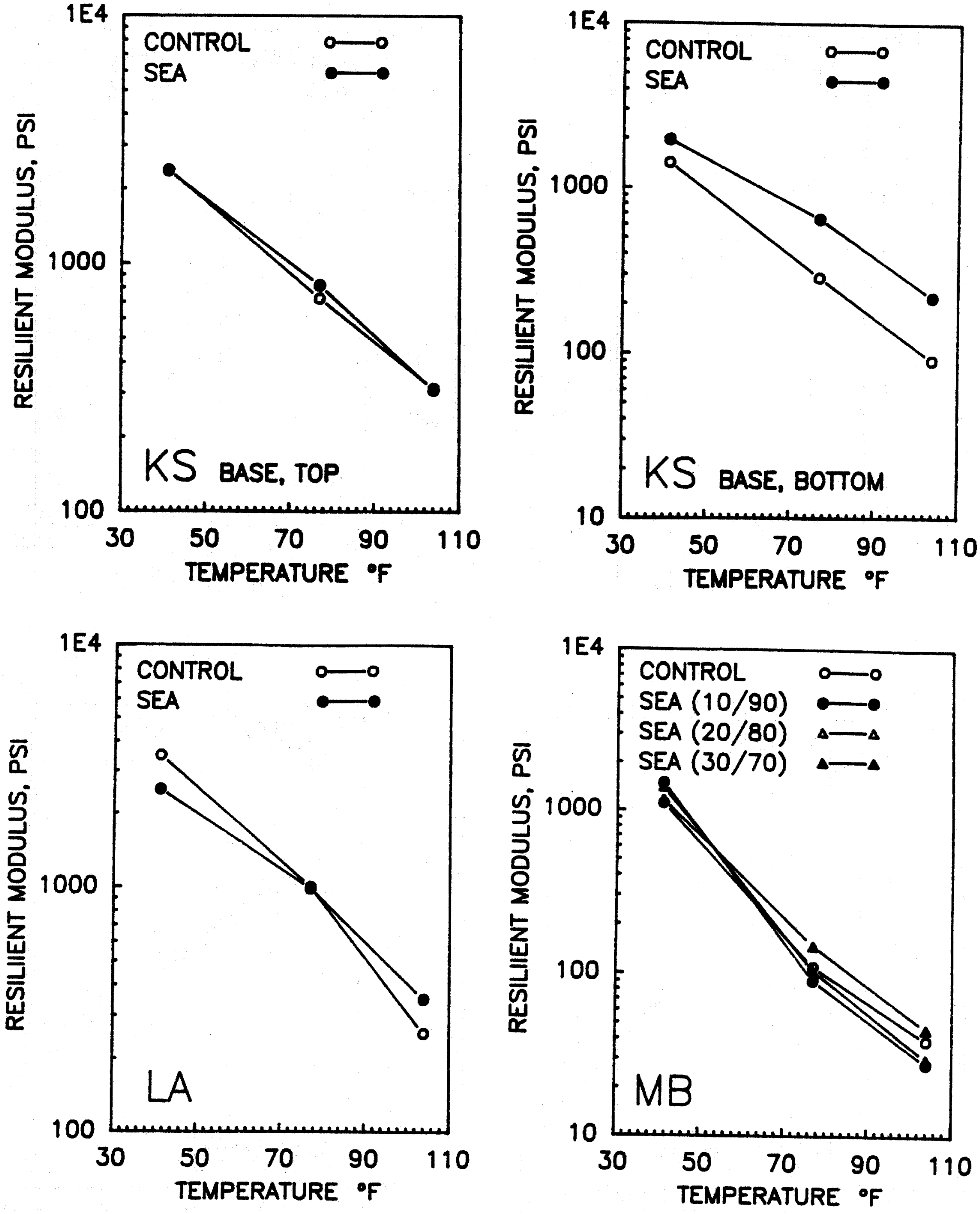
Project	Pavement Layer		Material	41 °F	77 °F	104 °F
CB	Surface		SEA (20/80)	D	I	I
	Surface		SEA (40/60)	I	I	I
DE	Surface		SEA (30/70)	NS	NS	NS
ID	Surface	Location #1	SEA (30/70)	NS	NS	NS
	Surface	Location #2	SEA (30/70)	NS	NS	NS
KS	Surface		SEA (30/70)	--	--	--
	Base, top half		SEA (30/70)	NS	NS	NS
	Base, bottom half		SEA (30/70)	NS	I	I
LA	Surface		SEA (40/60)	D	NS	NS
MB	Surface		SEA (10/90)	--	--	--
			SEA (20/80)	--	--	--
			SEA (30/70)	--	--	--
	Binder		SEA (10/90)	NS	D	NS
			SEA (20/80)	NS	NS	NS
			SEA (30/70)	NS	I	NS
MC	Surface		SEA (30/70)	--	--	--
	Binder		SEA (30/70)	NS	NS	NS
MN	Surface		SEA (40/60)	I	I	I
MS	Surface		SEA (30/70)	I	NS	NS
	Binder		SEA (30/70)	NS	NS	NS
	Base		SEA (30/70)	NS	NS	NS
ND	Surface	Location #1	SEA (30/70)	NS	I	I
	Surface	Location #2	SEA (25/75)	NS	I	I
NM	Surface		SEA (30/70)	D	D	D
	Base		SEA (30/70)	D	D	D
TC	Base		SEA (30/70)	NS	I	I
TP	Binder		SEA (30/70)	D	I	NS
TX	Surface		SEA (35/65)	--	--	--
WI	Surface		SEA (30/70)	I	I	I

((°F)-32)/1.8=(°C)



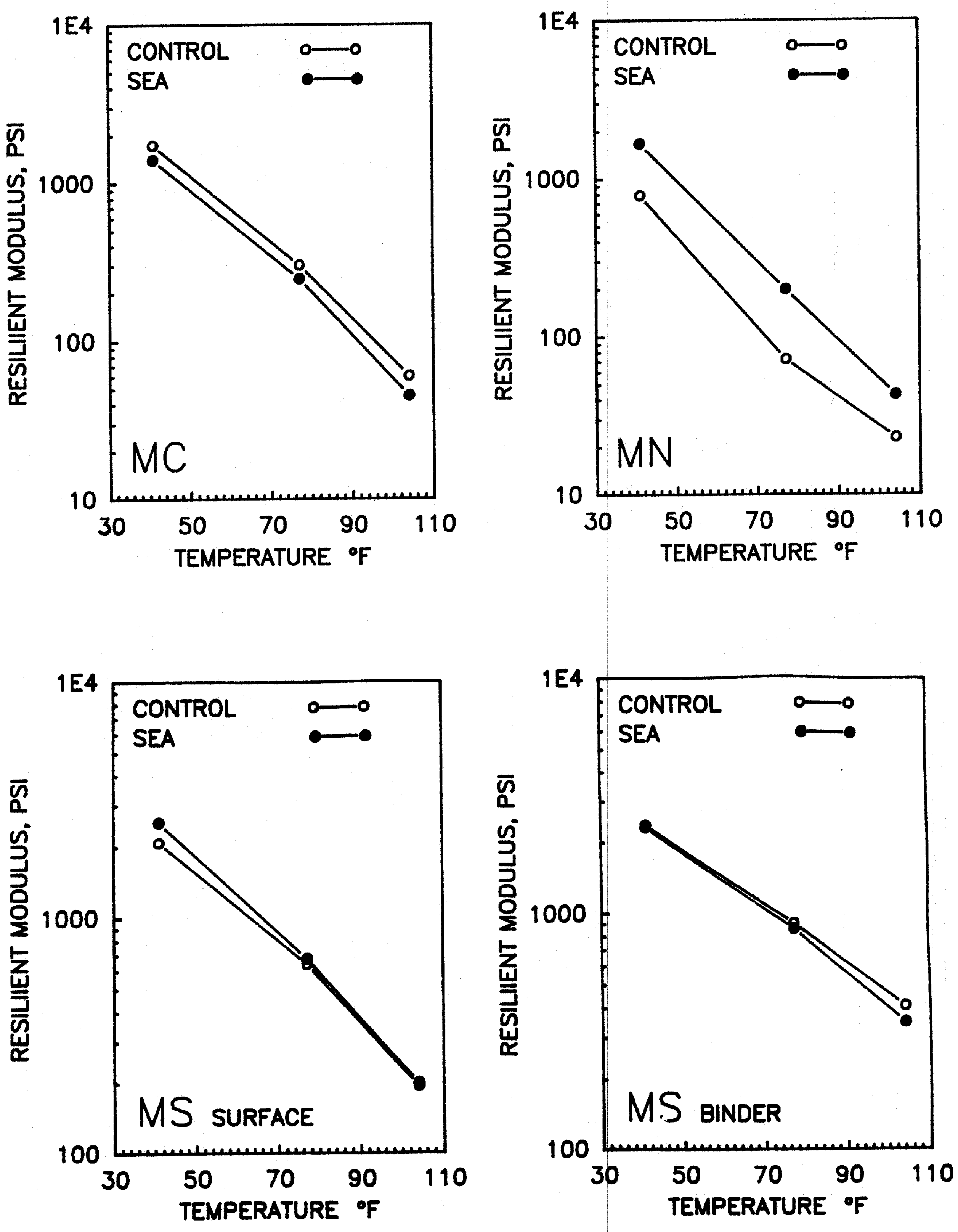
(ksi)(6895)=(KPa)   ((°F)-32)/1.8=(°C)

Figure 4. Resilient modulus versus test temperature.



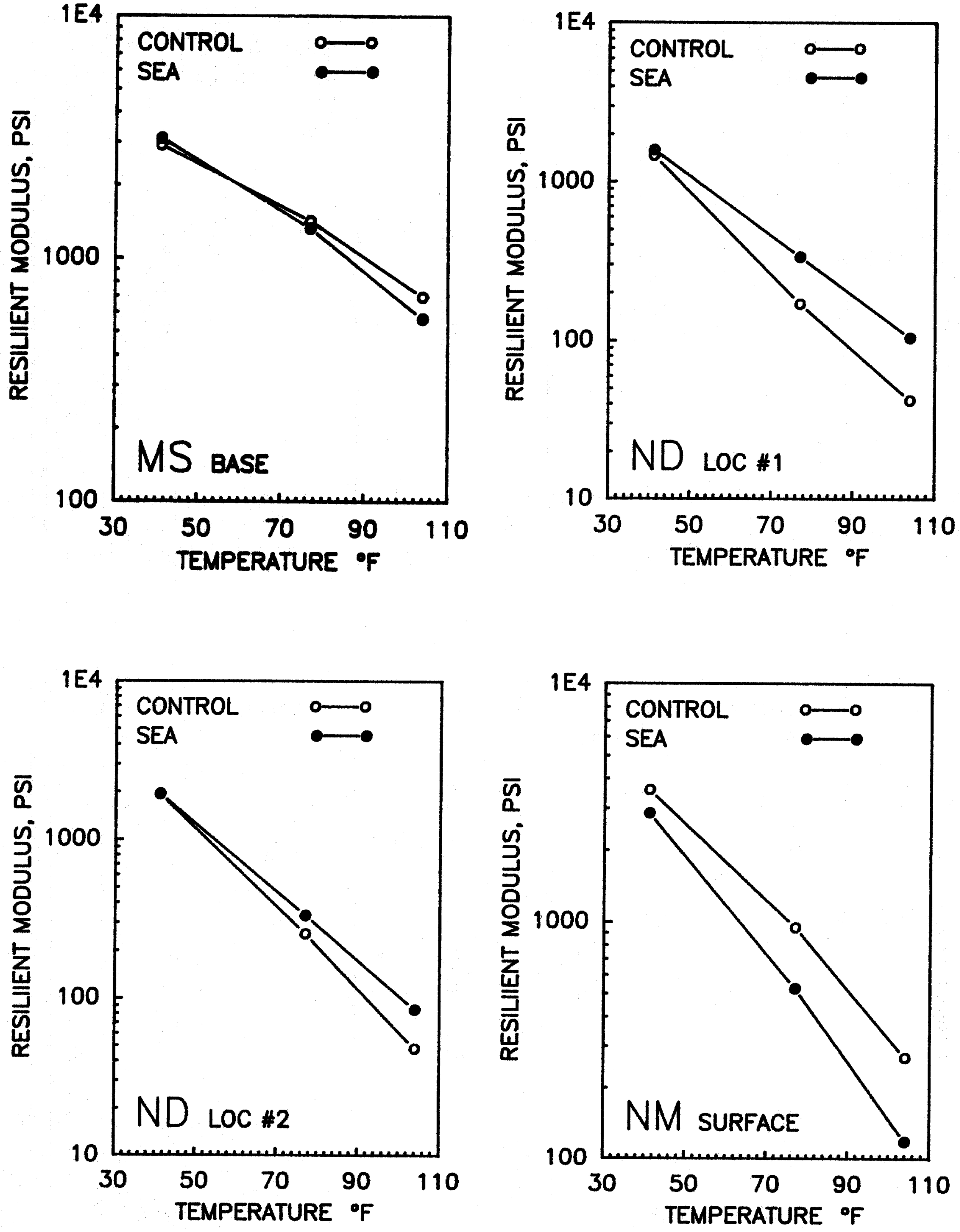
(ksi)(6895)=(KPa)   ((°F)-32)/1.8=(°C)

Figure 4. Resilient modulus versus test temperature (continued).



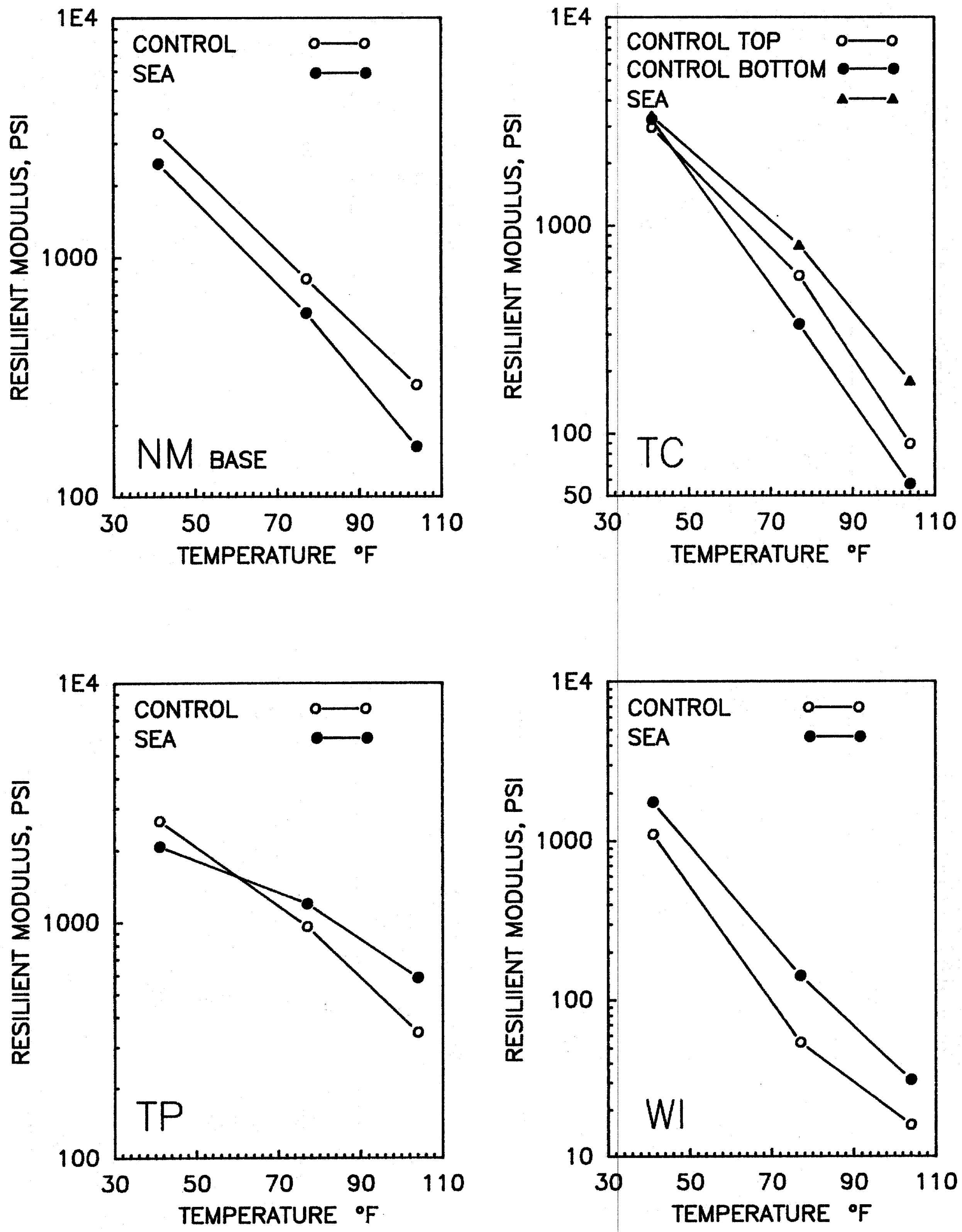
(ksi)(6895)=(KPa)   ((°F)-32)/1.8=(°C)

Figure 4. Resilient modulus versus test temperature (continued).



(ksi)(6895)=(KPa)   ((°F)-32)/1.8=(°C)

Figure 4. Resilient modulus versus test temperature (continued).



(ksi)(6895)=(KPa) ((°F)-32)/1.8=(°C)

Figure 4. Resilient modulus versus test temperature (continued).

Table 11. Slopes for $\log_{10}$(resilient moduli) versus temperature.

Project	Pavement Layer	Material	Slope	Coefficient of Determination r^2
CA	Surface	SEA (30/70)	-.010	.927
		SEA (30/70)	-.014	.960
CB	Surface[1] Location #1	AR-2000	-.019	.993
		SEA (20/80)	-.014	.981
	Surface[1] Location #2	AR-4000	-.016	.981
		SEA (40/60)	-.019	.981
DE	Surface	AC-20	-.761	.996
		SEA (30/70)	-.861	.993
GA	Surface	AC-20	-.021	1.000
		AC-20	-.021	.999
ID	Surface Location #1	AR-4000	-.020	.995
		SEA (30/70)	-.021	.998
	Surface Location #2	AR-4000	-.020	.994
		SEA (30/70)	-.020	.995
KS	Surface	AC-20	--	--
		SEA (30/70)	--	--
	Base, top half	AC-20	-.014	1.000
		SEA (30/70)	-.014	.997
	Base, bottom half	AC-20	-.019	1.000
		SEA (30/70)	-.015	.994
LA	Surface	AC-30	-.018	.988
		SEA (40/60)	-.013	.988
	Base under AC surface	SEA (40/60)	-.016	1.000
	Base under SEA surface	SEA (40/60)	-.016	.998
MB	Surface	AC-10	--	--
		SEA (10/90)	--	--
		SEA (20/80)	--	--
		SEA (30/70)	--	--
	Binder	AC-10	-.023	.982
		SEA (10/90)	-.028	.978
		SEA (20/80)	-.027	.987
		SEA (30/70)	-.022	.994
MC	Surface[2]	AC-10	--	--
		SEA (30/70)	--	--
	Binder[2]	AC-10	-.023	.996
		SEA (30/70)	-.024	.994

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[1] AR-2000 was used in SEA section.
[2] AC-5 was used in SEA section.

Table 11. Slopes for $\log_{10}$(resilient moduli) versus temperature (continued).

Project	Pavement Layer	Material	Slope	Coefficient of Determination r^2
MN	Surface	AC 200-300	-.025	.986
		SEA (40/60)	-.025	1.000
MS	Surface	AC-20	-.016	.993
		SEA (30/70)	-.017	.997
	Binder	AC-40	-.012	.999
		SEA (30/70)	-.013	.997
	Base	AC-40	-.010	.993
		SEA (30/70)	-.012	.994
ND	Surface Location #1	AC 120-150	-.025	.998
		SEA (30/70)	-.019	1.000
	Surface Location #2	AC 120-150	-.025	.999
		SEA (25/75)	-.022	1.000
NM	Surface	AC-10	-.018	.995
		SEA (30/70)	-.022	.998
	Base	AC-10	-.017	1.000
		SEA (30/70)	-.019	.997
TC	Base, top half	AC-20	-.024	.986
	Base, bottom half	AC-20	-.028	1.000
		SEA (30/70)	-.020	.991
TP	Binder	AC-20	-.014	.993
		SEA (30/70)	-.008	.976
TX	Surface	AC-20	--	--
		SEA (35/65)	--	--
WI	Surface	AC 120-150	-.030	.975
		SEA (30/70)	-.028	.997
WY	Surface	SEA (20/80)	-.021	1.000
		SEA (20/80)	-.024	.999

It was concluded from the data shown in table 11 that sulfur had no effect on temperature susceptibility within the temperature range of 41 °F (5 °C) to 104 °F (40 °C). The high coefficients of determination in table 11 indicate excellent regressions. However, using the $\log_{10}$ of the resilient moduli reduces the effects of the variation in the data compared to arithmetic plots.

Overall, the Mr data showed that sulfur had no effect on temperature susceptibility in the temperature range evaluated, and no effect on the resilient modulus at 41 °F (5 °C) and 77 °F (25 °C). At 104 °F (40 °C) the sulfur stiffened the mixtures in older projects, mainly where soft mixtures were used.

c. Sample Variability

Table 12 shows the average Mr at 77 °F (25 °C) along with the standard deviations. Standard deviations for densities were reported in table 5. Both tests were performed on all specimens, excluding those that were damaged. (The Mr tests at 41 °F (5 °C) and 104 °F (40 °C) were performed on smaller groups of specimens.) There were no obvious trends that sulfur either increased or decreased variability as measured by the Mr at 77 °F (25 °C) or density.

d. Additional Analyses

Densities and Mr at 77 °F (25 °C) for the 12 specimens taken "in the wheelpath" were compared to those for the three specimens taken "out of the wheelpath" for each project and layer. Based on 53 comparisons of densities (both AC and SEA), 16 showed significant differences. The "out of the wheelpath" samples had lower densities in 14 of 16 comparisons. These statistical results were highly dependent on the variability of the data for the two groups and differences between their variabilities. In many cases, the number of specimens from "out of the wheelpath" was inadequate for a valid statistical comparison.

Of 45 comparisons using the Mr at 77 °F (25 °C), only one showed a significant difference. The AC section of MN had a statistically significant lower Mr "out of the wheelpath" (64 ksi (440 MPa) versus 100 ksi (690 MPa)). It was originally planned to compare all other test data for the "in the wheelpath" sections to the "out of the wheelpath" sections, but based on the density and Mr results, it was decided to eliminate this part of the study.

Table 12. Averages and standard deviations for resilient moduli (Mr) at 77 °F.

			Resilient Modulus, ksi	
Project	Pavement Layer	Material	Average	Std. Deviation
CA	Surface	SEA (30/70)	1685	419
		SEA (30/70)	1414	160
CB	Surface[1] Location #1	AR-2000	696	43
		SEA (20/80)	1024	70
	Surface[1] Location #2	AR-4000	1016	80
		SEA (40/60)	874	85
DE	Surface	AC-20	761	138
		SEA (30/70)	861	141
GA	Surface	AC-20	216	120
		AC-20	241	101
ID	Surface Location #1	AR-4000	316	81
		SEA (30/70)	324	49
	Surface Location #2	AR-4000	294	71
		SEA (30/70)	318	65
KS	Surface	AC-20	--	--
		SEA (30/70)	--	--
	Base, top half	AC-20	721	94
		SEA (30/70)	814	245
	Base, bottom half	AC-20	288	108
		SEA (30/70)	652	166
LA	Surface	AC-30	1001	343
		SEA (40/60)	987	293
	Base under AC surface	SEA (40/60)	403	71
	Base under SEA surface	SEA (40/60)	471	92
MB	Surface	AC-10	--	--
		SEA (10/90)	--	--
		SEA (20/80)	--	--
		SEA (30/70)	--	--
	Binder	AC-10	110	19
		SEA (10/90)	91	30
		SEA (20/80)	105	24
		SEA (30/70)	148	55
MC	Surface[2]	AC-10	--	--
		SEA (30/70)	--	--
	Binder[2]	AC-10	302	202
		SEA (30/70)	247	155

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[1] AR-2000 was used in SEA section.
[2] AC-5 was used in SEA section.

(ksi)(6895)=(KPa)
((°F)-32)/1.8=(°C)

Table 12. Averages and standard deviations for resilient moduli (Mr) at 77 °F (continued).

			Resilient Modulus, ksi	
Project	Pavement Layer	Material	Average	Std. Deviation
MN	Surface	AC 200-300	72	18
		SEA (40/60)	199	29
MS	Surface	AC-20	639	78
		SEA (30/70)	674	53
	Binder	AC-40	910	116
		SEA (30/70)	862	212
	Base	AC-40	1420	224
		SEA (30/70)	1321	237
ND	Surface Location #1	AC 120-150	169	51
		SEA (30/70)	334	70
	Surface Location #2	AC 120-150	254	63
		SEA (25/75)	332	92
NM	Surface	AC-10	949	160
		SEA (30/70)	526	95
	Base	AC-10	813	309
		SEA (30/70)	586	122
TC	Base, top half	AC-20	573	71
	Base, bottom half	AC-20	335	44
		SEA (30/70)	806	123
TP	Binder	AC-20	958	185
		SEA (30/70)	1193	277
TX	Surface	AC-20	--	--
		SEA (35/65)	--	--
WI	Surface	AC 120-150	54	7
		SEA (30/70)	142	23
WY	Surface	SEA (20/80)	381	77
		SEA (20/80)	234	29

(ksi)(6895)=(KPa)
((°F)-32)/1.8=(°C)

For the DE project, half of the SEA specimens were cored from a section where the sulfur was added directly to the pugmill, while the other half were from a section where in-line blending was used. The results of t-tests performed on the densities and Mr at 77 °F (25 °C) indicated no differences in properties, and the specimens were combined into one group. Without combining these specimens, the entire testing program could not be carried out on the DE project. However, the data from this project could not be included in the analyses evaluating direct feed versus in-line blending methods.

2. Diametral Incremental Creep Test

a. General

The creep test was performed using a closed-loop electrohydraulic Materials Testing System (MTS) with a programmed incremental type of creep loading. As in the resilient modulus test, the specimens were tested in the indirect configuration; however, vertical compressive deformations were recorded instead of horizontal tensile deformations. An MTS extensometer, Model 632.06B-20 was used for measuring deformations. The apparatus which holds the specimen consisted of 0.5-in (1.3-cm) upper and lower loading strips curved to meet a 4-in (10.2-cm) diameter specimen, and two guide posts containing Thompson linear motion bushings connecting the upper and lower platens. As shown in figure 5, the upper loading strip was allowed to swivel along the length of the specimen. When testing cores, the upper loading strip cannot be fixed in this direction.

Loading times (creep durations) were 0.1, 0.3, 1.0, 3.0, 10, 30, and 100 seconds, while the rest period after each of these was 1.0, 1.0, 2.0, 2.0, 2.0, 4.0, 4.0 minutes respectively. A constant load was applied throughout the test and vertical, compressive deformations were recorded throughout each loading time and rest period. A typical plot for loading times of 10, 30, and 100 seconds is shown in figure 6.

In this study, creep compliances (D = strain/stress) were calculated from the total deformation (V_t) recorded immediately before the load was removed. The creep compliances were then inverted to a creep modulus (1/D = stress/strain). A modulus is more commonly used by the highway community. This testing approach was developed under another FHWA research study which is still in progress.(6)

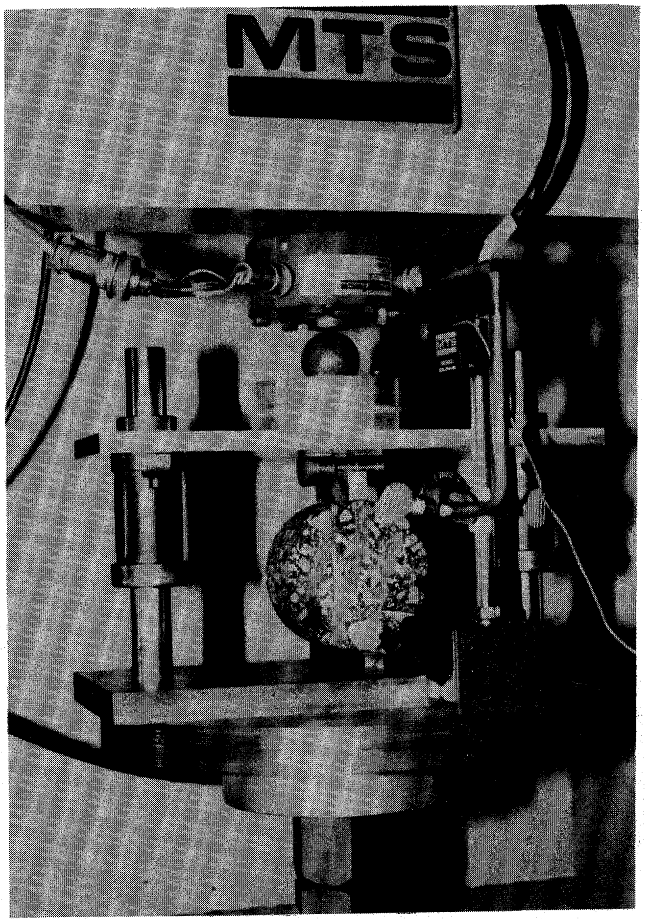
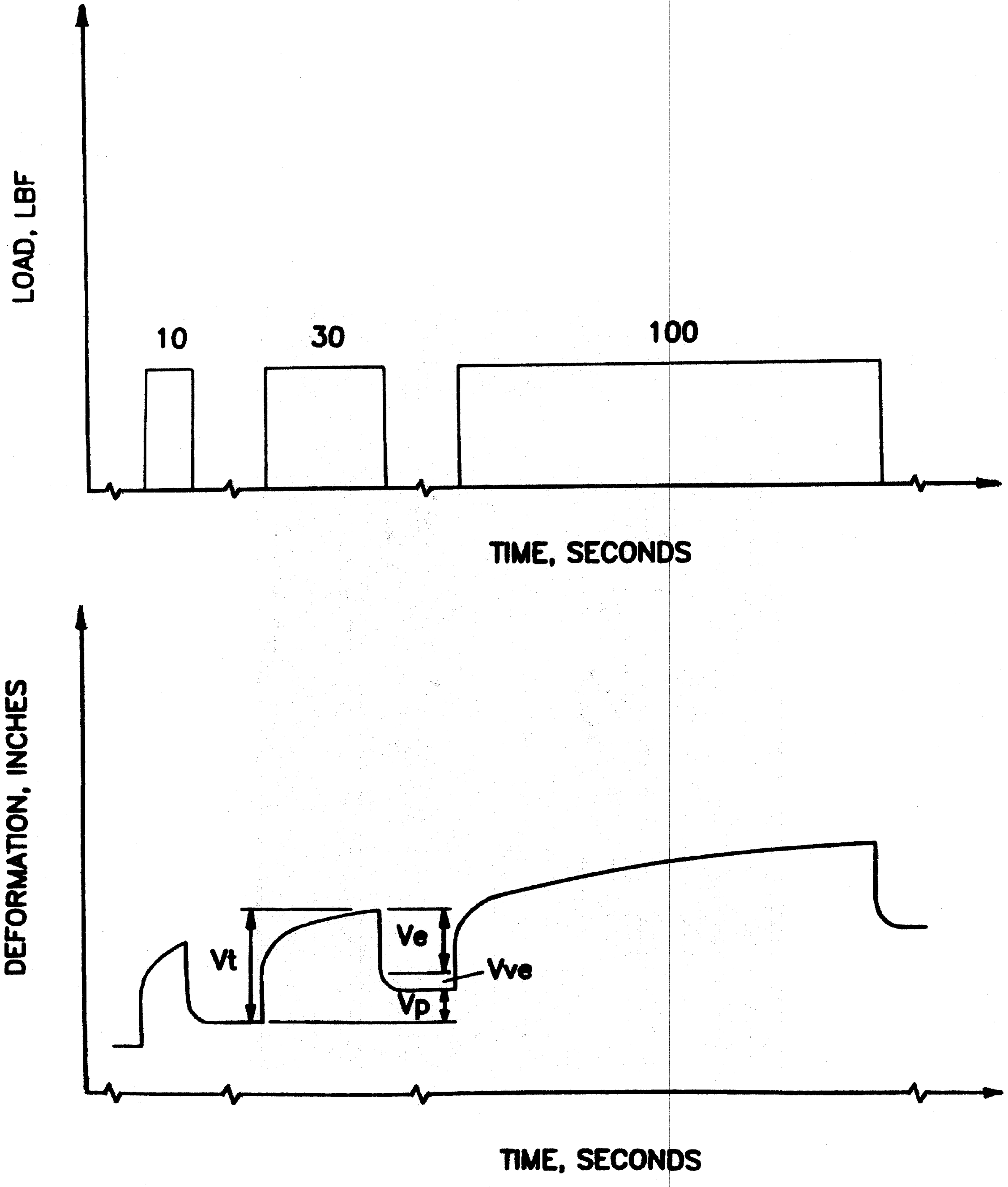


Figure 5. Loading configuration for the indirect creep test.



(lbf)(4.448)=(N)
(in)(2.54)=(cm)

Figure 6. Typical load and deformation graphs for the indirect creep test.

The equation used to compute the modulus was as follows:

$$Mc = \frac{1}{D} = \frac{(3.57)(L)}{(t)(V_t)} \qquad (2)$$

where

Mc = creep modulus, lbf/in^2;

D = creep compliance, (lbf/in^2)$^{-1}$;

L = load, lbf;

t = specimen thickness, in; and

V_t = vertical total deformation, in.

Typical plots for creep compliance and creep modulus are shown in figures 7 and 8. Plots for other temperatures and mixtures may not be linear as in these plots. Also, at higher and lower loading times, the plot will start to curve until minimum and maximum creep compliances and moduli are reached.

The elastic deformation (V_e), viscoelastic deformation (delayed elastic) (V_{ve}), and the permanent (V_p) deformation at the end of the rest period were measured. Deformations were plotted as $\log_{10}$(deformation) versus $\log_{10}$(loading time), and typical plots are shown in figures 9 through 11. Viscoelastic deformations approach zero at short loading times.

The loads used in the resilient modulus test were reviewed to determine loads for the creep test. However, trial creep test results indicated that even these loads were not always good choices as the specimens responded differently in the two tests. Loads were finally chosen based on the trial creep tests. At 41 °F (5 °C), the load was 400 lbf (1780 N). At 77 °F (25 °C), the load was 75 lbf (330 N). At 104 °F (40 °C), the load was 50 lbf (220 N). The load was most difficult to choose at 104 °F (40 °C). All loads listed here are for a sample thickness of 2.5 in (6.4 cm). These loads were adjusted for the various specimen thicknesses in order to maintain equivalent stress levels at each temperature.

The specimens were preconditioned. Preconditioning consisted of 20 repeated sinusoidal load cycles each having a 0.1-second load duration followed by a 0.9-second rest period. The load was 50 percent of the load to be used in the creep test.

Preloading was also used in each test to seat the specimen. The preload was adjusted so that it was less than 5 percent of the creep load. A preload must be low compared to the test load so it has little effect on the test results.

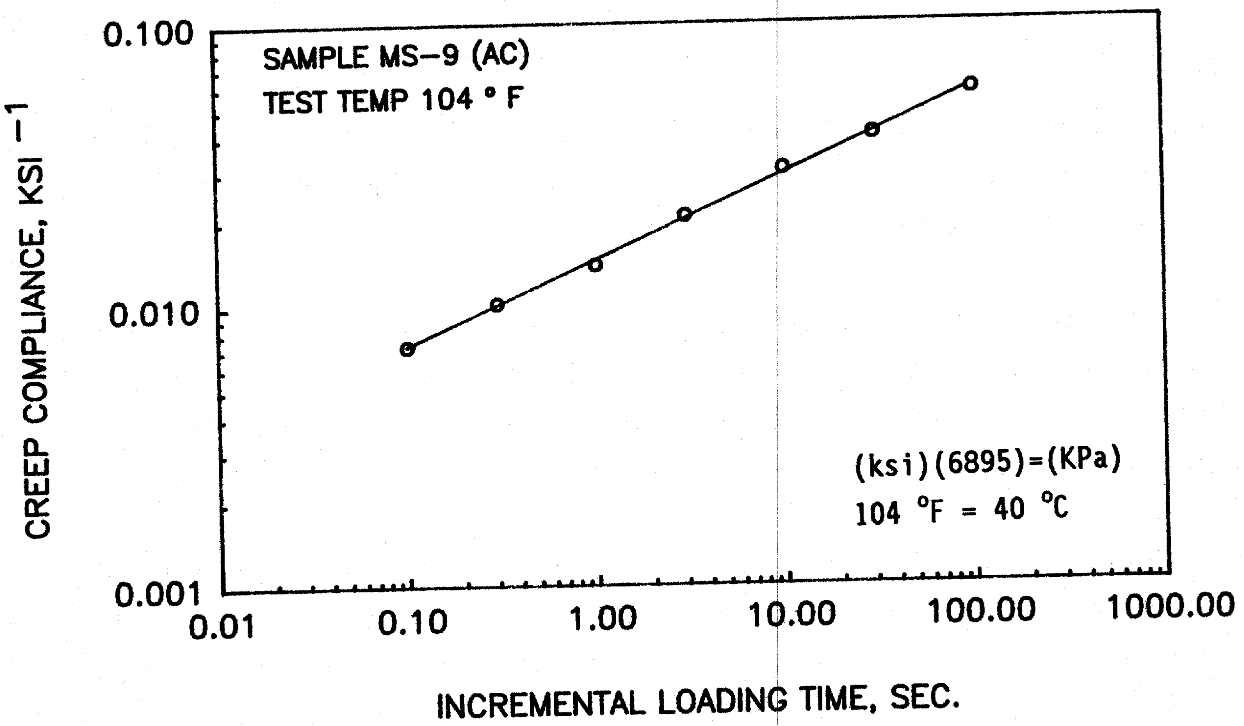


Figure 7. Typical graph of creep compliance versus incremental creep time.

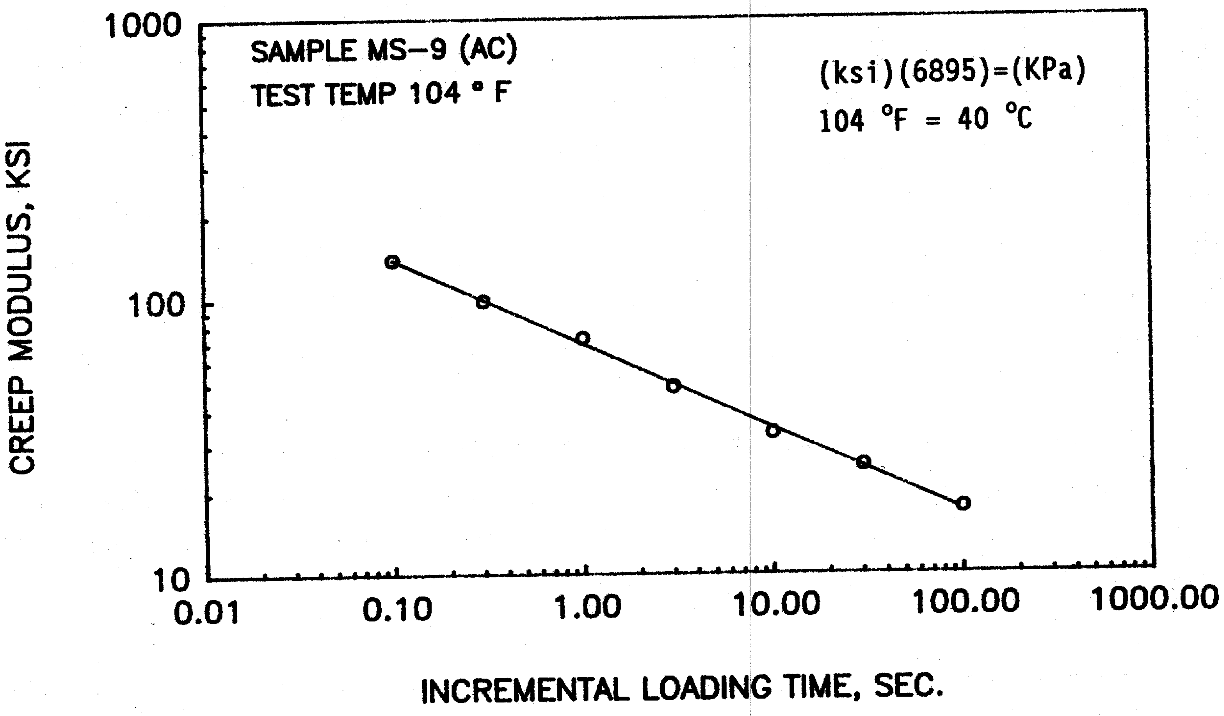


Figure 8. Typical graph of creep modulus versus incremental creep time.

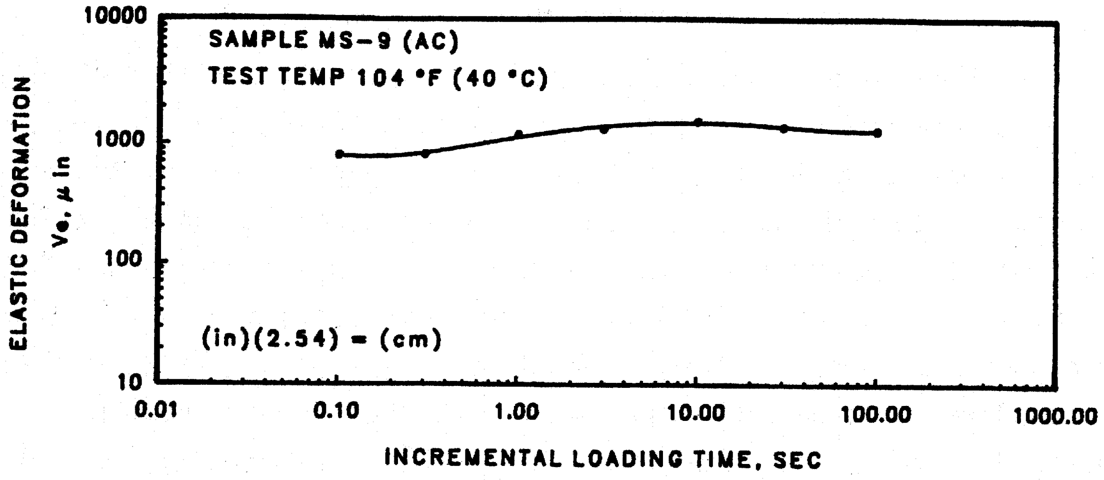


Figure 9. Typical graph of elastic deformation versus incremental creep time.

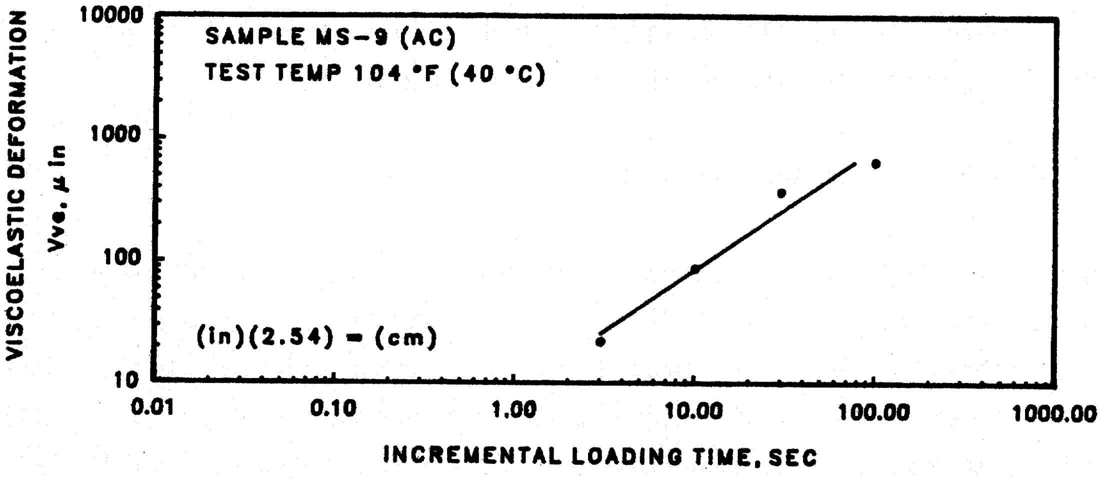


Figure 10. Typical graph of viscoelastic deformation versus incremental creep time.

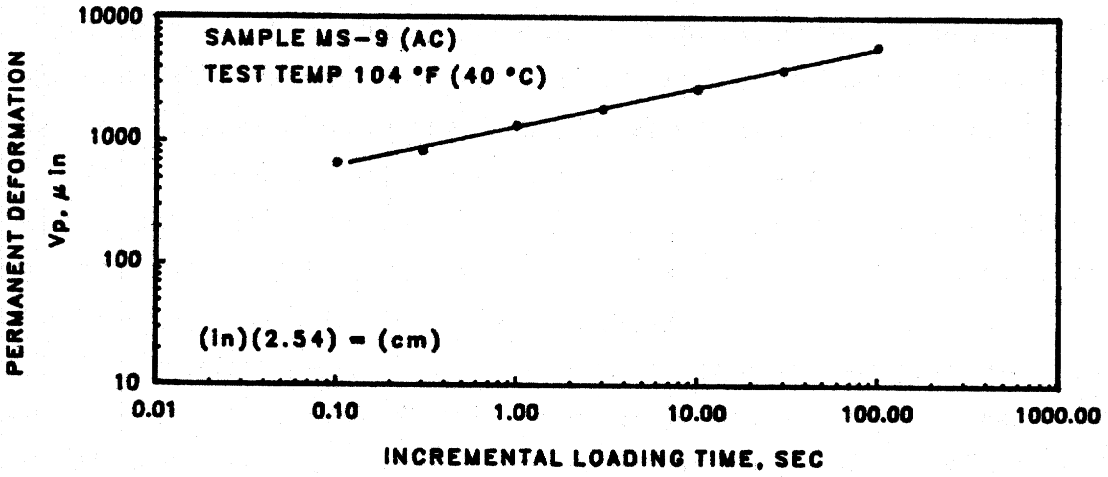


Figure 11. Typical graph of permanent deformation versus incremental creep time.

Data at the longer loading times may be out of the linear viscoelastic range. If so, the modulus is a function of the stress level, and the same stress level must be used at each temperature in order to compare data from temperature to temperature. However, no stress level could be chosen which would provide the data at all three temperatures. Stresses needed to obtain accurate data for the short loading times at 41 °F (5 °C) would break many specimens at 104 °F (40 °C). Permanent deformations are always a function of the stress level. However, within the linear viscoelastic range where the modulus is a constant, it is reasonable to assume that the level of permanent deformation is linearly proportional to the stress level. Out of the linear viscoelastic range, this is not true. Therefore, relationships between the creep data and temperature could not be developed. Another problem which could not be considered is that equation 2 may not be applicable outside of the linear range.

b. Methodology for Analyzing the Data

Moduli and deformations at short loading times, representing pavements under moving traffic, and at long loading times, representing pavements at traffic lights or in parking lots, are provided by the incremental creep test. Thus the data may be used to evaluate the response of a mixture under a variety of loadings. However, permanent deformations from creep tests performed only at a single long loading time (non-incremental test) have been used as surrogates for cumulative permanent deformations for repeated loadings. If this equivalency is accurate, then only the permanent deformations at the longer loading times used in this study are important. The test results from the incremental creep test have also been used to estimate cumulative permanent deformations for repeated loadings.(7) In this case, the permanent deformations at the longer loading times would be more important than at the short loading times. Again, emphasis would have to be placed on the data at the longer loading times used in this study. However, a relationship between cumulative permanent deformations from repeated load tests and creep test data has not been firmly established. It also must be noted that data recorded at short loading times, such as 0.1 second, under a short-term test may not be the same as the data collected per cycle after a long-term repeated load test, even if aged pavement cores are tested.

The test data in this study were evaluated at both the short and long loading times at all three temperatures. A simple test having one short loading time and one long loading time could be used to perform this evaluation, but the advantage of the incremental test is that if the relationships between the test data and loading time are linear, then slopes and average values at short and long loading times generated by a regression equation can be used for comparing mixtures. Using values generated from a regression line is beneficial because at very short loading times, such as 0.1 second, the measured data are sometimes less accurate than at the higher loading times. Changes in slopes, although not as important as changes in average data, may indicate trends in the data due to differences in the rheological responses at the short and long loading times. The AC and SEA cores were compared using the following data:

- Modulus at 0.1 and 100 seconds, and the slope.
- Permanent deformation at 0.1 and 100 seconds, and the slope.
- Resilient deformation at 0.1 and 10 seconds.
- Viscoelastic deformation at 100 seconds.

As shown in figure 9, resilient deformations varied little with the loading time and thus a slope was not computed. Resilient deformations generally peaked at a loading time of 10 seconds, so this loading time was used instead of 100 seconds.

Viscoelastic deformations were insignificant at short loading times and thus only the data at 100 seconds were analyzed. At 41, 77, and 104 °F (5, 25, and 40 °C), the viscoelastic deformations were not measurable until after loading times of 0.3, 10, and 10 seconds respectively.

After acquiring the data it was found that the moduli at 41 °F (5 °C) were not linear with the loading time so the slopes were not calculated. The moduli tended to approach a maximum value at the short loading times.

c. Statistical Analyses - Creep Test at 41 °F (5 °C)

The creep moduli at 41 °F (5 °C) are shown in table 13. Table 14 shows the effect of sulfur on the moduli for the groups. There was no significant difference between the SEA and AC sections for any group at either the short or long loading time. As shown by table 15, sulfur had little effect on a project-by-project basis.

Table 13. Creep moduli at 41 °F.

Project	Pavement Layer	Material	Moduli, ksi 0.1 sec.	Moduli, ksi 100 sec.
CA	Surface	SEA (30/70)	227.9	193.5
		SEA (30/70)	207.0	173.8
CB	Surface[1] Location #1	AR-2000	166.8	128.0
		SEA (20/80)	180.4	144.0
	Surface[1] Location #2	AR-4000	167.8	141.4
		SEA (40/60)	176.2	154.9
DE	Surface	AC-20	210.8	144.0
		SEA (30/70)	214.0	141.6
GA	Surface	AC-20	208.4	98.3
		AC-20	171.6	89.7
ID	Surface Location #1	AR-4000	126.5	83.4
		SEA (30/70)	115.5	81.1
	Surface Location #2	AR-4000	122.4	80.5
		SEA (30/70)	121.1	80.8
KS	Surface	AC-20	--	--
		SEA (30/70)	--	--
	Base, top half	AC-20	108.1	91.7
		SEA (30/70)	117.0	96.0
	Base, bottom half	AC-20	121.2	78.1
		SEA (30/70)	120.4	95.1
LA	Surface	AC-30	202.6	152.0
		SEA (40/60)	155.7	121.4
	Base under AC surface	SEA (40/60)	136.4	89.7
	Base under SEA surface	SEA (40/60)	138.7	95.7
MB	Surface	AC-10	--	--
		SEA (10/90)	--	--
		SEA (20/80)	--	--
		SEA (30/70)	--	--
	Binder	AC-10	186.0	77.9
		SEA (10/90)	136.7	58.7
		SEA (20/80)	131.6	59.4
		SEA (30/70)	134.9	67.1
MC	Surface[2]	AC-10	--	--
		SEA (30/70)	--	--
	Binder[2]	AC-10	152.8	77.4
		SEA (30/70)	149.7	65.3

[1] AR-2000 was used in SEA section.
[2] AC-5 was used in SEA section.

(ksi)(6895)=(KPa)
41 °F = 5 °C

Table 13. Creep moduli at 41 °F (continued).

Project	Pavement Layer		Material	Moduli, ksi 0.1 sec.	Moduli, ksi 100 sec.
MN	Surface		AC 200-300	162.3	41.6
			SEA (40/60)	161.1	72.1
MS	Surface		AC-20	220.1	132.0
			SEA (30/70)	182.5	116.8
	Binder		AC-40	188.4	137.9
			SEA (30/70)	216.6	141.5
	Base		AC-40	155.2	138.6
			SEA (30/70)	147.8	128.4
ND	Surface	Location #1	AC 120-150	124.5	61.7
			SEA (30/70)	119.5	76.4
	Surface	Location #2	AC 120-150	122.6	68.5
			SEA (25/75)	105.3	76.5
NM	Surface		AC-10	141.2	121.5
			SEA (30/70)	150.1	114.9
	Base		AC-10	145.5	126.4
			SEA (30/70)	162.8	116.8
TC	Base, top half		AC-20	195.1	140.6
	Base, bottom half		AC-20	139.5	90.6
			SEA (30/70)	130.9	106.0
TP	Binder		AC-20	188.2	162.9
			SEA (30/70)	186.2	166.3
TX	Surface		AC-20	--	--
			SEA (35/65)	--	--
WI	Surface		AC 120-150	115.5	49.4
			SEA (30/70)	133.6	75.1
WY	Surface		SEA (20/80)	146.9	97.2
			SEA (20/80)	162.8	98.9

(ksi)(6895)=(KPa)
41 °F = 5 °C

Table 14. Effect of sulfur on creep modulus at 41 °F for all projects, and projects by pavement age, blending method, and the stiffness of the mixture.

	Average AC Mc, ksi	Average SEA Mc, ksi	Degrees of Freedom	p
<u>Creep Time = 0.1 second</u>				
All projects	159.9	151.3	21	0.114 NS
Projects less than 5 years	163.9	155.4	13	0.282 NS
Projects more than 5 years	152.9	144.2	7	0.195 NS
In-Line Blending	147.5	146.0	10	0.802 NS
Direct Feed	171.7	153.1	8	0.102 NS
Soft Mixtures	142.7	130.9	10	0.102 NS
Stiff Mixtures	172.2	171.8	10	0.955 NS
<u>Creep Time = 100 seconds</u>				
All projects	102.3	102.8	21	0.883 NS
Projects less than 5 years	108.7	107.6	13	0.774 NS
Projects more than 5 years	90.9	94.4	7	0.616 NS
In-Line Blending	105.7	109.8	10	0.429 NS
Direct Feed	94.8	89.5	8	0.347 NS
Soft Mixtures	71.5	74.4	10	0.593 NS
Stiff Mixtures	133.0	131.1	10	0.700 NS

(ksi)(6895)=(KPa)
41 °F = 5 °C

Table 15. Effect of sulfur on creep modulus at 41 °F for each project.

Project	Pavement Layer		Material	0.1 sec.	100 sec.
CB	Surface		SEA (20/80)	NS	I
	Surface		SEA (40/60)	NS	NS
DE	Surface		SEA (30/70)	NS	NS
ID	Surface	Location #1	SEA (30/70)	NS	NS
	Surface	Location #2	SEA (30/70)	NS	NS
KS	Surface		SEA (30/70)	--	--
	Base, top half		SEA (30/70)	NS	NS
	Base, bottom half		SEA (30/70)	NS	NS
LA	Surface		SEA (40/60)	D	NS
MB	Surface		SEA (10/90)	--	--
			SEA (20/80)	--	--
			SEA (30/70)	--	--
	Binder		SEA (10/90)	D	D
			SEA (20/80)	D	D
			SEA (30/70)	D	NS
MC	Surface		SEA (30/70)	--	--
	Binder		SEA (30/70)	NS	NS
MN	Surface		SEA (40/60)	NS	I
MS	Surface		SEA (30/70)	D	NS
	Binder		SEA (30/70)	NS	NS
	Base		SEA (30/70)	NS	NS
ND	Surface	Location #1	SEA (30/70)	NS	NS
	Surface	Location #2	SEA (25/75)	NS	NS
NM	Surface		SEA (30/70)	NS	NS
	Base		SEA (30/70)	NS	NS
TC	Base		SEA (30/70)	NS	I
TP	Binder		SEA (30/70)	NS	NS
TX	Surface		SEA (35/65)	--	--
WI	Surface		SEA (30/70)	NS	I

41 °F = 5 °C

Permanent deformation data are shown in table 16. Table 17 shows the effect of sulfur on the permanent deformations for the groups. The permanent deformations of the SEA sections were higher for projects using soft mixtures at a loading time of 0.1 seconds and there was a significant reduction in the slope. The slope for in-line blended projects was also significantly reduced by the sulfur. The two lower slopes and an examination of the average permanent deformation at both loading times for these groups indicate a trend toward the sulfur increasing the deformations at the short loading time and decreasing the deformations at the long loading time. If it is assumed that the data at 100 seconds is more important than at 0.1 second and permanent deformations measured at 41 °F (5 °C) are due to viscous flow only and not to cracking, then there may be a tendency for sulfur to reduce rutting in some cases. However, firm conclusions regarding these slopes could not be made because the sulfur had no significant effect at the individual loading times, except for soft mixtures at 0.1 second, and it is unknown whether these assumptions are true. As shown by the table 18, the effect of sulfur on a project-by-project basis varied with the project, and no trends were evident.

Resilient and viscoelastic deformations are shown in table 19. As shown by table 20, sulfur had little effect on a project-by-project basis. Statistical analyses for the groups were deemed unnecessary for these data.

d. Statistical Analyses - Creep Test at 77 °F (25 °C)

The creep moduli at 77 °F (25 °C) are shown in table 21. Table 22 shows the effect of sulfur on the moduli for the groups. The moduli of the SEA sections were higher for older projects at a loading time of 100 seconds and this also significantly reduced the slope. Of the eight projects in this group, the SEA sections had higher moduli in seven, and an Mr equal to the control in the remaining project. However, five of these seven projects had softer mixtures. Therefore, as previously indicated when analyzing the resilient modulus data, age and stiffness are confounded. Nothing could be concluded from the other three significantly different slopes because the average moduli of the SEA and AC sections for each comparison at both loading times were virtually equal.

As shown by table 23, the effect of sulfur varied on a project-by-project basis, and no trends were evident.

Table 16. Permanent deformations at 41 °F.

Project	Pavement Layer		Material	Permanent Deformation (microinches) 0.1 sec.	100 sec.	Slope
CA	Surface		SEA (30/70)	20	302	.395
			SEA (30/70)	80	420	.241
CB	Surface[1]	Location #1	AR-2000	104	740	.284
			SEA (20/80)	58	570	.332
	Surface[1]	Location #2	AR-4000	114	478	.209
			SEA (40/60)	68	600	.314
DE	Surface		AC-20	309	1050	.177
			SEA (30/70)	140	830	.258
GA	Surface		AC-20	262	2019	.296
			AC-20	239	1896	.300
ID	Surface	Location #1	AR-4000	102	1538	.392
			SEA (30/70)	171	1604	.324
	Surface	Location #2	AR-4000	88	1689	.428
			SEA (30/70)	120	1483	.364
KS	Surface		AC-20	--	--	--
			SEA (30/70)	--	--	--
	Base, top half		AC-20	129	1022	.300
			SEA (30/70)	113	922	.304
	Base, bottom half		AC-20	262	1922	.289
			SEA (30/70)	36	1104	.494
LA	Surface		AC-30	27	362	.377
			SEA (40/60)	99	684	.280
	Base under AC surface		SEA (40/60)	247	1326	.229
	Base under SEA surface		SEA (40/60)	183	1182	.270
MB	Surface		AC-10	--	--	--
			SEA (10/90)	--	--	--
			SEA (20/80)	--	--	--
			SEA (30/70)	--	--	--
	Binder		AC-10	229	2518	.347
			SEA (10/90)	328	4108	.366
			SEA (20/80)	335	4414	.373
			SEA (30/70)	265	2696	.336
MC	Surface[2]		AC-10	--	--	--
			SEA (30/70)	--	--	--
	Binder[2]		AC-10	206	2738	.375
			SEA (30/70)	318	4321	.378

[1] AR-2000 was used in SEA section.
[2] AC-5 was used in SEA section.

(in)(2.54)=(cm)
41 °F = 5 °C

Table 16. Permanent deformations at 41 °F (continued).

Project	Pavement Layer		Material	Permanent Deformation (microinches)		
				0.1 sec.	100 sec.	Slope
MN	Surface		AC 200-300	375	7912	.441
			SEA (40/60)	373	2813	.292
MS	Surface		AC-20	116	1002	.313
			SEA (30/70)	120	1024	.311
	Binder		AC-40	48	602	.364
			SEA (30/70)	68	826	.361
	Base		AC-40	45	311	.280
			SEA (30/70)	26	388	.388
ND	Surface	Location #1	AC 120-150	181	3785	.440
			SEA (30/70)	189	1879	.332
	Surface	Location #2	AC 120-150	145	2392	.406
			SEA (25/75)	308	1681	.246
NM	Surface		AC-10	83	572	.279
			SEA (30/70)	183	1051	.253
	Base		AC-10	80	800	.333
			SEA (30/70)	128	917	.285
TC	Base, top half		AC-20	120	611	.235
	Base, bottom half		AC-20	128	2193	.411
			SEA (30/70)	160	923	.253
TP	Binder		AC-20	70	348	.232
			SEA (30/70)	78	320	.203
TX	Surface		AC-20	--	--	--
			SEA (35/65)	--	--	--
WI	Surface		AC 120-150	427	5175	.361
			SEA (30/70)	331	2172	.272
WY	Surface		SEA (20/80)	179	1173	.272
			SEA (20/80)	114	1460	.369

(in)(2.54)=(cm)
41 °F = 5 °C

Table 17. Effect of sulfur on permanent deformation at 41 °F for all projects, and projects by pavement age, blending method, and the stiffness of the mixture.

	Avg. AC Perm. Def. (microinches)	Avg. SEA Perm. Def. (microinches)	Degrees of Freedom	p
Creep Time = 0.1 second				
All projects	157	181	21	0.146 NS
Projects less than 5 years	140	163	13	0.170 NS
Projects more than 5 years	188	213	7	0.500 NS
In-Line Blending	128	158	10	0.212 NS
Direct Feed	178	216	8	0.068 NS
Soft Mixtures	213	263	10	0.037 I
Stiff Mixtures	102	98	10	0.857 NS
Creep Time = 100 seconds				
All projects	1933	1647	21	0.385 NS
Projects less than 5 years	1505	1584	13	0.792 NS
Projects more than 5 years	2682	1756	7	0.229 NS
In-Line Blending	1649	1178	10	0.170 NS
Direct Feed	2349	2390	8	0.954 NS
Soft Mixtures	3180	2554	10	0.352 NS
Stiff Mixtures	686	739	10	0.441 NS
Slope				
All projects	0.342	0.310	21	0.059 NS
Projects less than 5 years	0.328	0.320	13	0.588 NS
Projects more than 5 years	0.366	0.293	7	0.057 NS
In-Line Blending	0.347	0.291	10	0.012 D
Direct Feed	0.346	0.345	8	0.981 NS
Soft Mixtures	0.390	0.321	10	0.009 D
Stiff Mixtures	0.293	0.299	10	0.741 NS

(in)(2.54)=(cm)
41 °F = 5 °C

Table 18. Effect of sulfur on permanent deformation at 41 °F for each project.

Project	Pavement Layer		Material	0.1 sec.	100 sec.	slope
CB	Surface		SEA (20/80)	D	NS	NS
	Surface		SEA (40/60)	NS	NS	NS
DE	Surface		SEA (30/70)	D	NS	NS
ID	Surface	Location #1	SEA (30/70)	NS	NS	NS
	Surface	Location #2	SEA (30/70)	NS	NS	NS
KS	Surface		SEA (30/70)	--	--	--
	Base, top half		SEA (30/70)	NS	NS	NS
	Base, bottom half		SEA (30/70)	D	NS	NS
LA	Surface		SEA (40/60)	I	I	NS
MB	Surface		SEA (10/90)	--	--	--
			SEA (20/80)	--	--	--
			SEA (30/70)	--	--	--
	Binder		SEA (10/90)	NS	I	NS
			SEA (20/80)	I	I	NS
			SEA (30/70)	NS	NS	NS
MC	Surface		SEA (30/70)	--	--	--
	Binder		SEA (30/70)	I	I	NS
MN	Surface		SEA (40/60)	NS	D	D
MS	Surface		SEA (30/70)	NS	NS	NS
	Binder		SEA (30/70)	NS	I	NS
	Base		SEA (30/70)	NS	NS	NS
ND	Surface	Location #1	SEA (30/70)	NS	D	D
	Surface	Location #2	SEA (25/75)	I	NS	D
NM	Surface		SEA (30/70)	I	I	NS
	Base		SEA (30/70)	NS	NS	NS
TC	Base		SEA (30/70)	NS	D	D
TP	Binder		SEA (30/70)	NS	NS	NS
TX	Surface		SEA (35/65)	--	--	--
WI	Surface		SEA (30/70)	NS	D	NS

41 °F = 5 °C

Table 19. Resilient and viscoelastic deformations at 41 °F.

Project	Pavement Layer	Material	Resilient (microinches) 0.1 sec.	10 sec.	Visco-elastic 100 sec.
CA	Surface	SEA (30/70)	2246	2294	284
		SEA (30/70)	2384	2449	380
CB	Surface[1] Location #1	AR-2000	2950	3113	590
		SEA (20/80)	2711	2898	506
	Surface[1] Location #2	AR-4000	2949	3169	436
		SEA (40/60)	3838	2819	454
DE	Surface	AC-20	2284	2290	496
		SEA (30/70)	2363	2447	463
GA	Surface	AC-20	2326	2666	947
		AC-20	2884	3204	1024
ID	Surface Location #1	AR-4000	4139	4393	1045
		SEA (30/70)	4470	4724	1064
	Surface Location #2	AR-4000	4322	4547	1082
		SEA (30/70)	4307	4503	1063
KS	Surface	AC-20	--	--	--
		SEA (30/70)	--	--	--
	Base, top half	AC-20	4757	4781	646
		SEA (30/70)	4606	4786	700
	Base, bottom half	AC-20	4261	4600	1122
		SEA (30/70)	4545	4640	711
LA	Surface	AC-30	2508	2844	394
		SEA (40/60)	3155	3315	545
	Base under AC surface	SEA (40/60)	3448	3716	1191
	Base under SEA surface	SEA (40/60)	3530	3481	1148
MB	Surface	AC-10	--	--	--
		SEA (10/90)	--	--	--
		SEA (20/80)	--	--	--
		SEA (30/70)	--	--	--
	Binder	AC-10	2871	3132	1429
		SEA (10/90)	3752	4131	1481
		SEA (20/80)	3895	4131	1253
		SEA (30/70)	3843	4163	1371
MC	Surface[2]	AC-10	--	--	--
		SEA (30/70)	--	--	--
	Binder[2]	AC-10	3376	3636	1121
		SEA (30/70)	3359	3677	1272

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[1] AR-2000 was used in SEA section.
[2] AC-5 was used in SEA section.

(in)(2.54)=(cm)
41 °F = 5 °C

Table 19. Resilient and viscoelastic deformations at 41 °F (continued).

Project	Pavement Layer	Material	Resilient (microinches)		Visco-elastic
			0.1 sec.	10 sec.	100 sec.
MN	Surface	AC 200-300	3112	3883	2277
		SEA (40/60)	3139	3425	1390
MS	Surface	AC-20	2218	2520	740
		SEA (30/70)	2652	3021	721
	Binder	AC-40	2624	2836	528
		SEA (30/70)	2298	2570	517
	Base	AC-40	3234	3364	378
		SEA (30/70)	3448	3622	402
ND	Surface Location #1	AC 120-150	4150	4711	1533
		SEA (30/70)	4312	4767	1204
	Surface Location #2	AC 120-150	4209	4809	1201
		SEA (25/75)	4782	4987	1062
NM	Surface	AC-10	3713	3563	444
		SEA (30/70)	3510	3289	516
	Base	AC-10	3578	3367	528
		SEA (30/70)	3279	3441	568
TC	Base, top half	AC-20	2662	2878	352
	Base, bottom half	AC-20	3778	3720	764
		SEA (30/70)	4052	3980	535
TP	Binder	AC-20	2696	2765	335
		SEA (30/70)	2682	2696	338
TX	Surface	AC-20	--	--	--
		SEA (35/65)	--	--	--
WI	Surface	AC 120-150	4255	4737	2075
		SEA (30/70)	3811	4013	1246
WY	Surface	SEA (20/80)	3550	3667	914
		SEA (20/80)	3236	3328	1044

(in)(2.54)=(cm)
41 °F = 5 °C

Table 20. Effect of sulfur on resilient and viscoelastic deformations at 41 °F for each project.

Project	Pavement Layer	Material	Resilient 0.1 sec.	Resilient 10 sec.	Visco-elastic 100 sec.
CB	Surface	SEA (20/80)	NS	NS	NS
	Surface	SEA (40/60)	NS	NS	I
DE	Surface	SEA (30/70)	NS	NS	NS
ID	Surface Location #1	SEA (30/70)	NS	NS	NS
	Surface Location #2	SEA (30/70)	NS	NS	NS
KS	Surface	SEA (30/70)	--	--	--
	Base, top half	SEA (30/70)	NS	NS	NS
	Base, bottom half	SEA (30/70)	NS	NS	NS
LA	Surface	SEA (40/60)	I	NS	I
MB	Surface	SEA (10/90)	--	--	--
		SEA (20/80)	--	--	--
		SEA (30/70)	--	--	--
	Binder	SEA (10/90)	I	I	NS
		SEA (20/80)	I	I	NS
		SEA (30/70)	I	I	NS
MC	Surface	SEA (30/70)	--	--	--
	Binder	SEA (30/70)	NS	NS	NS
MN	Surface	SEA (40/60)	NS	NS	D
MS	Surface	SEA (30/70)	I	I	NS
	Binder	SEA (30/70)	NS	NS	NS
	Base	SEA (30/70)	NS	NS	NS
ND	Surface Location #1	SEA (30/70)	NS	NS	NS
	Surface Location #2	SEA (25/75)	NS	NS	NS
NM	Surface	SEA (30/70)	NS	NS	NS
	Base	SEA (30/70)	NS	NS	NS
TC	Base	SEA (30/70)	NS	NS	D
TP	Binder	SEA (30/70)	NS	NS	NS
TX	Surface	SEA (35/65)	--	--	--
WI	Surface	SEA (30/70)	NS	NS	NS

41 °F = 5 °C

Table 21. Creep moduli at 77 °F.

Project	Pavement Layer	Material	Moduli, ksi 0.1 sec.	Moduli, ksi 100 sec.	Slope
CA	Surface	SEA (30/70)	129.8	50.2	-.137
		SEA (30/70)	132.6	52.4	-.134
CB	Surface[1] Location #1	AR-2000	78.9	23.5	-.175
		SEA (20/80)	84.7	36.8	-.121
	Surface[1] Location #2	AR-4000	82.9	31.5	-.140
		SEA (40/60)	84.2	28.0	-.159
DE	Surface	AC-20	148.7	39.0	-.194
		SEA (30/70)	153.0	53.9	-.151
GA	Surface	AC-20	79.9	17.5	-.220
		AC-20	97.0	20.9	-.220
ID	Surface Location #1	AR-4000	89.6	23.1	-.196
		SEA (30/70)	72.2	22.1	-.171
	Surface Location #2	AR-4000	75.6	18.9	-.200
		SEA (30/70)	75.3	23.4	-.169
KS	Surface	AC-20	--	--	--
		SEA (30/70)	--	--	--
	Base, top half	AC-20	84.6	37.1	-.119
		SEA (30/70)	94.4	37.0	-.136
	Base, bottom half	AC-20	75.4	20.9	-.186
		SEA (30/70)	85.5	33.9	-.134
LA	Surface	AC-30	106.9	34.0	-.166
		SEA (40/60)	92.8	45.2	-.104
	Base under AC surface	SEA (40/60)	67.5	19.9	-.177
	Base under SEA surface	SEA (40/60)	78.0	23.1	-.177
MB	Surface	AC-10	--	--	--
		SEA (10/90)	--	--	--
		SEA (20/80)	--	--	--
		SEA (30/70)	--	--	--
	Binder	AC-10	91.0	22.3	-.204
		SEA (10/90)	70.2	14.3	-.230
		SEA (20/80)	78.3	13.7	-.253
		SEA (30/70)	67.5	20.3	-.174
MC	Surface[2]	AC-10	--	--	--
		SEA (30/70)	--	--	--
	Binder[2]	AC-10	84.2	13.9	-.260
		SEA (30/70)	69.8	19.2	-.187

(ksi)(6895)=(KPa)
77 °F = 25 °C

[1] AR-2000 was used in SEA section.
[2] AC-5 was used in SEA section.

Table 21. Creep moduli at 77 °F (continued).

Project	Pavement Layer		Material	Moduli, ksi 0.1 sec.	Moduli, ksi 100 sec.	Slope
MN	Surface		AC 200-300	43.5	7.0	-.265
			SEA (40/60)	57.4	11.5	-.232
MS	Surface		AC-20	113.3	33.8	-.175
			SEA (30/70)	103.7	33.0	-.166
	Binder		AC-40	100.2	51.3	-.097
			SEA (30/70)	114.5	48.7	-.124
	Base		AC-40	70.4	45.3	-.064
			SEA (30/70)	72.5	46.1	-.065
ND	Surface	Location #1	AC 120-150	72.2	13.4	-.243
			SEA (30/70)	64.2	24.8	-.138
	Surface	Location #2	AC 120-150	77.0	13.2	-.255
			SEA (25/75)	65.8	21.5	-.162
NM	Surface		AC-10	103.6	37.9	-.146
			SEA (30/70)	119.5	30.0	-.200
	Base		AC-10	102.7	38.4	-.142
			SEA (30/70)	106.4	32.1	-.174
TC	Base, top half		AC-20	141.1	23.5	-.260
	Base, bottom half		AC-20	91.0	12.9	-.283
			SEA (30/70)	102.4	27.2	-.192
TP	Binder		AC-20	111.0	52.4	-.109
			SEA (30/70)	100.2	59.2	-.076
TX	Surface		AC-20	--	--	--
			SEA (35/65)	--	--	--
WI	Surface		AC 120-150	55.5	7.6	-.289
			SEA (30/70)	60.0	14.1	-.210
WY	Surface		SEA (20/80)	79.0	26.8	-.156
			SEA (20/80)	76.4	21.7	-.182

(ksi)(6895)=(KPa)
77 °F = 25 °C

Table 22. Effect of sulfur on creep modulus at 77 °F for all projects, and projects by pavement age, blending method, and the stiffness of the mixture.

	Average AC Mc, ksi	Average SEA Mc, ksi	Degrees of Freedom	p
<u>Creep Time = 0.1 second</u>				
All projects	89.1	86.8	21	0.376 NS
Projects less than 5 years	89.5	86.4	13	0.375 NS
Projects more than 5 years	88.5	87.5	7	0.815 NS
In-Line Blending	86.5	84.1	10	0.461 NS
Direct Feed	85.5	80.9	8	0.385 NS
Soft Mixtures	78.3	71.2	10	0.093 NS
Stiff Mixtures	99.9	102.4	10	0.438 NS
<u>Creep Time = 100 seconds</u>				
All projects	27.0	30.1	21	0.059 NS
Projects less than 5 years	30.2	30.1	13	0.975 NS
Projects more than 5 years	21.3	30.0	7	0.002 I
In-Line Blending	26.0	30.7	10	0.052 NS
Direct Feed	28.4	27.1	8	0.447 NS
Soft Mixtures	16.1	19.3	10	0.181 NS
Stiff Mixtures	37.8	40.9	10	0.217 NS
<u>Slope</u>				
All projects	-0.189	-0.163	21	0.017 D
Projects less than 5 years	-0.170	-0.164	13	0.562 NS
Projects more than 5 years	-0.223	-0.163	7	0.004 D
In-Line Blending	-0.191	-0.153	10	0.030 D
Direct Feed	-0.177	-0.174	8	0.834 NS
Soft Mixtures	-0.237	-0.193	10	0.015 D
Stiff Mixtures	-0.142	-0.134	10	0.509 NS

(ksi)(6895)=(KPa)
77 °F = 25 °C

Table 23. Effect of sulfur on creep modulus at 77 °F for each project.

Project	Pavement Layer		Material	0.1 sec.	100 sec.	Slope
CB	Surface		SEA (20/80)	NS	I	D
	Surface		SEA (40/60)	NS	I	NS
DE	Surface		SEA (30/70)	NS	I	D
ID	Surface	Location #1	SEA (30/70)	D	NS	NS
	Surface	Location #2	SEA (30/70)	NS	I	D
KS	Surface		SEA (30/70)	--	--	--
	Base, top half		SEA (30/70)	NS	NS	NS
	Base, bottom half		SEA (30/70)	NS	I	NS
LA	Surface		SEA (40/60)	D	I	D
MB	Surface		SEA (10/90)	--	--	--
			SEA (20/80)	--	--	--
			SEA (30/70)	--	--	--
	Binder		SEA (10/90)	D	D	I
			SEA (20/80)	D	D	I
			SEA (30/70)	D	NS	NS
MC	Surface		SEA (30/70)	--	--	--
	Binder		SEA (30/70)	NS	I	D
MN	Surface		SEA (40/60)	I	I	D
MS	Surface		SEA (30/70)	NS	NS	NS
	Binder		SEA (30/70)	NS	NS	NS
	Base		SEA (30/70)	NS	NS	NS
ND	Surface	Location #1	SEA (30/70)	NS	I	D
	Surface	Location #2	SEA (25/75)	D	I	D
NM	Surface		SEA (30/70)	NS	D	I
	Base		SEA (30/70)	NS	D	NS
TC	Base		SEA (30/70)	NS	I	D
TP	Binder		SEA (30/70)	NS	I	D
TX	Surface		SEA (35/65)	--	--	--
WI	Surface		SEA (30/70)	NS	I	D

77 °F = 25 °C

Permanent deformation data are shown in table 24. Table 25 shows the effect of sulfur on the permanent deformations for the groups. The permanent deformation when considering all projects was decreased by the sulfur at a loading time of 100 seconds. The permanent deformations of the SEA sections were also lower in older projects at both loading times. Again it is noted that these older projects tended to have softer mixtures. Sulfur decreased the slope for the in-line blended projects. This was due to the significant decrease in permanent deformation at the a loading time of 100 seconds. Trends showing that the use of sulfur can decrease permanent deformations were more evident at 77 °F (25 °C) than at 41 °F (5 °C). At higher temperatures this may reduce the amount of rutting. As shown by the table 26, the effect of sulfur varied on a project-by-project basis, and no trends were evident.

Resilient and viscoelastic deformations are shown in table 27. As shown in table 28, sulfur had little effect on a project-by-project basis.

e. Statistical Analyses - Creep Test at 104 °F (40 °C)

The creep moduli at 104 °F (40 °C) are shown in table 29. Table 30 shows the effect of sulfur on the moduli for the groups. The significantly lower slopes for most of the groups and an examination of the moduli at both loading times show that there was a tendency for the SEA to decrease the modulus at 0.1 second and to increase the modulus at 100 seconds. The SEA did decrease the average modulus of stiff mixtures at short loading durations (usually undesirable), and increase the average modulus of soft mixtures at long loading durations (usually desirable). This indicates a difference in the rheological responses of the two binders with the time of loading. However, most of the differences in moduli were insignificant in terms of their expected effect on performance or structural design, and thus the effect on the permanent deformations would be more important.

The data again show that age and stiffness are confounded. Most projects less than 5 years old contained stiff mixtures and most projects more than 5 years old contained soft mixtures. The statistical findings in table 30 for projects less than 5 years old and for stiff mixtures agree. The statistical findings for projects more than 5 years old and for soft mixtures also agree. As shown by table 31, the effect of sulfur varied on a project-by-project basis, and no trends were evident.

Table 24. Permanent deformations at 77 °F.

Project	Pavement Layer	Material	Permanent Deformation (microinches)		Slope
			0.1 sec.	100 sec.	
CA	Surface	SEA (30/70)	155	967	.265
		SEA (30/70)	146	894	.262
CB	Surface[1] Location #1	AR-2000	378	2737	.287
		SEA (20/80)	244	1254	.239
	Surface[1] Location #2	AR-4000	367	1930	.240
		SEA (40/60)	391	2206	.251
DE	Surface	AC-20	243	1646	.277
		SEA (30/70)	245	1006	.204
GA	Surface	AC-20	503	3787	.292
		AC-20	352	3078	.314
ID	Surface Location #1	AR-4000	351	2980	.310
		SEA (30/70)	389	2772	.284
	Surface Location #2	AR-4000	501	4018	.301
		SEA (30/70)	292	2808	.328
KS	Surface	AC-20	--	--	--
		SEA (30/70)	--	--	--
	Base, top half	AC-20	265	1389	.240
		SEA (30/70)	188	1503	.301
	Base, bottom half	AC-20	370	3386	.321
		SEA (30/70)	301	1517	.234
LA	Surface	AC-30	199	1767	.316
		SEA (40/60)	141	884	.266
	Base under AC surface	SEA (40/60)	359	3022	.308
	Base under SEA surface	SEA (40/60)	383	2595	.277
MB	Surface	AC-10	--	--	--
		SEA (10/90)	--	--	--
		SEA (20/80)	--	--	--
		SEA (30/70)	--	--	--
	Binder	AC-10	478	3278	.279
		SEA (10/90)	743	5640	.293
		SEA (20/80)	520	6166	.358
		SEA (30/70)	517	3356	.271
MC	Surface[2]	AC-10	--	--	--
		SEA (30/70)	--	--	--
	Binder[2]	AC-10	722	6221	.312
		SEA (30/70)	587	3960	.276

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[1] AR-2000 was used in SEA section.
[2] AC-5 was used in SEA section.

(in)(2.54)=(cm)
77 °F = 25 °C

Table 24. Permanent deformations at 77 °F (continued).

Project	Pavement Layer		Material	Permanent Deformation (microinches) 0.1 sec.	100 sec.	Slope
MN	Surface		AC 200-300	2188	13121	.259
			SEA (40/60)	1505	7296	.229
MS	Surface		AC-20	370	1632	.214
			SEA (30/70)	238	1490	.266
	Binder		AC-40	143	675	.225
			SEA (30/70)	167	887	.242
	Base		AC-40	125	556	.216
			SEA (30/70)	78	530	.277
ND	Surface	Location #1	AC 120-150	640	6594	.338
			SEA (30/70)	469	2291	.230
	Surface	Location #2	AC 120-150	739	6385	.312
			SEA (25/75)	493	2857	.254
NM	Surface		AC-10	139	1607	.355
			SEA (30/70)	359	2531	.283
	Base		AC-10	293	1590	.245
			SEA (30/70)	246	2070	.309
TC	Base, top half		AC-20	430	3633	.309
	Base, bottom half		AC-20	592	7152	.361
			SEA (30/70)	248	2500	.335
TP	Binder		AC-20	125	879	.282
			SEA (30/70)	134	468	.181
TX	Surface		AC-20	--	--	--
			SEA (35/65)	--	--	--
WI	Surface		AC 120-150	955	13642	.385
			SEA (30/70)	673	5925	.315
WY	Surface		SEA (20/80)	313	1994	.268
			SEA (20/80)	468	3230	.280

(in)(2.54)=(cm)
77 °F = 25 °C

Table 25. Effect of sulfur on permanent deformation at 77 °F for all projects, and projects by pavement age, blending method, and the stiffness of the mixture.

	Avg. AC Perm. Def. (microinches)	Avg. SEA Perm. Def.	Degrees of Freedom	p
<u>Creep Time = 0.1 second</u>				
All projects	490	403	21	0.052 NS
Projects less than 5 years	371	357	13	0.722 NS
Projects more than 5 years	698	485	7	0.028 D
In-Line Blending	427	348	10	0.107 NS
Direct Feed	583	505	8	0.388 NS
Soft Mixtures	738	585	10	0.071 NS
Stiff Mixtures	242	221	10	0.496 NS
<u>Creep Time = 100 seconds</u>				
All projects	3962	2745	21	0.038 D
Projects less than 5 years	3063	2722	13	0.609 NS
Projects more than 5 years	5534	2787	7	0.009 D
In-Line Blending	4085	2370	10	0.049 D
Direct Feed	3714	3425	8	0.743 NS
Soft Mixtures	6359	4143	10	0.053 NS
Stiff Mixtures	1565	1348	10	0.308 NS
<u>Slope</u>				
All projects	0.289	0.272	21	0.177 NS
Projects less than 5 years	0.282	0.278	13	0.829 NS
Projects more than 5 years	0.302	0.262	7	0.053 NS
In-Line Blending	0.311	0.267	10	0.018 D
Direct Feed	0.256	0.279	8	0.136 NS
Soft Mixtures	0.310	0.288	10	0.178 NS
Stiff Mixtures	0.268	0.256	10	0.564 NS

(in)(2.54)=(cm)
77 °F = 25 °C

Table 26. Effect of sulfur on permanent deformation at 77 °F for each project.

Project	Pavement Layer		Material	0.1 sec.	100 sec.	slope
CB	Surface		SEA (20/80)	D	D	NS
	Surface		SEA (40/60)	NS	NS	NS
DE	Surface		SEA (30/70)	NS	D	D
ID	Surface	Location #1	SEA (30/70)	NS	NS	NS
	Surface	Location #2	SEA (30/70)	D	D	NS
KS	Surface		SEA (30/70)	--	--	--
	Base, top half		SEA (30/70)	D	NS	NS
	Base, bottom half		SEA (30/70)	NS	D	NS
LA	Surface		SEA (40/60)	NS	D	NS
MB	Surface		SEA (10/90)	--	--	--
			SEA (20/80)	--	--	--
			SEA (30/70)	--	--	--
	Binder		SEA (10/90)	I	I	NS
			SEA (20/80)	NS	I	I
			SEA (30/70)	NS	NS	NS
MC	Surface		SEA (30/70)	--	--	--
	Binder		SEA (30/70)	NS	D	NS
MN	Surface		SEA (40/60)	D	D	NS
MS	Surface		SEA (30/70)	D	NS	NS
	Binder		SEA (30/70)	NS	NS	NS
	Base		SEA (30/70)	NS	NS	NS
ND	Surface	Location #1	SEA (30/70)	D	D	D
	Surface	Location #2	SEA (25/75)	D	D	D
NM	Surface		SEA (30/70)	I	I	NS
	Base		SEA (30/70)	NS	I	NS
TC	Base		SEA (30/70)	D	D	NS
TP	Binder		SEA (30/70)	NS	D	D
TX	Surface		SEA (35/65)	--	--	--
WI	Surface		SEA (30/70)	D	D	D

77 °F = 25 °C

Table 27. Resilient and viscoelastic deformations at 77 °F.

Project	Pavement Layer	Material	Resilient (microinches) 0.1 sec.	Resilient (microinches) 10 sec.	Visco-elastic 100 sec.
CA	Surface	SEA (30/70)	533	791	239
		SEA (30/70)	493	790	270
CB	Surface[1] Location #1	AR-2000	1057	1451	607
		SEA (20/80)	1097	1286	398
	Surface[1] Location #2	AR-4000	1086	1360	401
		SEA (40/60)	964	1395	455
DE	Surface	AC-20	229	554	131
		SEA (30/70)	215	535	124
GA	Surface	AC-20	--	1321	680
		AC-20	594	1077	509
ID	Surface Location #1	AR-4000	897	1296	579
		SEA (30/70)	1051	1437	666
	Surface Location #2	AR-4000	1010	1437	560
		SEA (30/70)	1018	1501	548
KS	Surface	AC-20	--	--	--
		SEA (30/70)	--	--	--
	Base, top half	AC-20	998	1233	343
		SEA (30/70)	988	1209	293
	Base, bottom half	AC-20	1011	1294	450
		SEA (30/70)	940	1233	398
LA	Surface	AC-30	767	1053	431
		SEA (40/60)	969	1184	411
	Base under AC surface	SEA (40/60)	1042	1683	992
	Base under SEA surface	SEA (40/60)	979	1435	816
MB	Surface	AC-10	--	--	--
		SEA (10/90)	--	--	--
		SEA (20/80)	--	--	--
		SEA (30/70)	--	--	--
	Binder	AC-10	594	1090	300
		SEA (10/90)	783	1474	326
		SEA (20/80)	718	1436	456
		SEA (30/70)	955	1566	463
MC	Surface[2]	AC-10	--	--	--
		SEA (30/70)	--	--	--
	Binder[2]	AC-10	694	1245	322
		SEA (30/70)	744	1273	297

[1] AR-2000 was used in SEA section.
[2] AC-5 was used in SEA section.

(in)(2.54)=(cm)
77 °F = 25 °C

Table 27. Resilient and viscoelastic deformations at 77 °F (continued).

Project	Pavement Layer	Material	Resilient (microinches) 0.1 sec.	10 sec.	Visco-elastic 100 sec.
MN	Surface	AC 200-300	581	1469	137
		SEA (40/60)	541	1234	202
MS	Surface	AC-20	567	940	346
		SEA (30/70)	705	1096	405
	Binder	AC-40	685	1013	299
		SEA (30/70)	654	877	227
	Base	AC-40	1292	1522	342
		SEA (30/70)	1219	1464	348
ND	Surface Location #1	AC 120-150	1011	1592	528
		SEA (30/70)	1048	1561	494
	Surface Location #2	AC 120-150	809	1436	483
		SEA (25/75)	1062	1590	570
NM	Surface	AC-10	920	1129	387
		SEA (30/70)	600	914	241
	Base	AC-10	747	959	280
		SEA (30/70)	739	1018	318
TC	Base, top half	AC-20	457	724	300
	Base, bottom half	AC-20	855	1299	515
		SEA (30/70)	933	1187	417
TP	Binder	AC-20	777	973	254
		SEA (30/70)	803	1018	222
TX	Surface	AC-20	--	--	--
		SEA (35/65)	--	--	--
WI	Surface	AC 120-150	1292	2069	599
		SEA (30/70)	1057	1671	672
WY	Surface	SEA (20/80)	894	1409	607
		SEA (20/80)	796	1294	449

(in)(2.54)=(cm)
77 °F = 25 °C

Table 28. Effect of sulfur on resilient and viscoelastic deformations at 77 °F for each project.

Project	Pavement Layer	Material	Resilient 0.1 sec.	Resilient 10 sec.	Visco-elastic 100 sec.
CB	Surface	SEA (20/80)	NS	NS	D
	Surface	SEA (40/60)	NS	NS	D
DE	Surface	SEA (30/70)	NS	NS	NS
ID	Surface Location #1	SEA (30/70)	NS	NS	NS
	Surface Location #2	SEA (30/70)	NS	NS	NS
KS	Surface	SEA (30/70)	--	--	--
	Base, top half	SEA (30/70)	NS	NS	NS
	Base, bottom half	SEA (30/70)	NS	NS	NS
LA	Surface	SEA (40/60)	NS	NS	NS
MB	Surface	SEA (10/90)	--	--	--
		SEA (20/80)	--	--	--
		SEA (30/70)	--	--	--
	Binder	SEA (10/90)	NS	NS	NS
		SEA (20/80)	NS	NS	NS
		SEA (30/70)	NS	NS	NS
MC	Surface	SEA (30/70)	--	--	--
	Binder	SEA (30/70)	NS	NS	NS
MN	Surface	SEA (40/60)	NS	D	NS
MS	Surface	SEA (30/70)	I	NS	NS
	Binder	SEA (30/70)	I	NS	NS
	Base	SEA (30/70)	NS	NS	NS
ND	Surface Location #1	SEA (30/70)	NS	NS	NS
	Surface Location #2	SEA (25/75)	I	NS	NS
NM	Surface	SEA (30/70)	D	NS	D
	Base	SEA (30/70)	NS	NS	NS
TC	Base	SEA (30/70)	NS	NS	NS
TP	Binder	SEA (30/70)	NS	NS	NS
TX	Surface	SEA (35/65)	--	--	--
WI	Surface	SEA (30/70)	NS	NS	NS

77 °F = 25 °C

Table 29. Creep moduli at 104 °F.

Project	Pavement Layer	Material	Moduli, ksi		
			0.1 sec.	100 sec.	Slope
CA	Surface	SEA (30/70)	102.2	23.5	-.212
		SEA (30/70)	87.3	20.7	-.208
CB	Surface[1] Location #1	AR-2000	56.2	11.1	-.235
		SEA (20/80)	56.8	14.6	-.198
	Surface[1] Location #2	AR-4000	58.9	9.5	-.264
		SEA (40/60)	48.9	11.6	-.208
DE	Surface	AC-20	90.2	17.9	-.234
		SEA (30/70)	77.5	23.0	-.176
GA	Surface	AC-20	33.1	8.1	-.204
		AC-20	37.8	7.7	-.231
ID	Surface Location #1	AR-4000	40.9	6.0	-.277
		SEA (30/70)	39.2	8.3	-.225
	Surface Location #2	AR-4000	35.6	6.7	-.241
		SEA (30/70)	38.9	9.5	-.204
KS	Surface	AC-20	--	--	--
		SEA (30/70)	--	--	--
	Base, top half	AC-20	65.1	17.4	-.191
		SEA (30/70)	70.2	14.6	-.227
	Base, bottom half	AC-20	44.3	8.4	-.241
		SEA (30/70)	59.8	10.7	-.250
LA	Surface	AC-30	81.4	13.3	-.262
		SEA (40/60)	78.6	21.2	-.190
	Base under AC surface	SEA (40/60)	48.5	8.0	-.262
	Base under SEA surface	SEA (40/60)	39.7	7.8	-.235
MB	Surface	AC-10	--	--	--
		SEA (10/90)	--	--	--
		SEA (20/80)	--	--	--
		SEA (30/70)	--	--	--
	Binder	AC-10	34.3	8.3	-.206
		SEA (10/90)	27.5	7.0	-.198
		SEA (20/80)	24.0	6.1	-.198
		SEA (30/70)	36.1	8.0	-.219
MC	Surface[2]	AC-10	--	--	--
		SEA (30/70)	--	--	--
	Binder[2]	AC-10	28.7	5.4	-.243
		SEA (30/70)	22.4	8.7	-.137

[1] AR-2000 was used in SEA section.
[2] AC-5 was used in SEA section.

(ksi)(6895)=(KPa)
104 °F = 40 °C

Table 29. Creep moduli at 104 °F (continued).

Project	Pavement Layer		Material	Moduli, ksi 0.1 sec.	 100 sec.	Slope
MN	Surface		AC 200-300	18.8	1.4	-.376
			SEA (40/60)	40.9	4.9	-.307
MS	Surface		AC-20	112.0	17.7	-.267
			SEA (30/70)	80.6	18.9	-.210
	Binder		AC-40	101.6	32.9	-.163
			SEA (30/70)	74.8	24.9	-.159
	Base		AC-40	93.2	38.4	-.128
			SEA (30/70)	74.1	30.2	-.130
ND	Surface	Location #1	AC 120-150	34.3	5.6	-.262
			SEA (30/70)	33.7	10.7	-.167
	Surface	Location #2	AC 120-150	29.1	6.2	-.224
			SEA (25/75)	33.3	11.0	-.160
NM	Surface		AC-10	73.9	16.6	-.216
			SEA (30/70)	49.7	13.1	-.193
	Base		AC-10	72.1	17.2	-.208
			SEA (30/70)	61.1	15.2	-.201
TC	Base, top half		AC-20	49.0	6.2	-.300
	Base, bottom half		AC-20	29.5	3.2	-.322
			SEA (30/70)	46.9	4.9	-.325
TP	Binder		AC-20	110.2	30.8	-.184
			SEA (30/70)	95.9	57.3	-.075
TX	Surface		AC-20	--	--	--
			SEA (35/65)	--	--	--
WI	Surface		AC 120-150	24.2	4.4	-.246
			SEA (30/70)	34.3	7.2	-.227
WY	Surface		SEA (20/80)	41.0	10.7	-.195
			SEA (20/80)	41.1	9.1	-.218

(ksi)(6895)=(KPa)
104 °F = 40 °C

Table 30. Effect of sulfur on creep modulus at 104 °F for all projects, and projects by pavement age, blending method, and the stiffness of the mixture.

	Average AC Mc, ksi	Average SEA Mc, ksi	Degrees of Freedom	p
<u>Creep Time = 0.1 second</u>				
All projects	57.1	52.1	21	0.094 NS
Projects less than 5 years	62.8	53.0	13	0.011 D
Projects more than 5 years	47.1	50.4	7	0.451 NS
In-Line Blending	55.8	51.9	10	0.202 NS
Direct Feed	58.0	50.1	8	0.188 NS
Soft Mixtures	31.3	34.3	10	0.345 NS
Stiff Mixtures	82.9	69.8	10	0.004 D
<u>Creep Time = 100 seconds</u>				
All projects	13.1	15.0	21	0.197 NS
Projects less than 5 years	15.6	16.6	13	0.654 NS
Projects more than 5 years	8.8	12.4	7	0.015 I
In-Line Blending	11.7	16.3	10	0.083 NS
Direct Feed	15.3	13.7	8	0.281 NS
Soft Mixtures	5.8	7.8	10	0.017 I
Stiff Mixtures	20.4	22.2	10	0.540 NS
<u>Slope</u>				
All projects	-0.233	-0.197	21	0.001 D
Projects less than 5 years	-0.216	-0.189	13	0.007 D
Projects more than 5 years	-0.264	-0.211	7	0.017 D
In-Line Blending	-0.235	-0.186	10	0.001 D
Direct Feed	-0.221	-0.198	8	0.177 NS
Soft Mixtures	-0.255	-0.215	10	0.008 D
Stiff Mixtures	-0.211	-0.179	10	0.023 D

(ksi)(6895)=(KPa)
104 °F = 40 °C

Table 31. Effect of sulfur on creep modulus at 104 °F for each project.

Project	Pavement Layer		Material	0.1 sec.	100 sec.	Slope
CB	Surface		SEA (20/80)	NS	I	D
	Surface		SEA (40/60)	D	I	D
DE	Surface		SEA (30/70)	D	I	D
ID	Surface	Location #1	SEA (30/70)	NS	I	D
	Surface	Location #2	SEA (30/70)	NS	I	NS
KS	Surface		SEA (30/70)	--	--	--
	Base, top half		SEA (30/70)	NS	NS	NS
	Base, bottom half		SEA (30/70)	I	I	NS
LA	Surface		SEA (40/60)	NS	I	D
MB	Surface		SEA (10/90)	--	--	--
			SEA (20/80)	--	--	--
			SEA (30/70)	--	--	--
	Binder		SEA (10/90)	D	NS	NS
			SEA (20/80)	D	D	NS
			SEA (30/70)	NS	NS	NS
MC	Surface		SEA (30/70)	--	--	--
	Binder		SEA (30/70)	D	I	D
MN	Surface		SEA (40/60)	I	I	D
MS	Surface		SEA (30/70)	D	NS	D
	Binder		SEA (30/70)	D	D	NS
	Base		SEA (30/70)	D	D	NS
ND	Surface	Location #1	SEA (30/70)	NS	I	D
	Surface	Location #2	SEA (25/75)	NS	I	D
NM	Surface		SEA (30/70)	D	D	NS
	Base		SEA (30/70)	NS	NS	NS
TC	Base		SEA (30/70)	I	I	NS
TP	Binder		SEA (30/70)	NS	I	D
TX	Surface		SEA (35/65)	--	--	--
WI	Surface		SEA (30/70)	I	I	NS

104 °F = 40 °C

Permanent deformation data are shown in table 32. Table 33 shows the effect of sulfur on the permanent deformations for the groups. Overall, the conclusions drawn from the analyses of the permanent deformation data did not match the conclusions drawn from the analyses of the moduli data. Sulfur decreased the deformations of the in-line blended projects at both 0.1 and 100 seconds. The slope also decreased, which means that the decrease was more significant at 100 seconds. Thus at high temperatures, and especially at high loading times, there may be a difference between binders produced by in-line blending and direct feed methods, with in-line blending being the better method. The other three significantly different slopes were different because the SEA had a greater effect at the longer duration than at the shorter duration. However, the effects at either loading time were not significant. As shown in table 34, the effect of sulfur varied on a project-by-project basis, and no trends were evident.

Resilient and viscoelastic deformations are shown in table 35. As shown by table 36, sulfur had little effect on a project-by-project basis.

f. Creep Test Conclusions

Overall, sulfur had little effect on the creep moduli. Where there were statistically significant effects, the effects were generally insignificant in terms of their expected effect on pavement performance or structural design, and they generally did not correspond to significant differences in permanent deformations.

More emphasis was placed on the results of the permanent deformations measurements than on the creep moduli. However, no consistent statistical inferences could be made across temperature except that at the higher temperatures, in-line blending produced lower deformations primarily at a loading time of 100 seconds compared to the direct feed method. This means that in-line blending may be a better method of addition as long as the properties at low temperatures are not adversely affected. However, it must be noted that the analyses are confounded by the type of mixture. The two methods of addition were used in different projects.

Table 32. Permanent deformations at 104 °F.

Project	Pavement Layer		Material	Permanent Deformation (microinches) 0.1 sec.	100 sec.	Slope
CA	Surface		SEA (30/70)	156	1674	.343
			SEA (30/70)	214	1892	.316
CB	Surface[1]	Location #1	AR-2000	1082	4189	.196
			SEA (20/80)	582	1634	.149
	Surface[1]	Location #2	AR-4000	953	5141	.244
			SEA (40/60)	787	3593	.220
DE	Surface		AC-20	384	2598	.277
			SEA (30/70)	446	1878	.208
GA	Surface		AC-20	364	6070	.142
			AC-20	2052	6725	.172
ID	Surface	Location #1	AR-4000	2368	8848	.191
			SEA (30/70)	1998	5802	.154
	Surface	Location #2	AR-4000	2012	7280	.186
			SEA (30/70)	1415	4862	.179
KS	Surface		AC-20	--	--	--
			SEA (30/70)	--	--	--
	Base, top half		AC-20	608	2897	.226
			SEA (30/70)	594	3587	.260
	Base, bottom half		AC-20	950	7367	.297
			SEA (30/70)	635	5108	.302
LA	Surface		AC-30	571	3961	.280
			SEA (40/60)	445	2192	.231
	Base under AC surface		SEA (40/60)	762	6681	.314
	Base under SEA surface		SEA (40/60)	856	7054	.305
MB	Surface		AC-10	--	--	--
			SEA (10/90)	--	--	--
			SEA (20/80)	--	--	--
			SEA (30/70)	--	--	--
	Binder		AC-10	2205	6522	.157
			SEA (10/90)	2418	8852	.188
			SEA (20/80)	3125	8598	.146
			SEA (30/70)	2190	6830	.165
MC	Surface[2]		AC-10	--	--	--
			SEA (30/70)	--	--	--
	Binder[2]		AC-10	2670	10380	.197
			SEA (30/70)	3115	5625	.086

[1] AR-2000 was used in SEA section.
[2] AC-5 was used in SEA section.

(in)(2.54)=(cm)
104 °F = 40 °C

Table 32. Permanent deformations at 104 °F (continued).

Project	Pavement Layer		Material	Permanent Deformation (microinches) 0.1 sec.	100 sec.	Slope
MN	Surface		AC 200-300	7095	52042	.288
			SEA (40/60)	2710	15508	.253
MS	Surface		AC-20	333	2775	.307
			SEA (30/70)	356	2571	.286
	Binder		AC-40	222	1174	.241
			SEA (30/70)	327	1860	.252
	Base		AC-40	107	678	.267
			SEA (30/70)	184	957	.238
ND	Surface	Location #1	AC 120-150	1892	11035	.255
			SEA (30/70)	1588	4405	.148
	Surface	Location #2	AC 120-150	2125	9212	.212
			SEA (25/75)	1555	4030	.138
NM	Surface		AC-10	616	2836	.221
			SEA (30/70)	793	4049	.236
	Base		AC-10	424	2781	.272
			SEA (30/70)	473	3182	.276
TC	Base, top half		AC-20	2755	9172	.174
	Base, bottom half		AC-20	3040	18788	.264
			SEA (30/70)	1848	12178	.273
TP	Binder		AC-20	203	1426	.282
			SEA (30/70)	155	328	.108
TX	Surface		AC-20	--	--	--
			SEA (35/65)	--	--	--
WI	Surface		AC 120-150	3105	14075	.219
			SEA (30/70)	2032	8118	.200
WY	Surface		SEA (20/80)	1495	4402	.156
			SEA (20/80)	1680	5580	.174

(in)(2.54)=(cm)
104 °F = 40 °C

Table 33. Effect of sulfur on permanent deformation at 104 °F for all projects, and projects by pavement age, blending method, and the stiffness of the mixture.

	Avg. AC Perm. Def. (microinches)	Avg. SEA Perm. Def. (microinches)	Degrees of Freedom	p
Creep Time = 0.1 second				
All projects	1662	1324	21	0.135 NS
Projects less than 5 years	1298	1203	13	0.456 NS
Projects more than 5 years	2298	1538	7	0.206 NS
In-Line Blending	1407	1075	10	0.011 D
Direct Feed	1961	1669	8	0.590 NS
Soft Mixtures	2811	2181	10	0.165 NS
Stiff Mixtures	512	467	10	0.471 NS
Creep Time = 100 seconds				
All projects	8215	5029	21	0.074 NS
Projects less than 5 years	4986	4374	13	0.326 NS
Projects more than 5 years	13864	6175	7	0.112 NS
In-Line Blending	6348	3836	10	0.008 D
Direct Feed	9946	6043	8	0.373 NS
Soft Mixtures	13747	7710	10	0.089 NS
Stiff Mixtures	2682	2348	10	0.358 NS
Slope				
All projects	0.229	0.200	21	0.014 D
Projects less than 5 years	0.218	0.200	13	0.205 NS
Projects more than 5 years	0.250	0.200	7	0.028 D
In-Line Blending	0.228	0.185	10	0.036 D
Direct Feed	0.222	0.208	8	0.380 D
Soft Mixtures	0.208	0.175	10	0.047 NS
Stiff Mixtures	0.251	0.224	10	0.155 NS

(in)(2.54)=(cm)
104 °F = 40 °C

Table 34. Effect of sulfur on permanent deformation at 104 °F for each project.

Project	Pavement Layer		Material	0.1 sec.	100 sec.	slope
CB	Surface		SEA (20/80)	D	D	NS
	Surface		SEA (40/60)	D	D	NS
DE	Surface		SEA (30/70)	NS	D	D
ID	Surface	Location #1	SEA (30/70)	NS	D	NS
	Surface	Location #2	SEA (30/70)	D	D	NS
KS	Surface		SEA (30/70)	--	--	--
	Base, top half		SEA (30/70)	NS	NS	NS
	Base, bottom half		SEA (30/70)	D	D	NS
LA	Surface		SEA (40/60)	NS	D	NS
MB	Surface		SEA (10/90)	--	--	--
			SEA (20/80)	--	--	--
			SEA (30/70)	--	--	--
	Binder		SEA (10/90)	NS	I	NS
			SEA (20/80)	NS	NS	NS
			SEA (30/70)	NS	NS	NS
MC	Surface		SEA (30/70)	--	--	--
	Binder		SEA (30/70)	NS	D	D
MN	Surface		SEA (40/60)	D	D	NS
MS	Surface		SEA (30/70)	NS	NS	NS
	Binder		SEA (30/70)	NS	I	NS
	Base		SEA (30/70)	I	I	NS
ND	Surface	Location #1	SEA (30/70)	NS	D	D
	Surface	Location #2	SEA (25/75)	D	D	D
NM	Surface		SEA (30/70)	NS	I	NS
	Base		SEA (30/70)	NS	NS	NS
TC	Base		SEA (30/70)	D	D	NS
TP	Binder		SEA (30/70)	NS	D	D
TX	Surface		SEA (35/65)	--	--	--
WI	Surface		SEA (30/70)	D	D	NS

104 °F = 40 °C

Table 35. Resilient and viscoelastic deformations at 104 °F.

			Resilient		Visco-elastic
			(microinches)		
Project	Pavement Layer	Material	0.1 sec.	10 sec.	100 sec.
CA	Surface	SEA (30/70)	631	892	620
		SEA (30/70)	697	1005	606
CB	Surface[1] Location #1	AR-2000	834	1340	483
		SEA (20/80)	1113	1398	673
	Surface[1] Location #2	AR-4000	873	1373	769
		SEA (40/60)	895	1543	626
DE	Surface	AC-20	468	776	329
		SEA (30/70)	454	677	271
GA	Surface	AC-20	378	882	252
		AC-20	758	1260	315
ID	Surface Location #1	AR-4000	732	1360	378
		SEA (30/70)	778	1408	410
	Surface Location #2	AR-4000	895	1678	528
		SEA (30/70)	1030	1595	462
KS	Surface	AC-20	--	--	--
		SEA (30/70)	--	--	--
	Base, top half	AC-20	794	995	284
		SEA (30/70)	661	964	227
	Base, bottom half	AC-20	1019	1312	280
		SEA (30/70)	714	1184	353
LA	Surface	AC-30	641	962	443
		SEA (40/60)	714	835	209
	Base under AC surface	SEA (40/60)	907	1456	798
	Base under SEA surface	SEA (40/60)	1120	1647	797
MB	Surface	AC-10	--	--	--
		SEA (10/90)	--	--	--
		SEA (20/80)	--	--	--
		SEA (30/70)	--	--	--
	Binder	AC-10	820	1240	105
		SEA (10/90)	850	1732	125
		SEA (20/80)	820	1512	125
		SEA (30/70)	866	1302	168
MC	Surface[2]	AC-10	--	--	--
		SEA (30/70)	--	--	--
	Binder[2]	AC-10	862	1585	158
		SEA (30/70)	1008	1480	190

[1] AR-2000 was used in SEA section.
[2] AC-5 was used in SEA section.

(in)(2.54)=(cm)
104 °F = 40 °C

Table 35. Resilient and viscoelastic deformations at 104 °F (continued).

Project	Pavement Layer		Material	Resilient (microinches) 0.1 sec.	10 sec.	Visco-elastic 100 sec.
MN	Surface		AC 200-300	62	1532	0
			SEA (40/60)	82	735	0
MS	Surface		AC-20	434	750	374
			SEA (30/70)	593	838	376
	Binder		AC-40	541	651	313
			SEA (30/70)	634	807	269
	Base		AC-40	730	882	398
			SEA (30/70)	772	1046	401
ND	Surface	Location #1	AC 120-150	692	1492	232
			SEA (30/70)	802	1545	520
	Surface	Location #2	AC 120-150	552	1608	395
			SEA (25/75)	772	1498	410
NM	Surface		AC-10	687	1032	337
			SEA (30/70)	805	1164	242
	Base		AC-10	666	988	401
			SEA (30/70)	683	1077	385
TC	Base, top half		AC-20	285	915	95
	Base, bottom half		AC-20	820	1575	72
			SEA (30/70)	755	1240	295
TP	Binder		AC-20	510	708	300
			SEA (30/70)	596	670	162
TX	Surface		AC-20	--	--	--
			SEA (35/65)	--	--	--
WI	Surface		AC 120-150	420	1448	252
			SEA (30/70)	460	1428	358
WY	Surface		SEA (20/80)	882	1365	398
			SEA (20/80)	820	1355	315

(in)(2.54)=(cm)
104 °F = 40 °C

Table 36. Effect of sulfur on resilient and viscoelastic deformations at 104 °F for each project.

Project	Pavement Layer		Material	Resilient 0.1 sec.	Resilient 10 sec.	Visco-elastic 100 sec.
CB	Surface		SEA (20/80)	I	NS	NS
	Surface		SEA (40/60)	NS	NS	D
DE	Surface		SEA (30/70)	NS	NS	NS
ID	Surface	Location #1	SEA (30/70)	NS	NS	NS
	Surface	Location #2	SEA (30/70)	NS	NS	NS
KS	Surface		SEA (30/70)	--	--	--
	Base, top half		SEA (30/70)	NS	NS	NS
	Base, bottom half		SEA (30/70)	D	NS	NS
LA	Surface		SEA (40/60)	NS	NS	D
MB	Surface		SEA (10/90)	--	--	--
			SEA (20/80)	--	--	--
			SEA (30/70)	--	--	--
	Binder		SEA (10/90)	NS	NS	NS
			SEA (20/80)	NS	I	NS
			SEA (30/70)	NS	NS	NS
MC	Surface		SEA (30/70)	--	--	--
	Binder		SEA (30/70)	NS	NS	NS
MN	Surface		SEA (40/60)	NS	D	NS
MS	Surface		SEA (30/70)	NS	NS	NS
	Binder		SEA (30/70)	NS	NS	NS
	Base		SEA (30/70)	I	I	NS
ND	Surface	Location #1	SEA (30/70)	NS	NS	I
	Surface	Location #2	SEA (25/75)	NS	NS	NS
NM	Surface		SEA (30/70)	NS	NS	NS
	Base		SEA (30/70)	NS	NS	NS
TC	Base		SEA (30/70)	NS	D	NS
TP	Binder		SEA (30/70)	NS	NS	NS
TX	Surface		SEA (35/65)	--	--	--
WI	Surface		SEA (30/70)	NS	NS	NS

104 °F = 40 °C

A visual examination of the average permanent deformations in tables 17, 25 and 33 indicated that there may be an overall trend for the SEA sections to have lower permanent deformations, or a reduced susceptibility to rutting, at the higher temperatures. However, some of the differences in the averages were due to only a few projects where the differences were large. The temperatures used in this study may not have been low enough to determine low temperature properties, as the data for the SEA and AC mixtures were close at 41 °F (5 °C).

No trends were evident when evaluating the data on a project-by-project basis. Sulfur also had little to no effect on viscoelastic or resilient deformations at any temperature or loading time.

CHAPTER 4: MOISTURE SUSCEPTIBILITY

The susceptibility to damage by moisture was evaluated in accordance with ASTM D 4867.(8) In this test, the indirect splitting tensile strengths of unconditioned (dry) and conditioned (wet) specimens are measured. Retained ratios (wet/dry values) are then computed in terms of percents. Conditioned specimens were first partially saturated by vacuum so that 55 to 80 percent of the air void level was filled with water. The specimens were then frozen for 15 hours at 0 °F (-17.8 °C), soaked in a 140 °F (60 °C) water bath for 24 hours, and tested at 77 °F (25 °C) along with the unconditioned specimens. Freezing is optional in the standard test method. The resilient modulus test was also included in this evaluation, along with a visual estimate of stripping. Sufficient cores for the KS project were only available for one section, so this project was eliminated from the statistical analyses.

Testing was performed in this study to estimate the future performance of the pavement sections rather than to determine the current performance. None of the unconditioned cores visually showed any stripping, except for minor amounts in those from the KS project. Thus it appears that there was little or no moisture-related damage in the pavements except for the KS pavement section. However, moisture damage as manifested by stripping can reverse in the laboratory over time. It was noted during the visual examination of the cores in chapter 2 that the outsides of the LA cores were stripped. The lack of stripping in the LA unconditioned cores indicates that healing probably occurred. Also, the minor amount of stripping in the KS cores was much less than what would be expected for a pavement which reportedly failed from moisture damage. Whether healing occurred in cores from other projects is not known. To determine the level of stripping in pavements, the cores should be broken open immediately after removal from the pavement.

The test for moisture susceptibility used in this study is generally performed on specimens prepared in the laboratory which are compacted to a required air void level. The cores tested in this study do not necessarily meet these air void requirements and thus it is not known if the test results really predict pavement performance. The use of a certain level of air voids may be one testing requirement which helps accelerate damage in laboratory testing, and thus testing at lower air void levels may give misleading results. The air voids of the cores varied from project to project and thus comparisons between the projects should not be made. The air void levels were not always the same even between an SEA section and its corresponding AC section.

Tensile strength ratios (TSR), resilient modulus ratios (MrR), and the percent stripping are given in table 37. Table 38 shows the effect of sulfur on these data for the groups. When considering all projects, sulfur decreased both ratios but not the percent stripping. Thus it was concluded that the lower ratios were related to a loss of cohesion rather than a loss of adhesion. The SEA binders were weakened by the conditioning processes.

The TSR of each AC group in table 38 was virtually equal to its corresponding MrR. However, the MrR were lower than the TSR for the SEA groups. For example, when considering all projects, the TSR and MrR of the AC sections were 79.8 and 79.1 respectively, while for the SEA projects they were 67.4 and 54.9. Thus for the SEA mixtures, the MrR were more sensitive to the damage in the binder. There were significant decreases in the MrR because of the sulfur for nearly every group compared to the AC mixtures. Sulfur decreased both the TSR and MrR of soft mixtures, most of which were used in older projects.

For both the AC and SEA binders, stiff mixtures had lower ratios and more stripping than the soft mixtures. These moisture damage results are unusual because increased strength and stiffness generally decreases the susceptibility to moisture damage, except for very soft mixtures in pavements which can heal easily. It was later found that the stiff mixtures had air void levels which averaged twice those of the soft mixtures. Stiff mixtures generally had air void levels above 5.0 percent, while soft mixtures had air void levels generally below 5.0 percent.

Statistical analyses could not be performed on a project-by-project basis because there is only one average ratio or visual estimate of damage per section.

Dry and wet tensile strengths and resilient moduli are given in table 39. Table 40 shows the effects of sulfur on the dry and wet tensile strengths (S_t) for the groups. When considering all projects, sulfur decreased both the dry and wet tensile strengths. There was also an overall tendency for the sulfur to decrease either the dry or wet tensile strengths, or both, for the other groups.

Table 37. Moisture susceptibility results.

Project	Pavement Layer		Material	TSR	MrR	Visual
CA	Surface		SEA (30/70)	65.5	54.2	50
			SEA (30/70)	60.2	57.9	40
CB	Surface[1]	Location #1	AR-2000	32.5	39.9	75
			SEA (20/80)	31.1	31.1	35
	Surface[1]	Location #2	AR-4000	40.9	55.4	75
			SEA (40/60)	43.6	45.6	65
DE	Surface		AC-20	44.1	33.4	70
			SEA (30/70)	47.3	33.5	50
GA	Surface		AC-20	89.5	105.4	10
			AC-20	97.2	106.9	2
ID	Surface	Location #1	AR-4000	82.5	81.2	0
			SEA (30/70)	80.6	62.1	0
	Surface	Location #2	AR-4000	86.0	99.3	0
			SEA (30/70)	70.6	68.3	0
KS	Surface		AC-20	--	--	--
			SEA (30/70)	--	--	--
	Base, top half		AC-20	--	--	--
			SEA (30/70)	68.3	53.1	5
	Base, bottom half		AC-20	--	--	--
			SEA (30/70)	--	--	--
LA	Surface		AC-30	101.6	97.2	5
			SEA (40/60)	113.3	91.4	5
	Base under AC surface		SEA (40/60)	52.7	44.5	25
	Base under SEA surface		SEA (40/60)	40.8	36.0	25
MB	Surface		AC-10	--	--	--
			SEA (10/90)	--	--	--
			SEA (20/80)	--	--	--
			SEA (30/70)	--	--	--
	Binder		AC-10	99.7	78.1	5
			SEA (10/90)	97.7	65.0	5
			SEA (20/80)	82.3	66.8	5
			SEA (30/70)	93.9	61.0	5
MC	Surface[2]		AC-10	--	--	--
			SEA (30/70)	--	--	--
	Binder[2]		AC-10	88.5	73.4	10
			SEA (30/70)	79.8	57.7	7

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[1] AR-2000 was used in SEA section.
[2] AC-5 was used in SEA section.

Table 37. Moisture susceptibility results (continued).

Project	Pavement Layer	Material	TSR	MrR	Visual
MN	Surface	AC 200-300	85.5	74.4	12
		SEA (40/60)	78.1	62.9	5
MS	Surface	AC-20	79.9	103.8	17
		SEA (30/70)	78.1	79.2	8
	Binder	AC-40	79.6	82.3	17
		SEA (30/70)	55.0	53.0	15
	Base	AC-40	53.6	56.6	30
		SEA (30/70)	71.6	49.2	35
ND	Surface Location #1	AC 120-150	102.7	101.0	0
		SEA (30/70)	57.3	40.4	0
	Surface Location #2	AC 120-150	100.7	103.3	2
		SEA (25/75)	77.1	58.3	2
NM	Surface	AC-10	80.4	86.8	7
		SEA (30/70)	55.3	45.0	15
	Base	AC-10	30.5	21.1	10
		SEA (30/70)	47.0	35.8	15
TC	Base, top half	AC-20	101.6	102.9	8
	Base, bottom half	AC-20	90.7	108.4	30
		SEA (30/70)	34.1	35.3	30
TP	Binder	AC-20	89.7	84.4	0
		SEA (30/70)	35.4	25.7	5
TX	Surface	AC-20	--	--	--
		SEA (35/65)	--	--	--
WI	Surface	AC 120-150	115.3	140.5	6
		SEA (30/70)	85.7	84.6	5
WY	Surface	SEA (20/80)	80.7	80.8	2
		SEA (20/80)	90.2	92.7	2

Table 38. Effect of sulfur on moisture susceptibility for all projects, and projects by pavement age, blending method, and the stiffness of the mixture.

	Average AC	Average SEA	Degrees of Freedom	p
Tensile Strength Ratio (TSR)				
All projects	79.8	67.4	20	0.016 D
Projects less than 5 years	75.8	66.3	13	0.094 NS
Projects more than 5 years	87.7	69.6	6	0.106 NS
In-Line Blending	77.7	63.4	10	0.073 NS
Direct Feed	85.8	79.6	7	0.203 NS
Soft Mixtures	95.5	76.1	10	0.005 D
Stiff Mixtures	62.4	57.8	9	0.540 NS
Resilient Modulus Ratio (MrR)				
All projects	79.1	54.9	20	0.000 D
Projects less than 5 years	76.4	55.2	13	0.002 D
Projects more than 5 years	84.4	54.2	6	0.033 D
In-Line Blending	81.3	53.5	10	0.006 D
Direct Feed	78.1	61.9	7	0.000 D
Soft Mixtures	92.3	60.2	10	0.001 D
Stiff Mixtures	64.5	49.0	9	0.058 NS
Visual Stripping, Percent				
All projects	18.1	14.9	20	0.163 NS
Projects less than 5 years	18.0	15.2	13	0.394 NS
Projects more than 5 years	18.4	14.1	6	0.177 NS
In-Line Blending	16.4	13.4	10	0.465 NS
Direct Feed	12.6	10.6	7	0.240 NS
Soft Mixtures	6.8	5.8	10	0.161 NS
Stiff Mixtures	30.6	24.8	9	0.248 NS

Table 39. Tensile strengths and resilient moduli from the moisture susceptibility tests.

Project	Pavement Layer	Material	Tensile Strength Dry psi	Tensile Strength Wet psi	Resilient Modulus Dry ksi	Resilient Modulus Wet ksi
CA	Surface	SEA (30/70)	232.3	152.1	1207	654
		SEA (30/70)	304.5	183.3	1407	814
CB	Surface[1] Location #1	AR-2000	294.1	95.5	1006	402
		SEA (20/80)	122.7	59.9	1182	367
	Surface[1] Location #2	AR-4000	335.1	137.1	1286	712
		SEA (40/60)	289.2	126.1	1147	523
DE	Surface	AC-20	220.5	97.2	898	300
		SEA (30/70)	194.2	91.9	1041	348
GA	Surface	AC-20	124.6	111.5	245	259
		AC-20	105.3	102.4	248	266
ID	Surface Location #1	AR-4000	166.5	137.4	521	423
		SEA (30/70)	158.0	127.4	619	384
	Surface Location #2	AR-4000	142.2	122.3	433	430
		SEA (30/70)	142.7	110.8	488	333
KS	Surface	AC-20	--	--	--	--
		SEA (30/70)	--	--	--	--
	Base, top half	AC-20	--	--	--	--
		SEA (30/70)	136.1	93.0	872	464
	Base, bottom half	AC-20	--	--	--	--
		SEA (30/70)	--	--	--	--
LA	Surface	AC-30	286.5	291.2	1096	1065
		SEA (40/60)	245.1	277.8	1085	991
	Base under AC surface	SEA (40/60)	136.3	71.8	476	212
	Base under SEA surface	SEA (40/60)	172.9	70.6	516	186
MB	Surface	AC-10	--	--	--	--
		SEA (10/90)	--	--	--	--
		SEA (20/80)	--	--	--	--
		SEA (30/70)	--	--	--	--
	Binder	AC-10	116.7	116.3	235	184
		SEA (10/90)	83.5	81.6	166	108
		SEA (20/80)	98.1	80.6	197	132
		SEA (30/70)	82.2	77.2	215	131
MC	Surface[2]	AC-10	--	--	--	--
		SEA (30/70)	--	--	--	--
	Binder[2]	AC-10	121.8	107.8	324	238
		SEA (30/70)	85.2	68.0	294	170

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[1] AR-2000 was used in SEA section.
[2] AC-5 was used in SEA section.

(psi)(6895)=(Pa)
(ksi)(6895)=(KPa)

Table 39. Tensile strengths and resilient moduli from the moisture susceptibility tests (continued).

Project	Pavement Layer		Material	Tensile Strength Dry psi	Tensile Strength Wet psi	Resilient Modulus Dry ksi	Resilient Modulus Wet ksi
MN	Surface		AC 200-300	88.8	75.9	109	81
			SEA (40/60)	92.0	71.9	219	139
MS	Surface		AC-20	204.4	163.4	738	766
			SEA (30/70)	179.9	140.5	775	614
	Binder		AC-40	164.8	131.1	1040	856
			SEA (30/70)	142.6	78.5	904	479
	Base		AC-40	229.3	122.8	1807	1022
			SEA (30/70)	216.3	154.8	1638	806
ND	Surface	Location #1	AC 120-150	95.0	97.6	223	225
			SEA (30/70)	100.2	57.4	386	156
	Surface	Location #2	AC 120-150	114.8	115.6	301	311
			SEA (25/75)	123.2	95.0	458	267
NM	Surface		AC-10	213.5	171.6	1056	917
			SEA (30/70)	144.2	79.8	639	288
	Base		AC-10	216.5	66.1	1262	354
			SEA (30/70)	153.6	72.2	799	286
TC	Base, top half		AC-20	231.0	234.8	764	786
	Base, bottom half		AC-20	159.3	144.5	487	528
			SEA (30/70)	180.5	61.5	902	319
TP	Binder		AC-20	184.0	165.2	1095	924
			SEA (30/70)	164.3	58.2	1200	308
TX	Surface		AC-20	--	--	--	--
			SEA (35/65)	--	--	--	--
WI	Surface		AC 120-150	88.4	102.1	140	196
			SEA (30/70)	120.0	102.8	344	291
WY	Surface		SEA (20/80)	146.0	117.8	516	417
			SEA (20/80)	114.4	103.2	300	278

(psi)(6895)=(Pa)
(ksi)(6895)=(KPa)

Table 40. Effect of sulfur on dry and wet tensile strengths for all projects, and projects by pavement age, blending method, and the stiffness of the mixture.

	Average AC S_t	Average SEA S_t	Degrees of Freedom	p
<u>Dry Tensile Strength, psi</u>				
All projects	173.1	148.5	20	0.014 D
Projects less than 5 years	182.0	149.8	13	0.024 D
Projects more than 5 years	155.2	145.8	6	0.350 NS
In-Line Blending	190.5	160.3	10	0.103 NS
Direct Feed	144.9	122.5	7	0.002 D
Soft Mixtures	120.6	115.1	10	0.439 NS
Stiff Mixtures	230.8	185.2	9	0.016 D
<u>Wet Tensile Strength, psi</u>				
All projects	126.3	98.8	20	0.002 D
Projects less than 5 years	123.0	96.5	13	0.028 D
Projects more than 5 years	132.8	103.4	6	0.031 D
In-Line Blending	132.7	106.1	10	0.057 D
Direct Feed	118.7	94.1	7	0.036 D
Soft Mixtures	113.8	84.9	10	0.002 D
Stiff Mixtures	140.0	114.0	9	0.114 NS

(psi)(6895)=(Pa)

Of note is that the average dry tensile strength of the stiff mixtures was decreased by the sulfur but not for the soft mixtures. This finding is consistent with the findings according to age. The average dry tensile strength of projects less than 5 years old was decreased by the sulfur but not for projects more than 5 years old. Many stiff mixtures were used in newer projects.

As shown by table 41, sulfur had little effect on the dry or wet tensile strengths on a project-by-project basis, but more decreases where there was a significant effect. More wet strengths were affected than dry strengths.

Table 42 shows the effects of sulfur on the dry and wet resilient moduli for the groups. Sulfur increased the dry resilient moduli of the soft mixtures. The finding drawn from table 9 for the same test at 77 °F (25 °C) was that sulfur had no effect. Although these findings are not the same, the effects of sulfur on the moduli in both tables are algebraically similar. Specimens used for evaluating moisture damage were a subset of the specimens used to generate the data in table 9. The finding from table 9 is paramount.

It was also noted that all of the resilient moduli are higher in table 42 compared to table 9. This indicates hardening occurred in the laboratory. This hardening occurred over a period of one year and could not be taken into account in this study.

When considering all projects, sulfur decreased the wet resilient moduli compared to the AC sections. Thus the decrease in the MrR for all projects in table 38 was largely a result of the conditioning processes and increased damage in the SEA mixtures. Decreases in wet resilient moduli also appear to be the reason for most of the other lower MrR in table 38. One factor which may have led to more significant decreases in the MrR in table 38 compared to the TSR was that the sulfur reduced the dry tensile strengths in some cases.

As shown in table 43, sulfur had little effect on the dry or wet resilient moduli on a project-by-project basis. This appears to conflict with the findings from table 42. However, as discussed in chapter 1, the statistical analyses used in table 42 show trends in the data.

Table 41. Effect of sulfur on tensile strengths for each project.

Project	Pavement Layer		Material	Dry S_t	Wet S_t
CB	Surface		SEA (20/80)	D	D
	Surface		SEA (40/60)	D	NS
DE	Surface		SEA (30/70)	D	NS
ID	Surface	Location #1	SEA (30/70)	NS	NS
	Surface	Location #2	SEA (30/70)	NS	NS
KS	Surface		SEA (30/70)	--	--
	Base, top half		SEA (30/70)	--	--
	Base, bottom half		SEA (30/70)	--	--
LA	Surface		SEA (40/60)	NS	NS
MB	Surface		SEA (10/90)	--	--
			SEA (20/80)	--	--
			SEA (30/70)	--	--
	Binder		SEA (10/90)	NS	NS
			SEA (20/80)	NS	D
			SEA (30/70)	D	D
MC	Surface		SEA (30/70)	--	--
	Binder		SEA (30/70)	NS	D
MN	Surface		SEA (40/60)	NS	NS
MS	Surface		SEA (30/70)	NS	NS
	Binder		SEA (30/70)	NS	NS
	Base		SEA (30/70)	NS	NS
ND	Surface	Location #1	SEA (30/70)	NS	D
	Surface	Location #2	SEA (25/75)	NS	D
NM	Surface		SEA (30/70)	NS	NS
	Base		SEA (30/70)	NS	NS
TC	Base		SEA (30/70)	NS	D
TP	Binder		SEA (30/70)	NS	D
TX	Surface		SEA (35/65)	--	--
WI	Surface		SEA (30/70)	I	NS

Table 42. Effect of sulfur on dry and wet resilient moduli for all projects, and projects by pavement age, blending method, and the stiffness of the mixture.

	Average AC Mr	Average SEA Mr	Degrees of Freedom	p
Dry Resilient Modulus, ksi				
All projects	687.4	699.9	20	0.630 NS
Projects less than 5 years	772.1	736.4	13	0.527 NS
Projects more than 5 years	491.1	626.4	6	0.051 NS
In-Line Blending	739.9	758.8	10	0.795 NS
Direct Feed	590.4	551.0	7	0.252 NS
Soft Mixtures	294.8	389.8	10	0.049 I
Stiff Mixtures	1100.4	1041.0	9	0.439 NS
Wet Resilient Modulus, ksi				
All projects	475.8	354.3	20	0.011 D
Projects less than 5 years	513.4	364.5	13	0.038 D
Projects more than 5 years	392.6	341.2	6	0.179 NS
In-Line Blending	513.5	390.4	10	0.141 NS
Direct Feed	439.4	322.3	7	0.040 D
Soft Mixtures	271.3	220.8	10	0.059 NS
Stiff Mixtures	700.8	501.0	9	0.039 D

(ksi)(6895)=(KPa)

Table 43. Effect of sulfur on resilient moduli for each project.

Project	Pavement Layer		Material	Dry Mr	Wet Mr
CB	Surface		SEA (20/80)	NS	NS
	Surface		SEA (40/60)	NS	D
DE	Surface		SEA (30/70)	NS	NS
ID	Surface	Location #1	SEA (30/70)	NS	NS
	Surface	Location #2	SEA (30/70)	NS	NS
KS	Surface		SEA (30/70)	--	--
	Base, top half		SEA (30/70)	--	--
	Base, bottom half		SEA (30/70)	--	--
LA	Surface		SEA (40/60)	NS	NS
MB	Surface		SEA (10/90)	--	--
			SEA (20/80)	--	--
			SEA (30/70)	--	--
	Binder		SEA (10/90)	NS	NS
			SEA (20/80)	NS	NS
			SEA (30/70)	NS	NS
MC	Surface		SEA (30/70)	--	--
	Binder		SEA (30/70)	NS	NS
MN	Surface		SEA (40/60)	I	I
MS	Surface		SEA (30/70)	NS	NS
	Binder		SEA (30/70)	NS	NS
	Base		SEA (30/70)	NS	NS
ND	Surface	Location #1	SEA (30/70)	I	NS
	Surface	Location #2	SEA (25/75)	NS	NS
NM	Surface		SEA (30/70)	NS	NS
	Base		SEA (30/70)	D	NS
TC	Base		SEA (30/70)	I	D
TP	Binder		SEA (30/70)	NS	D
TX	Surface		SEA (35/65)	--	--
WI	Surface		SEA (30/70)	NS	NS

Dry and wet tensile strains at failure (similar to Marshall flow) are given in table 44. Table 45 shows the effects of sulfur on these strains for the groups. When considering all projects, sulfur decreased both the dry and wet tensile strain. The dry tensile strain also decreased for all other groups. Because strain generally increases with damage and the dry tensile strains of the SEA mixtures are initially lower, the data is difficult to analyze and interpret. The damage in the SEA mixtures could be greater than in the AC mixtures but the wet tensile strains be similar. The wet tensile strains of the groups which are not significantly different in table 45 could mean these are the groups where damage in the SEA mixtures were highest as measured by strain. Possibly, some form of retained ratio could be developed for strain, but this was not done in this study.

As shown in table 46, the effect of sulfur varied on a project-by-project basis. Sulfur generally decreased the strain where there were significant differences. Sulfur affected the dry strains of more projects than the wet strains.

The lower dry tensile strain at failure for all projects in table 45 together with the lower dry tensile strength in table 40 indicates a trend that the SEA mixtures may be more susceptible to tensile fatigue cracking at 77 °F (25 °C). The decreases in these two properties generally did not occur on the same projects. A decrease in both would be the worst possible case with regards to fatigue cracking.

Figure 44. Tensile strain (inches) at failure from the moisture susceptibility tests.

Project	Pavement Layer	Material	Dry Specimens (in)	Wet Specimens (in)
CA	Surface	SEA (30/70)	0.097	0.077
		SEA (30/70)	0.062	0.073
CB	Surface[1] Location #1	AR-2000	0.100	0.093
		SEA (20/80)	0.060	0.068
	Surface[1] Location #2	AR-4000	0.087	0.052
		SEA (40/60)	0.082	0.073
DE	Surface	AC-20	0.095	0.080
		SEA (30/70)	0.078	0.060
GA	Surface	AC-20	0.105	0.108
		AC-20	0.108	0.120
ID	Surface Location #1	AR-4000	0.093	0.102
		SEA (30/70)	0.075	0.088
	Surface Location #2	AR-4000	0.102	0.092
		SEA (30/70)	0.083	0.087
KS	Surface	AC-20	--	--
		SEA (30/70)	--	--
	Base, top half	AC-20	--	--
		SEA (30/70)	0.050	0.072
	Base, bottom half	AC-20	--	--
		SEA (30/70)	--	--
LA	Surface	AC-30	0.090	0.082
		SEA (40/60)	0.077	0.087
	Base under AC surface	SEA (40/60)	0.102	0.105
	Base under SEA surface	SEA (40/60)	0.105	0.127
MB	Surface	AC-10	--	--
		SEA (10/90)	--	--
		SEA (20/80)	--	--
		SEA (30/70)	--	--
	Binder	AC-10	0.100	0.113
		SEA (10/90)	0.085	0.112
		SEA (20/80)	0.092	0.098
		SEA (30/70)	0.075	0.087
MC	Surface[2]	AC-10	--	--
		SEA (30/70)	--	--
	Binder[2]	AC-10	0.098	0.118
		SEA (30/70)	0.073	0.090

(in)(2.54)=(cm)

[1] AR-2000 was used in SEA section.
[2] AC-5 was used in SEA section.

Figure 44. Tensile strain (inches) at failure from the moisture susceptibility tests (continued).

Project	Pavement Layer	Material	Dry Specimens (in)	Wet Specimens (in)
MN	Surface	AC 200-300	0.128	0.172
		SEA (40/60)	0.083	0.107
MS	Surface	AC-20	0.083	0.077
		SEA (30/70)	0.073	0.093
	Binder	AC-40	0.052	0.060
		SEA (30/70)	0.050	0.053
	Base	AC-40	0.053	0.045
		SEA (30/70)	0.050	0.058
ND	Surface Location #1	AC 120-150	0.112	0.143
		SEA (30/70)	0.077	0.115
	Surface Location #2	AC 120-150	0.102	0.143
		SEA (25/75)	0.087	0.117
NM	Surface	AC-10	0.065	0.080
		SEA (30/70)	0.080	0.078
	Base	AC-10	0.063	0.062
		SEA (30/70)	0.057	0.073
TC	Base, top half	AC-20	0.097	0.103
	Base, bottom half	AC-20	0.107	0.110
		SEA (30/70)	0.080	0.097
TP	Binder	AC-20	0.053	0.057
		SEA (30/70)	0.043	0.047
TX	Surface	AC-20	--	--
		SEA (35/65)	--	--
WI	Surface	AC 120-150	0.150	0.173
		SEA (30/70)	0.100	0.132
WY	Surface	SEA (20/80)	0.080	0.098
		SEA (20/80)	0.082	0.095

(in)(2.54)=(cm)

Table 45. Effect of sulfur on the tensile strain at failure for all projects, and projects by pavement age, blending method, and the stiffness of the mixture.

	Average AC	Average SEA	Degrees of Freedom	p
Dry Tensile Strain at Failure, in				
All projects	0.093	0.074	20	0.001 D
Projects less than 5 years	0.087	0.072	13	0.004 D
Projects more than 5 years	0.105	0.079	6	0.001 D
In-Line Blending	0.094	0.075	10	0.005 D
Direct Feed	0.089	0.073	7	0.014 D
Soft Mixtures	0.108	0.083	10	0.001 D
Stiff Mixtures	0.076	0.065	9	0.043 D
Wet Tensile Strain at Failure, in				
All projects	0.101	0.087	20	0.003 D
Projects less than 5 years	0.091	0.082	13	0.057 NS
Projects more than 5 years	0.121	0.096	6	0.021 D
In-Line Blending	0.102	0.087	10	0.014 D
Direct Feed	0.101	0.090	7	0.171 NS
Soft Mixtures	0.127	0.103	10	0.001 D
Stiff Mixtures	0.073	0.069	9	0.429 NS

(in)(2.54)=(cm)

Table 46. Effect of sulfur on tensile strains for each project.

Project	Pavement Layer		Material	Dry	Wet
CB	Surface		SEA (20/80)	D	NS
	Surface		SEA (40/60)	NS	I
DE	Surface		SEA (30/70)	NS	NS
ID	Surface	Location #1	SEA (30/70)	D	NS
	Surface	Location #2	SEA (30/70)	D	NS
KS	Surface		SEA (30/70)	--	--
	Base, top half		SEA (30/70)	--	--
	Base, bottom half		SEA (30/70)	--	--
LA	Surface		SEA (40/60)	NS	NS
MB	Surface		SEA (10/90)	--	--
			SEA (20/80)	--	--
			SEA (30/70)	--	--
	Binder		SEA (10/90)	NS	NS
			SEA (20/80)	NS	NS
			SEA (30/70)	NS	NS
MC	Surface		SEA (30/70)	--	--
	Binder		SEA (30/70)	NS	NS
MN	Surface		SEA (40/60)	D	D
MS	Surface		SEA (30/70)	NS	NS
	Binder		SEA (30/70)	NS	NS
	Base		SEA (30/70)	NS	NS
ND	Surface	Location #1	SEA (30/70)	D	NS
	Surface	Location #2	SEA (25/75)	NS	NS
NM	Surface		SEA (30/70)	I	NS
	Base		SEA (30/70)	NS	NS
TC	Base		SEA (30/70)	D	NS
TP	Binder		SEA (30/70)	NS	NS
TX	Surface		SEA (35/65)	--	--
WI	Surface		SEA (30/70)	D	D

CHAPTER 5: MARSHALL PROPERTIES

Marshall stabilities and flows as measured by AASHTO T 245 are given in table 47.(5) All Marshall stabilities are adjusted for a thickness of 2.5 in (6.4 cm). The cores were lightly ground to provide a smooth testing surface. Some projects did not have sufficient cores to perform this test.

Table 48 shows the effect of sulfur on the data for the groups. When considering all projects, sulfur had no effect on stability or flow. The statistically significant decreases in stability or flow due to the sulfur for the other groups have little practical significance. The decreases are too small to relate them to changes in rutting or cracking.

As shown by table 49, sulfur had little to no effect on Marshall stability and flow on a project-by-project basis. No trends were evident, except that the sulfur always decreased the flow when there was an effect.

Figure 47. Marshall test results.

Project	Pavement Layer	Material	Stability (lbf)	Flow (in)
CA	Surface	SEA (30/70	4317	0.148
		SEA (30/70)	3305	0.145
CB	Surface[1] Location #1	AR-2000	--	--
		SEA (20/80)	2693	0.193
	Surface[1] Location #2	AR-4000	3049	0.210
		SEA (40/60)	3298	0.155
DE	Surface	AC-20	3610	0.105
		SEA (30/70)	4371	0.088
GA	Surface	AC-20	2846	0.115
		AC-20	3089	0.113
ID	Surface Location #1	AR-4000	--	--
		SEA (30/70)	--	--
	Surface Location #2	AR-4000	1937	0.230
		SEA (30/70)	--	--
KS	Surface	AC-20	--	--
		SEA (30/70)	--	--
	Base, top half	AC-20	--	--
		SEA (30/70)	--	--
	Base, bottom half	AC-20	--	--
		SEA (30/70)	--	--
LA	Surface	AC-30	2171	0.152
		SEA (40/60)	2506	0.137
	Base under AC surface	SEA (40/60)	1338	0.145
	Base under SEA surface	SEA (40/60)	1499	0.140
MB	Surface	AC-10	--	--
		SEA (10/90)	--	--
		SEA (20/80)	--	--
		SEA (30/70)	--	--
	Binder	AC-10	2541	0.118
		SEA (10/90)	1978	0.157
		SEA (20/80)	1857	0.158
		SEA (30/70)	2199	0.125
MC	Surface[2]	AC-10	--	--
		SEA (30/70)	--	--
	Binder[2]	AC-10	1889	0.238
		SEA (30/70)	1828	0.152

[1] AR-2000 was used in SEA section.
[2] AC-5 was used in SEA section.

(lbf)(4.448)=(N)
(in)(2.54)=(cm)

Figure 47. Marshall test results (continued).

Project	Pavement Layer		Material	Stability (lbf)	Flow (in)
MN	Surface		AC 200-300	--	--
			SEA (40/60)	520	0.240
MS	Surface		AC-20	2973	0.128
			SEA (30/70)	2413	0.133
	Binder		AC-40	4322	0.102
			SEA (30/70)	3210	0.114
	Base		AC-40	3672	0.169
			SEA (30/70)	3703	0.153
ND	Surface	Location #1	AC 120-150	1533	0.175
			SEA (30/70)	1505	0.148
	Surface	Location #2	AC 120-150	1704	0.153
			SEA (25/75)	1899	0.133
NM	Surface		AC-10	2757	0.150
			SEA (30/70)	1808	0.118
	Base		AC-10	2133	0.171
			SEA (30/70)	1577	0.165
TC	Base, top half		AC-20	1453	0.083
	Base, bottom half		AC-20	1015	0.100
			SEA (30/70)	--	--
TP	Binder		AC-20	3328	0.123
			SEA (30/70)	2745	0.085
TX	Surface		AC-20	--	--
			SEA (35/65)	--	--
WI	Surface		AC 120-150	1186	0.182
			SEA (30/70)	1403	0.160
WY	Surface		SEA (20/80)	2030	0.148
			SEA (20/80)	2232	0.157

(lbf)(4.448)=(N)
(in)(2.54)=(cm)

Table 48. Effect of sulfur on the Marshall data for all projects, and projects by pavement age, blending method, and the stiffness of the mixture.

	Average AC	Average SEA	Degrees of Freedom	p
<u>Stability, lbf</u>				
All projects	2622	2394	15	0.098 NS
Projects less than 5 years	2822	2381	10	0.008 D
Projects more than 5 years	2181	2422	4	0.182 NS
In-Line Blending	2233	2093	7	0.442 NS
Direct Feed	2933	2389	6	0.022 D
Soft Mixtures	1991	1810	6	0.228 NS
Stiff Mixtures	3113	2848	8	0.246 NS
<u>Flow, inches</u>				
All projects	0.151	0.136	15	0.091 NS
Projects less than 5 years	0.144	0.138	10	0.527 NS
Projects more than 5 years	0.165	0.132	4	0.070 NS
In-Line Blending	0.165	0.138	7	0.002 D
Direct Feed	0.142	0.142	6	0.993 NS
Soft Mixtures	0.157	0.148	6	0.573 NS
Stiff Mixtures	0.146	0.128	8	0.034 D

(lbf)(4.448)=(N)
(in)(2.54)=(cm)

Table 49. Effect of sulfur on the Marshall data for each project.

Project	Pavement Layer		Material	Stability	Flow
CB	Surface		SEA (20/80)	--	--
	Surface		SEA (40/60)	I	D
DE	Surface		SEA (30/70)	NS	NS
ID	Surface	Location #1	SEA (30/70)	--	--
	Surface	Location #2	SEA (30/70)	--	--
KS	Surface		SEA (30/70)	--	--
	Base, top half		SEA (30/70)	--	--
	Base, bottom half		SEA (30/70)	--	--
LA	Surface		SEA (40/60)	NS	NS
MB	Surface		SEA (10/90)	--	--
			SEA (20/80)	--	--
			SEA (30/70)	--	--
	Binder		SEA (10/90)	NS	NS
			SEA (20/80)	D	NS
			SEA (30/70)	NS	NS
MC	Surface		SEA (30/70)	--	--
	Binder		SEA (30/70)	NS	D
MN	Surface		SEA (40/60)	--	--
MS	Surface		SEA (30/70)	NS	NS
	Binder		SEA (30/70)	NS	NS
	Base		SEA (30/70)	NS	NS
ND	Surface	Location #1	SEA (30/70)	NS	D
	Surface	Location #2	SEA (25/75)	NS	D
NM	Surface		SEA (30/70)	NS	NS
	Base		SEA (30/70)	NS	NS
TC	Base		SEA (30/70)	--	--
TP	Binder		SEA (30/70)	NS	D
TX	Surface		SEA (35/65)	--	--
WI	Surface		SEA (30/70)	I	NS

CHAPTER 6: FATIGUE TEST RESULTS

Stress-controlled, repeated load tests were performed to failure to determine the resistance of the mixtures to cracking. The fatigue tests were performed using a closed-loop electrohydraulic Materials Testing System (MTS) with a programmed repeated load of 0.1-second duration sine wave, truncated to apply only compression, followed by a 0.4-second rest period. As with the resilient modulus and creep tests, the specimens were tested in the diametral (indirect) configuration.

The apparatus used to test the specimens is shown in figure 12. It has four vertical posts to hold transducers. These measure the horizontal and lateral (or longitudinal) deformations. The vertical deformation was measured by the same extensometer used in the creep test. The lower platen and the upper loading head each had a 0.5-in (1.3-cm) loading strip curved to meet a 4-in (10.2-cm) diameter specimen. Four Thompson linear motion bushings are used to make sure that the load is applied vertically without the specimen rocking. The upper loading strip

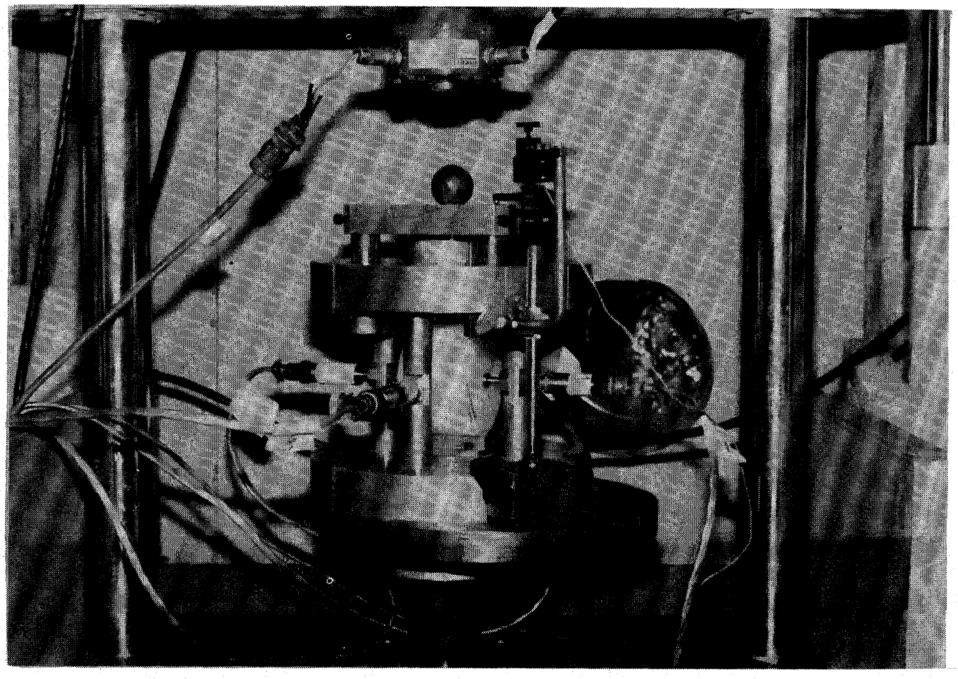

Figure 12. Loading configuration for the repeated load test.

was allowed to swivel along the length of the specimen. The white polyethylene specimen being tested in figure 12 is used to check the calibrations of the transducers and the load cell. The apparatus was developed under a recent FHWA study performed by the Michigan State University.(10)

Deformations per cycle (total, elastic, viscoelastic, and permanent) can be measured in the vertical, horizontal, and lateral directions. These can be used to calculate the modulus and Poisson's ratio. Cumulative permanent deformations can also be measured in each direction. Difficulties arose in measuring accurate and repeatable deformations per cycle under this study. Therefore, it was decided to report the cycles to failure only. All tests were performed at 77 °F (25 °C) and at a maximum tensile stress level of 63.7 lbf/in (439 KPa). Sufficient specimens were not available to perform tests at any other conditions.

Fatigue lives in terms of the number of cycles to failure are given in table 50. Some projects did not have sufficient cores to perform this test. Also, although all of the replicate test data for the AC section of the TP project were higher than those of its corresponding SEA section, the data for the AC section were extremely variable. It was decided not to include the TP project in the analyses for the groups. Table 51 shows the effect of sulfur on the data for the groups. When considering all projects, sulfur decreased the fatigue life. Sulfur also decreased the fatigue life for projects containing stiff mixtures and when in-line blending was used.

The test results are similar to typical stress-controlled results from tests performed on beam specimens in that stiff mixtures provided longer fatigue lives than soft mixtures. Strain-controlled tests often provide the opposite relationship, where soft mixtures provide the longer fatigue lives. Stress-controlled tests may be more applicable to pavement layers greater than 4 in (10.2 cm), whereas strain-controlled tests may be more applicable to pavement layers less than 2 in (5.1 cm). It is unknown which test procedure should be used when the thickness is between these two values. Stress-controlled tests have always been used with the indirect testing configuration.

Table 50. Fatigue test results at 77 °F.

Project	Pavement Layer		Material	Average Cycles to Failure
CA	Surface		SEA (30/70)	180000
			SEA (30/70)	190000
CB	Surface[1]	Location #1	AR-2000	28007
			SEA (20/80)	14105
	Surface[1]	Location #2	AR-4000	70574
			SEA (40/60)	30105
DE	Surface		AC-20	14030
			SEA (30/70)	7896
GA	Surface		AC-20	1610
			AC-20	1427
ID	Surface	Location #1	AR-4000	7245
			SEA (30/70)	5801
	Surface	Location #2	AR-4000	4553
			SEA (30/70)	2638
KS	Surface		AC-20	--
			SEA (30/70)	--
	Base, top half		AC-20	10008
			SEA (30/70)	10882
	Base, bottom half		AC-20	2307
			SEA (30/70)	5833
LA	Surface		AC-30	35477
			SEA (40/60)	9423
	Base under AC surface		SEA (40/60)	3817
	Base under SEA surface		SEA (40/60)	4406
MB	Surface		AC-10	--
			SEA (10/90)	--
			SEA (20/80)	--
			SEA (30/70)	--
	Binder		AC-10	887
			SEA (10/90)	813
			SEA (20/80)	552
			SEA (30/70)	775
MC	Surface[2]		AC-10	--
			SEA (30/70)	--
	Binder[2]		AC-10	930
			SEA (30/70)	485

[1] AR-2000 was used in SEA section.
[2] AC-5 was used in SEA section.

77 °F = 25 °C

Table 50. Fatigue test results at 77 °F (continued).

Project	Pavement Layer		Material	Average Cycles to Failure
MN	Surface		AC 200-300	240
			SEA (40/60)	283
MS	Surface		AC-20	4946
			SEA (30/70)	5286
	Binder		AC-40	4504
			SEA (30/70)	815
	Base		AC-40	29812
			SEA (30/70)	26995
ND	Surface	Location #1	AC 120-150	1710
			SEA (30/70)	1050
	Surface	Location #2	AC 120-150	1670
			SEA (25/75)	1290
NM	Surface		AC-10	25298
			SEA (30/70)	3115
	Base		AC-10	12940
			SEA (30/70)	2201
TC	Base, top half		AC-20	3572
	Base, bottom half		AC-20	1385
			SEA (30/70)	4720
TP	Binder		AC-20	65987
			SEA (30/70)	2432
TX	Surface		AC-20	--
			SEA (35/65)	--
WI	Surface		AC 120-150	915
			SEA (30/70)	1660
WY	Surface		SEA (20/80)	5400
			SEA (20/80)	2290

77 °F = 25 °C

Table 51. Effect of sulfur on fatigue life at 77 °F for all projects, and projects by pavement age, blending method, and the stiffness of the mixture.

	Average AC Cycles to Failure	Average SEA Cycles to Failure	Degrees of Freedom	p
All projects	9848	6215	22	0.041 D
Projects less than 5 years	11453	7297	13	0.057 NS
Projects more than 5 years	7529	4651	9	0.372 NS
In-Line Blending	14582	7139	10	0.047 D
Direct Feed	5540	5272	10	0.674 NS
Soft Mixtures	1937	1824	11	0.787 NS
Stiff Mixtures	17758	10605	11	0.039 D

77 °F = 25 °C

Whether the SEA mixtures would perform better under a strain-controlled test is unknown. However, the measured reduction in fatigue life for all projects is consistent with the finding obtained in chapter 4 when evaluating the data from the tensile strength test. It was indicated in chapter 4 that the SEA mixtures may be more susceptible to tensile fatigue cracking at 77 °F (25 °C). In some cases sulfur reduced the dry tensile strength. In other cases it reduced the dry tensile strain at failure. Therefore, in some cases sulfur may reduce the fatigue life under a stress-controlled test, and in other cases, it may reduce the fatigue life under a strain-controlled test.

As shown by table 52, sulfur affected the fatigue life in slightly less than one-half of the cases on a project-by-project basis. Sulfur generally decreased the fatigue life where there was an effect. This supports the previous conclusions concerning fatigue life under a stress-controlled test.

Table 52. Effect of sulfur on fatigue life at 77 °F for each project.

Project	Pavement Layer		Material	Effect on Fatigue Life
CB	Surface		SEA (20/80)	D
	Surface		SEA (40/60)	NS
DE	Surface		SEA (30/70)	D
ID	Surface	Location #1	SEA (30/70)	NS
	Surface	Location #2	SEA (30/70)	NS
KS	Surface		SEA (30/70)	--
	Base, top half		SEA (30/70)	NS
	Base, bottom half		SEA (30/70)	I
LA	Surface		SEA (40/60)	D
MB	Surface		SEA (10/90)	--
			SEA (20/80)	--
			SEA (30/70)	--
	Binder		SEA (10/90)	NS
			SEA (20/80)	NS
			SEA (30/70)	NS
MC	Surface		SEA (30/70)	--
	Binder		SEA (30/70)	D
MN	Surface		SEA (40/60)	NS
MS	Surface		SEA (30/70)	NS
	Binder		SEA (30/70)	D
	Base		SEA (30/70)	NS
ND	Surface	Location #1	SEA (30/70)	NS
	Surface	Location #2	SEA (25/75)	NS
NM	Surface		SEA (30/70)	D
	Base		SEA (30/70)	D
TC	Base		SEA (30/70)	I
TP	Binder		SEA (30/70)	D
TX	Surface		SEA (35/65)	--
WI	Surface		SEA (30/70)	NS

CHAPTER 7: MIXTURE COMPOSITION

Several studies using samples prepared in the laboratory were performed to determine how the composition of an SEA mixture could be measured. In all of these studies, the SEA binders contained 40 percent precipitated sulfur by weight. After these studies were completed, the SEA and AC cores were tested for air voids, gradation, binder content, asphalt properties, and the percent sulfur. The rheological properties of the SEA binders were not determined.

1. Preliminary Studies

Crystalline sulfur is often visible on aged SEA mixtures and cores, but not on the recovered binders. If the extraction and recovery processes change the properties of the sulfur in the binder (the percent crystalline sulfur, percent dissolved sulfur, sizes of crystalline particles, etc.), then the properties of the recovered binder may not be representative of the properties of the binder in the pavement. The hardening, extraction, and recovery studies of this section deal with this topic and also with determining whether standardized procedures for the analysis of conventional asphalt binders and mixtures can be applied to SEA binders and mixtures. The SEA specific gravity and aggregate specific gravity studies provided additional supplemental information.

a. Hardening Study

A study was performed to determine and compare the hardening rates of SEA and conventional AC binders over a thirty-five day period as measured by penetration. Differences in these rates and in the amount of steric hardening that is reversed during the extraction and recovery procedures could affect the interpretation of the recovered binder properties. A second objective was to determine whether SEA binder properties can be measured using standardized penetration and viscosity methods developed for semi-solid asphalt cements. This latter information would also be useful for future studies where SEA binder properties are needed, such as in mixture designs and for quality control purposes.

The results of this study are documented in appendix A. Differences in hardening rates of the SEA and conventional asphalt binders, and the amount of steric hardening in the SEA binders that is reversed during heating, could not be determined. Measuring the penetrations of the SEA binders at 77 °F (25 °C) in accordance with AASHTO T 49 was found to be very difficult. The data was highly variable (1) from replicate sample to replicate sample, (2) for the replicate penetration determinations on a given sample, and (3) for repeated tests on a given sample after reheating and stirring.(5) The sulfur in the binders settled to the bottom of the penetration container during preparation and over the thirty-five day period. Measuring the viscosities of the SEA binders at 140 °F (60 °C) and 275 °F (135 °C) in accordance with AASHTO T 201 and T 202 was found to be even more difficult, and viscosities often could not be obtained.(5) It was also found that sulfur can leave an invisible film in the viscometers which is difficult to remove and can affect the test results.

It was concluded that the rheological properties of SEA binders need to be verified by retesting the samples or by testing replicate samples. However, with some SEA binders, the data may be so erratic that the properties cannot be obtained. Tests in this study were performed on unaged SEA binders containing 40 percent sulfur by weight. How age-hardened pavement binders and binders with lower sulfur contents would respond during testing is unknown. It did appear that SEA binders at 40 percent sulfur by weight are initially softer than the conventional asphalt cements by approximately one viscosity grade.

b. Extraction Study

An extraction study was performed to determine the most efficient method for extracting aggregates and binders from SEA mixtures. This study was also performed to determine whether the sulfur is removed with the binder or whether a part of it remains with the aggregate.

The results of this study are documented in appendix B. It was determined that SEA mixtures could be extracted using trichloroethylene and the reflux method of AASHTO T 164, or the centrifuge method of AASHTO T 164 if the trichloroethylene is heated to 150 °F (65.6 °C.)(5) The majority of an SEA binder, greater than 95 percent in most cases, was removed with the effluent. The generally high efficiencies of the extraction procedures indicated that most of the sulfur was removed. The efficiencies for the asphalt controls were slightly higher, but less than 100 percent.

c. Recovery Study

A study was performed to determine whether an SEA binder can be recovered according to the Abson method of AASHTO T 170.(5) Procedures for both the reflux and centrifuge/hot solvent methods of extraction were used to condition unaged SEA binders.

The results of this study are documented in appendix C. The majority of the sulfur was recovered; however, the recovery process significantly softened the SEA binders. It was concluded that determining recovered SEA binder properties was of questionable value.

For additional information, the SEA binders were tested for solubility in trichloroethylene in accordance with AASHTO T 44.(5) It was found that even though the extraction and recovery processes removed most of the SEA binders, 16 to 21 percent by weight of an SEA binder was not soluble in trichloroethylene. The amount of sulfur that was soluble ranged from 38 to 52 percent by weight of the sulfur. Measuring this solubility appeared to be of little value for the following reasons: (1) it has no relationship to the recoverability of an SEA binder; (2) it probably does not represent active versus inactive cementing constituents; and (3) the test procedure most likely alters the amount of sulfur which is in solution with the asphalt.

d. SEA Specific Gravity Study

This study was undertaken to determine if the specific gravities of SEA binders can be measured by the standardized methods of AASHTO T 228 and T 229, or by alternate means if these tests could not be used.(5) The specific gravity of a binder at 77 °F (25 °C) is used to calculate the effective specific gravity of an aggregate and the amount of asphalt absorbed into an aggregate. It is also needed to convert poise to centistokes so that viscosity versus temperature relationships can be established for the binder. These relationships are used to obtain mixing and compaction temperatures and to calculate log-log viscosity-temperature susceptibility relationships. This study was performed mainly for additional information.

The results of this study are documented in appendix D. The specific gravities of the SEA binders could not be obtained. The degree of mixing that was used to blend the sulfur and asphalt significantly affected the values.

e. Aggregate Specific Gravity Study

This study was performed to determine whether extracted aggregates can be tested by AASHTO T 84 (fine aggregate) and T 85 (coarse aggregate).(5) The bulk dry specific gravity of the aggregate in a mixture, obtained through these tests, is needed to determine the amount of absorbed asphalt and the voids in the mineral aggregate (VMA) of a compacted mixture. These tests also give the bulk saturated surface-dry specific gravity, apparent specific gravity, and the percent water absorption of an aggregate. Both SEA and conventional AC mixtures were tested.

VMA criteria are generally used only as a mixture design tool to ensure that the aggregate has a sufficiently thick coating of asphalt. When evaluating aged pavement cores, the specific gravities of the aggregates are often unknown. Either the original project data cannot be found, or the specific gravities and VMA were never measured during the mixture design phase. Testing extracted aggregates for specific gravity is generally not performed. It is often indicated by asphalt technologists that residual oily coatings on extracted aggregates prohibit an aggregate from being thoroughly wetted with water during the test for specific gravity, and absorbed asphalt which is not removed by the extraction process may affect the test result. However, there is little published data to verify this statement. For recycled mixtures, the specific gravities of the recycled aggregates are generally not obtained, and VMA is generally not used as a mixture design criteria for these mixtures.

The results of this study are documented in appendix E. Overall, the data indicated that the bulk dry specific gravity of a coarse aggregate extracted from either an SEA or asphalt mixture can be determined. Whether the properties of fine aggregates can be obtained could not be conclusively determined for the asphalt mixtures. The inherent variability in performing AASHTO T 84 was compounded by the inefficiency of the extraction procedure to remove all of the binder. However, it appears that extraction methods can be developed so that these aggregate properties can be obtained. For recycled mixtures, where less than 50 percent of the mixture is recycled asphalt pavement, the data in this study indicated that the error would be low enough that a VMA requirement can be used. However, mixtures with asphalts harder than those used in this study would have to be tested to verify this conclusion.

The properties for the fine aggregates extracted from the SEA mixtures were often erroneous. The extraction processes for SEA mixtures may not be efficient enough to obtain either fine or combined aggregate properties. Based on this result, it was decided not to measure the specific gravities of extracted aggregates in this study.

2. Air Voids Analysis

The maximum specific gravities of the SEA and AC cores measured according to AASHTO T 209 and the total air voids calculated using AASHTO T 269 are given in table 53.(5) Bulk densities were previously given in table 5. Table 54 shows the effect of sulfur on the data for the groups. As expected, sulfur increased the maximum specific gravity. When considering all projects, sulfur increased the percent air void level. Significant increases are also shown for older projects, where in-line blending was used, and for projects with stiff mixtures. The confounding relationship between stiffness and age, as noted previously for some mechanical properties, was not evident for the air void data. Many stiff mixtures were less than 5 years of age. As shown in table 55, the effect of sulfur varied on a project-by-project basis.

Projects with the greatest differences in air void levels, which could affect pavement performance, were found for CB Location #1 (4.0 percent greater in the SEA section), KS Surface (3.7 percent greater in the SEA section), MN Surface (3.7 percent greater in the SEA section), ND Surface Location #1 (4.6 percent greater in the SEA section), TC Base Bottom Half (4.4 percent greater in the SEA section), TP Binder (3.9 percent greater in the SEA section), and TX Surface (10.0 percent greater in the SEA section). These differences in air void levels were checked against the pavement performances given in table 2. Only a few effects were evident. The AC section of the MN project bled while the SEA section developed potholes. The air void level was higher in the SEA section. The binder contents by volume and the gradations for these two sections were found to be equivalent. Thus the differences in the performances could possibly

Table 53. Maximum specific gravity of the mixtures and air void levels.

Project	Pavement Layer	Material	MSG	Percent Air Voids
CA	Surface	SEA (30/70)	2.387	8.7
		SEA (30/70)	2.452	9.0
CB	Surface[1] Location #1	AR-2000	2.407	6.6
		SEA (20/80)	2.455	10.6
	Surface[1] Location #2	AR-4000	2.408	7.6
		SEA (40/60)	2.413	5.0
DE	Surface	AC-20	2.534	5.3
		SEA (30/70)	2.551	5.5
GA	Surface	AC-20	2.407	1.3
		AC-20	2.398	1.2
ID	Surface Location #1	AR-4000	2.507	4.8
		SEA (30/70)	2.521	4.8
	Surface Location #2	AR-4000	2.495	4.4
		SEA (30/70)	2.507	5.2
KS	Surface	AC-20	2.393	6.8
		SEA (30/70)	2.448	10.5
	Base, top half	AC-20	2.491	9.9
		SEA (30/70)	2.508	11.1
	Base, bottom half	AC-20	2.481	9.9
		SEA (30/70)	2.511	10.5
LA	Surface	AC-30	2.380	2.3
		SEA (40/60)	2.390	3.7
	Base under AC surface	SEA (40/60)	2.402	11.9
	Base under SEA surface	SEA (40/60)	2.385	10.6
MB	Surface	AC-10	2.460	1.1
		SEA (10/90)	2.460	0.7
		SEA (20/80)	2.476	0.8
		SEA (30/70)	2.478	1.2
	Binder	AC-10	2.483	1.6
		SEA (10/90)	2.499	0.8
		SEA (20/80)	2.495	0.8
		SEA (30/70)	2.500	0.9
MC	Surface[2]	AC-10	2.463	2.0
		SEA (30/70)	2.483	1.3
	Binder[2]	AC-10	2.490	2.0
		SEA (30/70)	2.497	1.3

[1] AR-2000 was used in SEA section.
[2] AC-5 was used in SEA section.

Table 53. Maximum specific gravity of the mixtures and air void levels (continued).

Project	Pavement Layer		Material	MSG	Percent Air Voids
MN	Surface		AC 200-300	2.432	2.4
			SEA (40/60)	2.492	6.1
MS	Surface		AC-20	2.398	6.4
			SEA (30/70)	2.402	7.1
	Binder		AC-40	2.410	8.2
			SEA (30/70)	2.422	9.7
	Base		AC-40	2.411	9.9
			SEA (30/70)	2.428	8.6
ND	Surface	Location #1	AC 120-150	2.424	2.1
			SEA (30/70)	2.456	6.7
	Surface	Location #2	AC 120-150	2.446	3.1
			SEA (25/75)	2.454	3.2
NM	Surface		AC-10	2.590	7.2
			SEA (30/70)	2.577	8.4
	Base		AC-10	2.556	6.3
			SEA (30/70)	2.572	8.1
TC	Base, top half		AC-20	2.425	2.4
	Base, bottom half		AC-20	2.421	3.1
			SEA (30/70)	2.460	7.5
TP	Binder		AC-20	2.408	6.8
			SEA (30/70)	2.422	10.7
TX	Surface		AC-20	2.298	12.3
			SEA (35/65)	2.431	22.3
WI	Surface		AC 120-150	2.418	2.0
			SEA (30/70)	2.440	1.9
WY	Surface		SEA (20/80)	2.418	4.0
			SEA (20/80)	2.399	1.2

Table 54. Effect of sulfur on the maximum specific gravity and air voids for all projects, and projects by pavement age, blending method, and the stiffness of the mixture.

	Average AC	Average SEA	Degrees of Freedom	p
<u>Maximum Specific Gravity</u>				
All projects	2.451	2.474	28	0.001 I
Projects less than 5 years	2.461	2.475	16	0.001 I
Projects more than 5 years	2.438	2.473	11	0.005 I
In-Line Blending	2.458	2.473	10	0.008 I
Direct Feed	2.444	2.471	15	0.005 I
Soft Mixtures	2.462	2.481	14	0.002 I
Stiff Mixtures	2.451	2.469	12	0.004 I
<u>Air Voids, percent</u>				
All projects	4.8	6.0	28	0.011 I
Projects less than 5 years	4.5	5.0	16	0.247 NS
Projects more than 5 years	5.1	7.5	11	0.022 I
In-Line Blending	4.8	6.2	10	0.033 I
Direct Feed	4.9	5.9	15	0.184 NS
Soft Mixtures	2.3	2.9	14	0.239 NS
Stiff Mixtures	7.1	8.4	12	0.019 I

Table 55. Effect of sulfur on air voids for each project.

Project	Pavement Layer		Material	Air Voids
CB	Surface		SEA (20/80)	I
	Surface		SEA (40/60)	D
DE	Surface		SEA (30/70)	NS
ID	Surface	Location #1	SEA (30/70)	NS
	Surface	Location #2	SEA (30/70)	NS
KS	Surface		SEA (30/70)	I
	Base, top half		SEA (30/70)	NS
	Base, bottom half		SEA (30/70)	NS
LA	Surface		SEA (40/60)	NS
MB	Surface		SEA (10/90)	D
			SEA (20/80)	D
			SEA (30/70)	NS
	Binder		SEA (10/90)	NS
			SEA (20/80)	NS
			SEA (30/70)	NS
MC	Surface		SEA (30/70)	D
	Binder		SEA (30/70)	D
MN	Surface		SEA (40/60)	I
MS	Surface		SEA (30/70)	NS
	Binder		SEA (30/70)	I
	Base		SEA (30/70)	D
ND	Surface	Location #1	SEA (30/70)	I
	Surface	Location #2	SEA (25/75)	NS
NM	Surface		SEA (30/70)	I
	Base		SEA (30/70)	I
TC	Base		SEA (30/70)	I
TP	Binder		SEA (30/70)	I
TX	Surface		SEA (35/65)	I
WI	Surface		SEA (30/70)	NS

be due to compaction and mixture design problems. The AC section of the TC project had more rutting, cracking, and potholes compared to the SEA section. This could not be explained only by the difference in air void level. The air void level was high in the SEA section and reasonable in the AC section. The minus #200 aggregate content was found to be significantly lower in the SEA section, and thus it was difficult to draw any firm conclusions. The AC section of the TX open-graded surface course had bled and lost most of its open-graded texture. Its air void level of 12.3 is slightly low for an open-graded mixture.

3. Aggregate Gradations

Aggregate gradations as measured by AASHTO T 30 are given in table 56.(5) These gradations were visually compared to make sure the gradations for each AC section and its corresponding SEA section were similar. Most gradations were close. The only differences in the coarse fractions were with the four MB binder sections where two of the gradations were finer than the other two. A greater number of discrepancies was noted for the fine fractions. Discrepancies in the minus #200 sieve material which were greater than or equal to 1.0 percent were found for MC Surface (1.0 percent greater in the SEA section), MS Binder (1.3 percent greater in the AC section), ND Surface Location #1 (1.6 percent greater in the SEA section), NM Surface (1.0 percent greater in the SEA section), TC Base Bottom (2.5 percent greater in the AC section), TP Binder (3.4 percent greater in the SEA section), and WI Surface (1.3 percent greater in the SEA section). Using an old "rule-of-thumb" which states that a 1.0-percent to 1.5-percent change in dust content is equivalent to a 0.5-percent change in binder content, it could be expected that some of these variations in dust contents could affect mechanical properties and pavement performance.

These differences in the level of dust were checked against the pavement performances given in table 2. No patterns were evident. This could be expected as dust could have either a stiffening effect or may partially act to extend the binder. It is unknown what effect an increase or decrease in dust content should have on each mixtures. The effects of these differences in the dust contents are also confounded by the effects of the differences in air void levels, binder contents, and binder properties.

Table 56. Gradations, percent binder, and asphalt properties.

	Percent Passing					
	CA Surface		CB Surface Location #1		CB Surface Location #2	
Sieve Size	SEA	SEA	AR-2000	SEA	AR-4000	SEA
1 1/2 in	100.0	100.0	100.0	100.0	100.0	100.0
1 in	100.0	100.0	100.0	100.0	100.0	100.0
3/4 in	100.0	100.0	100.0	100.0	100.0	100.0
1/2 in	99.5	99.6	98.2	98.2	98.8	98.8
3/8 in	93.1	91.7	88.3	87.4	89.1	86.3
#4	68.8	68.3	58.5	59.3	61.4	59.7
#8	47.9	48.2	45.1	44.3	46.3	43.2
#16	35.0	35.7	33.3	32.0	33.8	31.5
#30	24.8	25.2	23.4	22.2	23.6	22.2
#50	15.3	15.6	15.0	14.1	15.0	14.4
#100	9.8	10.1	9.8	9.1	9.6	9.3
#200	7.2	7.4	6.1	5.9	5.9	5.9
Binder, percent	6.4	6.6	5.3	4.4	5.4	7.1
Pen 77 °F, dmm	15		16		10	
Vis 140 °F, P	25106		17451		40411	
Vis 275 °F, cSt	446		749		1080	

(°F-32)/1.8 = °C (in)(2.54) = cm (P)(0.1) = Pa-sec (cSt)(1E-06) = m^2/s

Table 56. Gradations, percent binder, and asphalt properties (continued).

	Percent Passing					
	DE Surface		GA Surface		ID Surface Location #1	
Sieve Size	AC-20	SEA	AC-20	AC-20	AR-4000	SEA
1 1/2 in	100.0	100.0	100.0	100.0	100.0	100.0
1 in	100.0	100.0	100.0	100.0	100.0	100.0
3/4 in	100.0	100.0	100.0	100.0	100.0	100.0
1/2 in	100.0	100.0	100.0	100.0	92.1	96.6
3/8 in	96.5	95.4	98.8	98.4	83.0	84.9
#4	65.7	63.8	72.3	74.9	57.0	57.5
#8	43.8	44.9	50.9	51.7	40.2	40.5
#16	32.1	33.7	40.5	39.6	29.8	30.3
#30	23.8	24.6	33.2	32.1	22.6	23.1
#50	17.9	18.1	23.1	22.5	16.6	17.0
#100	13.3	13.3	13.8	13.6	11.6	11.8
#200	9.6	10.0	7.5	7.7	7.8	7.8
Binder, percent	5.2	6.0	6.9	7.3	6.0	7.2
Pen 77 °F, dmm	19		50		26	
Vis 140 °F, P	29136		13240		15463	
Vis 275 °F, cSt	1213		979		772	

(°F-32)/1.8 = °C (in)(2.54) = cm (P)(0.1) = Pa-sec (cSt)(1E-06) = m^2/s

Table 56. Gradations, percent binder, and asphalt properties (continued).

	Percent Passing					
	ID Surface Location #2		KS Surface		KS Base, top half	
Sieve Size	AR-4000	SEA	AC-20	SEA	AC-20	SEA
1 1/2 in	100.0	100.0	100.0	100.0	100.0	100.0
1 in	100.0	100.0	100.0	100.0	100.0	100.0
3/4 in	100.0	100.0	100.0	100.0	92.6	90.6
1/2 in	94.5	95.5	100.0	100.0	74.5	73.4
3/8 in	84.4	86.0	98.4	98.9	58.3	56.5
#4	55.0	59.5	68.2	69.8	39.1	39.8
#8	38.7	41.6	45.9	47.5	29.9	29.5
#16	28.9	30.9	32.8	34.0	21.8	20.9
#30	22.3	23.4	23.8	25.0	15.2	14.8
#50	16.6	17.3	15.9	17.6	11.5	11.6
#100	11.7	12.1	11.6	11.9	9.2	9.5
#200	7.9	8.1	8.8	9.2	7.5	8.1
Binder, percent	6.1	7.6	5.8	6.0	4.1	4.3
Pen 77 °F, dmm	29		19		23	
Vis 140 °F, P	12807		24546		24728	
Vis 275 °F, cSt	708		1077		985	

(°F-32)/1.8 = °C   (in)(2.54) = cm   (P)(0.1) = Pa-sec   (cSt)(1E-06) = m^2/s

Table 56. Gradations, percent binder, and asphalt properties (continued).

Sieve Size	Percent Passing KS Base, bottom half AC-20	SEA	LA Surface AC-30	SEA	LA Base under AC surface SEA
1 1/2 in	100.0	100.0	100.0	100.0	100.0
1 in	100.0	100.0	100.0	100.0	100.0
3/4 in	97.3	95.5	100.0	100.0	100.0
1/2 in	76.5	73.0	91.7	95.4	100.0
3/8 in	61.7	58.2	80.3	82.1	100.0
#4	44.3	41.9	55.5	55.0	98.8
#8	33.1	32.2	43.6	44.2	94.3
#16	23.0	22.8	37.9	38.1	87.3
#30	15.3	15.8	33.2	32.5	76.4
#50	11.6	12.3	22.4	21.4	43.1
#100	9.4	10.1	14.6	14.9	24.1
#200	7.7	8.4	9.2	9.4	13.5
Binder, percent	4.6	4.5	5.1	5.8	8.2
Pen 77 °F, dmm	34		20		
Vis 140 °F, P	9504		38860		
Vis 275 °F, cSt	703		1760		

(°F-32)/1.8 = °C (in)(2.54) = cm (P)(0.1) = Pa-sec (cSt)(1E-06) = m^2/s

Table 56. Gradations, percent binder, and asphalt properties (continued).

Sieve Size	Percent Passing LA Base under SEA layer SEA	MB Surface AC-10	MB Surface SEA (10/90)	MB Surface SEA (20/80)	MB Surface SEA (30/70)
1 1/2 in	100.0	100.0	100.0	100.0	100.0
1 in	100.0	100.0	100.0	100.0	100.0
3/4 in	100.0	100.0	100.0	100.0	100.0
1/2 in	100.0	97.1	94.9	96.9	96.8
3/8 in	100.0	73.4	74.7	70.9	75.4
#4	99.1	51.2	49.5	47.3	50.6
#8	95.1	44.4	42.1	40.3	43.0
#16	87.6	33.4	31.9	31.1	32.5
#30	76.5	21.4	20.5	20.2	20.5
#50	44.1	13.9	13.4	13.2	13.3
#100	26.0	9.4	9.0	9.0	9.4
#200	13.8	6.5	6.2	6.4	6.8
Binder, percent	7.5	5.9	5.9	5.9	6.7
Pen 77 °F, dmm		54			
Vis 140 °F, P		7375			
Vis 275 °F, cSt		685			

(°F-32)/1.8 = °C (in)(2.54) = cm (P)(0.1) = Pa-sec (cSt)(1E-06) = m^2/s

Table 56. Gradations, percent binder, and asphalt properties (continued).

Sieve Size	Percent Passing					
	MB Binder		MB Binder		MC Surface	
	AC-10	SEA (10/90)	SEA (20/80)	SEA (30/70)	AC-10	SEA
1 1/2 in	100.0	100.0	100.0	100.0	100.0	100.0
1 in	100.0	100.0	100.0	100.0	100.0	100.0
3/4 in	100.0	97.9	100.0	98.6	100.0	100.0
1/2 in	76.2	69.2	77.0	68.6	98.4	98.8
3/8 in	65.2	54.5	60.3	53.3	82.7	86.7
#4	50.4	43.1	43.8	41.6	59.3	60.3
#8	42.7	38.0	37.1	36.3	47.2	46.9
#16	35.5	31.9	30.8	30.2	38.0	37.2
#30	25.0	22.7	21.6	21.1	27.3	26.9
#50	14.5	13.8	13.3	12.6	16.6	17.2
#100	8.8	8.6	8.4	8.1	10.7	12.0
#200	5.9	5.9	5.8	5.7	7.9	8.9
Binder, percent	5.5	5.3	6.0	6.0	5.6	6.9
Pen 77 °F, dmm	44				50	
Vis 140 °F, P	8986				4624	
Vis 275 °F, cSt	716				609	

(°F-32)/1.8 = °C (in)(2.54) = cm (P)(0.1) = Pa-sec (cSt)(1E-06) = m^2/s

Table 56. Gradations, percent binder, and asphalt properties (continued).

Sieve Size	MC Binder AC-10	MC Binder SEA	MN Surface AC 200-300	MN Surface SEA	MS Surface AC-20	MS Surface SEA
1 1/2 in	100.0	100.0	100.0	100.0	100.0	100.0
1 in	100.0	100.0	100.0	100.0	100.0	100.0
3/4 in	99.3	97.8	100.0	100.0	100.0	100.0
1/2 in	74.1	83.5	91.1	93.8	99.5	99.4
3/8 in	59.8	64.7	83.2	86.3	94.5	94.1
#4	42.2	43.9	68.8	71.0	69.2	67.8
#8	35.3	37.4	55.0	57.1	56.3	56.0
#16	29.4	31.1	40.5	42.3	49.8	50.2
#30	21.6	22.3	24.7	25.8	42.9	42.3
#50	14.1	14.4	10.6	10.9	20.8	19.3
#100	9.7	9.7	6.1	6.3	11.5	10.5
#200	6.7	6.8	4.9	5.0	7.2	6.8
Binder, percent	5.1	6.2	5.7	6.7	5.5	6.7
Pen 77 °F, dmm	53		59		26	
Vis 140 °F, P	4080		2393		35410	
Vis 275 °F, cSt	578		388		1662	

Percent Passing (column group heading).

(°F-32)/1.8 = °C   (in)(2.54) = cm   (P)(0.1) = Pa-sec   (cSt)(1E-06) = m^2/s

Table 56. Gradations, percent binder, and asphalt properties (continued).

Sieve Size	Percent Passing MS Binder AC-40	 MS Binder SEA	 MS Base AC-40	 MS Base SEA	 ND Surface Location #1 AC 120-150	 ND Surface Location #1 SEA
1 1/2 in	100.0	100.0	100.0	100.0	100.0	100.0
1 in	100.0	100.0	100.0	100.0	100.0	100.0
3/4 in	100.0	100.0	100.0	100.0	100.0	100.0
1/2 in	88.9	93.1	91.9	91.2	94.4	94.4
3/8 in	75.5	82.4	79.9	78.9	84.4	87.3
#4	51.8	56.3	53.9	56.0	64.8	70.4
#8	46.0	50.8	46.0	49.8	50.8	57.3
#16	43.6	49.1	44.1	48.4	37.9	44.2
#30	39.2	42.8	39.6	43.1	26.6	32.3
#50	24.6	21.4	22.5	21.2	17.0	21.3
#100	13.7	10.5	11.2	10.5	11.5	14.2
#200	8.1	6.8	6.8	6.7	8.5	10.1
Binder, percent	4.4	5.0	4.7	4.9	6.8	7.7
Pen 77 °F, dmm	22		13		53	
Vis 140 °F, P	269068		530100		3036	
Vis 275 °F, cSt	3228		6976		412	

(°F-32)/1.8 = °C (in)(2.54) = cm (P)(0.1) = Pa-sec (cSt)(1E-06) = m^2/s

Table 56. Gradations, percent binder, and asphalt properties (continued).

	Percent Passing					
	ND Surface Location #2		NM Surface		NM Base	
Sieve Size	AC 120-150	SEA	AC-10	SEA	AC-10	SEA
1 1/2 in	100.0	100.0	100.0	100.0	100.0	100.0
1 in	100.0	100.0	100.0	100.0	100.0	100.0
3/4 in	100.0	100.0	100.0	100.0	100.0	99.1
1/2 in	91.1	94.6	87.6	94.2	95.7	92.5
3/8 in	80.1	85.7	75.9	85.1	88.0	82.5
#4	62.3	67.4	55.6	63.8	61.3	59.2
#8	50.0	53.4	38.3	44.9	42.9	42.8
#16	38.8	41.2	26.6	31.5	31.1	31.4
#30	28.1	30.0	19.2	22.9	23.3	23.7
#50	18.9	20.1	13.3	15.9	17.4	18.0
#100	12.4	13.5	9.0	10.7	13.3	14.0
#200	8.6	9.4	6.6	7.6	9.3	10.1
Binder, percent	6.5	6.8	4.2	5.6	4.9	5.7
Pen 77 °F, dmm	52		19		24	
Vis 140 °F, P	2664		14666		12140	
Vis 275 °F, cSt	358		728		692	

(°F-32)/1.8 = °C (in)(2.54) = cm (P)(0.1) = Pa-sec (cSt)(1E-06) = m^2/s

Table 56. Gradations, percent binder, and asphalt properties (continued).

	Percent Passing				
Sieve Size	TC Base, top AC-20	TC Base, bottom AC-20	TC Base, bottom SEA	TP Binder AC-20	TP Binder SEA
1 1/2 in	100.0	100.0	100.0	100.0	100.0
1 in	100.0	100.0	100.0	100.0	100.0
3/4 in	100.0	97.8	98.6	100.0	100.0
1/2 in	99.5	96.5	96.5	91.8	93.2
3/8 in	98.1	95.1	94.5	74.8	82.4
#4	69.9	69.4	75.8	50.2	55.7
#8	46.0	48.6	53.4	37.2	40.4
#16	40.9	43.1	47.3	29.0	33.2
#30	37.3	38.6	41.8	24.5	28.8
#50	26.6	26.5	25.9	21.6	25.7
#100	15.2	15.7	9.6	14.9	18.5
#200	5.4	7.5	5.0	10.3	13.7
Binder, percent	5.4	5.1	5.9	4.3	5.3
Pen 77 °F, dmm	27	30		19	
Vis 140 °F, P	7528	6125		18523	
Vis 275 °F, cSt	670	582		821	

(°F-32)/1.8 = °C (in)(2.54) = cm (P)(0.1) = Pa-sec (cSt)(1E-06) = m^2/s

Table 56. Gradations, percent binder, and asphalt properties (continued).

Sieve Size	Percent Passing TX Surface AC-20	 SEA	 WI Surface AC 120-150	 SEA	 WY Surface SEA	 SEA
1 1/2 in	100.0	100.0	100.0	100.0	100.0	100.0
1 in	100.0	100.0	100.0	100.0	100.0	100.0
3/4 in	100.0	100.0	100.0	100.0	100.0	100.0
1/2 in	98.0	98.4	97.6	98.9	100.0	99.7
3/8 in	77.5	72.0	89.1	90.5	95.6	93.3
#4	30.6	25.0	69.3	72.1	67.3	67.9
#8	19.4	17.3	57.1	59.2	48.0	48.5
#16	15.3	14.6	46.3	48.7	35.9	36.2
#30	13.2	13.2	35.8	38.8	26.7	27.0
#50	11.8	12.0	22.0	25.5	19.5	19.8
#100	9.5	9.6	13.3	15.5	14.1	14.3
#200	6.8	6.9	9.1	10.4	9.7	9.9
Binder, percent	8.8	5.7	6.9	7.6	6.3	6.4
Pen 77 °F, dmm	35		52			
Vis 140 °F, P	14977		3574			
Vis 275 °F, cSt	1057		454			

(°F-32)/1.8 = °C   (in)(2.54) = cm   (P)(0.1) = Pa-sec   (cSt)(1E-06) = m^2/s

4. Binder Contents and Binder Properties

Binder contents by weight of the mixture and the properties of the asphalts are also given in table 56. The properties of the asphalt are given as supplementary information as the properties of the SEA binders were not obtained. Therefore, differences in the amount of hardening of the SEA and AC binders could not be determined.

Binder contents should be compared on a volume basis; however, because the specific gravities of the SEA binders could not be measured, this comparison could not be made. Gross comparisons were made by assuming that the AC binders had a specific gravity of 1.0 and the SEA binders had a specific gravity of 1.2 at a 25/75 blend. For these assumed specific gravities, the weight of an SEA binder should be around 1.2 times the weight of the asphalt binder. The specific gravity of the SEA binder does depend on the amount of sulfur in the binder. This was considered in this analysis.

Projects where the binders contents were approximately equal by weight, which means that there was less volume of SEA binder, were KS Surface, KS Base Top Half, KS Base Bottom Half, MB Surface (except for the 30/70 section), MS Base, and ND Surface Location #2. The SEA mixtures had significantly less binder by weight and volume in CB Location #1 and TX Surface. The MB Binder sections could not be categorized as to whether the SEA binder was added on a weight or volume basis. This means that the SEA binders in approximately 17 out of 29 projects were probably used on an equal volume basis. Construction reports on the projects were reviewed. In most projects, the sulfur was simply substituted for asphalt and the design for the asphalt control mixture was used. However, whether the sulfur was added on a weight or volume basis was generally not reported. The basis for adding sulfur is another variable which was not considered when analyzing the mechanical test properties in this study.

The differences in binder content were checked against the pavement performances given in table 2. The only obvious effect was that the AC section of the TX open-graded surface course contained 3.1 percent more binder by weight than the SEA section. This section had bled and lost most of its open-graded texture.

All projects used the same grade of asphalt in the SEA section as in the AC section, except for the MC project which used an AC-10 in the AC section and an AC-5 in the SEA section. The effect of changing the grade of asphalt, if any, was not discernable.

5. Percent Sulfur Content

The total percent sulfur was determined for all binders, both AC and SEA. Additionally, at the start of this research study, suspect cores were tested for sulfur through energy dispersive X-ray fluorescence (EDXRF), which is used in conjunction with the FHWA's scanning electron microscope (SEM). This method can only qualitatively detect the presence of sulfur and cannot give the percent sulfur. For sets of AC and SEA cores where the sulfur in the SEA cores was readily visible, any supposed AC core which visually showed the presence of sulfur was checked for sulfur along with any supposed SEA core which did not visually show the presence of sulfur. Some cores were eliminated based on these results. Some sets of SEA cores did not visually show any sulfur even if they did contain sulfur. As to whether all AC cores only contained asphalt and all SEA cores only contained SEA could not be thoroughly evaluated. For some projects, cores were selectively chosen for determining the sulfur content.

At the end of this study, the percent total sulfur by total binder weight in each AC and SEA section was obtained according to ASTM Method D 4239, which uses high temperature combustion and an infrared (IR) absorption detector to determine the percent sulfur.(9) The percent sulfur by total binder weight which was added to the asphalt at the mixing plant was calculated from these data. The results of these analyses are presented in table 57. Based on these results, three projects had to be eliminated from this study: CA, GA, and WY. Both sets of cores from the CA project contained a high amount of sulfur, and it is probable that some of the AC cores were taken from the SEA section. Both sets of cores from the GA project had very little sulfur, and thus both sets came from the AC section. Both sets of cores from the WY project contained sulfur, and thus both sets came from the SEA section. The descriptions under the heading "Material" were not changed in table 57 so that the discrepancies could be shown. In all other data tables of this report, the descriptions were changed to match the actual material received.

Table 57. Percent sulfur in the binders.

Project	Pavement Layer	Material	Percent Sulfur By Weight of Binder	Percent Sulfur Added
CA	Surface	AR-4000	19.62	
		SEA (30/70)	28.29	10.8
CB	Surface[1] Location #1	AR-2000	1.90	
		SEA (20/80)	20.77	19.2
	Surface[1] Location #2	AR-4000	1.89	
		SEA (40/60)	33.16	31.9
DE	Surface	AC-20	4.35	
		SEA (30/70)	27.50	24.2
GA	Surface	AC-20	6.17	
		SEA (30/70)	7.07	1.0
ID	Surface Location #1	AR-4000	5.62	
		SEA (30/70)	31.78	27.7
	Surface Location #2	AR-4000	4.70	
		SEA (30/70)	30.36	26.9
KS	Surface	AC-20	2.45	
		SEA (30/70)	25.71	23.9
	Base, top half	AC-20	2.91	
		SEA (30/70)	19.14	16.7
	Base, bottom half	AC-20	2.66	
		SEA (30/70)	16.12	13.8
LA	Surface	AC-30	4.65	
		SEA (40/60)	36.30	33.2
	Base under AC surface	SEA (40/60)	36.23	
	Base under SEA surface	SEA (40/60)	29.88	
MB	Surface	AC-10	3.38	
		SEA (10/90)	13.88	10.9
		SEA (20/80)	21.56	18.8
		SEA (30/70)	31.37	29.0
	Binder	AC-10	3.29	
		SEA (10/90)	14.22	11.3
		SEA (20/80)	21.77	19.1
		SEA (30/70)	29.96	27.6
MC	Surface[2]	AC-10	5.56	
		SEA (30/70)	30.75	26.7
	Binder[2]	AC-10	4.78	
		SEA (30/70)	30.00	26.5

[1] AR-2000 was used in SEA section.
[2] AC-5 was used in SEA section.

Table 57. Percent sulfur in the binders (continued).

Project	Pavement Layer	Material	Percent Sulfur By Weight of Binder	Percent Sulfur Added
MN	Surface	AC 200-300	4.28	
		SEA (40/60)	28.55	25.4
MS	Surface	AC-20	5.80	
		SEA (30/70)	34.44	30.4
	Binder	AC-40	4.79	
		SEA (30/70)	22.87	19.0
	Base	AC-40	5.57	
		SEA (30/70)	30.26	26.1
ND	Surface Location #1	AC 120-150	3.79	
		SEA (30/70)	30.78	28.0
	Surface Location #2	AC 120-150	3.30	
		SEA (25/75)	18.82	16.0
NM	Surface	AC-10	3.90	
		SEA (30/70)	24.94	21.9
	Base	AC-10	3.78	
		SEA (30/70)	28.60	25.8
TC	Base, top half	AC-20	3.58	
	Base, bottom half	AC-20	3.64	
		SEA (30/70)	28.62	26.0
TP	Binder	AC-20	3.55	
		SEA (30/70)	20.05	17.1
TX	Surface	AC-20	4.80	
		SEA (35/65)	25.62	21.9
WI	Surface	AC 120-150	4.16	
		SEA (30/70)	30.42	27.4
WY	Surface	AC-20	20.93	
		SEA (20/80)	21.90	1.2

The percent sulfur added to each pavement, as shown in table 57, can be compared to the target value listed under the heading "Material." The average amount of sulfur added to the sections was 23.2 percent by total binder weight with a range of 10.9 to 33.2 percent. It was expected that the sulfur content would average approximately 29 percent. Most projects had less sulfur than intended and some were significantly low in sulfur content. Based on the extraction study documented in appendix B, it was assumed that most of the sulfur would be removed from the aggregates. Some of the sulfur contents are so low compared to the target values that they were obviously deficient.

Formal analyses to determine the effect of the measured percent sulfur on the test properties were not performed. Because the effect of sulfur on most test properties was small, performing these analyses did not seem necessary. The only possible analysis would be to form two groups, designated as low and high sulfur contents, by dividing the projects according to the average sulfur content of 23.2. Some trial analyses were performed on the percent air voids, fatigue cycles to failure, and moisture susceptibility data. Sulfur had the greatest effect on these properties. The findings indicated that the sulfur contents of the two groups were too close to each other for proper statistical analyses. Either more projects or projects with a wider range in sulfur content would be needed.

CHAPTER 8: DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

1. Discussion

a. Results From the Tests Performed on Cores

Statistical analyses were performed to evaluated the effects of sulfur on a given property for (1) all projects grouped together, (2) projects grouped according to pavement age ("less than 5 years" versus "more than 5 years"), (3) projects grouped according to the method of incorporating the sulfur into the mixture ("in-line blending" versus "direct feed"), (4) projects grouped according to the stiffnesses of the mixtures, and (5) on a project-by-project basis.

(1) Project-by-Project Analyses

On a project-by-project basis, sulfur did not overall increase or decrease most test properties, and often it had no effect on a given test property of a mixture. Generally, the findings from the various projects would average out to indicate no overall significant differences. Only some minor trends were shown by the tensile strengths, tensile strains at failure, fatigue lives, Marshall flows, and the creep data at 104 °F (40 °C). These effects were consistent with the trends obtained from the analyses where all projects were grouped together. These are given in the next section according to the type of test. Sulfur did tend to decrease the retained ratios from the moisture susceptibility test but not the percent stripping determined visually.

(2) Analyses by Groups

Most of the significant trends were found when analyzing the data for all projects grouped together. Only a few trends for the other analyses by groups were found. Trends according to the type of test were as follows:

Density - Sulfur had no effect.

Diametral resilient modulus (Mr) - The only effect was that soft mixtures used in older projects were stiffened at 104 °F (40 °C). There was no effect at 41 or 77 °F (5 or 25 °C) for any of the groups. The effect of pavement age was found to be confounded by stiffness. Many of the softer mixtures were used in the projects greater than 5 years old, while many stiffer mixtures were used in the projects less than 5 years old. This made all of the test data difficult to analyze.

Temperature susceptibility as measured by Mr - Sulfur had no effect.

Variability of density and Mr data - Sulfur had no effect.

Diametral incremental creep test modulus (Mc) - Overall, sulfur had little or no effect on the creep moduli at 41, 77, or 104 °F (5, 25, or 40 °C). Where there were statistically significant effects, they were generally insignificant in terms of expected changes in pavement performance or structural design. The effects also did not correspond to significant differences in permanent deformations. Permanent deformation is a more important property in terms of pavement performance.

Diametral incremental creep test permanent deformation - No consistent statistical inferences concerning permanent deformation across temperature could be made, except that at the higher temperatures, in-line blending produced lower deformations primarily at the longer loading times. This means that in-line blending may be a better method of addition than the direct feed method as long as the properties at low temperatures are not adversely affected. A visual examination of the average permanent deformations for all of the groups indicated there may be an overall trend for the SEA sections to have lower permanent deformations, or a reduced susceptibility to rutting, at the higher temperatures. However, some of the differences in these averages were due to only a few projects where the differences in permanent deformation were large. The temperatures used in this study may not have been low enough to determine differences in low temperature properties, as the data for the SEA and AC mixtures were nearly the same at 41 °F (5 °C).

Diametral incremental creep test resilient and viscoelastic deformation - Sulfur had little or no effect at any temperature or loading time.

Moisture susceptibility - When considering all projects, sulfur decreased both the tensile strength and resilient modulus ratios (TSR and MrR) but not the percent stripping determined visually. (The ratio is the wet/dry value.) It was concluded that the lower ratios were related to a loss of cohesion rather than a loss of adhesion. The SEA binders were weakened by the moisture conditioning processes. There were also significant decreases in the MrR due to the sulfur for nearly every other group compared to the AC mixtures. The TSR for soft mixtures was decreased by the sulfur. The AC and SEA sections for the other groups had nearly equal TSR. Most soft mixtures were used in older projects.

The average TSR of each AC group was virtually equal to its corresponding MrR. However, the MrR were lower than the TSR for the SEA groups. Thus for the SEA mixtures, the MrR were more sensitive to the damage in the binder.

For both the AC and SEA binders, stiff mixtures had lower ratios and more stripping than the soft mixtures. These moisture damage results are unusual because increased strength or stiffness generally decreases the susceptibility to moisture damage, except for very soft mixtures in pavements which can heal easily. It was later found that the stiff mixtures had air void levels which averaged twice those of the soft mixtures. Stiff mixtures generally had air void levels above 5.0 percent, while soft mixtures generally had air void levels below 5.0 percent.

<u>Tensile strengths</u> - When considering all projects, sulfur decreased both the dry and wet tensile strengths. Wet strengths were more sensitive to the sulfur content than dry strengths. There was also an overall tendency for the sulfur to decrease either the dry or wet tensile strengths, or both, for the other groups. The average dry tensile strengths of the stiff mixtures and mixtures less than 5 years old were decreased by the sulfur. These two results were in agreement since many stiff mixtures were used in newer projects.

<u>Tensile strains at failure</u> - Sulfur decreased the dry tensile strain of all groups. The lower dry tensile strain at failure together with the lower dry tensile strength indicates a trend that the SEA mixtures may be more susceptible to tensile fatigue cracking at 77 °F (25 °C). The decreases in these two properties generally did not occur on the same projects.

<u>Stability and flow</u> - When considering all projects, sulfur had no effect on stability or flow. Some statistically significant decreases in stability and

flow were obtained for other groups, but they were too small to relate them to expected changes in pavement rutting or cracking. Sulfur always decreased the flow when there was an effect.

Fatigue life - When considering all projects, sulfur decreased the fatigue life under stress-controlled testing. Sulfur also decreased the fatigue life of projects containing stiff mixtures and when in-line blending was used.

Maximum specific gravity - Sulfur increased the maximum specific gravities of the mixtures. SEA binders have higher specific gravities compared to AC binders.

Air voids - When considering all projects, sulfur increased the percent air void level. These higher air void levels could have help to increase the susceptibility of the SEA mixtures to moisture damage, but they do not fully explain why the retained ratios decreased but not visual stripping.

Significant increases in air voids were also shown for (1) older projects, (2) where in-line blending was used, and (3) for projects with stiff mixtures. The confounding relationship between stiffness and age, as noted previously for some mechanical properties, was not evident for the air void data. However, these differences in air void levels are another confounding factor. Each pair of data sets for a group (for example, the SEA and AC data set for the in-line blended projects and the SEA and AC data set for the direct feed projects), did not contain the same mixtures. The difference in air void levels between the in-line and direct feed groups could be the result of using different mixtures. If so, the data sets may not be representative of the population of data as assumed. In order to effectively evaluate factors such as in-line blending and direct feed, both methods should be tried on the same projects. If not, a large number of projects may be needed. Eleven projects used the in-line blending method and nine projects used the direct feed method in this study. This may not have been a sufficient number of sections.

(3) Miscellaneous Results

Some additional results were also found through the tests performed on the cores. Most SEA sections in this study contained less sulfur than intended, plus, the method of substituting SEA binders for the asphalt binders at the mixing plants was not consistent. On some projects the substitution was by volume while for other projects it was by weight. These variables could not be considered when analyzing the mechanical test properties in this study.

The differences in air void levels, aggregate gradations, and binder contents between SEA and AC sections were checked against the pavement performances to see if these variables had any effect. Very few effects were evident, and these are given in chapter 7. Most pavements were performing well at the time of coring, and an examination of the cores verified the generally good condition of the pavements. Based on this, it is recommended that the performances of these pavements be determined again. Some of the results of the predictive tests, such as those for moisture susceptibility, rutting, and fatigue cracking, indicated that some small differences in performance may be found in the future. The field study indicated no overall significant differences in rutting, alligator cracking, longitudinal cracking, reflective cracking, and distresses associated with moisture damage. The SEA sections evaluated in the field study had a lower average amount of transverse cracking, although there was no difference in average transverse cracking for the particular set of pavements evaluated in this laboratory study. Cores were not received from all field sites.

Other factors also support another field review. There were very few differences in densities and resilient moduli at 77 °F (25 °C) between the cores taken "in the wheelpath" and those taken "out of the wheelpath." This indicates that the levels of traffic that the pavements received before they were evaluated were low. Furthermore, the effect of aging on mixture performance was not considered in the laboratory study because adequate methods for aging do not exist. It is also important to verify that the moisture conditioning processes used to determine the susceptibility to moisture are applicable to SEA binders.

b. Results From the Tests Performed on Samples Prepared in the Laboratory

It was concluded that the rheological properties of SEA binders need to be verified by retesting the samples or by testing replicate samples. However, with some SEA binders, the data may be so erratic that the properties cannot be obtained. It did appear that SEA binders at 40 percent sulfur by weight are initially softer than conventional asphalt controls by approximately one viscosity grade.

It was determined that SEA mixtures could be extracted using trichloroethylene and the reflux method of AASHTO T 164, or the centrifuge method of AASHTO T 164 if the trichloroethylene is heated to 150 °F (65.6 °C).⁽⁵⁾ The majority of an SEA binder, greater than 95 percent in most cases, was removed with the solution. The generally high efficiencies of the extraction procedures indicated that most of the sulfur was removed. The efficiencies for the asphalt controls were slightly higher, but less than 100 percent.

The extraction and Abson recovery processes significantly softened the SEA binders. It was concluded that determining recovered SEA binder properties was of questionable value. The majority of the sulfur remains in the binder but it probably is dispersed differently in the binder.

Even though the extraction and recovery processes remove most of an SEA binder, 16 to 21 percent by weight of an SEA binder was not soluble in trichloroethylene. The amount of sulfur that was soluble ranged from 38 to 52 percent by weight of the sulfur. Measuring this solubility appeared to be of little value because of the following: (1) it has no relationship to the recoverability of an SEA binder, (2) it probably does not represent active versus inactive cementing constituents, and (3) the test procedure most likely alters the amount of sulfur which is in solution with the asphalt.

The specific gravities of the SEA binders prepared in the laboratory also could not be measured. The degree of mixing that was used to blend the sulfur and asphalt significantly affected the values.

The bulk dry specific gravities of coarse aggregates extracted from either an SEA or conventional asphalt mixture can be determined. The bulk dry specific gravities of fine aggregates extracted from SEA mixtures were often erroneous. It appears that the extraction processes for SEA mixtures may not be efficient enough to obtain either fine or combined aggregate properties. It was not conclusively determined whether the bulk dry specific gravities of fine aggregates extracted from conventional asphalt mixtures can be measured. The inherent variability in performing the test method was compounded with the inefficiency of the extraction procedure to remove all of the binder. However, it appears that extraction methods can be developed so that aggregate properties can be obtained. For recycled mixtures, where less than 50 percent of the mixture is recycled asphalt pavement, the data in this study indicated that the error in the combined bulk dry specific aggregate gravity would be low enough that a VMA requirement can be used. However, mixtures with asphalts harder than those used in this study would have to be tested to verify this conclusion.

2. Conclusions

Conclusions drawn from the tests performed on the pavement cores are listed below. Statistical analyses were performed to evaluated the effects of sulfur on a given property for (1) all projects grouped together, (2) projects grouped according to pavement age ("less than 5 years" versus "more than 5 years"), (3) projects grouped according to the method of incorporating the sulfur into the mixture ("in-line blending" versus "direct feed"), (4) projects grouped according to the stiffnesses of the mixtures, and (5) on a project-by-project basis.

- In general, the laboratory test results support the results of the field study which showed that there was no difference in overall field performance between the SEA and AC sections. Sulfur did not overall increase or decrease most test properties, and often it had no effect on a given test property of a mixture. This would not normally be expected for a mixture where an additive or extender is simply added to it, and compatibility and the degree of dispersion are not considered.

- Sulfur decreased the overall resistance to moisture susceptibility in the laboratory. Sulfur decreased both retained ratios (TSR and MrR) but not the percent stripping determined visually. It was concluded that the lower ratios were related to a loss of cohesion, or damage to the binder, rather than a loss of adhesion. The Mr test was more sensitive to this damage than the tensile strength test.

- Minor trends in properties were shown by some test results. There were trends indicating that for some mixtures, sulfur may reduce the susceptibility to rutting and/or increase the susceptibility to fatigue cracking (and cracking at pavement edges).

- Confounding variables were found to be a problem during this study. For example, the effect of pavement age was confounded by stiffness. Many of the softer mixtures were in the projects greater than 5 years old, while many stiffer mixtures were used in projects less than 5 years old.

- Unusual results were also obtained. For example, stiff SEA and AC mixtures had lower retained ratios and more visual stripping than the soft mixtures. (Increased strength and stiffness generally decreases the susceptibility to moisture damage, except for very soft mixtures in pavements which can heal easily.) It was found that the stiff mixtures had air void levels which averaged twice those of the soft mixtures.

- The following minor differences between the SEA and AC sections were obtained, but they could not be considered conclusive because of confounding factors. At the higher temperatures, in-line blending produced lower permanent deformations then the direct feed method. However, the fatigue life was decreased when in-line blending was used. The creep data indicated that soft mixtures were stiffened at 104 °F (40 °C). Sulfur also decreased both the TSR and MrR for soft mixtures. The average dry tensile strength of the stiff mixtures and mixtures less than 5 years old were decreased by the sulfur.

Several studies using samples prepared in the laboratory were also performed. The following conclusions were obtained from these studies:

- For the mixture design process, the rheological properties of SEA binders need to be verified by retesting the samples or by testing replicate samples. However, with some SEA binders, the data may be so erratic that the properties cannot be obtained. Sulfur tends to settle to the bottom of a binder when in bulk form.

- It appears that freshly prepared SEA binders at 40 percent sulfur by weight are approximately one viscosity grade softer than the conventional asphalt controls.

- The specific gravities of the SEA binders prepared in the laboratory could not be measured. The degree of mixing that was used to blend the sulfur and asphalt significantly affected the values. The degree of mixing should also affect the rheological properties.

- Measuring the solubility of sulfur in trichloroethylene appears to be of little value and hence not necessary.

- SEA mixtures can be extracted using trichloroethylene and the reflux method of AASHTO T 164, or the centrifuge method of AASHTO T 164 if the trichloroethylene is heated to 150 °F (65.6 °C). The majority of an SEA binder including the sulfur is removed with the solution, although the efficiencies for the conventional asphalt cements were slightly higher.

- The extraction and Abson recovery processes significantly softened the SEA binders. Determining recovered SEA binder properties is of questionable value.

- The bulk dry specific gravities of coarse aggregates extracted from either an SEA or conventional asphalt mixture can be determined. (The bulk dry specific gravities of the aggregates in a mixture are used to calculate the voids in the mineral aggregate (VMA)).

- The bulk dry specific gravities of fine aggregates extracted from SEA mixtures were often erroneous and thus were not adequately determined.

- It was not conclusively determined whether the bulk dry specific gravities of fine aggregates extracted from conventional asphalt mixtures can be measured.

3. Recommendations

- Both field and laboratory studies indicate that sulfur is a viable extender for asphalt and can be used in paving mixtures. SEA and conventional asphalt mixtures perform similarly. (However, the use of sulfur as an extender is not justified from an economic standpoint. If the two binders perform equally, the cost per ton of sulfur must be less than 55 percent of the cost per ton of asphalt to be economical.(1) The current price of sulfur is approximately $150 per ton.)

- Most of the pavements in the field study were performing very well when evaluated. An examination of the cores verified the generally good conditions of the pavements. It is recommended that the performances of these pavements be determined again.

- When evaluating SEA pavements, the percent sulfur in the mixture should be measured. Most projects had less sulfur than intended and some were significantly low in sulfur content. More efficient methods of metering the sulfur into the asphalt or mixture may be needed. Cores from three pavements had to be eliminated because of grossly incorrect sulfur contents. However, these cores were probably taken from the wrong areas of the pavement.

- Because the specific gravity of an SEA binder would be greater than the specific gravity of the AC binder, the substitution of sulfur for asphalt should be on an equal volume basis rather than an equal weight basis. However, the specific gravity of an SEA binder could not be measured in this study and thus it would have to be approximated.

- Mixture designs should be performed on SEA mixtures. In most projects, the sulfur was simply substituted for asphalt and the design for the AC mixture was used. The use of mixture designs deletes the problem of whether the substitution should be on a volume, weight, or any other basis. The optimal binder contents for the SEA and AC mixtures may also be slightly different.

- Extraction methods should be developed so that extracted aggregate properties can be obtained. For recycled mixtures, where less than 50 percent of the mixture is recycled asphalt pavement, the data in this study indicated that the error in the combined bulk dry specific aggregate gravity would be low enough that a VMA requirement can be used when recycling. However, mixtures with asphalts harder than those used in this study would have to tested to verify this conclusion.

- Confounding variables were found to be a problem during this study even though the number of pavements evaluated was higher than in most studies. This shows the difficulty with evaluating pavements and may explain why the findings from various smaller studies sometimes conflict with other. It also shows the importance of adequately designing experiments.

APPENDIX A: HARDENING STUDY

This study was undertaken to determine if SEA binders harden after recovery as measured by penetration. If the penetrations of SEA binders change rapidly over time after recovery compared to asphalts, then it may be desirable to store recovered SEA binders for some length of time before testing, or to test the binders both initially and after storing. However, if the penetrations of stored samples better represent in-situ binder properties, then the standard 140 °F (60 °C) and 275 °F (135 °C) viscosities of the in-situ binder cannot be obtained because they require heating the samples.

1. First Data Set

Eight binders consisting of four conventional asphalt cements and four SEA binders containing 40 percent precipitated sulfur were tested for penetration using AASHTO T 49 at 77 °F (25 °C) over a 35-day period.(5) The binders were stored in closed containers and were not reheated and stirred before testing as required by the test method. After 35 days, the binders were heated, stirred, and again tested for penetration. Samples were also tested for viscosities initially and after 35 days using AASHTO T 201 and T 202.(5) The results are shown in table 58 and figures 13 and 14.

For the asphalt cements, two samples of each asphalt were used because one sample was needed for the penetration study and another needed to measure the initial viscosities. The replicate samples for each asphalt cement had equal initial penetrations. These samples showed some hardening over time, with the changes being reversible as shown by the penetrations and viscosities after reheating. Normally, samples are reheated and stirred before penetration testing, and thus the penetrations can be matched to the viscosities, where samples must be reheated. Reversible hardening, as shown by the data in this study, is not considered during testing. Thus the data indicates that the properties of recovered asphalt cements may not exactly match in-situ properties.

The decreases in penetration over time were much greater for the SEA binders. The changes in properties were generally, but not always, reversible as shown by the penetrations and viscosities. Firm conclusions for the SEA binders could not be drawn though because of several problems that were encountered during testing.

Table 58. Hardening study - data set #1.

Asphalt		Penetration, 77 °F (25 °C) (100 g, 5 s), 0.1 mm			Viscosity, 275 °F (135 °C), cSt		Viscosity, 140 °F (60 °C), P	
		Initial	After 35 Days	After 35 Days, Reheated	Initial	After 35 Days, Reheated	Initial	After 35 Days, Reheated
Westbank	AC-20	62	51	60	433	437	2866	2810
ARCO	AC-20	77	65	76	427	416	2149	2181
Chevron	AC-5	161	134	158	220	229	541	574
Cenex	AC-10	87	70	90	306	291	1248	1336
Sulfur Extended Asphalt (40/60)								
Westbank	AC-20	107	53	89/106	205 *	169	1056 *	1111
ARCO	AC-20	130	51	121	157 *	161	856	882
Chevron	AC-5, #1	221	102	150	104	108	280	289
Chevron	AC-5, #2	165	99	156	104	106	280	269
Cenex	AC-10	164	65	167/143	114 *	115	505	532/646

* Data was difficult to obtain.

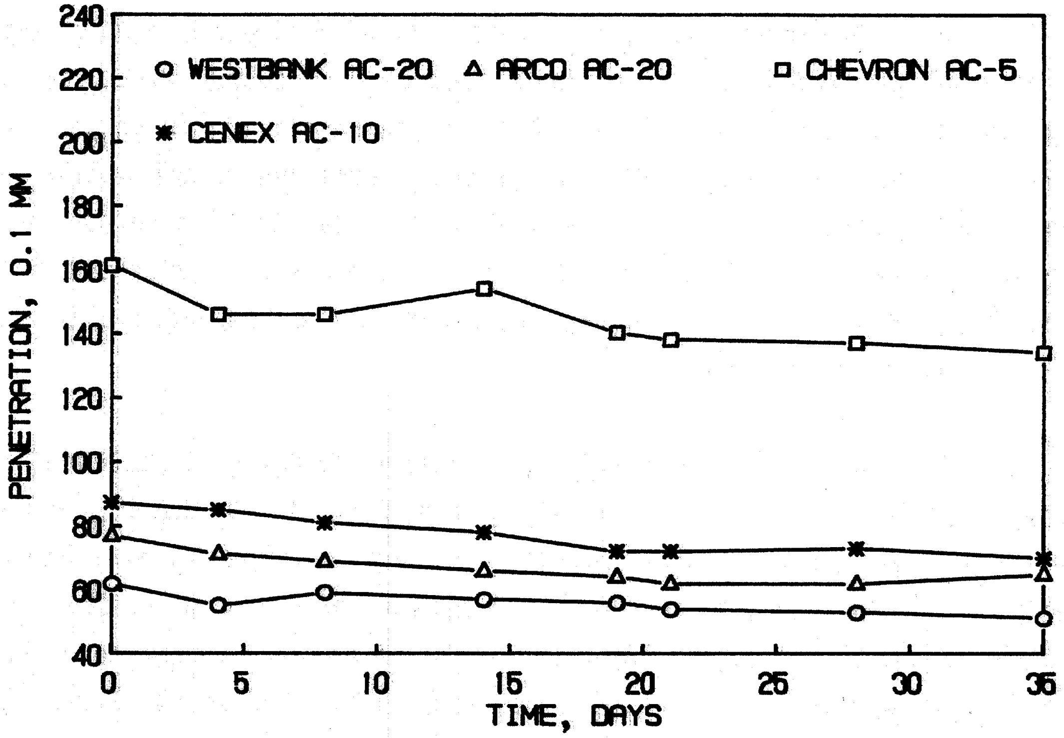

Figure 13. First data set - AC penetration versus time.

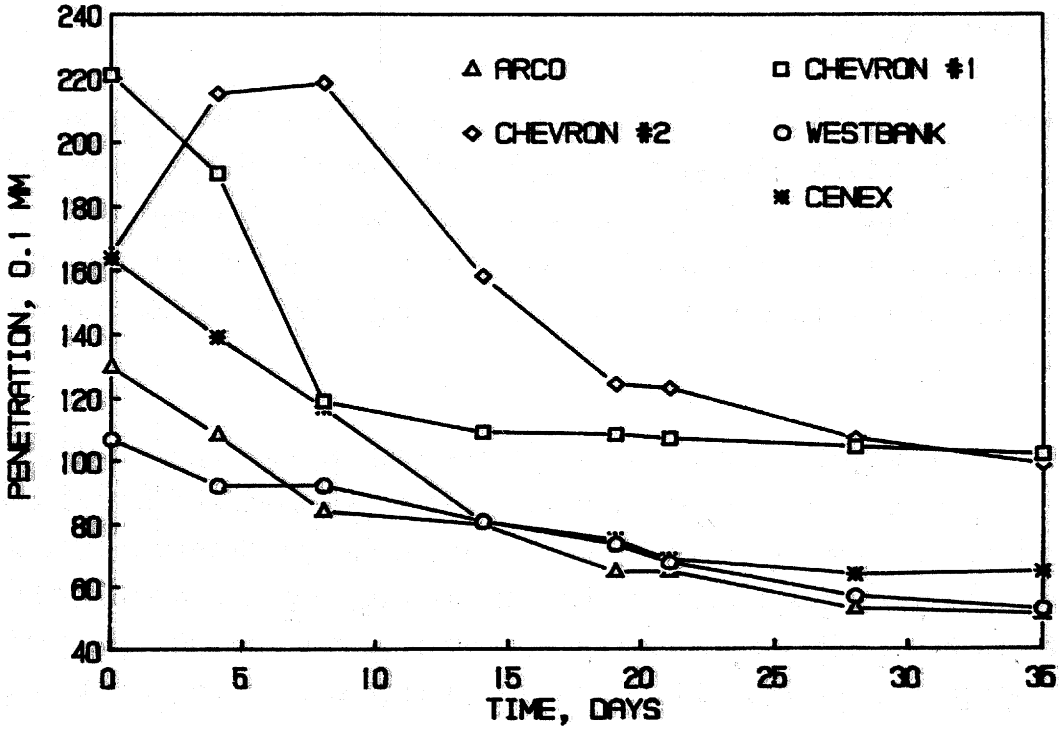

Figure 14. First data set - SEA penetration versus time.

For each SEA binder, three samples were used; two for the penetration study (it was decided to test duplicate samples) and one to measure the initial viscosities. For each SEA binder, excluding the Chevron AC-5, the replicate samples had equal initial penetrations. The three samples of Chevron AC-5 SEA provided unequal penetrations of 118, 187, and 207. A reason for this high variation was not evident, and the samples were discarded. Three new samples also provided unequal penetrations of 221, 165, and 208, and it was decided to use the sample having a penetration of 208 for determining the initial viscosities and to present the penetration data for the two other samples separately in table 58, and label them as #1 and #2.

After reheating the SEA penetration samples at 35 days, it was found that the replicate samples for the Westbank AC-20 and Cenex AC-10 SEA binders did not provide equal penetrations. Both penetrations are reported for each binder. The viscosities at 140 °F (60 °C) after reheating for the Cenex AC-10 SEA replicates were also not equal. Other viscosities for SEA binders, as marked in the table, were difficult to obtain. The flow times were either too short or very long, or the viscometer clogged and flow stopped. Tests had to be repeated in these cases to obtain a viscosity.

2. Second Data Set

Because of the various problems with the SEA data, the study was repeated. In this second study, five asphalt cements and five SEA binders were tested. The results are shown in table 59 and figures 15 and 16. Two replicate samples of each binder, both asphalt and SEA, were initially tested for penetration; one sample was then used for the penetration study and the other to measure the initial viscosities.

For each asphalt cement, the replicate samples had equal initial penetrations. The replicate samples for two of the SEA binders did not have equal penetrations. The Cenex AC-10 SEA sample used for determining the initial viscosities had a penetration of 106 compared to 99 given in the table 59. The Southland AC-20 SEA sample used for determining the initial viscosities had a penetration of 125 compared to 85. The replicate samples for the three other SEA binders provided equal penetrations.

Table 59. Hardening study - data set #2.

Asphalt		Penetration, 77 °F (25 °C) (100 g, 5 s), 0.1 mm			Viscosity, 275 °F (135 °C), cSt		Viscosity, 140 °F (60 °C), P	
		Initial	After 35 Days	After 35 Days, Reheated	Initial	After 35 Days, Reheated	Initial	After 35 Days, Reheated
ARCO	AC-20	73	61	74	420	428	2235	2203
Chevron	AC-5	150	130	153	231	229	589	606
Cenex	AC-10	86	72	88	281	286	1304	1299
Amoco	AC-30	65	57	65	606	587	3928	3725
Southland	AC-20	73	61	73	528	523	2568	2579
Sulfur Extended Asphalt (40/60)								
ARCO	AC-20	82	52	99/71/119 *	163 **	***	876	878
Chevron	AC-5	134	108	135/146/127 *	***	116	446	305 **
Cenex	AC-10	99	60	99/142/100 *	***	151 **	***	486
Amoco	AC-30	69	46	69/112/74 *	***	225	***	1352
Southland	AC-20	85	52	73/109/123 *	171	181	829	837

* Measurements were repeated on the same sample after reheating and stirring each time.
** Data was difficult to obtain.
*** Data could not be obtained.

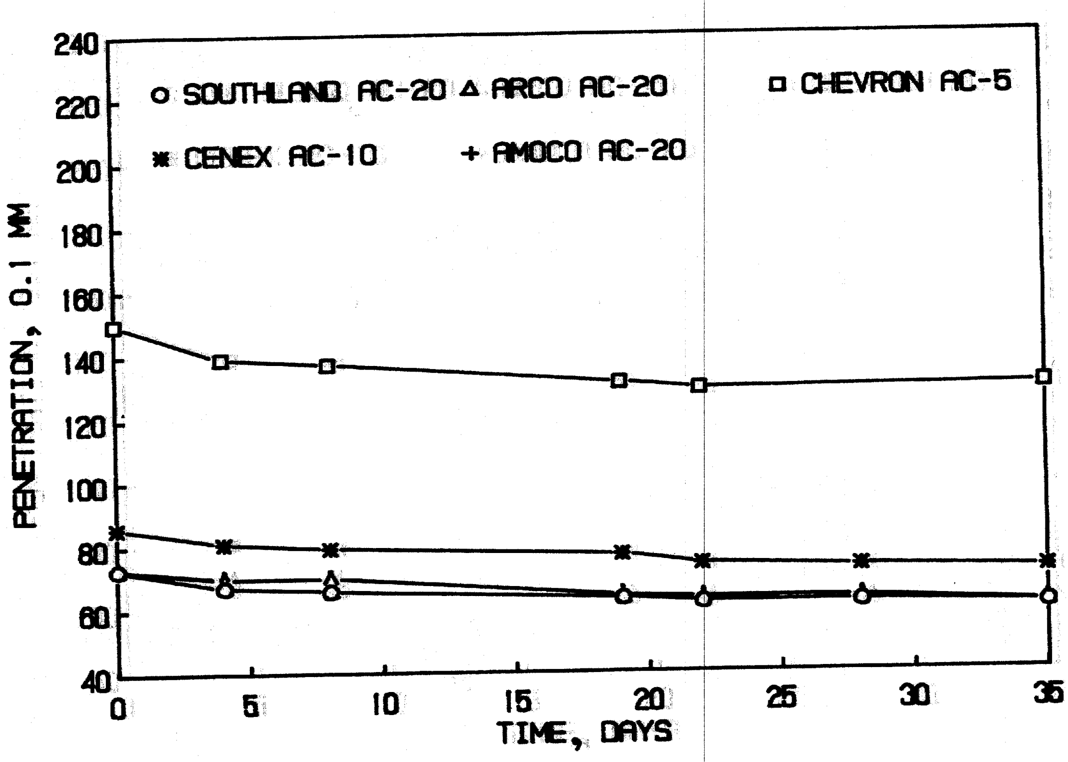

Figure 15. Second data set - AC penetration versus time.

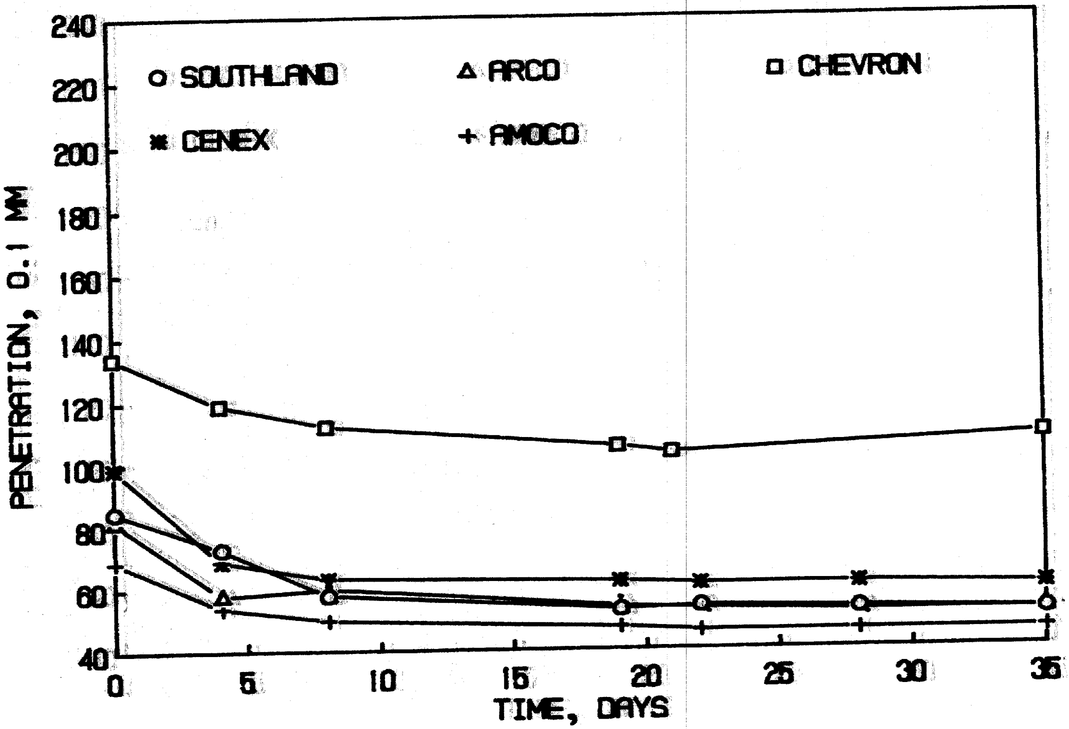

Figure 16. Second data set - SEA penetration versus time.

The responses of the asphalt cements over time were similar to those obtained in the first study, while the SEA binders provided even more problems. Viscosities were generally difficult to obtain or could not be obtained because of abrupt losses or changes in flow. Viscosity could not be measured with four attempts in some cases. The 35-day penetrations after reheating were not repeatable when tested on three successive days (reheated and stirred each time), plus the initial penetrations for the three SEA binders (ARCO AC-20, Chevron AC-5, and Cenex AC-10), common to both data sets #1 and #2, were significantly lower in this second study.

3. Third Data Set

Because half of the initial viscosities could not be measured, additional samples were made in order to obtain the data. As shown by table 60, two samples were tested for penetration and one was used to obtain the viscosities. Again, problems with measuring consistent penetrations for the SEA binders were encountered, and because the initial penetrations did not match those of data set #2, it was unknown whether the viscosity data could be added to the second set as intended. There were also some discrepancies between the viscosities of the two data sets (data sets #2 and #3) where data could be compared.

The following were concluded from observations made during the tests and from the test results:

- The problems with the penetrations were attributed to the sulfur settling during cooling. The rate of cooling would affect the settling process and thus the penetrations. In some cases, sulfur could be seen at the bottom of the container when the sample was cut out of the container at room temperature.

- The high decreases in penetration for the SEA binders over the 35-day period were also attributed mainly to settlement. Thus the study did not measure hardening due to changes in the properties of sulfur with age as intended.

- Initial penetrations were generally higher and viscosities lower for the SEA binders compared to the asphalt cements. Thus the binders are initially much softer. However, after 35 days, the SEA binders were generally harder

Table 60. Hardening study - data set #3.

		Penetration, 77 °F (25 °C) (100 g, 5 s), 0.1 mm			Viscosity, 275 °F (135 °C), cSt	Viscosity, 140 °F (60 °C), P
		Sample #1	Sample #2	Sample #2, Repeated	Sample #1	Sample #1
Asphalt						
ARCO	AC-20	74	75		426	2207
Chevron	AC-5	153	155		221	544
Cenex	AC-10	93	93		287	1274
Amoco	AC-30	71	72		605	3556
Southland	AC-20	81	82		517	2334
Sulfur Extended Asphalt (40/60)						
ARCO	AC-20	84	79	80	167	798 *
Chevron	AC-5	161	165	152	124	275
Cenex	AC-10	117	148	158	133	443
Amoco	AC-30	106	91	74	257 *	1192
Southland	AC-20	141	102	121	248	659

* Data was difficult to obtain.

than the asphalt cements as measured by penetration. Whether this was due to hardening of the sulfur, a build-up of sulfur with depth, or both, is unknown.

- For SEA binders, the maximum difference between the highest and lowest penetrations for a given sample were often higher than the allowable difference given by AASHTO T 49. Four or five determinations were often needed to obtain a penetration. (The data for these replicate determinations are not given in this report.)

- Samples must be constantly stirred while being poured into a viscometer in order to get a representative sample. Viscometers must be carefully cleaned after use because SEA binders can leave a film on the tube which may not be visible. It was noticed that tubes which appeared to be clean would become discolored if left empty in a heated bath. This film was found to affect the test results. Even with clean viscometers and careful stirring, viscosities may not be consistent, and three or four determinations may be needed. It is also more difficult to choose the correct tube, especially if the penetration can not be properly determined.

4. Fourth Data Set

In the previous study (data set #3), three extra replicate samples of each SEA binder were made but not tested. These additional samples were heated and cooled rapidly to try to minimize settlement of sulfur. Cooling samples with liquid nitrogen was tried, but it was found that the surface of the samples became extremely concave because of unequal cooling. Cooling in ice water had the same effect unless cooling was stopped when the temperature in the center of the sample was around 140 °F (60 °C). This occurred with 12 to 13 minutes of cooling.

The three additional replicate samples for each SEA binder were cooled using the ice water method, and penetrations labeled as "INITIAL" in table 61 were determined. The replicates are labeled as #3, #4, and #5. The data indicated that the cooling process was beneficial, but sample-to-sample variability can still be high. The variability decreased, as shown by the penetrations labeled as "INITIAL (REPEATED)," by repeating the process. This indicated that in order

Table 61. Hardening study - penetrations at 77 °F (100 g, 5 s) for SEA samples cooled by ice water.

		INITIAL			INITIAL (REPEATED)		
		Sample #3	Sample #4	Sample #5	Sample #3	Sample #4	Sample #5
ARCO	AC-20	115	115	116	113	115	115
Chevron	AC-5	195	192	183	191	189	190
Cenex	AC-10	140	163	144	138	141	149
Amoco	AC-30	110	125	111	108	113	110
Southland	AC-20	129	130	132	125	135	128

		AFTER 35 DAYS			AFTER 35 DAYS, REHEATED		
		Sample #3	Sample #4	Sample #5	Sample #3	Sample #4	Sample #5
ARCO	AC-20	49	47	48	123	---	---
Chevron	AC-5	93	92	93	141	146	166
Cenex	AC-10	65	66	71	138	142	---
Amoco	AC-30	51	51	51	106	99	108
Southland	AC-20	58	54	54	120	---	---

		AFTER 35 DAYS, 2nd REHEATING		
		Sample #3	Sample #4	Sample #5
ARCO	AC-20	108	78	75
Chevron	AC-5	184	---	188
Cenex	AC-10	131	141	143
Amoco	AC-30	108	108	107
Southland	AC-20	123	123	122

77 °F = 25 °C

to obtain the penetration of a given sample, several cycles of heating, stirring, and cooling are needed. Any small amount of hardening due to reheating cannot be avoided. Cooling with ice water also decreased the variability of the replicate penetration determinations recorded on each sample. (These data are not given in this report.)

The penetration versus time study was then repeated. The decreases in penetration with time labeled as "AFTER 35 DAYS" in table 61 and figure 17 were again attributed to settlement of the sulfur. After 35 days, the samples were reheated, stirred, and cooled using the ice water method. However, this data, labeled as "AFTER 35 DAYS, REHEATED," was variable and in some cases, the replicate determinations were so variable that an average penetration could not be obtained. This variability was attributed to inhomogeneity of the binder, although the binders appeared to be homogeneous after stirring. A second reheating reduced the variability of the data, but not to a satisfactory level. With additional cycles of heating and testing, the variability of the replicate determinations became so high that average penetrations could not be measured and thus are not reported. It appeared that although several cycles of heating, stirring, and cooling may be needed to obtain a penetration, there comes a point where heating adversely affects the binder and penetrations cannot be obtained.

5. Conclusions

It was concluded that the physical properties of SEA binders need to be verified by retesting samples or by testing multiple samples, and in some cases, the data may be so erratic that the properties cannot be obtained. Tests in this study were performed on neat SEA binders prepared in the laboratory. How aged binders from pavements would respond during testing is unknown. However, the 35-day aged, reheated samples produced the most variable results. Differences in the hardening rates of the SEA and asphalt binders, and the amount of steric hardening in the SEA binders that is reversed during heating, could not be determined.

Each SEA binder contained 40 percent sulfur by weight which is generally the highest percentage employed. Therefore, these binders contained the highest percentage of undissolved sulfur. It is possible that binders with lower percentages of sulfur may produce less variable results, but this was not studied. Also, the sulfur was blended with the asphalts by hand as opposed to high shear blending. High shear blending may produce a more uniform binder. However, high shear blending is not used in the field production of SEA binders.

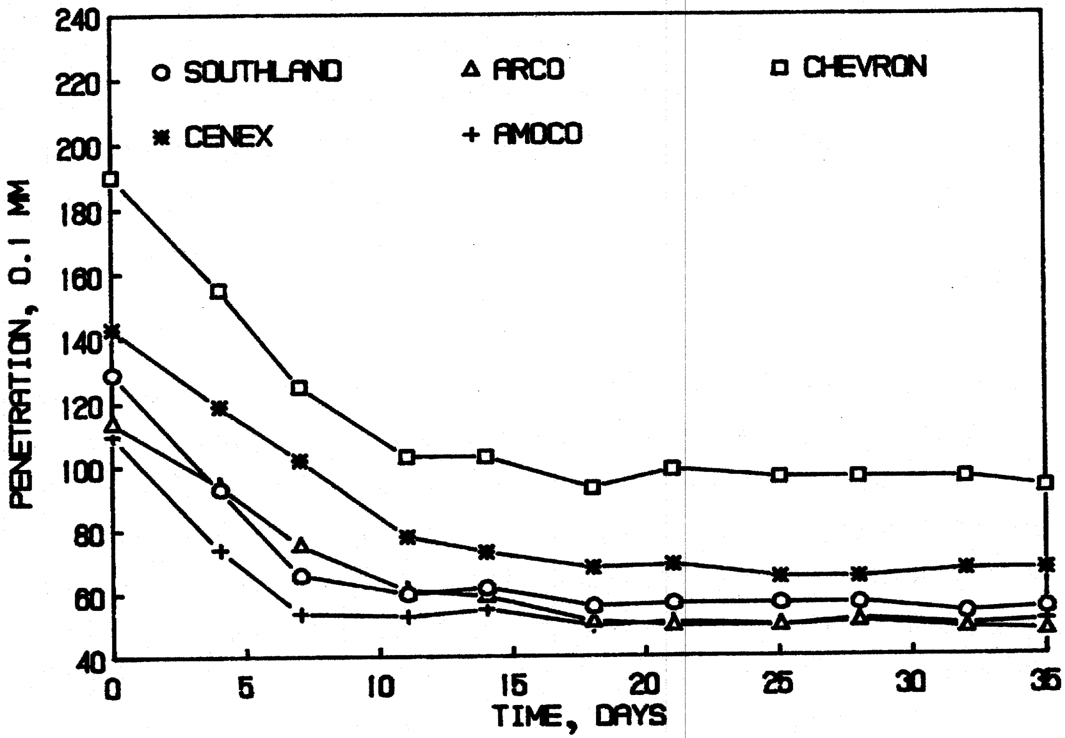

Figure 17. Fourth data set - SEA penetration versus time.

APPENDIX B: EXTRACTION STUDY

In order to determine the most efficient method for extracting aggregates from SEA mixtures, the four aggregates listed in table 62 and two asphalts containing 40 percent by weight precipitated sulfur were used to prepare eight mixtures per method of extraction. Each aggregate blend consisted of 1000 g of 50 percent coarse aggregate and 50 percent fine aggregate, except for the North Dakota blend which contained 40 percent coarse aggregate. These aggregate blends were used in paving mixtures. Additionally, mixtures containing only the North Dakota fine aggregate (minus #4 sieve) were tested in some of the extraction methods because this aggregate had an absorption of 3.1 which was the highest absorption of all the aggregates used. The Chevron AC-5 and the ARCO AC-20 used in the hardening study of appendix A were also employed in this study. The binder content of each mixture was six percent by mixture weight and the mixing temperature was 275 °F (135 °C). The Chevron AC-5 asphalt was used in the control.

The loose mixtures were stored in the laboratory for at least 1 month before extraction. Preliminary testing indicated that 96 to 100 percent of an asphalt or SEA binder could be removed if the materials were extracted one or two days after mixing. With increased time of curing at room temperature, the binders became more difficult to extract. Up to three weeks were needed for this effect to stop.

The following extraction methods were performed on the SEA mixtures: (1) centrifuge using trichloroethylene (AASHTO T 164, Method A), (2) centrifuge using a mixture of 8 percent ethyl alcohol and 92 percent trichloroethylene, (3) reflux using trichloroethylene (AASHTO T 164, Method B), (4) the proceeding aggregates were then washed with thiophene, (5) centrifuge using trichloroethylene heated to 150 °F (65.6 °C), and (6) the proceeding aggregates were then washed with carbon disulfide.(5) The efficiencies of these methods, in terms of the percent binder removed, are presented in table 63. Efficiencies were based on obtaining exact weights of the aggregate used in each mixture before and after extraction. Mixtures were carefully prepared so that no aggregate or moisture could be lost during mixing or curing. The centrifuge method (AASHTO T 164, Method A) of extraction was used on the control mixtures.

Table 62. Extraction study - properties of the aggregates.

Coarse Aggregates

Arizona (FHWA # B-5824)
Consists of 50% basalt, 40% rhyolite, and 10% miscellaneous igneous rocks, feldspar, and quartz. The basalt and rhyolite are 35% and 20% vesicular, respectively. The aggregate is 65% crushed overall (one or more faces), the remaining being well-rounded.

Mississippi (FHWA # B-5849)
Uncrushed gravel containing 47% non-porous chert, 22% porous chert, 17% chalcedony, and 14% vein quartz.

North Dakota (FHWA # B-5786)
Uncrushed gravel containing 40% to 45% limestone, 25% to 30% granite, 15% to 20% gabbro, 10% to 15% hemitilic siltstone, and less than 5% quartzite.

Virginia - Chantilly (FHWA # B-5742)
Consists of 100% crushed diabase.

Fine Aggregates (minus #4 sieve)

Arizona (FHWA # B-5827)
Consists of 90% crushed and 10% uncrushed sand containing various igneous rocks, feldspar, and quartz.

Mississippi (FHWA # B-5850 and B-5883)
Uncrushed gravel containing 61% non-porous chert, 29% porous chert, 2% chalcedony, and 8% vein quartz.

North Dakota (FHWA # B-5786)
Same as coarse aggregate from North Dakota.

Virginia - Chantilly (FHWA # B-5742)
Consists of 100% crushed diabase.

Table 63. Extraction study - efficiencies (percents) of various methods used to extract SEA binders compared to an asphalt control mixture.

			Asphalt Control	Sulfur Extended Asphalts					
Aggregate Type	Aggregate Absorption	Asphalt Grade	Cfg using TCE	Cfg using TCE	Cfg using 92% TCE with 8% Alcohol	Reflux using TCE	Reflux using TCE plus Thiophane Wash	Cfg using Hot TCE	Cfg using Hot TCE plus Carbon Disulfide Wash
North Dakota	2.2	AC-5	96.3	92.0	93.0	95.7	96.2	91.8	94.2
		AC-20		94.0	92.6	95.3	96.1	94.4	95.3
Arizona	2.0	AC-5	98.4	92.0	95.5	97.3	98.0	95.8	98.2
		AC-20		93.1	94.5	97.9	98.9	96.2	98.4
Mississippi	1.9	AC-5	97.0	94.9	92.4	97.2	97.7	94.7	96.5
		AC-20		93.5	93.9	97.7	98.1	94.6	95.5
Virginia (Chantilly)	1.4	AC-5	99.4	97.8	95.7	97.8	97.8	97.7	99.7
		AC-20		95.4	95.6	97.4	97.4	98.1	100.0
North Dakota (minus #4)	3.1	AC-5	94.5	93.9	----	91.4	----	95.8	95.8

Cfg = Centrifuge Method
TCE = Trichloroethylene

The extraction procedures were extended beyond the normal stopping point, where the effluent is essentially colorless or straw colored. The reflux method was continued until the solvent dripping from the cone was clear for 1 hour. Three additional washings were used in the centrifuge method after the solvent was clear. Because sulfur is light in color, it was decided that the aggregates should be thoroughly washed.

The efficiencies using the centrifuge plus trichloroethylene method were low compared to the asphalt control. The alcohol/trichloroethylene solvent blend reportedly is a better solvent for asphalt than trichloroethylene alone. However, alcohol is a poor solvent for sulfur and the efficiencies were not improved by using this blend of solvent. The efficiencies using the reflux method were close to those for the control while the thiophene wash provided little to no improvement. It should be noted that if the asphalt controls were extracted using the reflux method, some improvement in their efficiencies would be expected. The centrifuge plus hot trichloroethylene method was not as efficient as the reflux method, except for the North Dakota fine aggregate. Washing with carbon disulfide did provide improvement. Carbon disulfide is a good solvent for sulfur. However, it is highly flammable and toxic, and should not be routinely used unless absolutely necessary. The composition of any residual material left on the aggregates after extracting the SEA binders was not determined, but all of the efficiencies indicate that most of the sulfur was removed.

It was decided to determine whether SEA binders extracted using the reflux and the centrifuge/hot solvent methods could be recovered. These appeared to be the best methods for routine testing.

(Note: Thiophene was used as a solvent for Sulphlex, a sulfur binder containing no asphalt, which was developed under several FHWA contracts. Very little work was performed to determine its efficiency as a solvent for sulfur products. Limited tests indicated that it removed around 94 to 99 percent of a Sulphlex binder.)

APPENDIX C: RECOVERY STUDY

The five SEA binders used in the hardening study of appendix A (see table 61) were used to determine if the recovery process can affect SEA binder properties, and to determine differences in the reflux and centrifuge/hot solvent extraction methods. The reflux method provided slightly better extraction results, however, this method often hardens asphalts and thus is not recommended for asphalts. The SEA binders consisted of 40 percent precipitated sulfur and were made in 75 g quantities.

The SEA binders were not heated or mixed with aggregates in this study. The penetrations of duplicate samples of each SEA binder were first measured, and then the binders were subjected to conditions simulating the extraction procedures. For the centrifuge method, each SEA was soaked in approximately 1000 ml of trichloroethylene at 150 °F (65.6 °C) for 1 hour. For the reflux method, each binder was placed in the cone and the solvent refluxed until the solvent dripping from the cone was clear for 1 hour. The total procedure took approximately 2 hours. The binders were then recovered using the Abson procedure of AASHTO T 170, including the primary distillation procedure.(5) The ice water method of cooling the samples before penetration testing was used.

The data is shown in table 64. Penetrations for the samples before recovery provided the same problems as given in appendix A. For some binders, there were differences between the penetrations of the duplicate samples, and the variability of the replicate penetration determinations for a given SEA were occasionally very high.

The penetrations after recovery were lower than before recovery for four out of five binders, and they were dependent on the extraction procedure in most cases. The simulated reflux conditioning procedure generally provided higher penetrations than the centrifuge procedure. The variability of the replicate penetrations after recovery for any binder using either extraction method was very low, and thus it would appear that the recovery processes affected how the sulfur was dispersed in the binders. Repeating the penetration tests 3 weeks later produced different penetrations and unacceptably high variabilities. It was concluded that obtaining the properties of recovered SEA binders is of limited or no value.

Table 64. Recovery study - penetrations before and after recovery.

		Before Recovery, Sample #1	After Reflux		Before Recovery, Sample #2	After Centrifuge	
			Initial	Repeat[1]		Initial	Repeat[1]
ARCO	AC-20	100	85	58 63	97	79	61 83
		101	85	63 59	97	79	65 62
		100	86	59	97	80	73
	Avg.	100	85	60	97	79	-
Chevron	AC-5	207	154	76 86	201	135	60 61
		185	154	75 71	204	132	61
		204	153	71	198	134	61
	Avg.	199	154	74	201	134	61
Cenex	AC-10	128	97	54 61	105	86	66 59
		121	95	69 65	121	87	52 54
		130	97	73	109	86	68
	Avg.	126	96	-	109	86	-
Amoco	AC-30	110	84	56 55	106	83	45 52
		105	85	40 49	107	84	53 42
		100	82	41	102	84	61
	Avg.	105	84	-	105	84	-
Southland	AC-20	120	108	65 48	105	100	53 46
		120	109	54 55	99	102	47 57
		117	108	70	111	100	60
	Avg.	119	108	-	105	101	-

[1] Tested 3 weeks later.

The trichloroethylene distilled from each binder was checked for sulfur. It was found that the solvents recovered through the primary distillation contained small amounts of yellow sulfur mixed with a black to brown material. The weights of the residue ranged from 0.027 to 0.099 g. The weight was not dependent on the amount of solvent, which was approximately 1500 g for the centrifuge simulation method and 700 g for the reflux simulation method. The solvent distilled from the 250 ml Abson flasks contained small amounts of yellow sulfur, ranging from 0.019 to 0.039 g. Again, the amount of sulfur in the recovered solvent was not dependent on the amount of solvent collected, which ranged from 70 to 165 g. A small amount of sulfur of unknown weight was also deposited in the condenser. This could only be observed after several distillations using the same condenser. A yellow haze was observed inside each Abson flask near its top and sulfur could be smelled during the distillation procedure. Each SEA contained 25 to 30 g of sulfur, so the loss was very small and would not explain the changes in penetrations given in table 64. The filter paper used in the simulated reflux method showed no change in weight, and thus all of the sulfur went through the paper and into the effluent.

The five asphalts were also tested for solubility in trichloroethylene using AASHTO T 44.(5) However, because representative 2 g samples of SEA are difficult to obtain or make, the test was performed on large samples, approximately 75 g, using three or four crucibles per SEA binder. The percent insoluble material for each SEA was (1) ARCO AC-20: 16.8, (2) Chevron AC-5: 15.2, (3) Cenex AC-10: 17.1, (4) Amoco AC-30: 21.0, and (5) Southland AC-20: 16.8. When the SEA was mixed with trichloroethylene, the sulfur tended to settle out and form lumps. Because each SEA contained 40 percent sulfur by weight and the solubilities of the asphalts were close to 100 percent, the amount of sulfur that was not soluble ranged from 38 to 52 percent. Measuring this solubility appears to be of no value because it has no relationship to the recoverability of an SEA binder, probably does not represent active versus inactive cementing constituents, and the solubility procedure most likely alters the amount of sulfur which is in solution with the asphalt.

APPENDIX D: SEA BINDER SPECIFIC GRAVITY

The specific gravity of a binder at 77 °F (25 °C) is used to calculate the effective specific gravity of an aggregate and the amount of asphalt absorbed into an aggregate. It is also needed to convert poise to centistokes so that viscosity versus temperature relationships can be established for the asphalt. These relationships are used to obtain mixing and compaction temperatures for mixtures and to calculate log-log viscosity-temperature susceptibility relationships. This study was undertaken to determine if the specific gravities of SEA binders can be measured.

The standardized methods (AASHTO T 228 and T 229) for determining the specific gravities of semi-solid and solid bituminous materials could not be used to test the SEA binders because the small representative samples required by the methods could not be obtained.(5) Specific gravities were extremely erratic when these methods were tried. The pycnometer was also too small to blend an asphalt and sulfur in it. Specific gravities were then measured by making the SEA binders in three-ounce (90 ml) tins and measuring the gravity in the tin using a water displacement method similar to bowl method of AASHTO T 209 for determining the maximum specific gravity of an asphalt mixture. Care was taken to eliminate air bubbles. Each sample of binder weighed approximately 75 g.

The five SEA binders used in the hardening study of appendix A were also used in this study, and the data is given in table 65. Specific gravities for the asphalts are first given in the table along with specific gravities for the SEA binders calculated using the law of proportioning. These calculated values should not be correct as they assume that the volumes of the asphalt and sulfur are additive. They are included as supplemental information. All of the measured SEA specific gravities were less than these calculated values.

The SEA samples were heated to 240 °F (116 °C), stirred, and cooled using the ice water method each time. The tests on the SEA binders were repeated twice on the same samples. The data for "Measured SEA" and "Measured SEA, Repeat #1" indicate that the variability of replicate determinations was high. It was expected that the specific gravities should be within 0.0023 based on the precision statement of AASHTO T 228. No losses in sample weight, measured to 1 mg, due to heating could be measured. The data for "Measured SEA, Repeat #2" shows large

Table 65. SEA binder specific gravity study - specific gravities of SEA binders.

		Asphalt	Calculated SEA	Measured SEA	Measured SEA, Repeat #1	Measured SEA, Repeat #2
ARCO	AC-20	1.024	1.283	1.182	1.198	1.252
Chevron	AC-5	1.019	1.279	1.223	1.236	1.233
Cenex	AC-10	1.044	1.302	1.229	1.219	1.277
Amoco	AC-30	1.036	1.295	1.192	1.197	1.274
Southland	AC-20	1.034	1.293	1.224	1.225	1.275

Specific Gravity of Sulfur = 2.07

Table 66. SEA binder specific gravity study - specific gravities of SEA binders in triplicate.

		Calculated SEA	Measured, Sample 1	Measured, Sample 2	Measured, Sample 3	Measured, Average
ARCO	AC-20	1.283	1.195	1.201	1.200	1.199
Chevron	AC-5	1.279	1.233	1.232	1.222	1.229
Cenex	AC-10	1.302	1.215	1.244	1.251	1.237
Amoco	AC-30	1.295	1.225	1.233	1.260	1.239
Southland	AC-20	1.293	1.270	1.257	1.263	1.263

changes in the gravities and significant changes in the sample weights were recorded. The following percent losses in sample weight were obtained: (1) ARCO AC-20: 0.23, (2) Chevron AC-5: 0.24, (3) Cenex AC-10: 0.14, (4) Amoco AC-30: 0.09, and (5) Southland AC-20: 0.08. As concluded in appendix A, reheating and stirring may alter how the sulfur blends with the asphalt.

Additional samples of the SEA binders were made in triplicate. The data in table 66 show that the variation for replicate samples can be high. These specific gravities also differed from those given in table 65. As concluded in appendix A, the procedure for blending the asphalt and sulfur affects the makeup of the binder. It was concluded that obtaining the specific gravity of an SEA binder may be of limited or no value.

APPENDIX E: AGGREGATE SPECIFIC GRAVITY STUDY

The bulk dry specific gravity of the aggregate in a mixture, obtained through AASHTO test methods T 84 (fine aggregate) and T 85 (coarse aggregate), are needed to determine the amount of absorbed asphalt and the voids in the mineral aggregate (VMA) in a compacted mixture.(5) VMA criteria are generally used only as a mixture design tool to ensure that the aggregate has a sufficiently thick coating of asphalt. However, they can also be used to evaluate pavement cores if differences in the laboratory to field void levels and asphalt contents are considered. AASHTO methods T 84 and T 85 also give the percent water absorption of an aggregate, which generally indicates before the aggregate is used in a mixture whether the amount of asphalt absorption will be high or low. Highly absorptive aggregates require more asphalt, and may increase the cost of the mixture.

When evaluating aged pavement cores, the specific gravities (bulk dry, bulk saturated surface-dry, and apparent) of the aggregates are often unknown. Either the original project data can not be found, or the specific gravities and VMA were never measured. Testing extracted aggregates for specific gravity is generally not performed. It is often indicated by asphalt technologists that residual oily coatings on extracted aggregates prohibit an aggregate from being thoroughly wetted with water during the test for specific gravity, and absorbed asphalt which is not removed by the extraction process may affect the test result. However, there is little published data to verify this statement. For recycled mixtures, the specific gravities of the recycled aggregates are generally not obtained, and VMA is generally not used as a mixture design criteria for these mixtures.

This study was performed to determine whether extracted aggregates can be tested by AASHTO T 84 and T 85. Five coarse aggregates and five fine aggregates were mixed separately with an AC-5 asphalt (FHWA ID B5901) to determine if the specific gravities and percent water absorption of an aggregate can be measured after extraction. An SEA binder consisting of the AC-5 and 40 percent precipitated sulfur by weight was also used. The low viscosity grade of asphalt and a mixture curing period of 1 hour at 300 °F (149 °C) were used to promote asphalt absorption, although the percent asphalt absorption was not measured. The binders were added as 6 percent by mixture weight and all aggregates were visually thoroughly coated. As in the extraction study of appendix B, the mixtures were stored in the laboratory at room temperature for at least 1 month before extraction. The aggregates had various degrees of water absorption as measured by AASHTO T 84 and T 85, but all were in the range for aggregates with low to moderate absorption (generally less than 3 percent). Petrographic analyses of the aggregates are given in table 67.

The data for the aggregates extracted from the asphalt controls, using the centrifuge method (AASHTO T 164, Method A), are given in tables 68 and 69.(5) Specific gravities and absorptions were determined on aggregate sampled from the stockpile and after extraction using trichloroethylene. The extracted aggregates were then washed with a blend of 8 percent ethyl alcohol and 92 percent trichloroethylene, and the tests for specific gravity repeated. This blend of solvent reportedly cleans the aggregates more efficiently than trichloroethylene alone when extracting asphalt binders. Aggregates from additional mixtures were also extracted using the blend of solvent throughout the procedure. If a binder is to be recovered, this latter method would require experimentation proving that the binders can be recovered without a change in physical properties, as this blend of solvent is not allowed in the extraction procedure using the centrifuge method.

The data for the aggregates extracted from the SEA mixtures using the centrifuge/hot solvent and reflux methods (AASHTO T 164, Methods A and B) are given in tables 70 and 71. These two methods were found in the extraction study of appendix B to be the best methods for extracting asphalts and aggregates from SEA mixtures.

Table 72 shows the single-operator precision indexes for replicate samples tested using AASHTO T 84 and T 85. By applying the AASHTO D2S limits to the specific gravities and absorptions of the stockpiled aggregates (stockpiled aggregate data +/- D2S), it was found that most of the specific gravities and absorptions of the extracted coarse aggregates in tables 68 and 70 fell within these limits. It was assumed in this analysis that the data for each stockpiled aggregate are exact target data and all samples of each aggregate can be treated as replicates. Data not falling within the limits are marked by an asterisk. Most discrepancies were with the apparent specific gravities. The lower apparent specific gravities for the extracted aggregates appear to indicate that all of the asphalt was not removed.

Table 67. Aggregate gravity study - properties of the aggregates.

Coarse Aggregates

Arizona (FHWA # B-5824)
Consists of 50% basalt, 40% rhyolite, and 10% miscellaneous igneous rocks, feldspar, and quartz. The basalt and rhyolite are 35% and 20% vesicular, respectively. The aggregate is 65% crushed overall (one or more faces), the remaining being well-rounded.

Mississippi (FHWA # B-5849)
Uncrushed gravel containing 47% non-porous chert, 22% porous chert, 17% chalcedony, and 14% vein quartz.

North Dakota (FHWA # B-5786)
Uncrushed gravel containing 40% to 45% limestone, 25% to 30% granite, 15% to 20% gabbro, 10% to 15% hemitilic siltstone, and less than 5% quartzite.

Virginia - Chantilly (FHWA # B-5742)
Consists of 100% crushed diabase.

Virginia - Manassas (FHWA # B-5926)
Consists of 100% crushed diabase.

Fine Aggregates (minus #4 sieve)

Arizona (FHWA # B-5827)
Consists of 90% crushed and 10% uncrushed sand containing various igneous rocks, feldspar, and quartz.

Mississippi (FHWA # B-5850 and B-5883)
Uncrushed gravel containing 61% non-porous chert, 29% porous chert, 2% chalcedony, and 8% vein quartz.

North Dakota (FHWA # B-5786)
Same as coarse aggregate from North Dakota.

Virginia - Chantilly (FHWA # B-5742)
Consists of 100% crushed diabase.

Virginia - Manassas (FHWA # B-5926)
Consists of 75% crushed diabase and 25% natural quartzite sand.

Table 68. Aggregate gravity study - coarse aggregates with AC-5 binder.

	Stockpile Aggregate	After Extraction using Trichloro-ethelene	After Alcohol/ Trichloro-ethylene Wash	After Extraction using Alcohol/ Trichloro-ethylene
North Dakota (FHWA B5786)				
Bulk Dry Specific Gravity	2.647	2.653	2.655	2.633
Bulk SSD Specific Gravity	2.699	2.692	2.697	2.684
Apparent Specific Gravity	2.785	2.761*	2.772	2.774
Absorption, percent	1.9	1.5	1.6	1.9
Virginia - Manassas (FHWA B5926)				
Bulk Dry Specific Gravity	2.885	2.881	2.887	2.880
Bulk SSD Specific Gravity	2.908	2.903	2.907	2.901
Apparent Specific Gravity	2.954	2.946	2.947	2.940
Absorption, percent	0.80	0.76	0.71	0.71
Arizona (FHWA B5824)				
Bulk Dry Specific Gravity	2.470	2.468	2.476	2.473
Bulk SSD Specific Gravity	2.534	2.518	2.523	2.525
Apparent Specific Gravity	2.638	2.597*	2.596*	2.609*
Absorption, percent	2.6	2.0*	1.9*	2.1*
Mississippi (FHWA B5849)				
Bulk Dry Specific Gravity	2.502	2.494	2.494	2.493
Bulk SSD Specific Gravity	2.534	2.518	2.523	2.525
Apparent Specific Gravity	2.638	2.597*	2.596*	2.584*
Absorption, percent	1.6	1.3	1.4	1.4
Virginia - Chantilly (FHWA B5742)				
Bulk Dry Specific Gravity	2.963	2.957	2.963	2.960
Bulk SSD Specific Gravity	2.984	2.976	2.982	2.982
Apparent Specific Gravity	3.026	3.015	3.021	3.028
Absorption, percent	0.71	0.65	0.65	0.76

* - Not within AASHTO precision limits.

Table 69. Aggregate gravity study - fine aggregates with AC-5 binder.

	Stockpile Aggregate	After Extraction using Trichloro-ethelene	After Alcohol/ Trichloro-ethylene Wash	After Extraction using Alcohol/ Trichloro-ethylene
North Dakota (FHWA B5786)				
Bulk Dry Specific Gravity	2.519	2.466*	2.544	2.459*
Bulk SSD Specific Gravity	2.596	2.543*	2.594	2.548*
Apparent Specific Gravity	2.728	2.672*	2.677*	2.700*
Absorption, percent	3.1	3.1	2.0*	3.6
Virginia - Manassas (FHWA B5926)				
Bulk Dry Specific Gravity	2.681	2.698	2.703	2.715*
Bulk SSD Specific Gravity	2.736	2.754	2.758	2.768*
Apparent Specific Gravity	2.837	2.858	2.861	2.867
Absorption, percent	2.1	2.1	2.0	2.0
Arizona (FHWA B5824)				
Bulk Dry Specific Gravity	2.600	2.533*	2.599	2.585
Bulk SSD Specific Gravity	2.634	2.581*	2.629	2.620
Apparent Specific Gravity	2.681	2.660	2.680	2.678
Absorption, percent	1.3	1.9*	1.2	1.3
Mississippi (FHWA B5849)				
Bulk Dry Specific Gravity	2.497	2.449	2.501	2.517
Bulk SSD Specific Gravity	2.550	2.514*	2.546	2.561
Apparent Specific Gravity	2.637	2.621	2.620	2.633
Absorption, percent	2.1	2.7	1.8	1.8
Virginia - Chantilly (FHWA B5742)				
Bulk Dry Specific Gravity	2.827	2.793*	2.846	2.802
Bulk SSD Specific Gravity	2.884	2.856	2.893	2.866
Apparent Specific Gravity	2.996	2.980	2.984	2.993
Absorption, percent	2.0	2.2	1.6	2.3

* - Not within AASHTO precision limits.

Table 70. Aggregate gravity study - coarse aggregates with SEA binder.

	Stockpile Aggregate	Centrifuge Extraction	Reflux Extraction
North Dakota (FHWA B5786)			
Bulk Dry Specific Gravity	2.647	2.637	2.613*
Bulk SSD Specific Gravity	2.699	2.686	2.667*
Apparent Specific Gravity	2.785	2.773	2.762*
Absorption, percent	1.9	1.9	2.1
Virginia - Manassas (FHWA B5926)			
Bulk Dry Specific Gravity	2.885	2.881	2.880
Bulk SSD Specific Gravity	2.908	2.902	2.901
Apparent Specific Gravity	2.954	2.943	2.941
Absorption, percent	0.80	0.73	0.71
Arizona (FHWA B5824)			
Bulk Dry Specific Gravity	2.470	2.463	2.482
Bulk SSD Specific Gravity	2.534	2.521	2.536
Apparent Specific Gravity	2.638	2.615*	2.622
Absorption, percent	2.6	2.4	2.1*
Mississippi (FHWA B5849)			
Bulk Dry Specific Gravity	2.502	2.489	2.475
Bulk SSD Specific Gravity	2.534	2.527	2.516
Apparent Specific Gravity	2.638	2.586*	2.580*
Absorption, percent	1.6	1.5	1.6
Virginia - Chantilly (FHWA B5742)			
Bulk Dry Specific Gravity	2.963	2.968	2.976
Bulk SSD Specific Gravity	2.984	2.987	2.991
Apparent Specific Gravity	3.026	3.025	3.023
Absorption, percent	0.71	0.63	0.52

* - Not within AASHTO precision limits.

Table 71. Aggregate gravity study - fine aggregates with SEA binder.

	Stockpile Aggregate	Centrifuge Extraction	Reflux Extraction
North Dakota (FHWA B5786)			
Bulk Dry Specific Gravity	2.519	2.433*	2.432*
Bulk SSD Specific Gravity	2.596	2.490*	2.493*
Apparent Specific Gravity	2.728	2.580*	2.590*
Absorption, percent	3.1	2.4*	2.5*
Virginia - Manassas (FHWA B5926)			
Bulk Dry Specific Gravity	2.681	2.729*	2.740*
Bulk SSD Specific Gravity	2.736	2.766	2.773*
Apparent Specific Gravity	2.837	2.836	2.833
Absorption, percent	2.1	1.4*	1.2*
Arizona (FHWA B5824)			
Bulk Dry Specific Gravity	2.600	2.557*	2.584
Bulk SSD Specific Gravity	2.634	2.585*	2.605
Apparent Specific Gravity	2.681	2.629*	2.639*
Absorption, percent	1.3	1.1	0.8*
Mississippi (FHWA B5849)			
Bulk Dry Specific Gravity	2.497	2.508	2.501
Bulk SSD Specific Gravity	2.550	2.546	2.539
Apparent Specific Gravity	2.637	2.606*	2.601*
Absorption, percent	2.1	1.5*	1.5*
Virginia - Chantilly (FHWA B5742)			
Bulk Dry Specific Gravity	2.827	2.789*	2.829
Bulk SSD Specific Gravity	2.884	2.850*	2.878
Apparent Specific Gravity	2.996	2.973	2.975
Absorption, percent	2.0	2.2	1.7

* - Not within AASHTO precision limits.

Table 72. Aggregate gravity study - single-operator precision indexes for AASHTO test methods T 84 and T 85.(5)

	Standard Deviation (2S)	Difference Between Two Tests (D2S)
Coarse Aggregate, AASHTO T85		
Bulk Dry Specific Gravity	0.022	0.031
Bulk SSD Specific Gravity	0.016	0.023
Apparent specific Gravity	0.014	0.020
Absorption, percent	0.30	0.42
Fine Aggregate, AASHTO T84		
Specific Gravity (any)	0.020	0.030
Absorption, percent	0.3	0.4

Overall, the data indicated that the specific gravities and percent water absorption of an extracted coarse aggregate can be estimated. The data for the bulk dry specific gravities, which are used in designing asphalt mixtures, overall agreed with each other. The only discrepancy was with the SEA North Dakota aggregate in table 70 using the reflux method.

The same analyses were applied to the fine aggregates in tables 69 and 71. The fine aggregates were difficult to wet with water but they could be tested. However, the data were more variable and not as good as for the coarse aggregates. For the asphalt control mixtures, the alcohol/trichloroethylene solvent blend was found in the extraction study of appendix B to removed a small additional amount of asphalt (up to 0.05 percent). The data in table 69 indicates that washing the extracted aggregate with this solvent provided data closer to the data for the stockpiled aggregates and the bulk dry specific gravities were reasonably estimated. However, it was expected that the data in the two right hand columns of this table would be equivalent as both used the blend of solvent, but they are not. This could be due, at least partially, to operator error, but a firm reason for the discrepancies could not be established. Because of these discrepancies, it could not be concluded whether or not the properties of fine aggregates extracted from asphalt mixtures can be estimated. The variability in performing the test methods for specific gravity and absorption is compounded with the efficiency of the extraction procedure. Overall, the data for the fine aggregates extracted from the SEA mixtures in table 71 were poor.

Job mix formulas using these aggregates contained 50 percent coarse aggregate, except for the North Dakota blend which contained 40 percent coarse aggregate. The specific gravities and percent water absorptions for these blends using each data set of aggregate properties were first calculated. The percent difference between the stockpiled aggregate values and those for the extracted aggregates were then calculated as shown in tables 73 and 74. The differences varied with the aggregate and the method of extraction. In some cases, the percent water absorption was higher after extraction, as shown by the positive values. A reason for this is unknown.

Table 73. Aggregate gravity study - percent difference between the specific gravities and absorption of the stockpiled aggregates and the aggregates extracted from the AC-5 mixtures (fine and coarse aggregates combined).

	After Extraction using Trichloro-ethelene	After Alcohol/ Trichloro-ethylene Wash	After Extraction using Alcohol/ Trichloro-ethylene
North Dakota (FHWA B5786); 40 % coarse, 60 % fine aggregate			
Bulk Dry Specific Gravity	-1.21	0.70	-1.67
Bulk SSD Specific Gravity	-1.32	-0.08	-0.49
Apparent Specific Gravity	-1.60	-1.34	-0.80
Absorption	-3.8	-31.	12.
Virginia - Manassas (FHWA B5926); 50 % coarse, 50 % fine aggregate			
Bulk Dry Specific Gravity	0.25	0.47	0.58
Bulk SSD Specific Gravity	0.28	0.43	0.50
Apparent Specific Gravity	0.24	0.31	0.31
Absorption	0.0	0.0	0.0
Arizona (FHWA B5824); 50 % coarse, 50 % fine aggregate			
Bulk Dry Specific Gravity	-1.30	0.12	-0.20
Bulk SSD Specific Gravity	-1.32	-0.31	-0.43
Apparent Specific Gravity	-1.17	-0.83	-0.60
Absorption	0.0	-20.	-15.
Mississippi (FHWA B5849); 50 % coarse, 50 % fine aggregate			
Bulk Dry Specific Gravity	-1.12	-0.08	0.24
Bulk SSD Specific Gravity	-1.02	-0.31	0.04
Apparent Specific Gravity	-1.06	-1.10	-1.10
Absorption	11.	-11.	-11.
Virginia - Chantilly (FHWA B5742); 50 % coarse, 50 % fine aggregate			
Bulk Dry Specific Gravity	-3.80	0.35	-0.48
Bulk SSD Specific Gravity	-0.61	0.14	-0.34
Apparent Specific Gravity	-0.46	-0.30	-0.03
Absorption	0.0	-21.	7.1

Table 74. Aggregate gravity study - percent difference between the specific gravities and absorption of the stockpiled aggregates and the aggregates extracted from the SEA mixtures (fine and coarse aggregates combined).

	Centrifuge Extraction	Reflux Extraction
North Dakota (FHWA B5786); 40 % coarse, 60 % fine aggregate		
Bulk Dry Specific Gravity	-2.26	-2.65
Bulk SSD Specific Gravity	-2.69	-2.88
Apparent Specific Gravity	-3.53	-3.45
Absorption	-15.	-12.
Virginia - Manassas (FHWA B5926); 50 % coarse, 50 % fine aggregate		
Bulk Dry Specific Gravity	0.86	1.04
Bulk SSD Specific Gravity	0.46	0.60
Apparent Specific Gravity	-0.17	-0.28
Absorption	-21.	-31.
Arizona (FHWA B5824); 50 % coarse, 50 % fine aggregate		
Bulk Dry Specific Gravity	-0.95	-0.04
Bulk SSD Specific Gravity	-1.16	-0.50
Apparent Specific Gravity	-1.39	-1.09
Absorption	-10.	-30.
Mississippi (FHWA B5849); 50 % coarse, 50 % fine aggregate		
Bulk Dry Specific Gravity	-0.04	-0.44
Bulk SSD Specific Gravity	-0.24	-0.59
Apparent Specific Gravity	-1.55	-1.78
Absorption	-17.	-11.
Virginia - Chantilly (FHWA B5742); 50 % coarse, 50 % fine aggregate		
Bulk Dry Specific Gravity	-0.59	0.28
Bulk SSD Specific Gravity	-0.55	0.00
Apparent Specific Gravity	-0.40	-0.40
Absorption	0.0	-21.

The most important differences are for the bulk dry specific gravities, as this specific gravity is used to calculate the VMA. Although the percent differences may appear to be small, the percent changes in VMA are closely related to these differences. As the bulk dry specific gravity decreases, the VMA will also decrease. By assuming a 4-percent air void level, the VMA were estimated for the mixtures. This data given in tables 75 and 76 shows that some of the differences are not acceptable for paving applications, as many are above a half percent. The alcohol/trichloroethylene wash after the normal extraction process provided the best results for the mixtures containing AC-5. Thus, this method, or some modification of it, warrants further study. Again, it is stated for emphasis that the aggregates evaluated were low to moderate in absorption and the percent absorption could have an effect on the test data.

Neither of the SEA extraction procedures could be chosen over the other, and it appears that the efficiency of these extraction processes may not always be good enough to determine aggregate properties. The data for the North Dakota aggregate did not agree.

For recycled asphalt mixtures, where less than 50 percent of the mixture is recycled asphalt pavement, the error would be low enough that a VMA requirement can be used. However, mixtures with asphalts harder than those used in this study would have to used to be verify this conclusion.

Table 75. Aggregate gravity study - percent voids in the mineral aggregate (VMA) for the combined aggregate with AC-5 binder.

	Stockpile Aggregate	After Extraction using Trichloro-ethelene	After Alcohol/ Trichloro-ethylene Wash	After Extraction using Alcohol/ Trichloro-ethylene
North Dakota (FHWA B5786)	15.5	14.4	16.0	14.0
Virginia - Manassas (FHWA B5926)	17.2	17.4	17.6	17.7
Arizona (FHWA B5824)	15.7	14.6	15.8	15.6
Mississippi (FHWA B5849)	15.8	14.8	15.7	16.0
Virginia - Chantilly (FHWA B5742)	17.8	17.2	18.1	17.4

Table 76. Aggregate gravity study - percent voids in the mineral aggregate (VMA) for the combined aggregates with SEA binder.

	Stockpile Aggregate	Centrifuge Extraction	Reflux Extraction
North Dakota (FHWA B5786)	13.4	11.4	11.0
Virginia - Manassas (FHWA B5926)	15.1	15.8	15.9
Arizona (FHWA B5824)	13.7	12.9	13.7
Mississippi (FHWA B5849)	13.7	13.7	13.4
Virginia - Chantilly (FHWA B5742)	15.5	15.0	15.8

REFERENCES

1. T. Beatty, K. Dunn, E. T. Harrigan, K. Stuart, and H. Weber, "Performance Evaluation of Sulfur Extended Asphalt Pavements - Field Survey and Assessment," FHWA Report DP54-01, Demonstration Projects Division, Federal Highway Administration, Washington DC, 20590, 1987.

2. T. Beatty, K. Dunn, E. T. Harrigan, K. Stuart, and H. Weber, "Field Evaluation of Sulfur Extended Asphalt Pavements," Transportation Research Record 1115, Asphalt Materials and Mixtures, Transportation Research Board, Washington DC, 20590, 1987, pp 161-170.

3. S. H. Carpenter, M. Darter, and B. J. Dempsey, "A Pavement Moisture Accelerated Distress (MAD) Identification System, Users Manual - Volume 2," FHWA/RD-81/080, Federal Highway Administration, Washington DC, 20590, September 1981.

4. H. L. Alder, and E. B. Roessler, Introduction to Probability and Statistics, Sixth Edition, W. H. Freeman and Company, San Francisco CA, 1977, pp 178-181.

5. American Association of State Highway and Transportation Officials, Standard Specifications for Transportation Materials and Methods of Sampling and Testing, Part II, Methods of Sampling and Testing, 444 North Capital Street, N.W., Suite 225, Washington DC, 20001, August 1986.

6. Staff Research Study entitled "Comparison of Mechanical Tests For Bituminous Concrete," Pavements Division, HNR-20, Federal Highway Administration, McLean VA, 22101-2296.

7. W. J. Kenis, "Predictive Design Procedures, VESYS Users Manual," FHWA/RD-77/154, Federal Highway Administration, Washington DC, 20590, January 1978.

8. American Society for Testing and Materials, 1989 Annual Book of ASTM Standards, Section 4--Volume 04.03, 1916 Race Street, Philadelphia PA, 19103-1187, May 1989.

9. American Society for Testing and Materials, 1988 Annual Book of ASTM Standards, Section 5--Volume 05.05, 1916 Race Street, Philadelphia PA, 19103-1187, October 1988.

10. G. Y. Baladi, "Integrated Material and Structural Design Method for Flexible Pavements," Volume I. Technical Report, FHWA-RD-88-109, Federal Highway Administration, Washington DC, 20590, December 1988.

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