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MODIFIERS FOR ASPHALT CONCRETE

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The primary objective of this research was to identify the most promising types of asphalt modifiers for reducing permanent deformation (rutting) in flexible airfield pavements. Modifiers selected for evaluation included carbon black, sulfur, styrene-butadiene-styrene, ethyl-vinyl-acetate, and polyolefin.

A series of binder and mixture tests were performed in the laboratory to evaluate the modifiers effects on an AR-4000 asphalt cement, and an asphalt concrete mixture containing a subrounded river gravel. Binder tests were performed before and after aging in the rolling thin film oven, and included penetration, viscosity, and ductility. Mixture tests included Marshall stability and flow, resilient modulus, creep modulus, and indirect tension. The results were used to estimate the effects of the modifiers on pavement rutting.

All of the modifiers significaltly reduced the amount of rutting estimated for a thin and thick pavement in a hot climate.

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EXECUTIVE SUMMARY

The primary objective of this research was to identify the most promising types of asphalt modifiers for reducing permanent deformation (rutting) in flexible airfield pavements.

Available literature was reviewed, and promising modifier types were identified. Five modifiers, systematically selected for evaluation, included:

1. Carbon black
2. Sulphur
3. Styrene-butadiene-styrene
4. Ethyl-vinyl-acetate
5. `yolefin

A series of binder and mixture tests was performed in the laboratory to evaluate the effects of the modifiers. A California Coastal AR-4000 asphalt cement with favorable temperature susceptibility characteristics was used to investigate modifier performance limits. A river gravel was used in the asphalt concrete mixture to increase the mixture's sensitivity to properties of the binders.

Binder tests were performed before and after aging in the rolling thin film oven (RTFO), and included penetration and viscosity at two temperatures, and ductility and weight loss during aging. From the physical binder tests, viscosity-temperature susceptibility (VTS), penetration-viscosity numbers (PVN), and penetration indexes (PI) were calculated to evaluate the modifier effects on the temperature susceptibility of the binder.

Mixture tests included Marshall stability and flow, resilient modulus at three temperatures, creep modulus at two temperatures, and indirect tension at one temperature. The test results were used to estimate the effects of the modifiers on pavement rutting.

The conclusions from this study are as follows:

1. All of the modifiers increased the viscosity of the binder at 140°F, and all but sulphur increased the viscosity at 275°F.

2. All of the modifiers, except sulphur, reduced the penetration of the binder at 77°F. At 39.2°F the carbon black, EVA, and polyolefin modifiers generally reduced, the sulphur increased, and the SBS increased or did not affect penetration.

3. All of the modifiers, except sulphur, demonstrated the ability to improve the temperature susceptibility of the binder.

4. All of the modifiers generally reduced the ductility of the binder, especially after aging in the RTFO.

5. It appears that conventional mix design procedures, such as the Marshall and Hveem methods, may be useful for estimating the optimum binder content for modified mixtures. Additional research should be performed, however, to investigate the applicability of current stability, unit weight, and air void criteria for use with modified mixtures.

6. All of the modifiers increased the Marshall stability of the mixture.

7. All of the modifiers increased the resilient modulus of the mixture. The increase was proportionately greater at higher temperatures, indicating that the modifiers can reduce the temperature susceptibility of the mixture.

8. All of the modifiers increased the tensile strength of the mixture at 77°F.

9. All of the modifiers increased the creep modulus of the mixture at 140°F, and all but the SBS modifier increased the creep modulus at 77°F.

10. All of the modifiers significantly reduced the amount of rutting estimated for a thin and thick pavement subjected to F-15 aircraft loads in a hot climate. Performance estimates indicated that carbon black, sulphur, and polyolefin were the most effective for reducing rutting.

11. All of the modifiers were found to be cost-effective in terms of rut prevention.

PREFACE

This report was prepared by Harding Lawson Associates, 7655 Redwood Boulevard, Novato, California 94945, under contract F08635-87-C-0369, Small Business Innovative Research AF87-067, Phase I, for the Air Force Engineering and Services Center, Engineering and Services Laboratory, Tyndall Air Force Base, Florida 32403. This report was submitted as part of the SBIR program and has been published according to SBIR directives in the format in which it was submitted.

This report summarizes work performed between September 1987 and July 1988. Mrs. Patricia C. Suggs was the AFESC/RDCP Project Engineer.

Special appreciation is extended to Mr. David E. Newcomb and Dr. John Epps of the University of Nevada, Reno, and Mr. Carl L. Monismith of the University of California, Berkeley for their valued contributions to the project.

This report has been reviewed by the Public Affairs Office (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nationals.

This report has been reviewed and is approved for publication.

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SECTION I

INTRODUCTION

A. OBJECTIVE

Recent developments in testing technology and pavement performance modeling allow the engineer to evaluate the potential benefits of asphalt modifiers. This technology has been used to evaluate the potential benefits of asphalt modifiers for reducing permanent deformation (rutting) in flexible airfield pavements.

The objectives of this research program were to:

1. Identify the most promising types of asphalt modifiers for reducing permanent deformation in flexible airfield pavements.

2. Identify laboratory test procedures that are promising indicators for rutting potential.

3. Ascertain the economic feasibility of using modifiers in pavement mixtures to reduce rutting.

Achievement of these goals will provide a basis for more detailed research aimed at developing guidelines for modifier use and criteria for modifier acceptance.

B. BACKGROUND

One of the major problems affecting the performance of Air Force asphalt concrete pavements is permanent deformation associated with high temperature service. In recent years this problem has been intensified by the use of greater tire pressures for fighter aircraft. Rutted or otherwise permanently deformed pavements present serious safety and operational problems for aircraft. Furthermore, the repair of a rutted pavement can cause lengthy interruptions to normal operations, and can be very expensive.

The ability of asphalt mixtures to resist permanent deformation under moving or stationary wheel loads depends to a great extent on the properties of the binder. Asphalts are viscoelastic and thermoplastic materials; that is, their stress-versus-strain characteristics are both time and temperature dependent. The physical properties of asphalt cements are primarily established by their crude source and method of refining.

Research indicates that modifiers can be used to successfully reduce rutting by improving the high-temperature properties of a mixture (References 1,2,3,4,5). Also, improved high-temperature behavior can be obtained without significantly altering low-temperature characteristics; therefore, an asphalt with favorable low-temperature properties can be stiffened at high temperatures through modification, reducing its susceptibility to change in properties with temperature.

Asphalt modifiers have also been used to improve the properties of mixtures containing marginal quality aggregates. The use of modifiers for this purpose can be very significant in terms of cost savings and/or the ability to build in remote locations using locally available materials.

A generic classification of available asphalt modifiers is given on Table 1, and Table 2 lists modifier effects on the consistency of asphalt cement (Reference 6).

C. SCOPE

Work performed as part of this research project included the following:

1. Identifying promising modifier types for reducing permanent deformation and selecting five for testing and evaluation.
2. Testing to measure physical properties of the original and modified asphalt cement before and after aging in a rolling thin film oven.
3. Testing to measure physical properties of asphalt concrete mixtures containing the original and modified asphalt cements.
4. Estimating the performance of the standard and modified mixtures in terms of rutting potential.
5. Analyzing the cost effectiveness of the modifiers based on the performance estimates.

TABLE 1. GENERIC CLASSIFICATION OF ASPHALT MODIFIERS

Type	Examples
1. Filler	° Mineral filler: crusher fines, lime, Portland cement, fly ash ° Carbon black ° Sulphur
2. Extender	° Sulphur ° Lignin
3. Rubber	
a. Natural latex	° Natural rubber
b. Synthetic latex	° Styrene-butadiene or SBR
c. Block copolymer	° Styrene-butadiene-styrene or SBS
d. Reclaimed rubber	° Recycled tires
4. Plastic	° Polyethylene ° Polypropylene ° Ethyl-vinyl-acetate, EVA ° Polyvinyl chloride, PVC
5. Combination	° Blends of polymers in 3 & 4
6. Fiber	° Natural: Asbestos, Rock Wool ° Man-made: Polypropylene, Polyester, Fiberglass
7. Oxidant	° Manganese salts
8. Antioxidant	° Lead compounds ° Carbon ° Calcium salts
9. Hydrocarbon	° Recycling and rejuvenating oils ° Natural asphalts
10. Antistrip	° Amines ° Lime

(After Reference 6)

TABLE 2. GENERAL EFFECT OF MODIFIERS ON CONSISTENCY OF ASPHALT CEMENT

Modifier		Usual Effect on Asphalt Consistency
1	Mineral filler	Harden
2	Extender	Harden
3	Rubber	*
4	Plastics	Harden
5	Combinations of 2, 3, and 4 above	*
6	Fibers	Harden
7	Oxidants	Harden
8	Antioxidants	Soften
9	Hydrocarbons	Soften
10	Antistripping Agents	Soften

* Some materials both soften and harden asphalt cement depending upon the temperature range.

(After Reference 6)

SECTION II

MATERIAL SELECTION

A. SELECTION OF MODIFIERS

A literature search was conducted to identify asphalt modifiers. This literature review identified a large number of potential modifiers (Table 1). A detailed review of the literature indicated that a relatively small number of references existed (References 1-14) which sufficiently defined: (1) properties of the modifier, (2) properties of the modified asphalt cement, and (3) properties of the modified asphalt in an asphalt-aggregate mixture. These more detailed reports, and the experience of the research team, were used to select the five most promising modifiers. The factors of: (1) physical properties, (2) field performance, (3) availability, (4) cost, and (5) constructability were considered in the final selection.

1. Definition and Classification

For this study, the modifier definition and classification system presented in Reference 6 was adopted. In this system the term "asphalt modifier" includes both asphalt cement additives and asphalt cement extenders. An asphalt additive is a material added to the asphalt cement or asphalt aggregate mixture to improve the properties and/or performance of the resulting binder mix. An additive changes the binder properties, improves the bond between the aggregate and asphalt, or changes properties of the mixture. An asphalt cement extender is an additive which replaces a part of the asphalt cement that would normally be used in the mix. Its use may result in performance improvements, but its primary intent is improved economy.

Asphalt modifiers are classified according to type. The classification system used is shown in Table 1.

2. Modifier History

Asphalt additives and extenders have a long but somewhat limited history in pavement construction. Since the first use of lime and sulphur in asphalt mixtures, over 50 years ago, several hundred modifiers have been introduced. Except for some of the mineral fillers, asphalt modifiers have not been widely used in paving construction. Limited, comprehensive pavement performance data exists, making the comparison of conventional and modified asphalt concrete mixtures difficult.

Asphalt modifiers may be used for a number of reasons; however, current emphasis is directed at correcting pavement performance problems. These problems include rutting, thermal cracking, placement difficulties, and water susceptibility (References 1,2,6,7).

3. Promising Types

The objective of this phase of research was to identify the most promising types of modifiers for reducing permanent deformation in airfield pavements. Asphalts are viscoelastic and thermoplastic materials, meaning their stress-versus-strain characteristics are time-dependent, and their consistency or degree of hardness varies with temperature. Thus, modifiers are desired that reduce the effects of time on the stress-versus-strain properties and stiffen or harden the asphalt cement at high temperatures. The general effect that each of the modifier types has on asphalt consistency is shown in Table 2.

As indicated in this table, some antioxidants, hydrocarbons, and antistrip modifiers soften the asphalt cement. Stiff hydrocarbons and mineral filler types of antistrip modifiers can, however, improve mixture stiffness at high temperatures. These modifiers were not selected because improved benefits could be obtained with other types of products.

Fiber modifiers appear to be most effective for improving the resistance of asphalt concrete overlays to reflection cracking (References 2,8). Fibers do not significantly modify the properties of the asphalt binder but they can increase the tensile strength of the mix. The literature review suggests that fiber modification does not improve the resistance to rutting. Thus, this type of modifier was eliminated from further consideration.

Oxidant modifiers are metal compounds that catalyze the oxidation and polymerization of asphalt cement. Performance indicates that oxidants increase the asphalt stiffness and improve the mixture's resistance to rutting (References 1,2,9). The reaction between the oxidant modifier and the asphalt involves a curing period, and is somewhat difficult to control. Since the only commercial oxidant product was recently taken off the market, this modifier type was eliminated from further consideration.

The primary purpose of extender modifiers, as defined, is to replace a portion of the asphalt cement for economy. Sulphur-extended asphalts, however, show promise for reducing rutting, (References 1,10,11) and were included in the evaluation.

The promising modifier types selected for this study were:

a. Fillers
b. Extenders
c. Rubbers
d. Plastics
e. Combination of rubbers and plastics

4. Product Selection

From the list of promising modifier types, five specific products were chosen for evaluation in this study. They were, except for sulphur, commercial products marketed specifically for asphalt modification. Sulphur is currently marketed by several companies for use in asphalt modification; however, sulphur for this study was obtained from a local chemical supplier. The factors that influenced the selection of specific products from each classification group are briefly discussed below.

a. Filler: From the filler group, carbon black appeared the most promising. Research on carbon black (Reference 5) strongly suggests that its use can increase the resistance to high-temperature distortion, and by improving the viscosity-temperature characteristics of the binder, improve or retain the low-temperature properties that help reduce thermal cracking.

b. Extender: A considerable amount of research has been performed on sulphur-modified asphalts. Sulphur significantly stiffens the asphalt mixture at higher temperatures thereby improving resistance to permanent deformation (References 10,11). By using softer asphalts the potential for limiting low-temperature cracking also exists.

c. Rubber: The literature indicates that block copolymers such as synthetic latex, particularly styrene-butadiene rubber (SBR), and styrene-butadiene-styrenes (SBS) are successful in increasing asphalt binder stiffness at high temperatures (References 3,12). Natural latexes appear to be best suited for use in chip and slurry seals to improve aggregate retention (Reference 2). A recent study (Reference 13) that evaluated asphalts modified with reclaimed rubber for use in civilian airport pavements indicated that permanent deformation characteristics of the asphalt modified with the reclaimed rubber were not significantly better than the untreated control mixture. Of the synthetic latex and block copolymers currently available, the block copolymer (SBS) appears to have a greater effect on the viscosity of the asphalt at high temperatures (Reference 12), and was chosen for study.

d. Plastics: Literature indicates that polyethylene, polypropylene, and ethyl-vinyl-acetate (EVA) can be effective in increasing the binder stiffness at high temperatures (References 3,14). EVA was selected to represent the plastic modifier category and polyethylene product was selected for use as a combination-type modifier.

e. Combination: Polyethylene and polypropylene products have demonstrated the ability to stiffen asphalts at high temperatures (Reference 2). An ethylene-acrylic acid combination polyolefin product was chosen for use in this study.

The specific gravities of the modifiers, as determined from product literature, material safety data sheets, and Reference 15, were roughly:

a. Carbon Black - 1.75
b. Sulphur - 1.96
c. SBS - 0.96
d. EVA - 0.96
e. Polyolefin - 0.92

B. SELECTION OF ASPHALT

An AR-4000 grade paving asphalt from a California Coastal (Santa Maria) crude source with low viscosity-temperature susceptibility characteristics was chosen to investigate performance limits of the modifiers. This asphalt cement roughly corresponds to an AC-10, or a pen 120-150 grade used in other parts of the country. Its specific gravity was 1.03.

C. SELECTION OF AGGREGATE

A subrounded gravel from Healdsburg, California was used to make the asphalt concrete mixtures for testing. A gravel rather than a crushed aggregate was selected to increase the sensitivity of the asphalt concrete mixtures to the characteristics of the binders.

SECTION III

BINDER TESTING

A. SAMPLE PREPARATION

The basic modifier/asphalt mixing process involved heating approximately 1 gallon of asphalt to 290°F, then slowly adding the modifier, while blending the mixture with a paint stirrer, mounted in a variable-speed electric drill. The samples were mixed for 5 minutes and heated on a hot plate during mixing.

This method worked well for the EVA and polyolefin additives; however, it was necessary to modify the method for preparation of the sulphur, SBS, and carbon black blends. The sulphur-modified asphalt was prepared by melting the sulphur on the hot plate, then mixing it in liquid form with the asphalt as described above. Dispersion of the SBS additive into the asphalt required that the mixture be heated to more than 290°F; 350°F was utilized. To ensure that the SBS was completely heated before mixing, it was added to the hot asphalt 1 hour before blending. The pelletized carbon black used would not break down with the basic method of mixing. The manufacturer recommended that samples be prepared in a laboratory with a high-shear mixer. The mixing process used involved preheating the asphalt to 275°F and adding the carbon black during a 5-minute mixing period in the high-shear blender. The high-shearing action of the blender was required to break down and disperse the pelletized carbon black.

The unmodified asphalt (control sample) was also subjected to the 290°F heating and basic 5-minute blending process.

The modifiers were added in concentrations recommended by their respective manufacturers to maximize their effectiveness in preventing permanent deformation. The concentrations used for the various modifiers, in percent by weight of the total binder mixture, were as follows:

1. Carbon black - 14 percent
2. Sulphur - 30 percent
3. SBS - 12 percent
4. EVA - 5 percent
5. Polyolefin - 5 percent.

B. LABORATORY TESTING

The binder test sequence is illustrated in Figure 1, the laboratory test results are summarized in Table 3, and individual test data are presented in Appendix A.

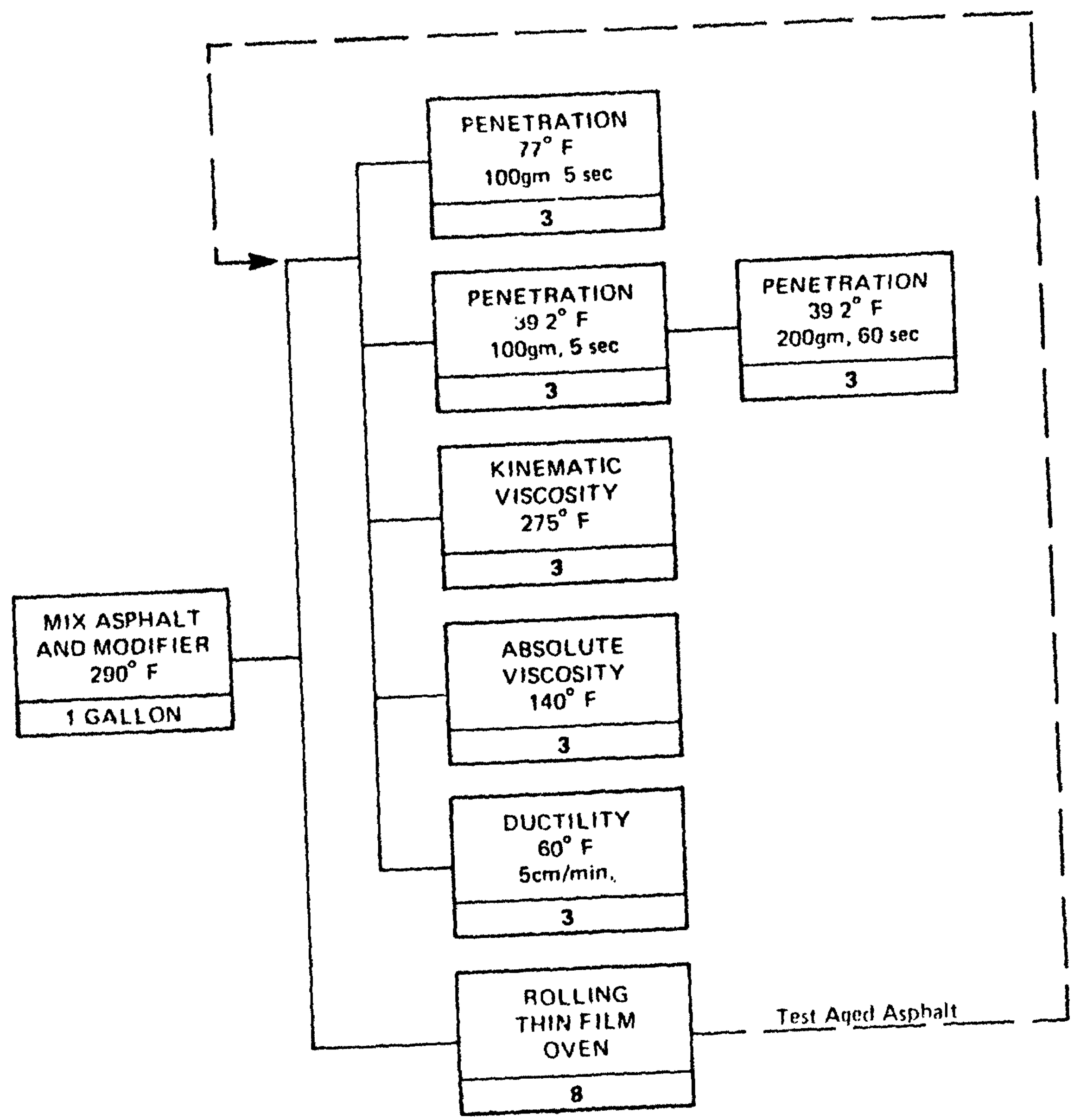


Figure 1. Binder Test Sequence

TABLE 3. BINDER PROPERTIES

Asphalt Source Grade Modifier Type (a) Asphalt,% Modifier,%	California Coastal AR-4000 ------- 100 0		CB 85 15		S 70 30		SBS 88 12		EVA 95 5		P 95 5	
	Unaged	Aged(i)	Unaged	Aged	Unaged	Aged(j)	Unaged	Aged	Unaged	Aged	Unaged	Aged
Viscosity at 140F (b),P	1023	2872	3127	11904	1174	1447	4644	10642	1726	5079	1756	6890
Viscosity at 275F(c),cSt	280	463	740	1632	154	199	1045	1885	856	1859	529	1269
Penetration at 77F(d), 100g, 5sec	112	63	90	42	192	101	93	57	92	46	99	44
Penetration at 39.2F, 100g, 5sec	16	14	13	8	23	15	19	14	17	10	17	12
Penetration at 39.2F, 200g, 60sec	53	35	42	24	84	41	54	34	48	27	46	27
VTS 140F to 275F (e)	3.54	3.54	3.21	3.14	4.15	3.99	3.11	3.01	2.86	2.75	3.23	3.12
PVN (f)	-0.6	-0.5	0.6	0.8	-1.0	-1.3	1.2	1.3	0.8	1.0	0.2	0.5
PI (g)	-0.04	1.74	-0.00	1.05	-0.61	0.09	1.35	2.24	0.92	1.64	0.63	2.80
Ductility (h)	150	150	150	83	37	27	108	89	80	20	150	55
Weight loss after rolling thin film oven test,%	0.2			1.4		2.29		1.54		1.22		1.29

(a) CB=Carbon black ; S=Sulfur ; SBS=Stryene-butadiene-styrene ; EVA=Ethyl-vinyl-acetate ; P=Polyolefin
(b) ASTM-D2171
(c) ASTM-D2170
(d) ASTM-D5
(e) VTS=(log log n1 - log log n2)/(log T2 - log T1) where n=viscosity in P, T=absolute temperature
(f) PVN=(-1.5)((4.258 - 0.7967 log P - log X)/(.7951 - 0.1858 log P)) where P=penetration at 77F (dmm), X=viscosity at 275F (cSt)
(g) PI=(20 - 500x)/(1 + 50x)
x=[log (pen2) - log (pen1)]/(T2 -T1)
where pen(x)=penetration at x (dmm), T(x)=temperature at x (C)
(h) ASTM-D113
(i) Aged residue from rolling thin film oven test
(j) Modified rolling thin film oven test

All laboratory testing was performed in accordance with American Society for Testing and Materials (ASTM) test procedures, except for the rolling thin film oven test (RTFO) performed on the sulphur-modified asphalt. For sulphur the RTFO test temperature was reduced from 325°F to 300°F to minimize the release of gases.

Binder testing, performed before and after aging in the rolling thin film oven (RTFO), included viscosity at 140°F and 275°F, penetration at 39.2°F and 77°F, and ductility at 60°F. Weight loss during aging in the RTFO was also measured.

Viscosity and penetration test results for the original asphalt after aging in the RTFO indicated that it did not meet criteria for an AR-4000 grading. After comparison with test data from the refinery, it was concluded that the oven used did not age the asphalt to the degree expected. Since this study is comparative, and the same procedure was followed on all samples, this should not affect conclusions.

C. BINDER PROPERTIES

1. Viscosity and Penetration

The test data indicates that all of the modifiers increased the viscosity of the binder at 140°F, and all except the sulphur at 275°F. The increased viscosity is important in terms of rut prevention. All of the modifiers except sulphur reduced penetration at 77°F. At 39.2°F the carbon black, EVA, and Polyolefin modifiers generally reduced penetration, while the sulphur increased, and the SBS modifier increased or did not affect the penetration. The modifier's effect on binder penetration was greater at 77°F than at 39.2°F, indicating that some of the low temperature properties of the original asphalt were retained.

2. Viscosity-Temperature Relationships

From the binder test data, the viscosity-temperature susceptibility (VTS), penetration-viscosity number (PVN), and the penetration index (PI) were calculated according to the following equations (Reference 16):

$$PVN = \frac{4.258 - 0.7967 \log P - \log X}{0.7951 - 0.1858 \log P} \quad (-1.5)$$

where P = penetration at 77°F (25°C), dmm
X = viscosity at 275°F (135°C), centistokes

$$VTS = \frac{\log \log(100\ _1) - \log \log(100\ _2)}{\log T_2 - \log T_1}$$

where 1 = viscosity @ T_1 (140°F), poises
2 = viscosity @ T_2 (275°F), poises
T = temperature, °Kelvin

$$PI = \frac{(20 - 500x)}{(T + 50x)}$$

$$\text{where } x = \frac{(\log P_2 - \log P_1)}{(T_2 - T_1)}$$

where P_1 = penetration at T_1, dmm
P_2 = penetration at T_2, dmm
T = temperature, °C

PVN, VTS, and PI are measures of the sensitivity of the consistency of a binder to changes with temperature, or the temperature susceptibility of the binder. A greater VTS and a lower PVN and PI indicate increased temperature susceptibility. PI is determined from penetration measurements; VTS is based on viscosity; and PVN is based on penetration and viscosity. PI defines the temperature susceptibility over the temperature range of 39.2°F to 77°F, PVN from 77°F to 275°F, and VTS from 140°F to 275°F. The PI, VTS, and PVN calculations for the binders are shown in Table 3.

All of the modifiers except sulphur improved the temperature susceptibility of the binder, as measured by VTS and PVN. The PI results indicate that the aged original asphalt has better temperature susceptibility characteristics than all but the SBS and polyolefin modified binders.

3. Ductility

The addition of the carbon black and polyolefin modifiers did not decrease the ductility of the unaged binder. Ductility of the unaged binder was decreased, however, with the addition of sulphur, SBS, and EVA (Table 3).

All of the modifiers lowered the ductility of the aged binder. The blends containing carbon black and SBS had the highest ductility after aging (Table 3).

4. Volatility

The weight loss associated with the use of the modifiers was greater than the unmodified asphalt cement. The sulphur-modified binder had the greatest weight loss (Table 3).

SECTION IV

ASPHALT CONCRETE MIXTURE TESTING

A. MIXTURE DESIGN

To maintain consistency with Air Force procedures for severe loading conditions, a 3/4-inch maximum, high-pressure wearing coarse mix, as specified in AFM88-6 (Reference 17), was chosen for testing. Sieve analysis and bulk specific gravity test results for the aggregate used are presented in Table 4.

Modified Marshall and Hveem design procedures were used to select the binder content of the mixtures tested. Both procedures involved testing a total of six specimens at three binder contents (two each) for each of the binder types. Binders contained the modifier concentrations recommended by their manufacturer.

The Marshall mixture design procedure included measurement of Marshall stability and flow, specimen bulk specific gravity, mixture maximum theoretical specific gravity, and determination of percent air voids and voids filled in the lab specimens. Test specimens were compacted at 250°F with 75 blows per side.

The Hveem design procedure included measurement of Hveem stability, specimen bulk specific gravity, mixture maximum theoretical specific gravity, and determination of percent air voids in the lab specimens. Hveem test specimens were compacted with the California kneading compactor at 230°F, in accordance with the design procedure.

Based on the mix design test results, a binder content of 5.7 percent, by weight of mix, was selected for preparation of the laboratory mixtures. This value was roughly the average binder content for all mixes at 4 percent air voids. The mixture design test results are shown in Appendix B.

B. SPECIMEN PREPARATION

Lab specimens for Marshall stability, resilient modulus, and indirect tension testing were prepared according to Marshall test procedures at a compaction temperature of 250°F. The compaction effort was adjusted from the standard 75 blows per side as necessary to maintain roughly 4 percent air voids in specimens of the various mixtures. The compaction efforts used are summarized in Appendix C.

Lab specimens for creep modulus testing were prepared in accordance with the procedures first suggested by Shell Researchers (Reference 18) and modified by Finn, et al. (Reference 19). Creep specimens were compacted at

TABLE 4. AGGREGATE TEST DATA

GRADATION TEST DATA

Sieve Size	Percent Passing Used	Percent Passing Specification Limits
3/4"	100	100
1/2"	89	89 ± 7
3/8"	82	82 ± 7
No. 4	66	66 ± 7
No. 8	54	53 ± 7
No. 16	41	41 ± 7
No. 30	32	31 ± 7
No. 50	21	21 ± 7
No. 100	14	13 ± 5
No. 200	5	4.5 ± 1.5

PHYSICAL TEST DATA

Specific Gravity (SSD Basis)	2.675
Specific Gravity (Apparent)	2.778
Absorption, %	2.2

230°F with the California kneading compactor. The compactive effort was adjusted as necessary to maintain roughly 4 percent air voids in the various mixtures. The compaction efforts used are summarized in Appendix C.

The lab specimens were tested according to the sequence illustrated in Figure 2.

C. MARSHALL STABILITY AND FLOW

Marshall stabilities and flow values were determined using a Marshall loading apparatus in accordance with ASTM D1559. The test specimens were loaded at 140°F at a constant deformation rate of 2 inches per minute. The test data are summarized in Table 5, and individual test results are presented in Appendix C.

As shown in Table 5, Marshall stabilities were greater for the modified mixtures than for the unmodified mixture. Of the modified mixtures, carbon black had the highest Marshall stability and EVA had the lowest. An increase in Marshall stability for a given aggregate at a fixed binder content is usually a result of an increase in binder stiffness, as measured by viscosity at 140°F. Flow values for the modified mixtures were the same or slightly higher than the unmodified mixture.

D. RESILIENT MODULUS

The resilient modulus (stiffness) was measured at three temperatures (34°F, 77°F, and 104°F) according to the procedures described in ASTM D4123. The diametral load was applied for a duration of 0.1 second with a 2.9-second rest period. The test data is summarized in Table 5, and individual test results are presented in Appendix C. The resilient modulus-temperature relationships are shown on Figure 3.

As shown on Figure 3, the resilient moduli of the unmodified mixture were less than the moduli of the modified mixtures. The moduli at the lowest temperature (34°F) were much closer together than at the higher temperatures where the modifiers display the ability to increase the resilient modulus of the mixture. Sulphur had the highest resilient moduli, and SBS had the lowest of the modified mixtures. The slope of the resilient modulus-temperature relationship is the lowest for the sulphur-modified binder.

E. INDIRECT TENSION

The indirect tensile test was used to estimate the tensile strength of the mixtures. Test specimens were loaded diametrally at a constant rate of deformation until complete failure occurred. Testing was performed at 77°F

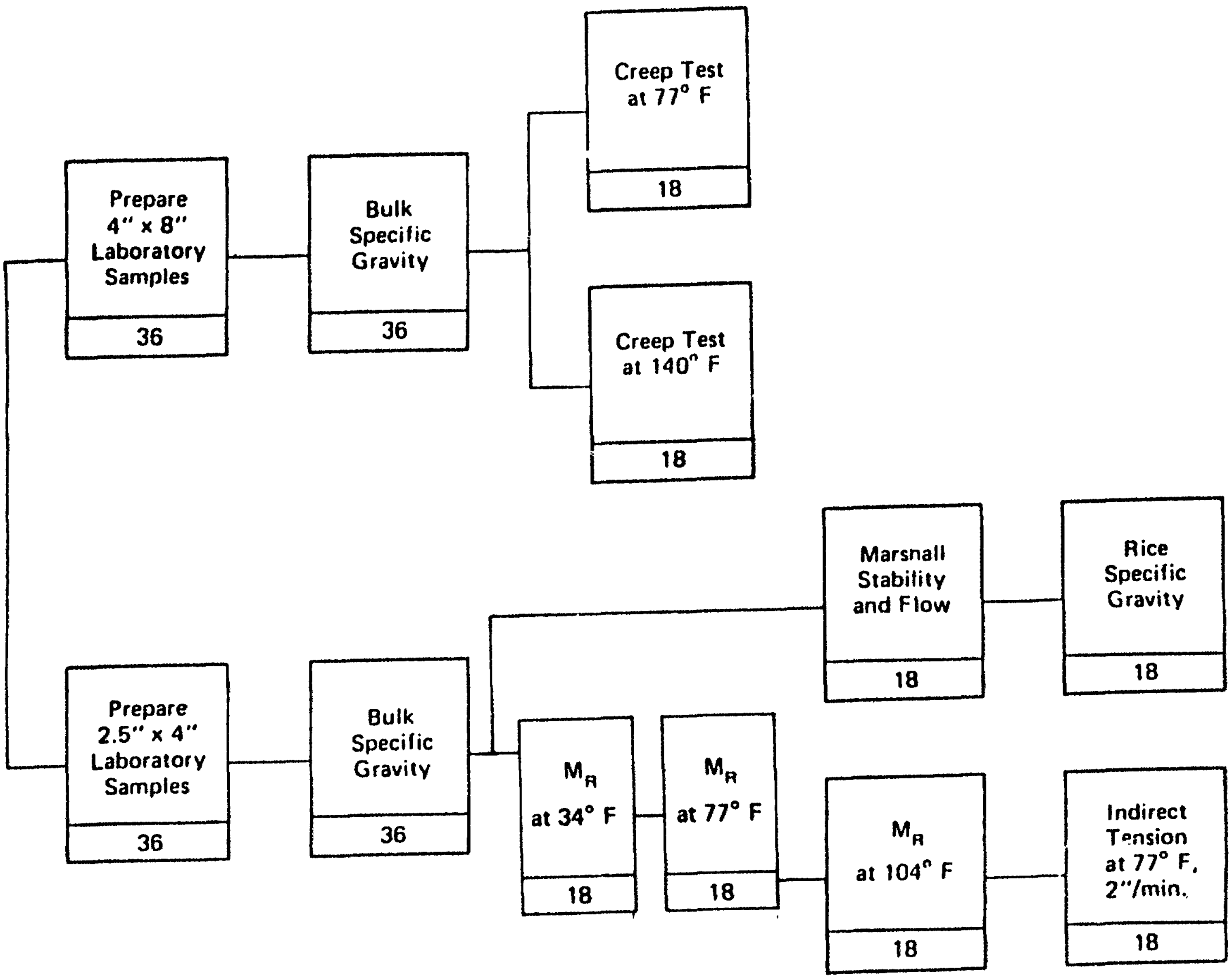


Figure 2. Asphalt Concrete Mixture Test Sequence

TABLE 5. MARSHALL STABILITY, RESILIENT MODULUS, INDIRECT TENSION, AND SPECIFIC GRAVITY TEST DATA

MODIFIER TYPE*	SPECIFIC GRAVITY		AIR VOIDS (%)	MARSHALL		RESILIENT MODULUS, (ksi)			INDIRECT TENSION, (psi) 77°F
	BULK	MAXIMUM THEO.		STABILITY (lbs)	FLOW (.001 in)	34°F	77°F	104°F	
NONE	2.374	2.476	3.8	2046	11	2278	148	31	101
CB	2.379	2.486	4.3	3407	12	2828	296	78	167
S	2.393	2.510	4.3	3196	11	3141	489	156	127
SBS	2.371	2.466	3.9	2543	13	2697	228	54	109
EVA	2.362	2.468	4.3	2200	11	3179	369	104	140
P	2.366	2.471	4.2	2453	12	2887	365	112	142

* CB=Carbon Black; S=Sulphur; SBS=Styrene-butadiene-styrene; EVA=Ethyl-vinyl-acetate; P=Polyolefin

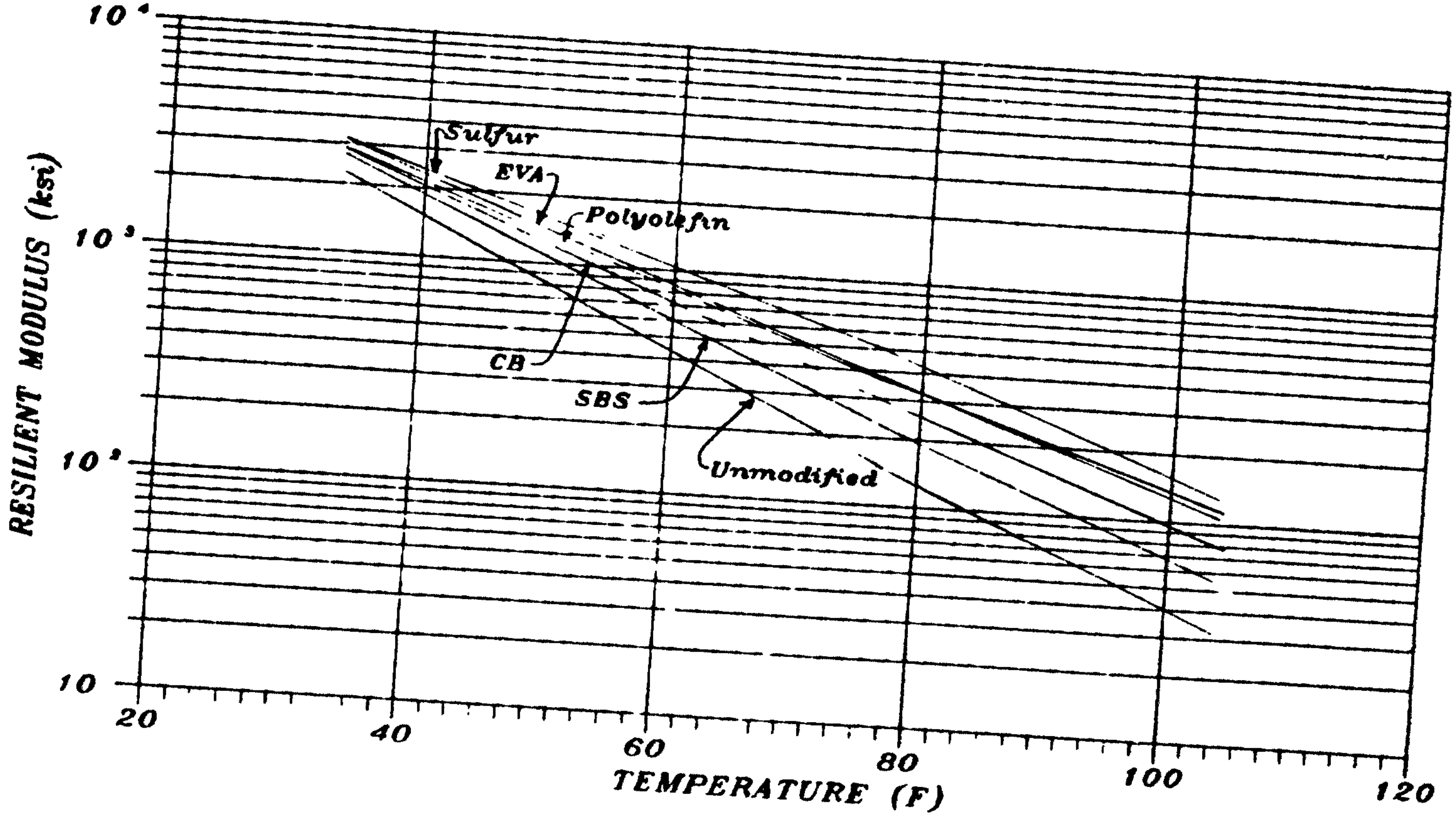


Figure 3. Resilient Modulus vs. Temperature

and a vertical deformation rate of 2 inches per minute. The test data are summarized in Table 5, and individual test results are presented in Appendix C.

The tensile strength of the unmodified mixture was less than the modified mixtures. Carbon black had the highest tensile strength and SBS had the lowest of the modified mixtures.

F. CREEP MODULUS

Unconfined creep tests were performed on 4-inch-diameter by 8-inch-high cylindrical specimens of the mixes at 77°F and 140°F according to the procedures first suggested by Shell Researchers (Reference 17) and modified by Finn, et al. (Reference 18). The tests at 77°F were conducted with an applied stress of 30 pounds per square inch (psi), while most of those at 140°F were conducted with a stress of 20 psi. At least three specimens were tested at each temperature for all of the mixtures. The average results of the creep tests plotted in the form of creep modulus versus time are shown in Figures 4 and 5, and individual creep test data is presented in Appendix C.

The creep modulus at a specific time, t, was determined from the following equation:

$$\text{Creep modulus, } S_{mix} = \frac{\text{applied stress (psi)}}{\text{strain at time t}}$$

The following was observed from the plots of creep modulus vs. time:

1. At 77°F, the creep moduli of the sulphur, polyolefin, carbon black, and EVA modified mixtures were all slightly higher than that of the unmodified asphalt at all times of loading. The creep modulus of the SBS-modified asphalt was lower than the unmodified asphalt mixture at all times of loading.

2. At 140°F the creep moduli of all the modified asphalt mixtures were significantly greater than that of the unmodified mixture at all times of loading. Of the modified mixtures, sulphur had the greatest creep modulus at all but very short times of loading, and SBS had the lowest creep modulus at all temperatures.

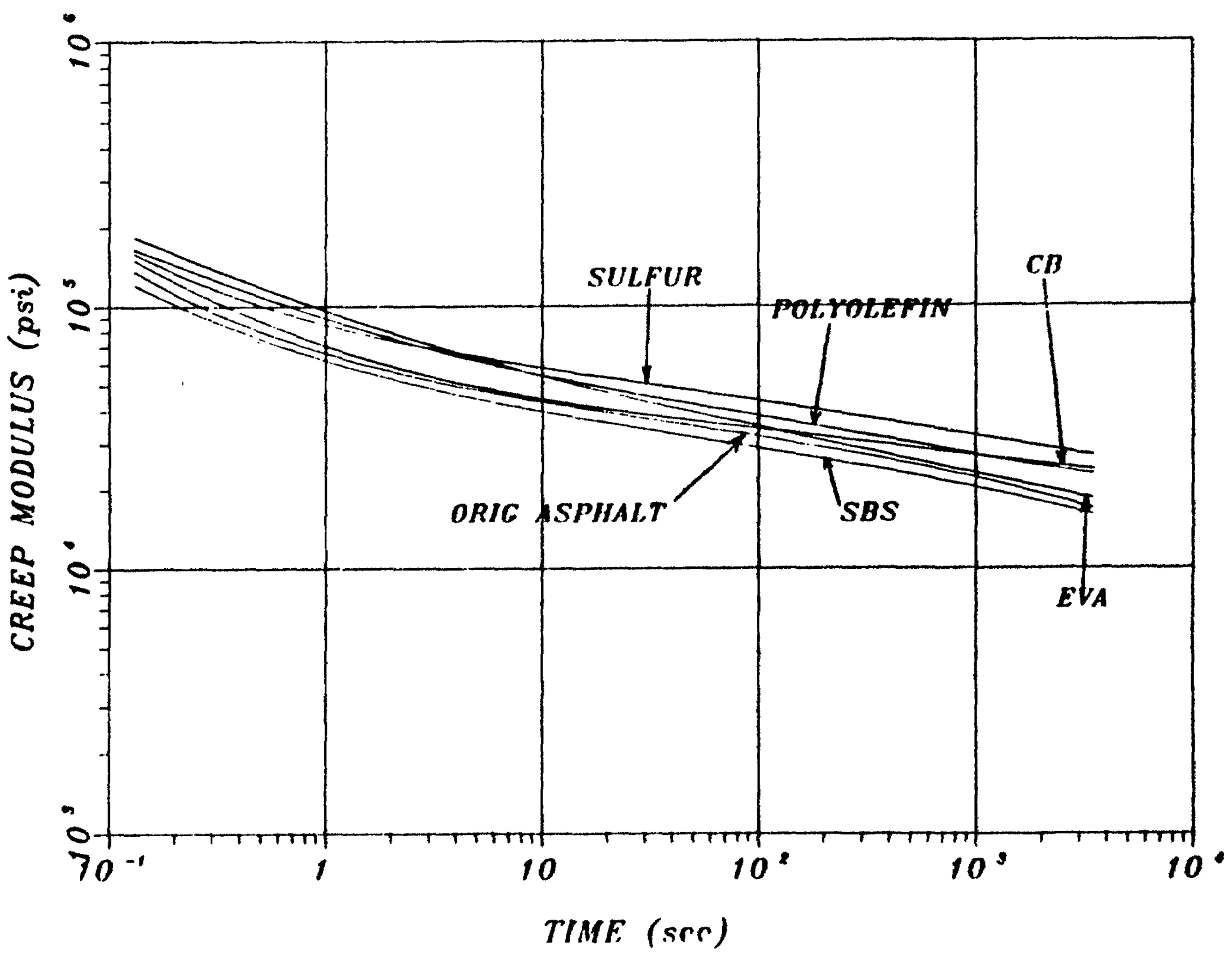


Figure 4. Creep Modulus vs. Time at 77°F

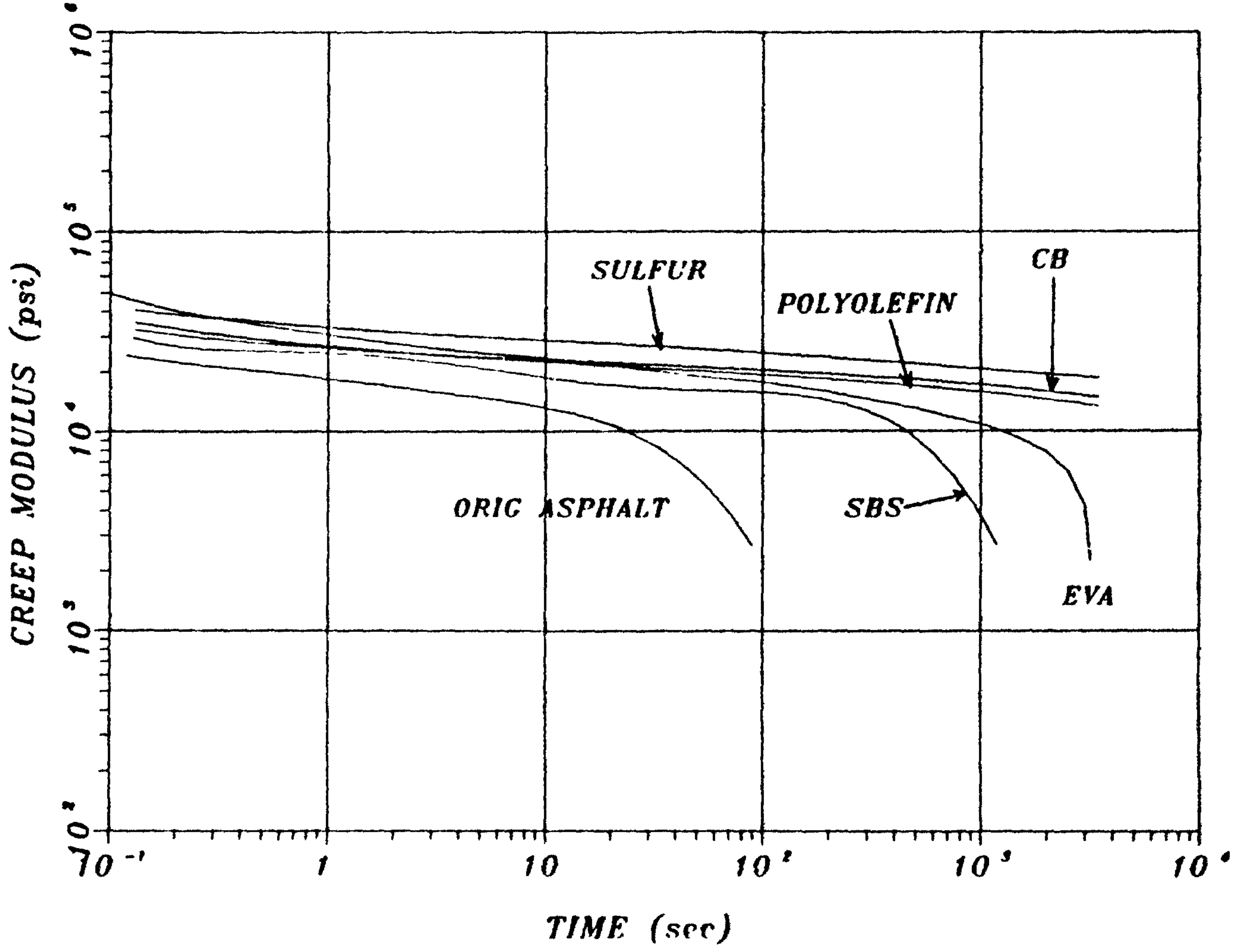


Figure 5. Creep Modulus vs. Time at 140°F

G. SPECIFIC GRAVITY

The bulk specific gravity (SSD basis) of each of the laboratory test specimens were measured in accordance with ASTM D2726 before testing. After testing, the maximum theoretical specific gravity of each mixture was measured in accordance with ASTM D2041. Using the specific gravity test data, the percent of air voids was calculated for the test specimens. The test data and air void calculations are summarized in Table 5, and individual test results are presented in Appendix C.

SECTION V

PERFORMANCE ESTIMATES

A. PERMANENT DEFORMATION ANALYSIS

The creep properties of the original and modified mixtures were used to comparatively evaluate the mixtures' propensity for rutting. Two pavement sections were analyzed: one containing a 4-inch-thick layer of asphalt concrete, the other a 12-inch-thick layer. The pavement sections are shown in Figure 6. Temperature conditions typically representative of a hot summer day in the southwestern United States and loading conditions representative of the F-15 aircraft (27,000-pound wheel load and 355 psi tire pressure) were used in the analysis. Temperatures recorded in Yuma, Arizona (Reference 20) were used with the Barber Equation (Reference 21) to estimate the temperature distribution with depth in the asphalt concrete pavement layer. The temperature versus depth relationship is shown in Figure 7. It was assumed that the traffic was relatively slow moving (load time of 0.1 second), and the rut depth was calculated after 500, 15,000, and 36,000 load repetitions (load times of 50, 1500, and 3600 seconds).

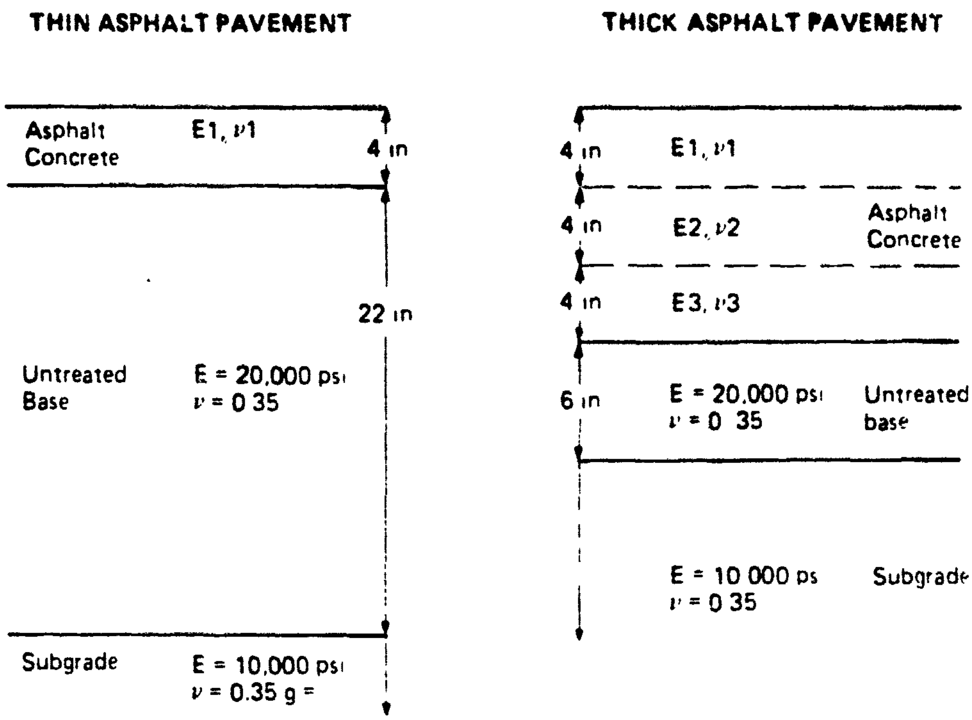
To account for the variations in mixture stiffness with depth, which occur in the asphalt layers because of the temperature gradient, the layers were subdivided as shown in Figure 6. The Poisson's ratios and the temperatures used to select layer stiffnesses are also shown in Figure 6. Stiffness versus temperature relationships for the mixtures were developed from the creep test data, and are shown in Figure 8 for a load time of 0.1 second, in Figure 9 for a load time of 50 seconds, in Figure 10 for a load time of 1500 seconds, and in Figure 11 for a load time of 3600 seconds.

Rut depths were calculated using a modified (Reference 17) Shell procedure. Permanent deformation was calculated with the following equation:

$$h = C \times h \; \frac{\text{average vertical compressive stress}}{S_{mix}}$$

where h = permanent change in layer thickness
C = correction factor (assumed to be 1.0)
h = layer thickness
S_{mix} = creep modulus at a specific time of loading and temperature

The average vertical compressive stress was determined from the CHEVPC elastic layer program using the mixture stiffness data in Figure 8 and the base and subgrade stiffness data shown in Figure 6. The creep modulus (S_{mix}) was obtained from Figure 9 for 500, Figure 10 for 15,000, and



ASPHALT LAYER PROPERTIES

LAYER NO	DEPTH RANGE (in)	DEPTH OF CENTER OF LAYER (in)	TEMPERATURE AT CENTER (F)	POISSON'S RATIO
1	0-4	2	126	0 48
2	4-8	6	109	0 46
3	8-12	10	101	0 45

Figure 6. Pavement Sections Used in Rutting Analysis

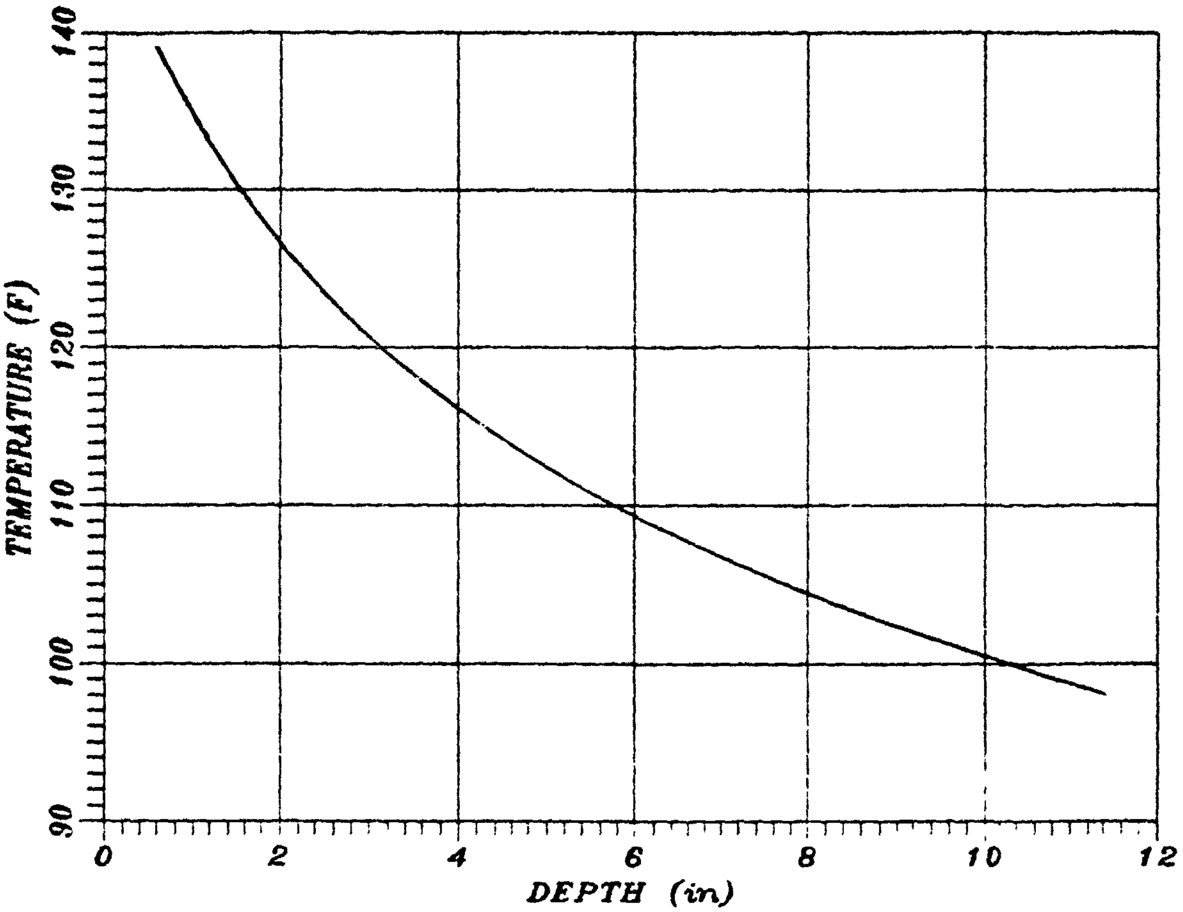


Figure 7. Temperature Distribution within the Pavement Section for a Hot Summer Day in Southwestern United States

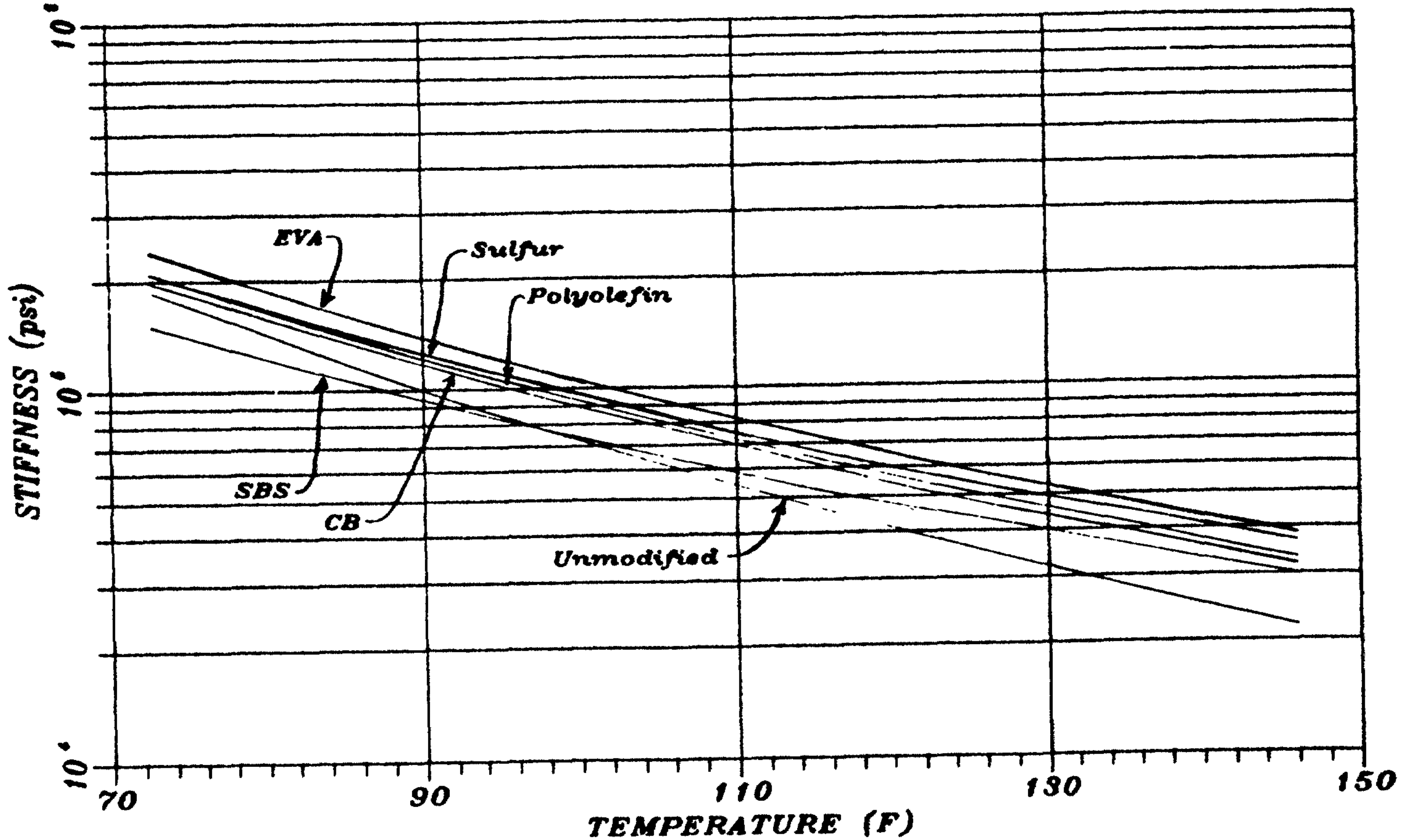


Figure 8. Mix Stiffness vs. Temperature at a Load Time of 0.1 Second

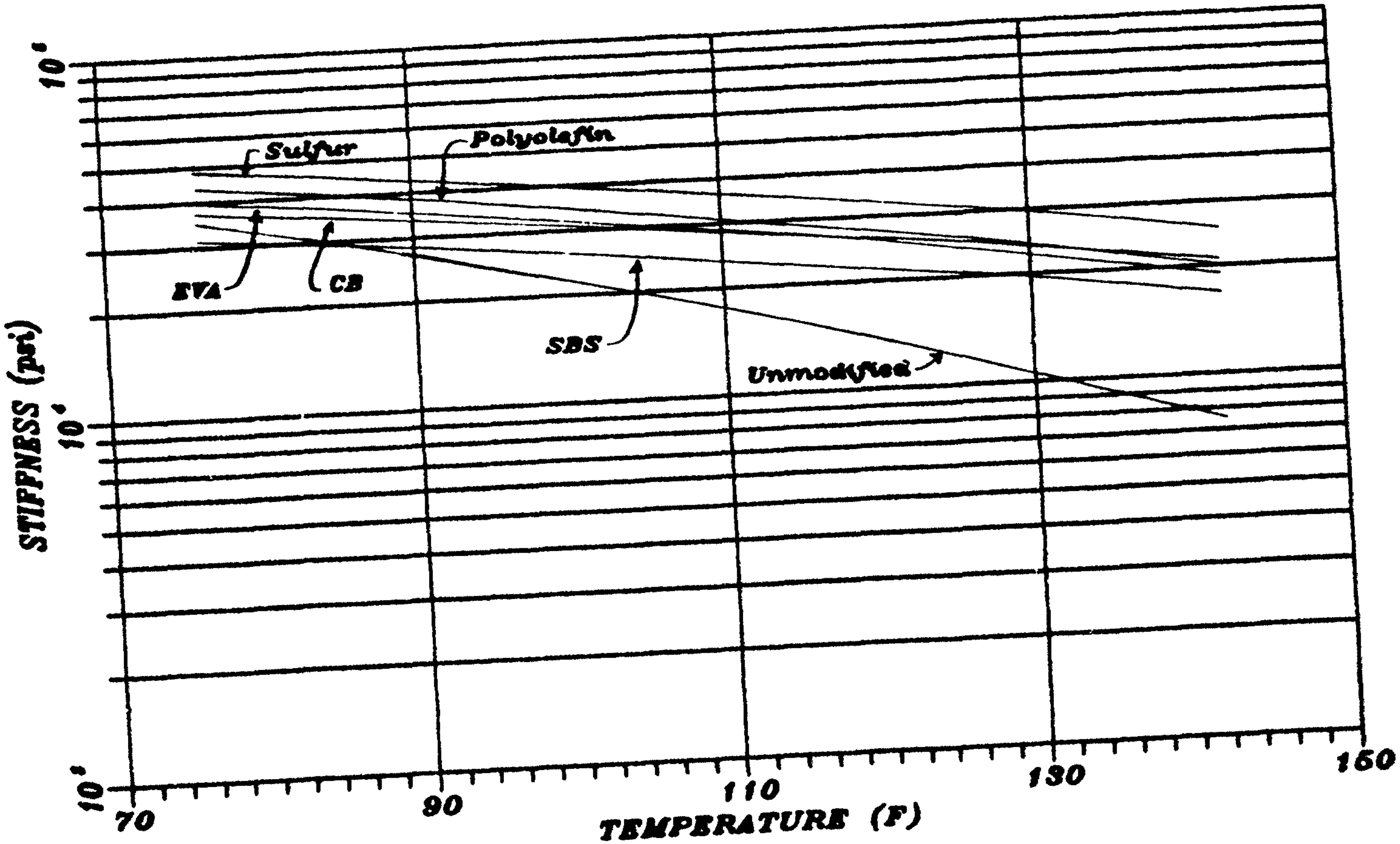


Figure 9. Mix Stiffness vs. Temperature at a Load Time of 50 Seconds

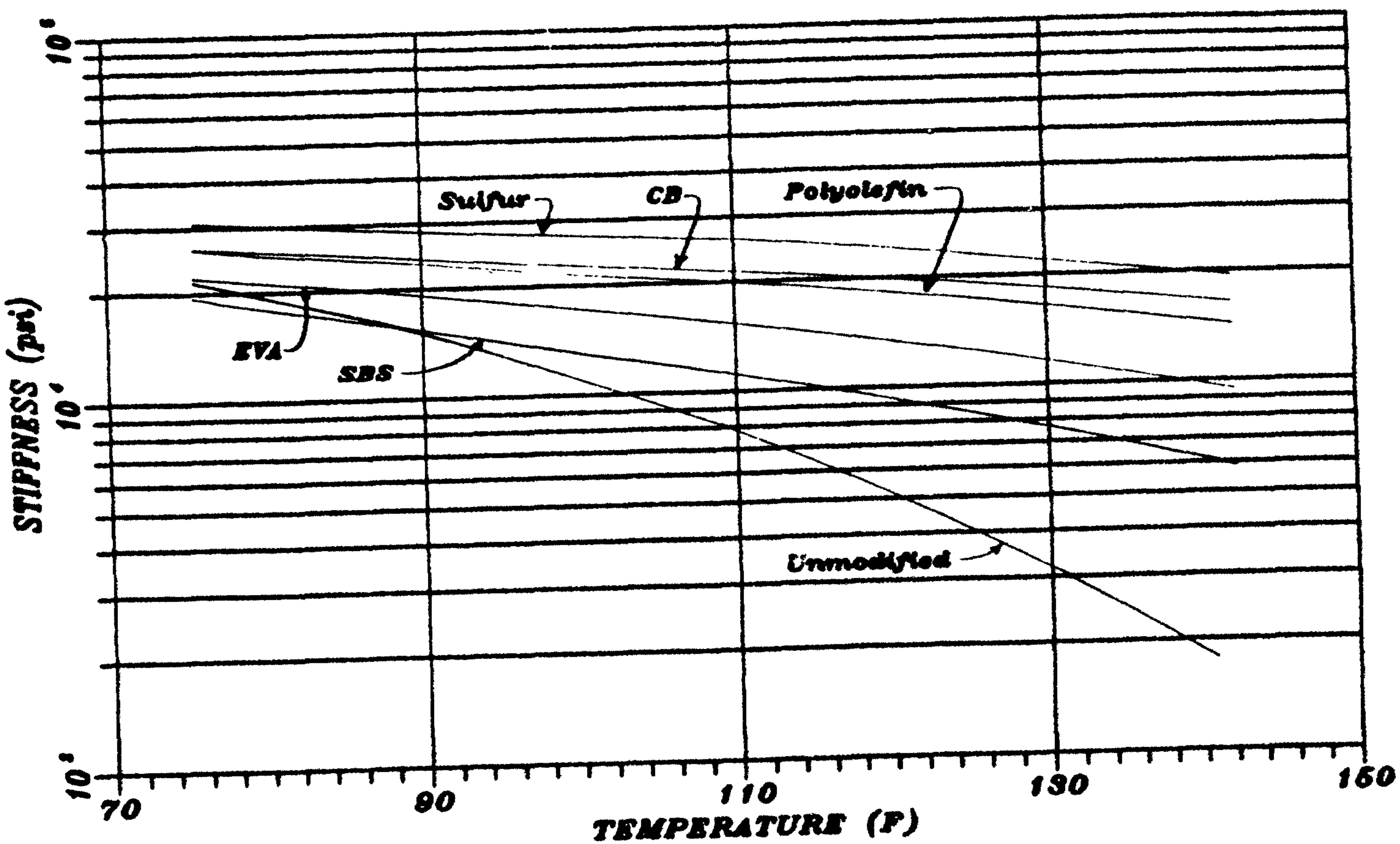


Figure 10. Mix Stiffness vs. Temperature at a Load Time of 1500 Seconds

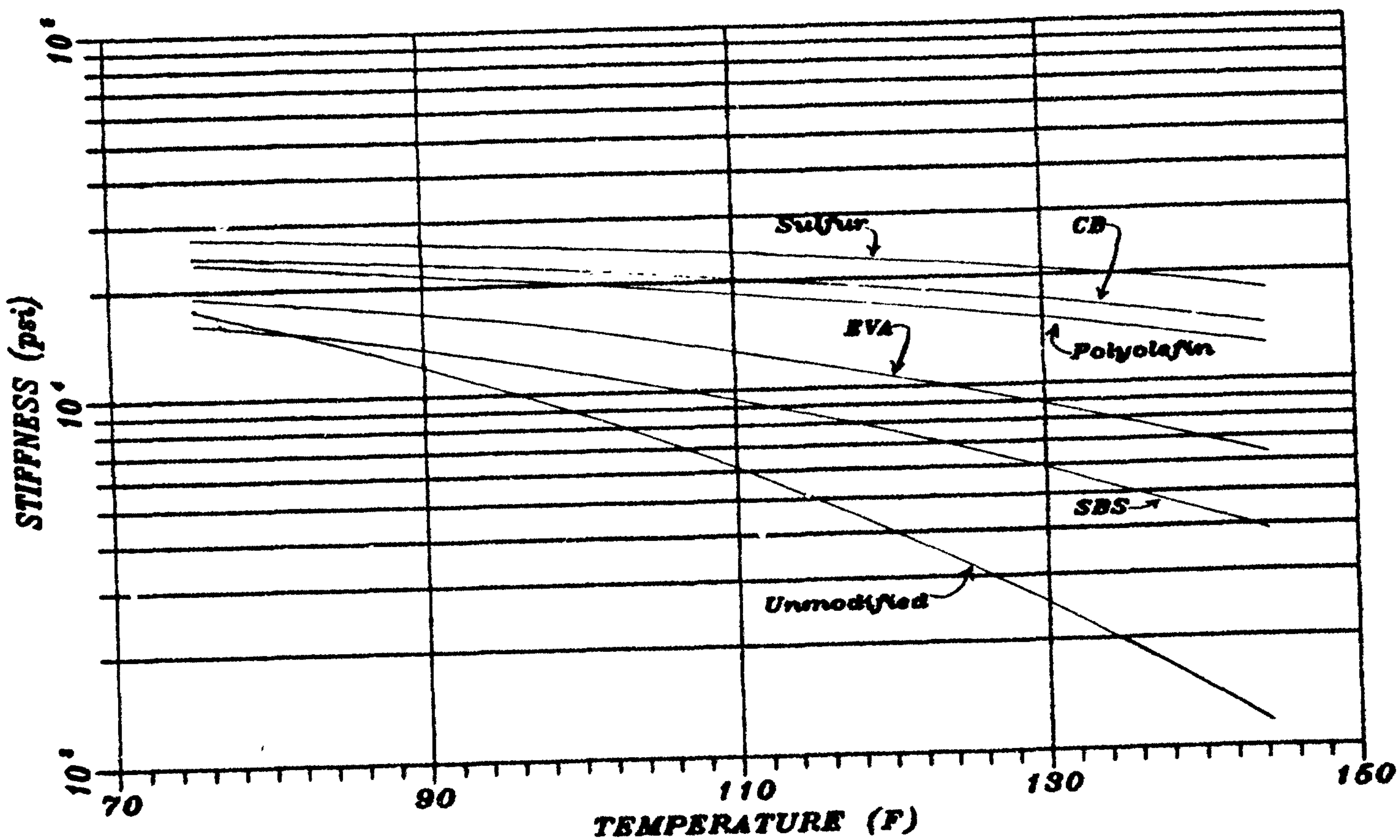


Figure 11. Mix Stiffness vs. Temperature at a Load Time of 3600 Seconds

Figure 11 for 36,000 load repetitions of the aircraft. The rut depth calculations are summarized in Tables 6 and 7, and the relationships between rut depth and number of load repetitions relationships for the thin and thick pavements are shown in Figures 12 and 13, respectively.

The reduction in predicted rut depth associated with the modifiers was significant for both the thin and thick pavements. The estimates indicated that the rut depth for the unmodified mixture was roughly two to seven times that of the modified mixtures for the thin pavement, and roughly two to six times that of the modified mixtures for the thick pavement after 36,000 repetitions of the aircraft. Of the modified mixtures, the SBS roughly doubled, and the EVA approximately tripled the pavement's resistance to rutting at 36,000 load repetitions. Because the rut depths estimated for the sulphur, carbon black, and polyolefin modified mixtures were relatively small (less than 0.15 inch), and the slope of the rut depth versus number of load repetition curves for these modifiers were fairly flat, it was estimated that pavement failure from excessive rutting would not be likely for these modifiers.

B. ECONOMIC ANALYSIS

The material and transportation costs of the modifiers studied were roughly:

1. Carbon Black - $0.40 per pound
2. Sulphur - 0.05 per pound
3. SBS - 0.90 per pound
4. EVA - 0.80 per pound
5. Polyolefin - 0.90 per pound

For the concentrations used in this research, these modifier costs result in an increase of roughly $7.00 for the carbon black, $2.00 for the sulphur, $12.50 for the SBS, $4.50 for the EVA, and $5.00 for the polyolefin per ton of asphalt concrete. The cost of plant modifications required to handle and incorporate the modifiers into the asphalt concrete were also considered. Plant modifications would depend on the type of plant and modifier used, but might include storage facilities, conveyor systems, and special blending units. Because information on modification costs was not readily available, a flat rate of $2.00 per ton of asphalt concrete was assumed for all of the modifiers in this analysis.

For the modifiers to be cost-effective, they should increase the life of the pavement to offset their initial costs. A present work analysis was used to determine the required increase in pavement life for each modifier. The analysis was based on an in-place pavement cost of $35.00 per ton of asphalt concrete and a pavement life of 10 years for the unmodified mixture. A discount rate of 4 percent per year was used. The required increases in pavement life are as follows:

TABLE 6. RUT DEPTH COMPUTATIONS FOR THE THIN ASPHALT CONCRETE LAYER

Load Repetitions	Modifier Type	Layer No.	Layer Thickness (in)	Stiffness (psi)	Average Stress (psi)	Rut Depth (in)
500	None	1	4.0	11,500	319.9	0.1113
	Carbon black	1	4.0	24,000	310.4	0.0517
	Sulphur	1	4.0	31,000	306.3	0.0395
	SBS	1	4.0	20,400	312.6	0.0625
	EVA	1	4.0	23,000	303.2	0.0527
	Polyolefin	1	4.0	25,000	309.0	0.0494
15,000	None	1	4.0	3,900	319.9	0.3281
	Carbon black	1	4.0	19,000	310.4	0.0654
	Sulphur	1	4.0	23,000	306.3	0.0533
	SBS	1	4.0	8,200	312.6	0.1525
	EVA	1	4.0	13,000	303.2	0.0933
	Polyolefin	1	4.0	18,500	309.0	0.0668
36,000	None	1	4.0	3,000	319.9	0.4265
	Carbon black	1	4.0	18,000	310.4	0.0688
	Sulphur	1	4.0	21,000	306.3	0.0583
	SBS	1	4.0	6,400	312.6	0.1954
	EVA	1	4.0	9,500	303.2	0.1277
	Polyolefin	1	4.0	16,000	309.0	0.0773

TABLE 7. RUT DEPTH COMPUTATIONS FOR THE THICK ASPHALT CONCRETE LAYER

Load Repetitions	Modifier Type	Layer No.	Layer Thickness (in)	Stiffness (psi)	Average Stress (psi)	Rut Depth (in)
500	None	1	4.0	11,500	345.2	0.1201
		2	4.0	18,000	190.9	0.0424
		3	4.0	21,000	71.9	0.0137
					Total	0.1762
	Carbon black	1	4.0	24,000	343.6	0.0573
		2	4.0	28,000	187.4	0.0268
		3	4.0	30,000	66.5	0.0089
					Total	0.0930
	Sulphur	1	4.0	31,000	342.7	0.0442
		2	4.0	37,000	184.2	0.0199
		3	4.0	40,000	64.3	0.0064
					Total	0.0705
	SBS	1	4.0	20,400	343.9	0.0688
		2	4.0	23,000	187.2	0.0326
		3	4.0	25,000	67.6	0.0108
					Total	0.1122
	EVA	1	4.0	23,000	343.2	0.0597
		2	4.0	28,000	183.1	0.0262
		3	4.0	31,000	61.9	0.0080
					Total	0.0939
	Polyolefin	1	4.0	25,000	343.2	0.0549
		2	4.0	31,000	186.4	0.0241
		3	4.0	34,000	65.8	0.0077
					Total	0.0[illegible]67

TABLE 7. RUT DEPTH COMPUTATIONS FOR THE THICK ASPHALT CONCRETE LAYER (CONTINUED)

Load Repetitions	Modifier Type	Layer No.	Layer Thickness (in)	Stiffness (psi)	Average Stress (psi)	Rut Depth (in)
15,000	None	1	4.0	3,900	345.2	0.3541
		2	4.0	8,100	190.9	0.0943
		3	4.0	10,500	71.9	0.0274
					Total	0.4758
	Carbon black	1	4.0	19,000	343.6	0.0723
		2	4.0	22,000	187.4	0.0341
		3	4.0	23,000	66.5	0.0116
					Total	0.1180
	Sulphur	1	4.0	23,000	342.7	0.0596
		2	4.0	27,000	184.2	0.0273
		3	4.0	28,000	64.3	0.0092
					Total	0.0961
	SBS	1	4.0	8,200	343.9	0.1678
		2	4.0	11,500	187.2	0.0651
		3	4.0	13,000	67.6	0.0208
					Total	0.2537
	EVA	1	4.0	13,000	343.2	0.1056
		2	4.0	16,000	183.1	0.0458
		3	4.0	17,000	61.9	0.0146
					Total	0.1660
	Polyolefin	1	4.0	18,500	343.2	0.0742
		2	4.0	20,000	186.4	0.0373
		3	4.0	21,000	65.8	0.0125
					Total	0.1240

TABLE 7. RUT DEPTH COMPUTATIONS FOR THE THICK ASPHALT CONCRETE LAYER (CONCLUDED)

Load Repetitions	Modifier Type	Layer No.	Layer Thickness (in)	Stiffness (psi)	Average Stress (psi)	Rut Depth (in)
36,000	None	1	4.0	3,000	345.2	0.4603
		2	4.0	6,800	190.9	0.1123
		3	4.0	8,700	71.9	0.0331
					Total	0.6057
	Carbon black	1	4.0	18,000	343.6	0.0764
		2	4.0	21,000	187.4	0.0357
		3	4.0	22,000	66.5	0.0121
					Total	0.1242
	Sulphur	1	4.0	21,000	342.7	0.0653
		2	4.0	25,000	184.2	0.0295
		3	4.0	26,000	64.3	0.0099
					Total	0.1047
	SBS	1	4.0	6,400	343.9	0.2149
		2	4.0	9,500	187.2	0.0788
		3	4.0	11,000	67.6	0.0246
					Total	0.3183
	EVA	1	4.0	9,500	343.2	0.1445
		2	4.0	14,000	183.1	0.0523
		3	4.0	16,000	61.9	0.0155
					Total	0.2123
	Polyolefin	1	4.0	16,000	343.2	0.0858
		2	4.0	19,000	186.4	0.0392
		3	4.0	20,000	65.8	0.0132
					Total	0.1382

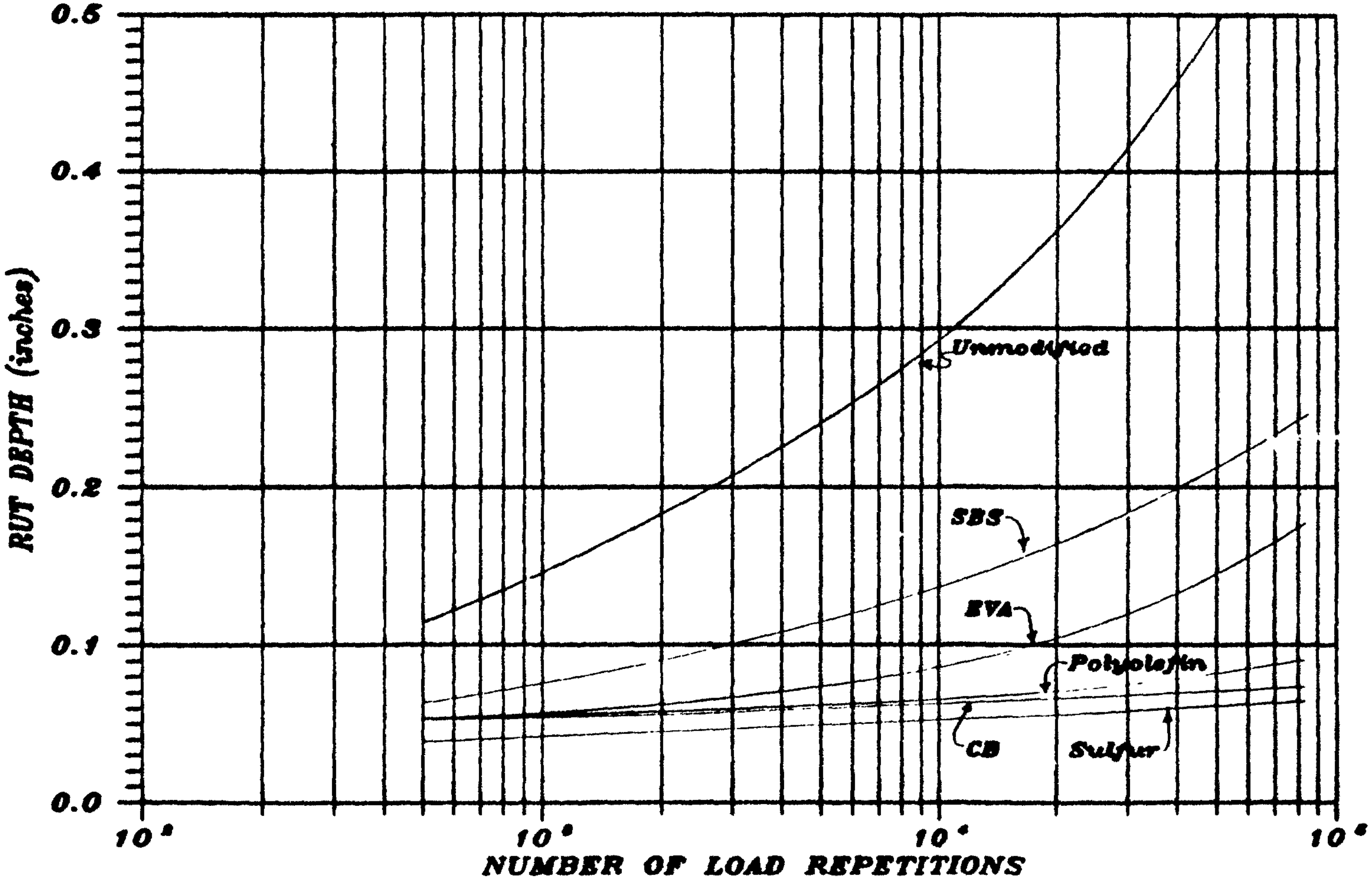


Figure 12. Rut Depth vs. Number of Load Repetitions for the Thin Asphalt Concrete Pavement

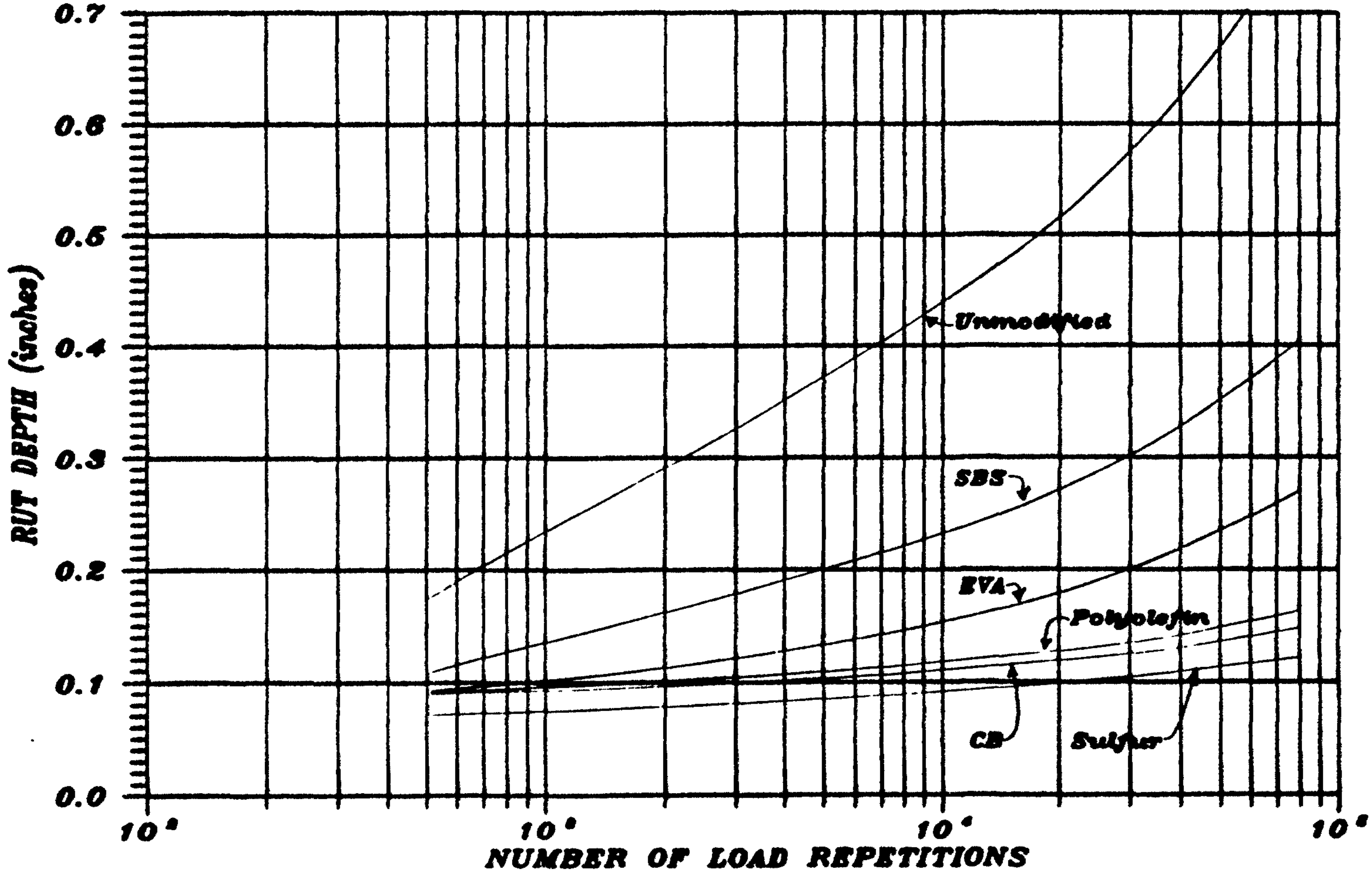


Figure 13. Rut Depth vs. Number of Load Repetitions for the Thick Asphalt Concrete Pavement

1. Carbon Black - 4 years
2. Sulfur - 2 year
3. SBS - 6 years
4. EVA - 3 years
5. Polyolefin - 3 years

Based on the results of the permanent deformation (rutting) analysis, all of the modifiers would be cost-effective.

SECTION VI

CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

Based on a review of the literature on asphalt modifiers, five modifier types were selected that showed the most potential for reducing permanent deformation. One modifier from each of the five types was tested in the laboratory to evaluate its effects on rheological properties of the asphalt cement and on mixture stability, stiffness, tensile strength, and creep properties. The creep test data were used with analytical procedures to estimate the modifier's effect on the propensity for pavement rutting. The following conclusions are based on the testing and literature review performed for this study:

1. All of the modifiers increased the viscosity of the binder at 140°F, and all but sulphur increased the viscosity at 275°F.

2. All of the modifiers, except sulphur, reduced the penetration of he binder at 77°F. At 39.2°F the carbon black, EVA, and polyolefin modifiers generally reduced, the sulphur increased, and the SBS increased or did not affect penetration.

3. All of the modifiers, except sulphur, demonstrated the ability to improve the temperature susceptibility of the binder.

4. All of the modifiers generally reduced the ductility of the binder, especially after aging in the RTFO.

5. It appears that conventional mix design procedures, such as the Marshall and Hveem methods, may be useful for estimating the optimum binder content for modified mixtures. Additional research should be performed, however, to investigate the applicability of current stability, unit weight, and air void criteria for use with modified mixtures (Appendix B).

6. All of the modifiers increased the Marshall stability of the mixture.

7. All of the modifiers increased the resilient modulus of the mixture. The increase was proportionately greater at higher temperatures, indicating that the modifiers can reduce the temperature susceptibility of the mixture.

8. All of the modifiers increased the tensile strength of the mixture at 77°F.

9. All of the modifiers increased the creep modulus of the mixture at 140°F, and all but the SBS modifier increased the creep modulus at 77°F.

10. All of the modifiers significantly reduced the amount of rutting estimated for a thin and thick pavement subjected to F-15 aircraft loads in a hot climate. Performance estimates indicated that carbon black, sulphur, and polyolefin were the most effective for reducing rutting.

11. All of the modifiers were found to be cost effective in terms of rut prevention.

B. RECOMMENDATIONS

Based on the findings of this study, further research should be performed to evaluate asphalt modifiers for use in limiting permanent deformation. Future research efforts should look at the effects of air voids and binder content on the properties of modified mixtures, and should include laboratory and field testing to develop performance models for estimating pavement rutting under actual loading conditions. The development of guidelines for modifier use and criteria for modifier acceptance should be primary goals.

SECTION VII

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Appendix A

BINDER TEST DATA

TABLE A-1. BINDER TEST DATA

MODIFIER TYPE*	TEST NUMBER	VISCOSITY @ 140F,(P) Unaged**	VISCOSITY @ 140F,(P) Aged***	VISCOSITY @ 275F,(cSt) Unaged	VISCOSITY @ 275F,(cSt) Aged	PENETRATION,(0.1mm) 77F,100gm,5sec Unaged	77F,100gm,5sec Aged	39.2F,100gm,5sec Unaged	39.2F,100gm,5sec Aged	39.2F,200gm,60sec Unaged	39.2F,200gm,60sec Aged	Ductility,(cm) Unaged	Ductility,(cm) Aged	RTFO Weight Loss,%
None	1	1020	2944	268	475	112	67	16	13	51	33	150	150	0.194
None	2	1025	2814	288	437	110	61	17	13	52	36	150	150	0.208
None	3	1025	2859	285	476	113	60	15	17	57	36	150	150	
Average		1023	2872	280	463	112	63	16	14	53	35	150	150	0.200
P	1	1783	7060	523	1228	103	45	15	11	45	27	150	57	1.270
P	2	1728	6577	531	1442	99	43	18	13	46	27	150	53	1.330
P	3	1757	7033	532	1138	95	44	17	12	46	27	150		
Average		1756	6890	529	1269	99	44	17	12	46	27	150	55	1.290
EVA	1	1679	5031	801	1967	90	46	17	10	48	28	76	18	1.199
EVA	2	1754	5041	790	1819	95	46	17	10	49	26	81	20	1.244
EVA	3	1746	5165	978	1791	92	46	17	10	48	28	84	23	
Average		1726	5079	856	1859	92	46	17	10	48	27	80	20	1.220
CB	1	3172	11620	732	1746	90	42	13	8	42	24	150	70	1.354
CB	2	3101	12202	731	1572	91	43	12	9	42	24	150	95	1.454
CB	3	3109	11889	758	1577	90	42	13	8	42	24	150		
Average		3127	11904	740	1632	90	42	13	8	42	24	150	83	1.400
SBS	1	5443	10665	1030	1854	93	57	19	14	53	35	101	83	1.550
SBS	2	4218	10281	1005	1852	92	56	18	14	54	33	109	96	1.520
SBS	3	4270	10981	1101	1948	93	57	19	14	54	35	114		
Average		4644	10642	1045	1885	93	57	19	14	54	34	108	89	1.540
S	1	1166	1433	151	203	191	103	23	15	85	40	30	20	2.170
S	2****	5154	1438	153	187	194	99	24	15	84	42	39	26	2.400
S	3	1182	1470	157	206	191	100	23	15	84	40	42	35	
Average		1174	1447	154	199	192	101	23	15	84	41	37	27	2.290

* CB=Carbon Black; S=Sulphur; SBS=Styrene-butadiene-styrene; EVA=Ethyl-vinyl-acetate; P=Polyolefin
** Before aging in the Rolling Thin Film Oven (RTFO).
*** After aging in the RTFO.
**** Not included in average.

Appendix B

MIXTURE DESIGN DATA

TABLE B-1. MARSHALL MIX DESIGN DATA

SPECIMEN NO.	MODIFIER*	BINDER CONTENT (%)	HEIGHT (in)	SPECIFIC GRAVITY BULK	SPECIFIC GRAVITY MAXIMUM THEO.	VOIDS** MIX (%)	VOIDS** FILLED (%)	UNIT WEIGHT (pcf)	MARSHALL STABILITY (lbs)	MARSHALL FLOW (.001 in)
25	NONE	5	2.48	2.344		5.3	68.4	146.3	3339	9
26	NONE	5	2.45	2.366	2.478	4.4	72.5	147.6	2860	12
AVERAGE				2.355	2.474 ***	4.8	70.4	147.0	3100	10.5
27	NONE	5.5	2.44	2.385	2.459	3.2	79.7	148.8	3028	12
28	NONE	5.5	2.43	2.384		3.3	79.5	148.8	3058	13
AVERAGE				2.385	2.465	3.3	79.6	148.8	3043	12.5
49	NONE	5.7	2.46	2.370	2.472	4.1	76.2	147.9	2687	13
50	NONE	5.7	2.43	2.379		3.7	78.0	148.4	2723	14
AVERAGE				2.375	2.471	3.9	77.1	148.2	2705	13.5
29	CB	5	2.55	2.273	2.495	9.5	53.8	141.8	2921	15
30	CB	5	2.51	2.283		9.1	55.0	142.5	3943	16
AVERAGE				2.278	2.511	9.3	54.4	142.1	3432	15.5
31	CB	5.5	2.51	2.326		6.5	65.5	145.1	3619	14
32	CB	5.5	2.52	2.323	2.474	6.7	65.0	145.0	3994	16
AVERAGE				2.325	2.489	6.6	65.3	145.0	3807	15.0
51	CB	5.7	2.48	2.340		6.4	67.1	146.0	3125	13
52	CB	5.7	2.51	2.319	2.495	7.2	64.1	144.7	2517	14
AVERAGE				2.330	2.499	6.8	65.6	145.4	2821	13.5
45	S	5	2.48	2.329		8.1	58.3	145.3	2174	11
46	S	5	2.44	2.355	2.525	7.1	61.8	147.0	2755	13
AVERAGE				2.342	2.534	7.6	60.0	146.1	2465	12.0
47	S	5.5	2.48	2.348	2.499	6.1	67.3	146.5	2256	11
48	S	5.5	2.47	2.360		5.6	69.2	147.3	2805	11
AVERAGE				2.354	2.500	5.8	68.3	146.9	2531	11
59	S	5.7	2.47	2.360		5.6	70.1	147.3	1928	11
60	S	5.7	2.44	2.384	2.498	4.6	74.1	148.8	2250	9
AVERAGE				2.372	2.499	5.1	72.1	148.0	2089	10
41	SBS	5	2.48	2.348	2.495	5.9	66.1	146.5	3339	12
42	SBS	5	2.44	2.369		5.0	69.6	147.8	4100	13
AVERAGE				2.359	2.494	5.4	67.9	147.2	3720	13
43	SBS	5.5	2.50	2.344		4.9	72.0	146.3	3286	13
44	SBS	5.5	2.44	2.377	2.475	3.5	78.2	148.3	4342	14
AVERAGE				2.361	2.464	4.2	75.1	147.3	3814	13.5
57	SBS	5.7	2.48	2.356	2.478	4.7	73.7	147.0	2522	14
58	SBS	5.7	2.46	2.364		4.3	75.1	147.5	2593	13
AVERAGE				2.360	2.471	4.5	74.4	147.3	2558	13.5

TABLE B-1. MARSHALL MIX DESIGN DATA (concluded)

SPECIMEN NO.	MODIFIER*	BINDER CONTENT (%)	HEIGHT (in)	SPECIFIC GRAVITY BULK	MAXIMUM THEO.	VOIDS** MIX (%)	FILLED (%)	UNIT WEIGHT (pcf)	MARSHALL STABILITY (lbs)	FLOW (.001 in)
37	EVA	5	2.51	2.321		7.2	61.0	144.8	2770	14
38	EVA	5	2.56	2.246	2.509	10.2	51.7	140.2	2562	15
AVERAGE			2.284	2.501 ***	8.7	56.3	142.5	2666	14.5	
39	EVA	5.5	2.62	2.211	2.489	10.7	52.4	138.0	2331	16
40	EVA	5.5	2.66	2.193		11.5	50.5	136.8	2337	14
AVERAGE			2.202	2.477	11.1	51.4	137.4	2334	15.0	
55	EVA	5.7	2.51	2.322		5.9	68.6	144.9	1698	10
56	EVA	5.7	2.49	2.343	2.466	5.0	72.1	146.2	2103	12
AVERAGE			2.333	2.467	5.5	70.3	145.5	1901	11	
33	P	5	2.50	2.327	2.489	7.1	61.5	145.2	2057	12
34	P	5	2.51	2.334		6.8	62.5	145.6	3215	15
AVERAGE			2.331	2.504	6.9	62.0	145.4	2636	13.5	
35	P	5.5	2.50	2.343		5.1	71.0	146.2	3913	13
36	P	5.5	2.52	2.318	2.473	6.1	66.9	144.6	3753	14
AVERAGE			2.331	2.469	5.6	69.0	145.4	3833	13.5	
53	P	5.7	2.44	2.373	2.471	3.8	77.7	148.1	2818	10
54	P	5.7	2.48	2.356		4.5	74.5	147.0	2532	13
AVERAGE			2.365	2.466	4.1	76.1	147.5	2675	11.5	

* CB=Carbon Black; S=Sulfur; SBS=Styrene-butadiene-styrene; EVA=Ethyl-vinyl-acetate; P=Polyolefin

** Percent voids in the mix determined using the average maximum theoretical specific gravity. Voids filled determined assuming that the asphalt specific gravity (1.029) equals the binder specific gravity.

*** Average maximum theoretical specific gravity of both Marshall and Hveem specimens.

TABLE B-2. HVEEM MIX DESIGN DATA

SPECIMEN NO.	MODIFIER*	BINDER CONTENT (%)	HEIGHT (in)	SPECIFIC GRAVITY BULK	SPECIFIC GRAVITY MAXIMUM THEO.	VOIDS** MIX (%)	VOIDS** FILLED (%)	UNIT WEIGHT (pcf)	STABILITY (lbs)
1	NONE	5	2.47	2.346	2.470	5.2	68.8	146.4	50.2
2	NONE	5	2.45	2.306		6.8	62.2	143.9	49.3
AVERAGE				2.326	2.474 ***	6.0	65.5	145.1	49.8
3	NONE	5.5	2.46	2.388	2.471	3.1	80.3	149.0	46.7
4	NONE	5.5	2.45	2.371		3.8	76.9	148.0	46.4
AVERAGE				2.380	2.465	3.5	78.6	148.5	46.6
69	NONE	5.7	2.45	2.373	2.470	4.0	76.8	148.1	44.4
70	NONE	5.7	2.46	2.370		4.1	76.2	147.9	42.1
AVERAGE				2.372	2.471	4.0	76.5	148.0	43.3
17	CB	5	2.50	2.304	2.526	8.2	57.6	143.8	53.6
18	CB	5	2.51	2.304		8.2	57.6	143.8	55.4
AVERAGE				2.304	2.511	8.2	57.6	143.8	54.5
19	CB	5.5	2.48	2.329	2.504	6.4	65.9	145.3	47.4
20	CB	5.5	2.50	2.344		5.8	68.2	146.3	46.5
AVERAGE				2.337	2.489	6.1	67.1	145.8	47.0
61	CB	5.7	2.47	2.348	2.502	6.0	68.3	146.5	44.2
62	CB	5.7	2.47	2.351		5.9	68.7	146.7	44.1
AVERAGE				2.350	2.499	6.0	68.5	146.6	44.2
5	S	5	2.45	2.363		6.7	63.0	147.5	48.8
6	S	5	2.46	2.359	2.543	6.9	62.4	147.2	48.8
AVERAGE				2.361	2.534	6.8	62.7	147.3	48.8
7	S	5.5	2.52	2.326		7.0	64.1	145.1	49.6
8	S	5.5	2.47	2.366	2.501	5.4	70.2	147.6	43.3
AVERAGE				2.346	2.500	6.2	67.1	146.4	46.5
71	S	5.7	2.46	2.367		5.3	71.3	147.7	46.1
72	S	5.7	2.45	2.368	2.499	5.2	71.4	147.8	46.7
AVERAGE				2.368	2.499	5.3	71.3	147.7	46.4
21	SBS	5	2.49	2.334		6.4	63.8	145.6	50.7
22	SBS	5	2.46	2.342	2.492	6.1	65.1	146.1	49.6
AVERAGE				2.338	2.494	6.3	64.5	145.9	50.2
23	SBS	5.5	2.49	2.333		5.3	70.1	145.6	49.8
24	SBS	5.5	2.46	2.362	2.452	4.1	75.3	147.4	44.4
AVERAGE				2.348	2.464	4.7	72.7	146.5	47.1
67	SBS	5.7	2.45	2.372		4.0	76.6	148.0	42.7
68	SBS	5.7	2.46	2.367	2.463	4.2	75.7	147.7	45.8
AVERAGE				2.370	2.471	4.1	76.1	147.9	44.3

TABLE B-2. HVEEM MIX DESIGN DATA (concluded)

SPECIMEN NO.	MODIFIER*	BINDER CONTENT (%)	HEIGHT (in)	SPECIFIC GRAVITY BULK	MAXIMUM THEO.	VOIDS** MIX (%)	FILLED (%)	UNIT WEIGHT (pcf)	STABILITY (lbs)
13	EVA	5	2.51	2.329	2.493	6.9	62.2	145.3	43.8
14	EVA	5	2.50	2.359		5.7	66.9	147.2	43.1
AVERAGE			2.344	2.501 ***	6.3	64.5	146.3	43.5	
15	EVA	5.5	2.46	2.356	2.464	4.9	72.0	147.0	49.9
16	EVA	5.5	2.48	2.361		4.7	72.9	147.3	34.9
AVERAGE			2.359	2.477	4.8	72.5	147.2	42.4	
63	EVA	5.7	2.46	2.371		3.9	77.1	148.0	47.7
64	EVA	5.7	2.45	2.379	2.467	3.6	78.7	148.4	49.9
AVERAGE			2.375	2.467	3.7	77.9	148.2	48.8	
9	P	5	2.52	2.325	2.519	7.1	61.2	145.1	52.8
10	P	5	2.47	2.357		5.9	66.1	147.1	44.0
AVERAGE			2.341	2.504	6.5	63.7	146.1	48.4	
11	P	5.5	2.45	2.368	2.464	4.1	75.6	147.8	47.3
12	P****	5.5	2.46	2.405		2.6	83.2	150.1	----
AVERAGE			2.368	2.469	4.1	75.6	147.8	47.3	
65	P	5.7	2.43	2.386	2.461	3.2	80.3	148.9	47.1
66	P	5.7	2.46	2.372		3.8	77.5	148.0	48.8
AVERAGE			2.379	2.466	3.5	78.9	148.4	48.0	

* CB=Carbon Black; S=Sulfur; SBS=Styrene-butadiene-styrene; EVA=Ethyl-vinyl-acetate; P=Polyolefin

** Percent voids in the mix determined from the average maximum theoretical specific gravity. Voids filled determined assuming that the asphalt specific gravity (1.029) equals the binder specific gravity.

*** Average maximum theoretical specific gravity of both Marshall and Hveem specimens.

**** Specimen No. 12 failed during the stability test. It is not included in the average.

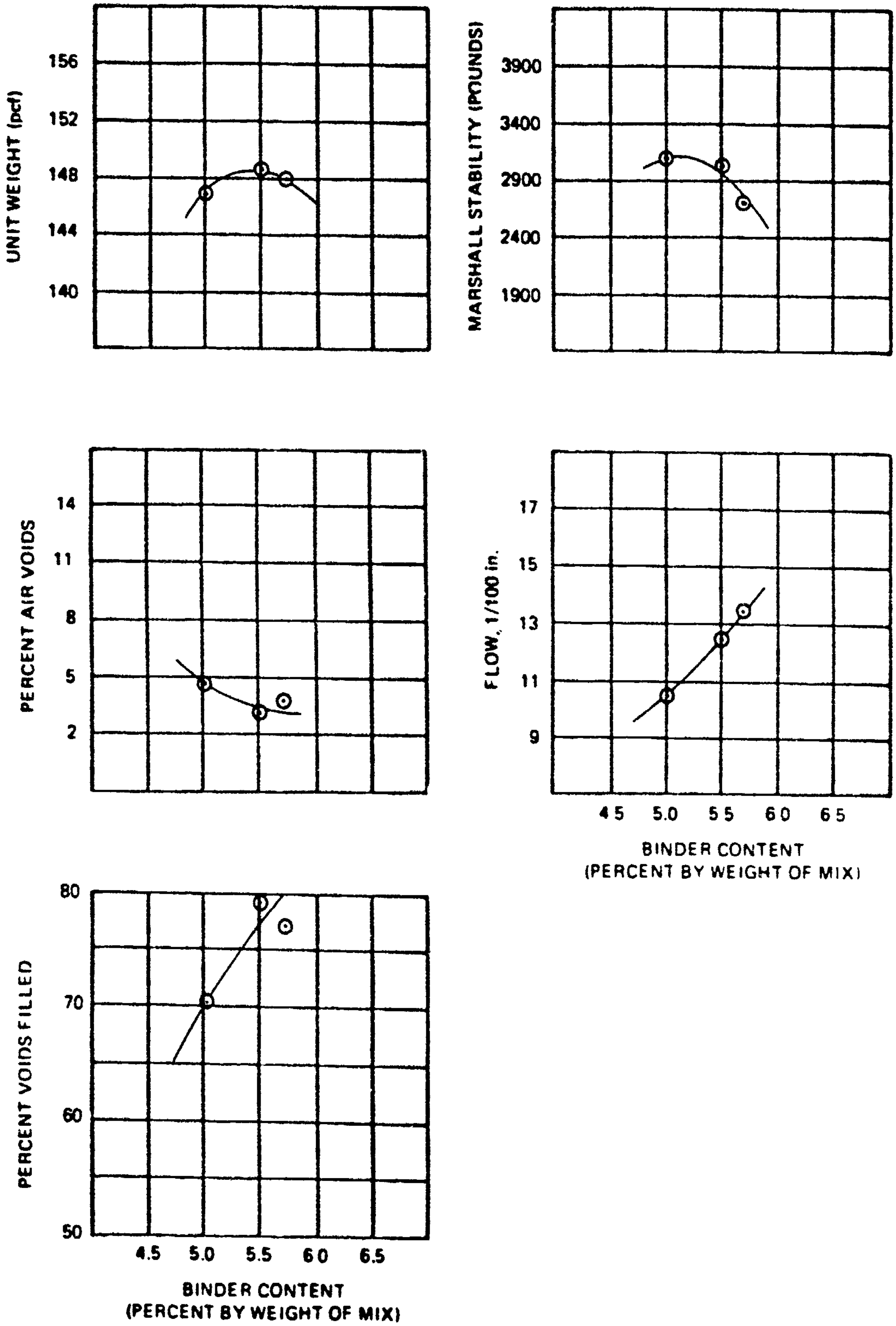

Figure B-1. Marshall Mix Design Plots, Unmodified Asphalt

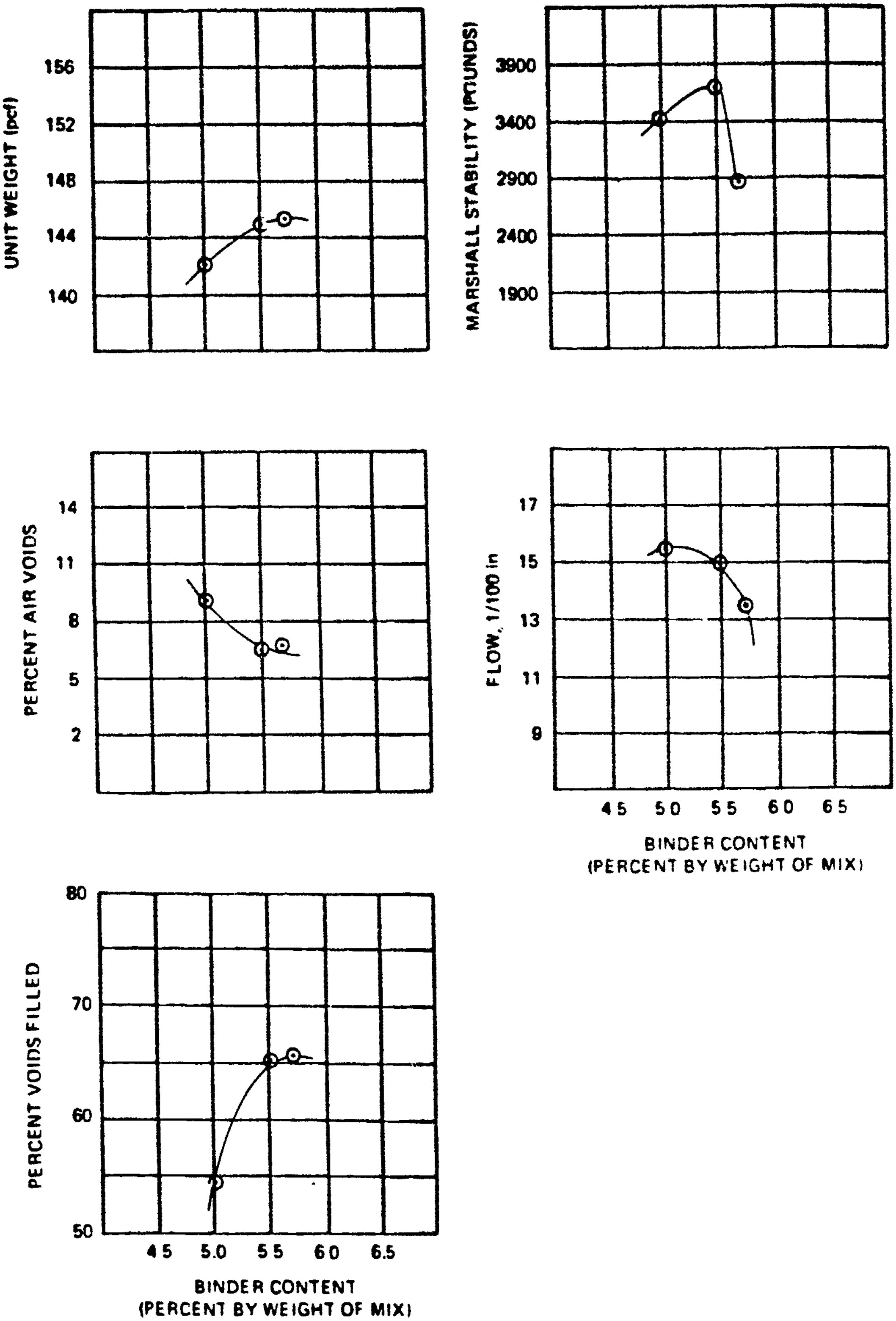

Figure B-2. Marshall Mix Design Plots, Carbon Black

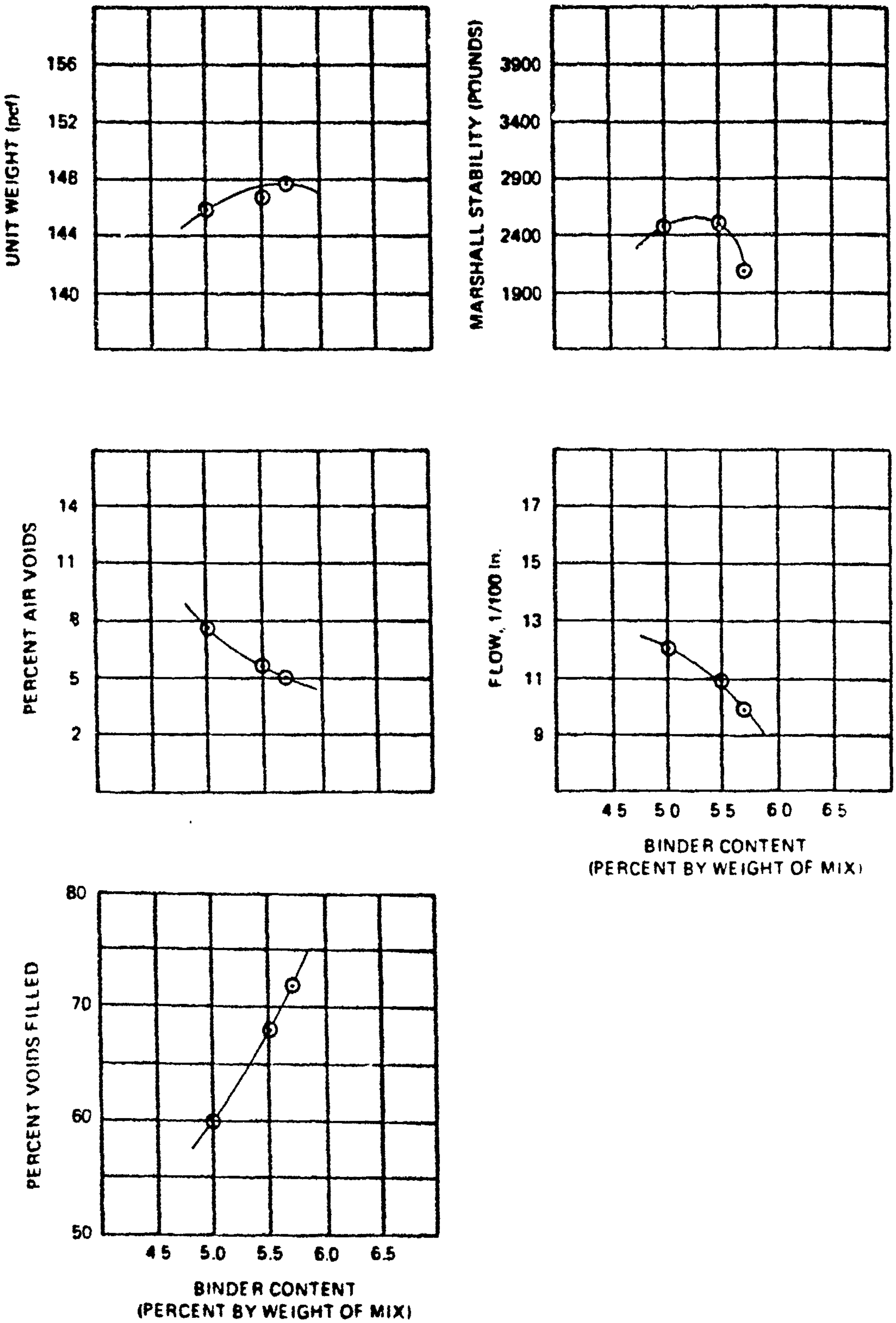

Figure B-3. Marshall Mix Design Plots, Sulfur

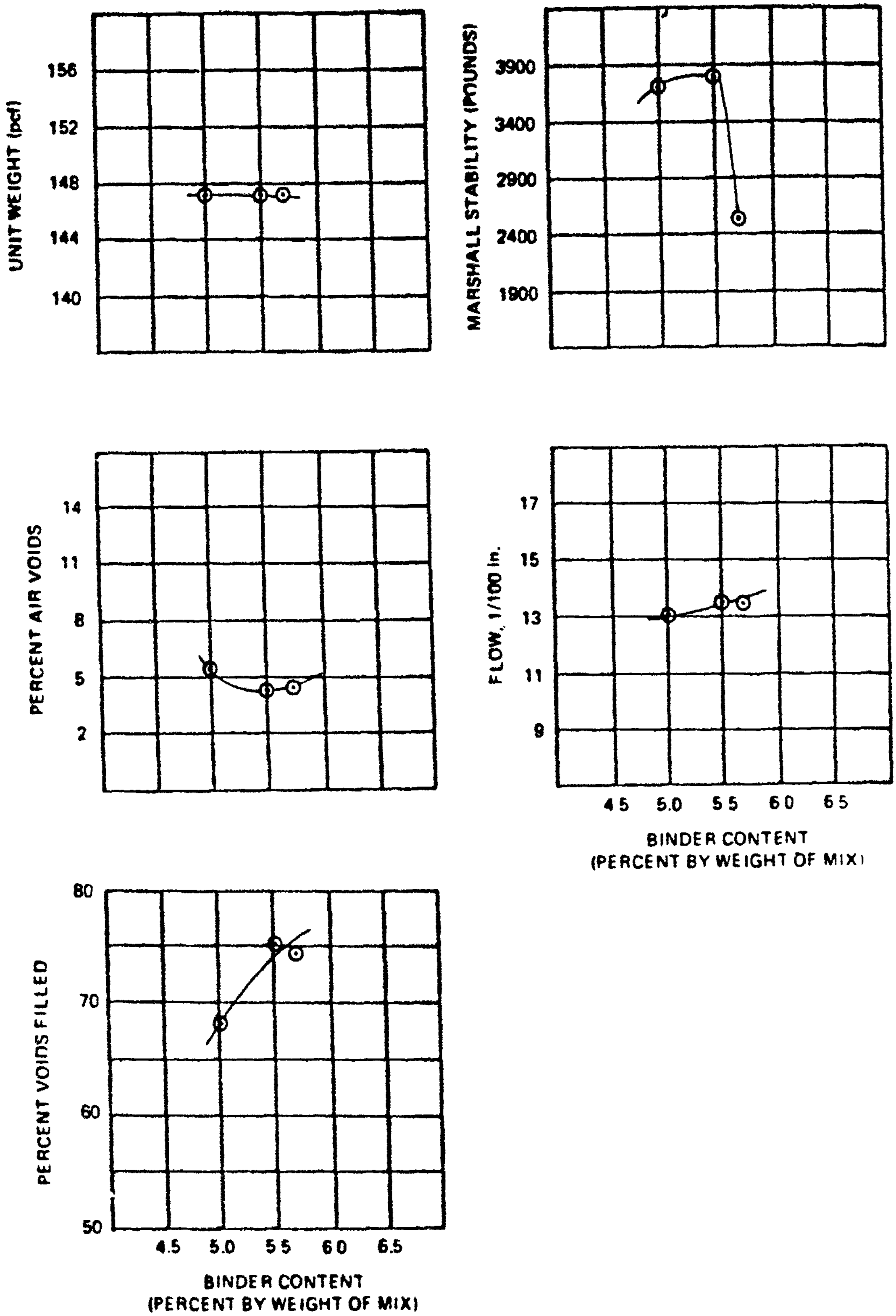

Figure B-4. Marshall Mix Design Plots, SBS

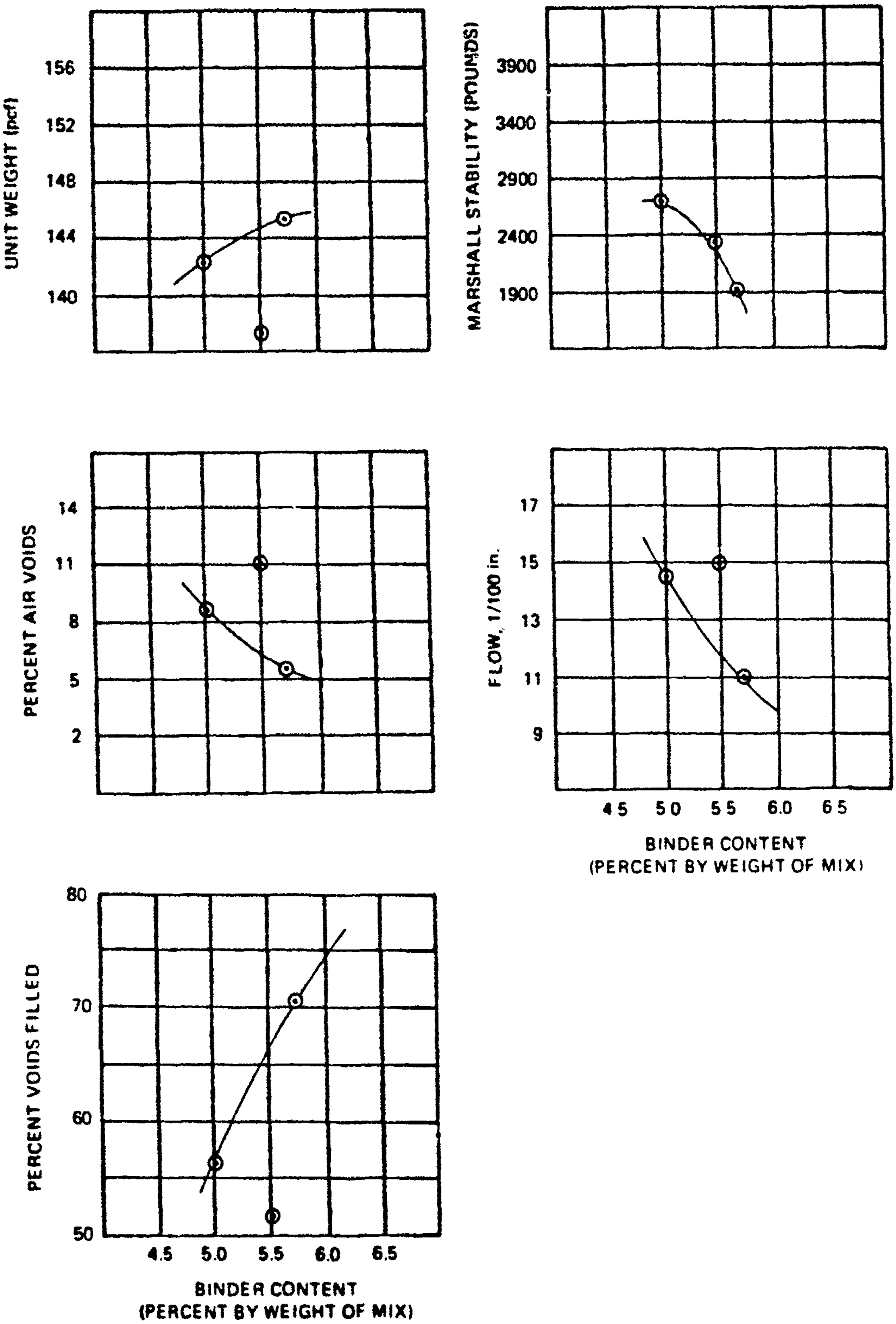

Figure B-5. Marshall Mix Design Plots, EVA

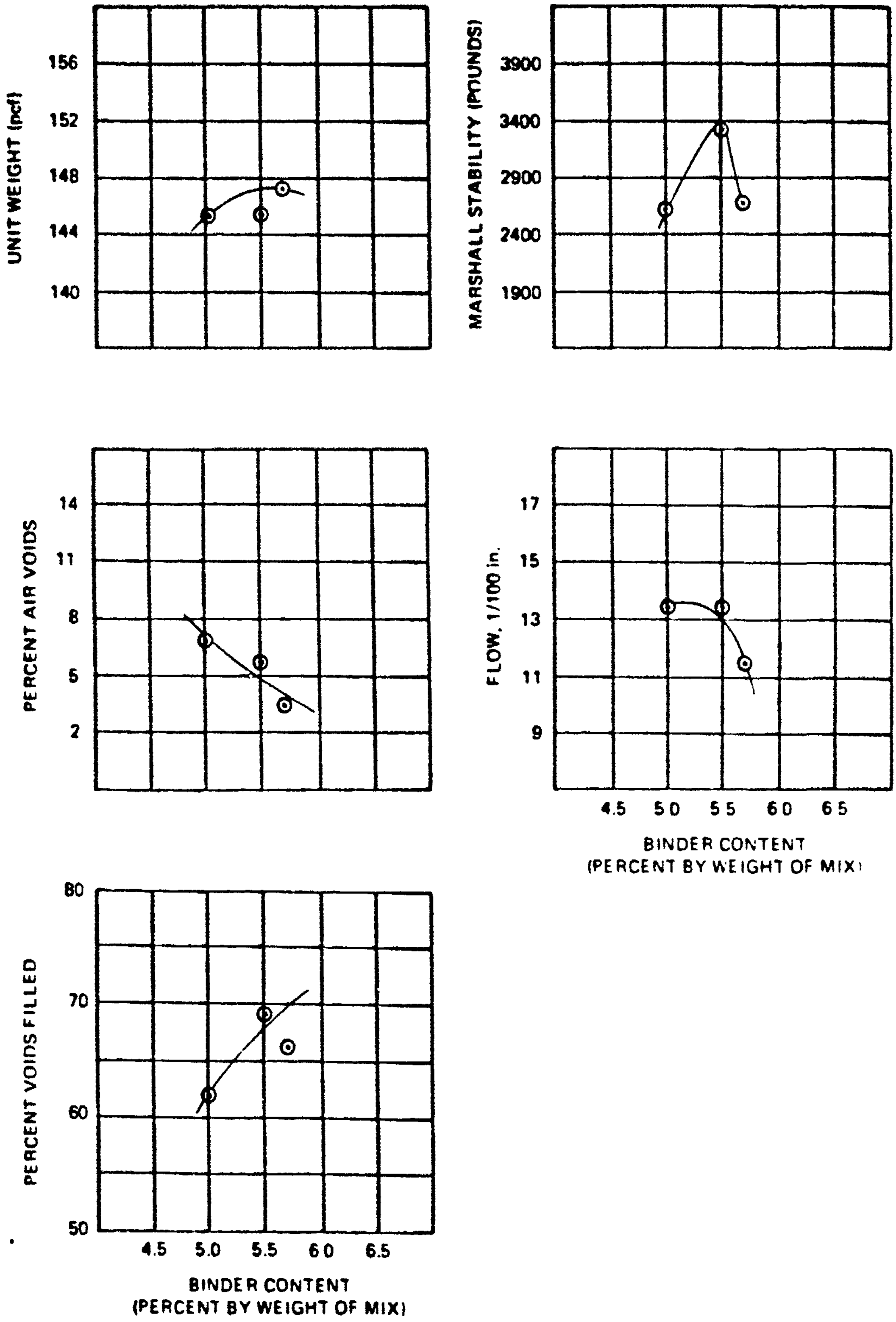

Figure B-6. Marshall Mix Design Plots, Polyolefin

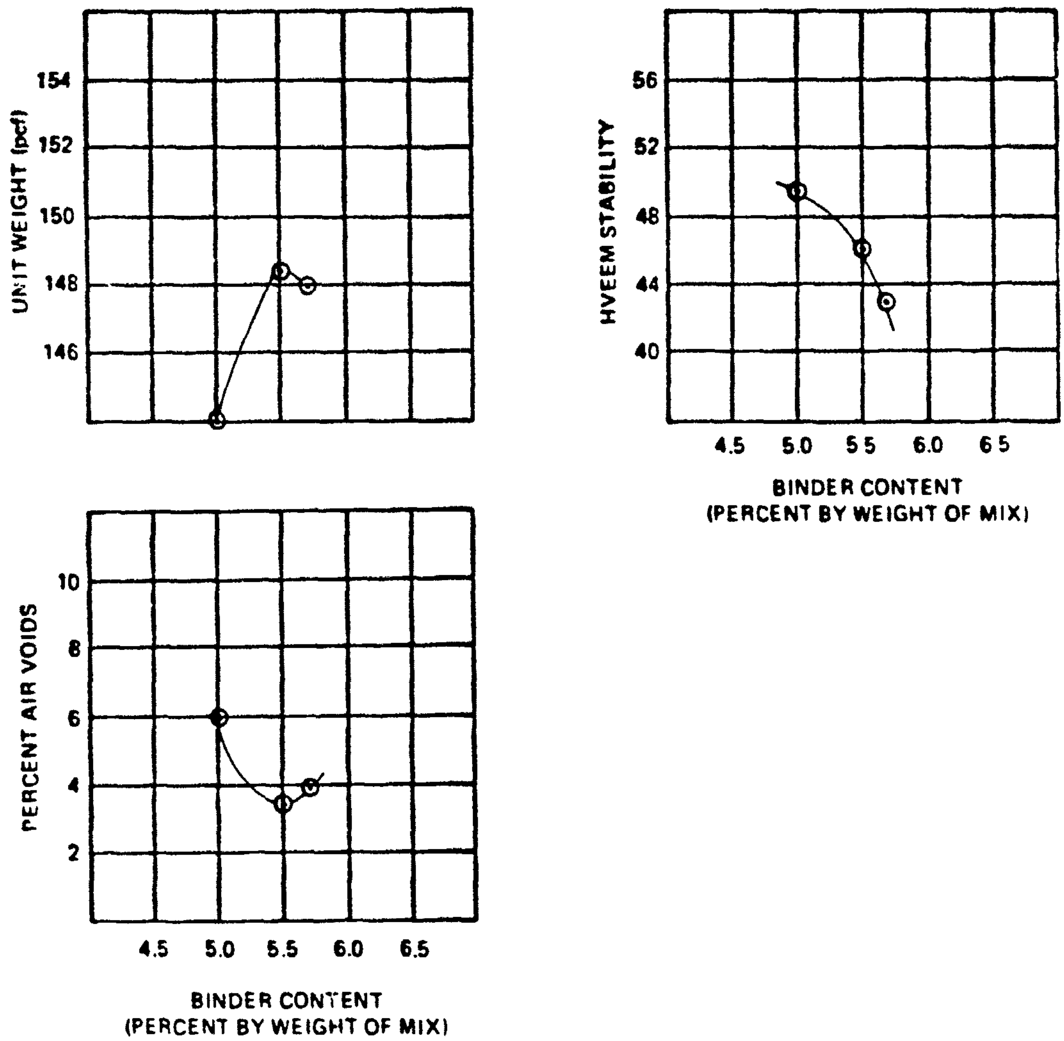

Figure B-7. Hveem Mix Design Plots, Unmodified Asphalt

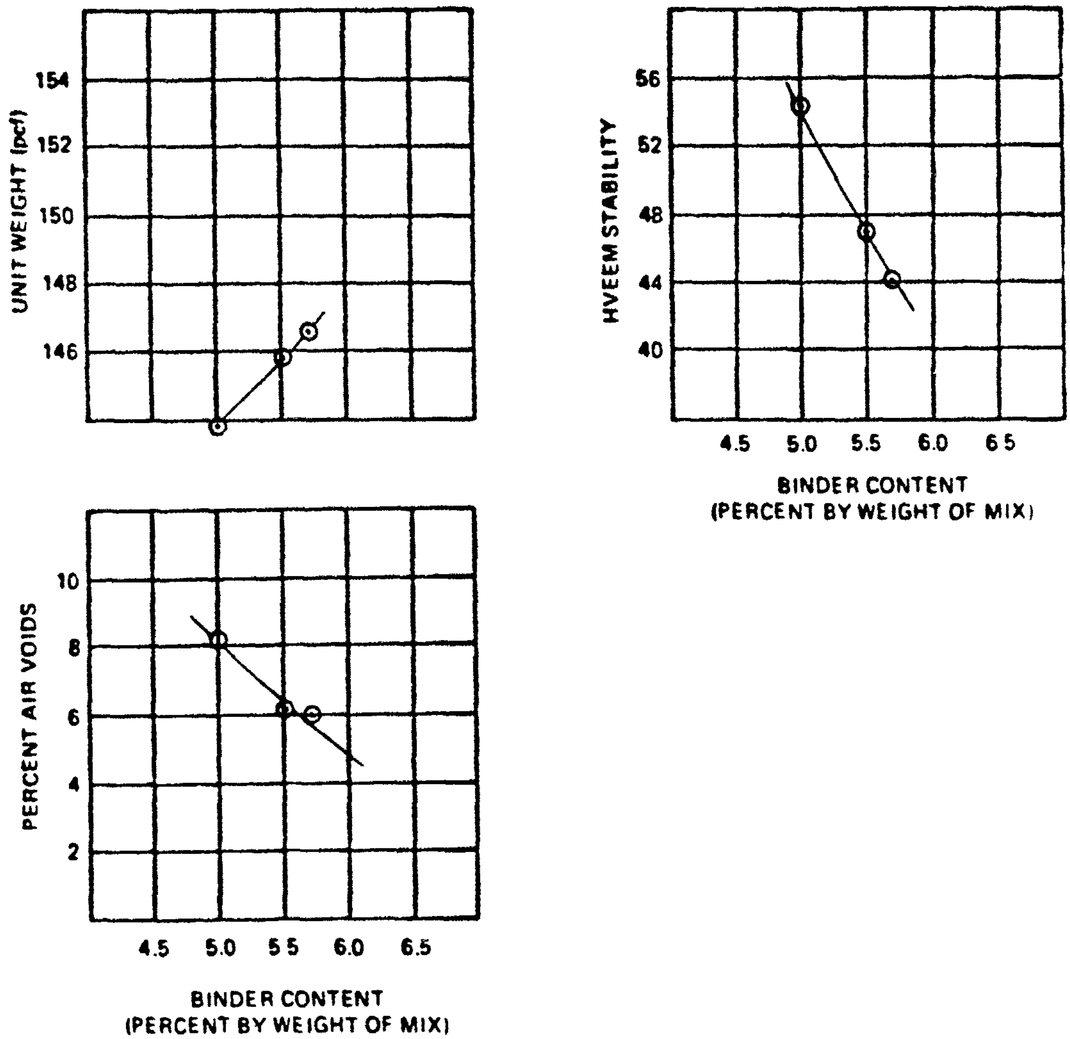

Figure B-8. Hveem Mix Design Plots, Carbon Black

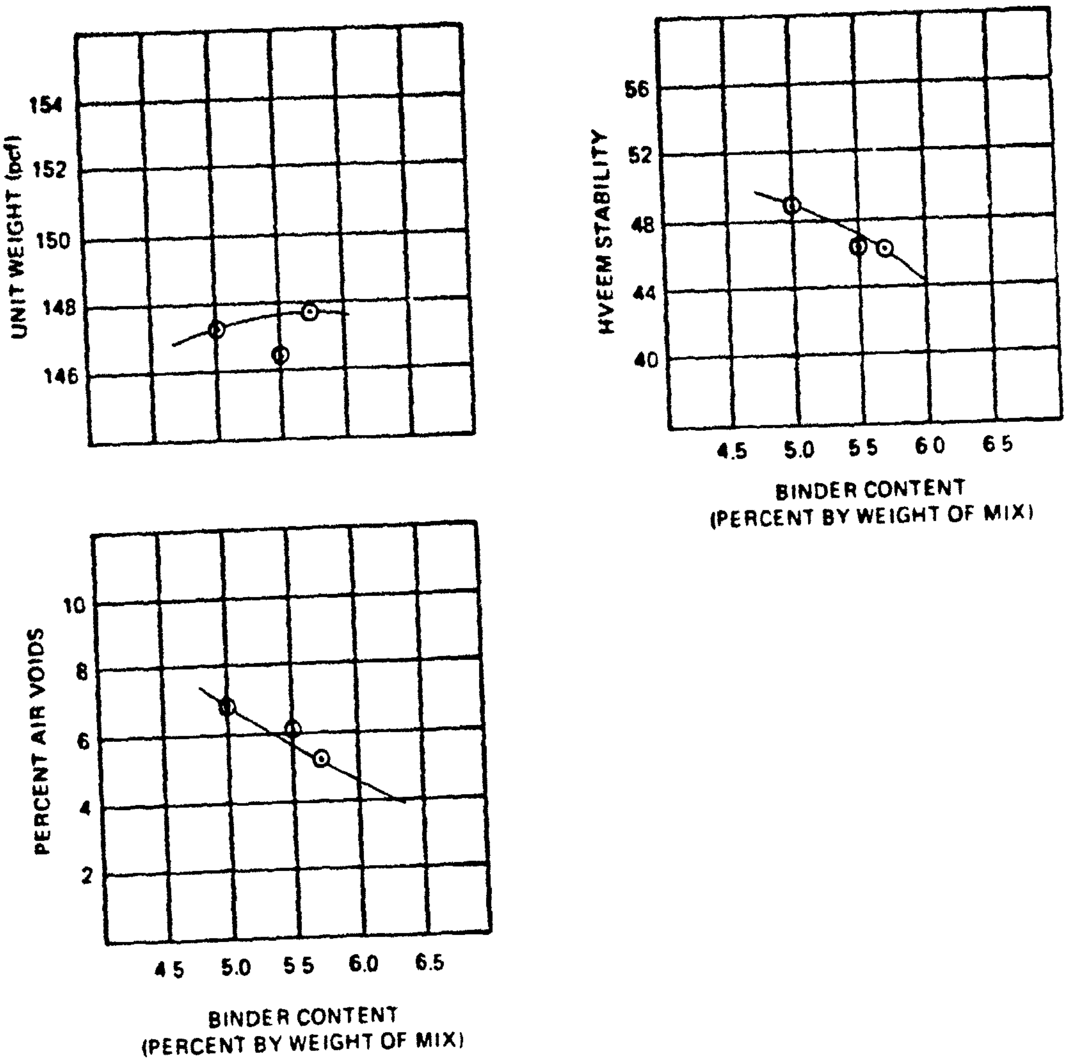

Figure B-9. Hveem Mix Design Plots, Sulfur

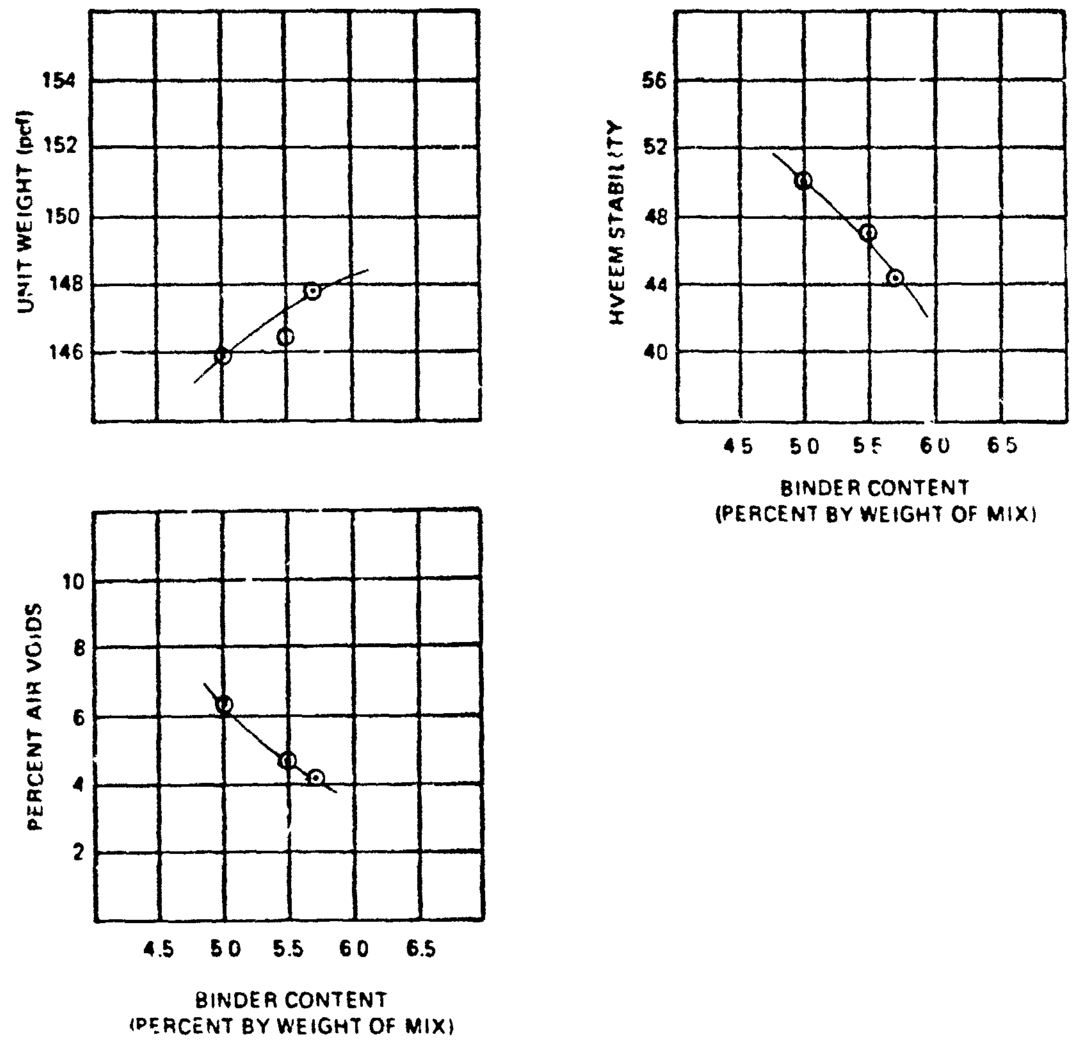

Figure B-10. Hveem Mix Design Plots, SBS

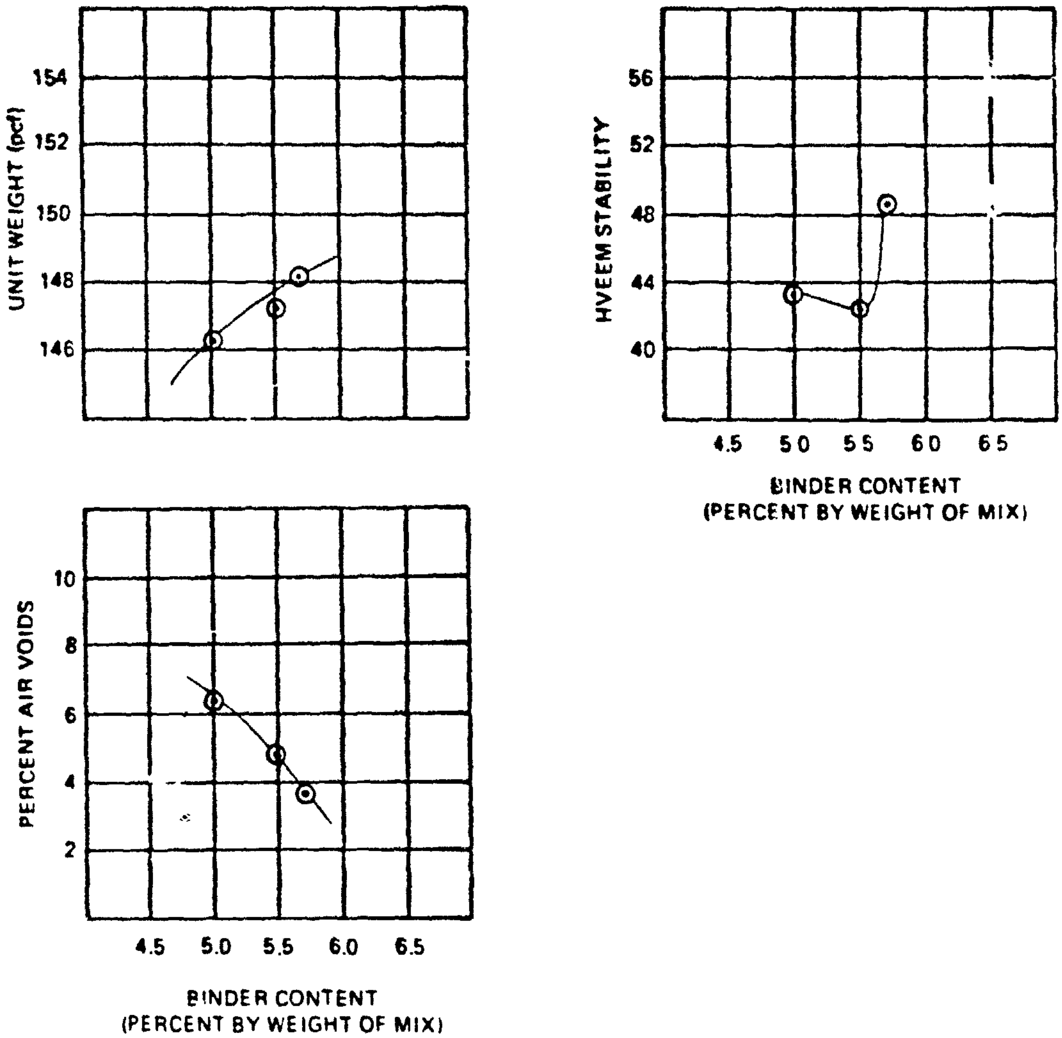

Figure B-11. Hveem Mix Design Plots, EVA

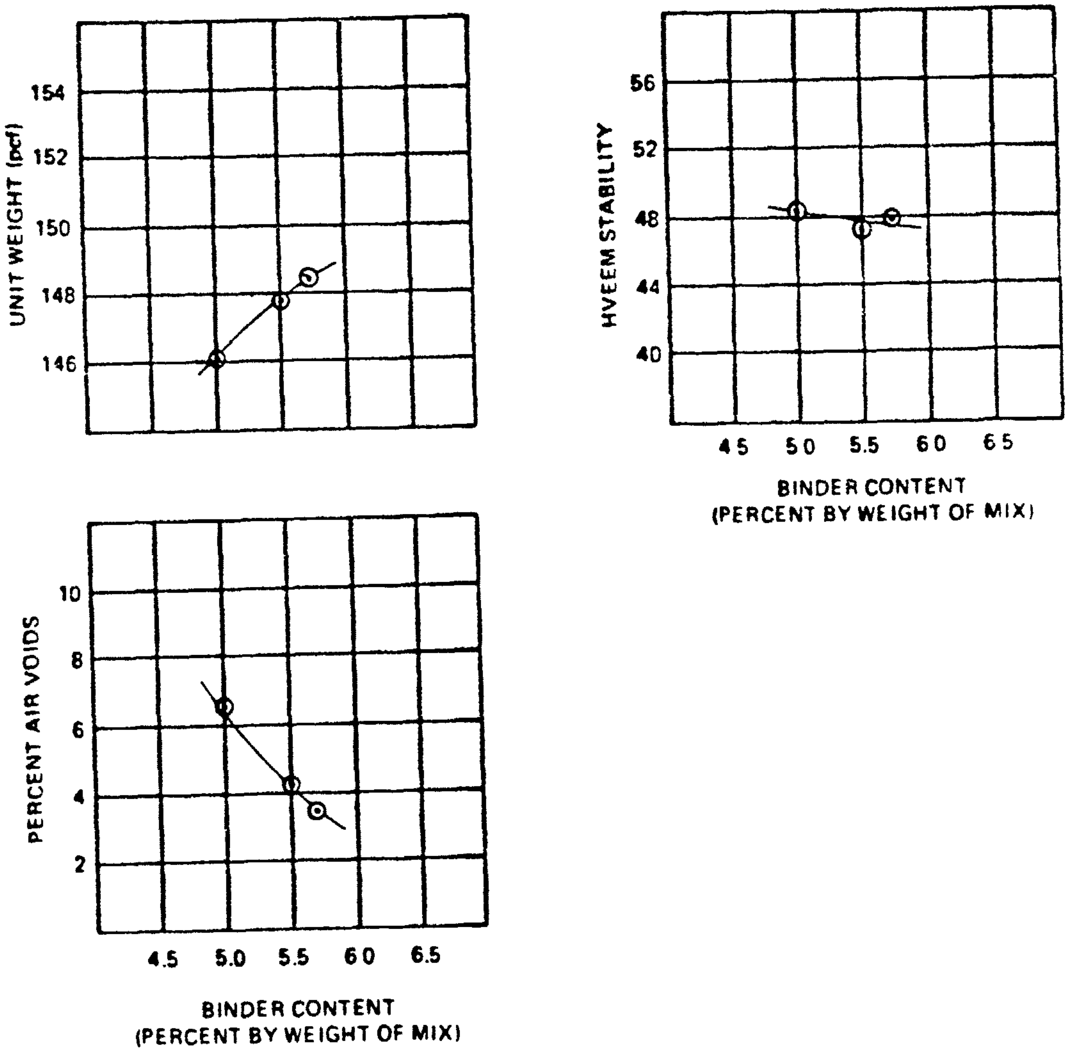

Figure B-12. Hveem Mix Design Plots, Polyolefin

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Appendix C

MIXTURE TEST DATA

TABLE C-1. COMPACTION EFFORTS USED ON LABORATORY TEST SPECIMENS

Modifier Type	Marshall Specimens,* (blows per side)	Creep Specimens,**(blows per layer) Layer Number 1	2	3	4	5
None	40	20	25	30	35	40
Carbon Black	70	50	60	70	80	90
Sulfur	70	50	60	70	80	90
SBS	52	20	25	30	35	40
EVA	47	20	25	30	35	40
Polyolefin	42	15	20	25	30	35

* Standard 10-pound Marshall hammer with 18-inch fall at 250F.
** Hveem, California, kneading compactor at 230F.

TABLE C-2. MARSHALL STABILITY, RESILIENT MODULUS, INDIRECT TENSION,AND SPECIFIC GRAVITY TEST DATA

SPECIMEN NO.	MODIFIER*	SPECIFIC GRAVITY BULK	SPECIFIC GRAVITY MAXIMUM THEO.	AIR** VOIDS (%)	MARSHALL STABILITY (lbs)	MARSHALL FLOW (.001 in)	RESILIENT MODULUS,(ksi) 34 F	RESILIENT MODULUS,(ksi) 77 F	RESILIENT MODULUS,(ksi) 104 F	INDIRECT TENSION,(psi) 77 F
97	NONE	2.369	2.484	4.0	2000	12				
98	NONE	2.379	2.427	3.6	2084	10				
99	NONE	2.381	2.474	3.5	2053	12				
100	NONE	2.367		4.1			2239	140	30	95
103	NONE	2.371		3.9			2299	150	29	101
104	NONE	2.374		3.8			2297	154	33	104
AVERAGE		2.374	2.467 ***	3.8	2046	11	2278	148	31	101
114	CB	2.373	2.524	4.5	3178	12				
115	CB	2.373	2.465	4.5	3572	12				
117	CB	2.374	2.445	4.5	3471	13				
118	CB	2.375		4.5			2610	288	79	165
119	CB	2.380		4.3			2842	289	70	154
120	CB	2.397		3.6			3033	311	85	182
AVERAGE		2.379	2.486	4.3	3407	12	2828	296	78	167
74	S	2.413	2.536	3.5	3325	9				
75	S	2.386	2.473	4.6	2936	13				
76	S	2.381	2.500	4.8	3326	11				
78	S	2.392		4.4			3566	496	171	123
79	S	2.406		3.8			3241	562	168	136
80	S	2.382		4.8			2616	408	130	121
AVERAGE		2.393	2.501	4.3	3196	11	3141	489	156	127
81	SBS	2.380	2.497	3.5	2505	13				
83	SBS	2.390	2.479	3.5	2595	13				
84	SBS	2.362	2.412	4.2	2529	12				
86	SBS	2.366		4.1			2736	223	50	120
87	SBS	2.356		4.5			2393	205	48	102
88	SBS	2.382		3.4			2962	257	64	106
AVERAGE		2.371	2.466	3.9	2543	13	2697	228	54	109
106	EVA	2.352	2.479	4.7	1962	12				
107	EVA	2.371		3.9	2293	10				
108	EVA	2.369	2.461	4.0	2345	10				
109	EVA	2.353		4.7			2825	346	110	139
110	EVA	2.376		3.7			3559	398	111	142
111	EVA	2.352		4.7			3152	362	92	138
AVERAGE		2.362	2.468 ***	4.3	2200	11	3179	369	104	140
89	P	2.362	2.476	4.4	2575	12				
90	P	2.357		4.6	2392	12				
91	P	2.361	2.474	4.5	2392	13				
94	P	2.365		4.3			2688	325	112	134
95	P	2.371		4.0			2734	393	111	140
96	P	2.381		3.6			3238	378	112	152
AVERAGE		2.366	2.471	4.2	2453	12	2887	365	112	142

* CB=Carbon Black; S=Sulfur, SBS=Styrene-butadiene-styrene; EVA=Ethyl-vinyl-acetate; P=Polyolefin

** Percent air voids determined from average theoretical specific gravity.

*** Average includes maximum theoretical values from mix design testing.

TABLE C-3. CREEP SPECIMEN SPECIFIC GRAVITY AND AIR VOID DATA

SPECIMEN NO.	SPECIFIC GRAVITY BULK	SPECIFIC GRAVITY MAXIMUM THEO.	AIR VOIDS (%)
ORIG 1	2.376		3.7
ORIG 3	2.379		3.6
ORIG 4	2.360		4.3
ORIG 5	2.364		4.2
ORIG 6	2.366		4.1
ORIG 7	2.381		3.5
AVERAGE	2.371	2.467 *	3.9
CB 1	2.396		3.6
CB 2	2.390		3.9
CB 3	2.370		4.7
CB 4	2.389		3.9
CB 6	2.400		3.5
CB 7	2.385		4.1
AVERAGE	2.388	2.486	3.9
SULF 1	2.395		4.2
SULF 2	2.390		4.4
SULF 3	2.385		4.6
SULF 4	2.393		4.3
SULF 5	2.384		4.7
SULF 6	2.394		4.3
AVERAGE	2.390	2.501	4.4
SBS 3	2.350		4.7
SBS 4	2.362		4.2
SBS 5	2.357		4.4
SBS 6	2.362		4.2
SBS 7	2.361		4.3
SBS 8	2.378		3.6
AVERAGE	2.362	2.466	4.2
EVA 3	2.344		5.0
EVA 4	2.352		4.7
EVA 5	2.359		4.4
EVA 6	2.355		4.6
EVA 7	2.356		4.5
EVA 8	2.368		4.1
EVA 9	2.378		3.6
AVERAGE	2.361	2.468	4.3
POLY 3	2.352		4.8
POLY 4	2.376		3.8
POLY 5	2.380		3.7
POLY 6	2.377		3.8
POLY 8	2.382		3.6
POLY 9	2.381		3.6
AVERAGE	2.375	2.471	3.9

* Average Maximum Tneoretical Specific Gravity from Mix Design and Mix Testing.

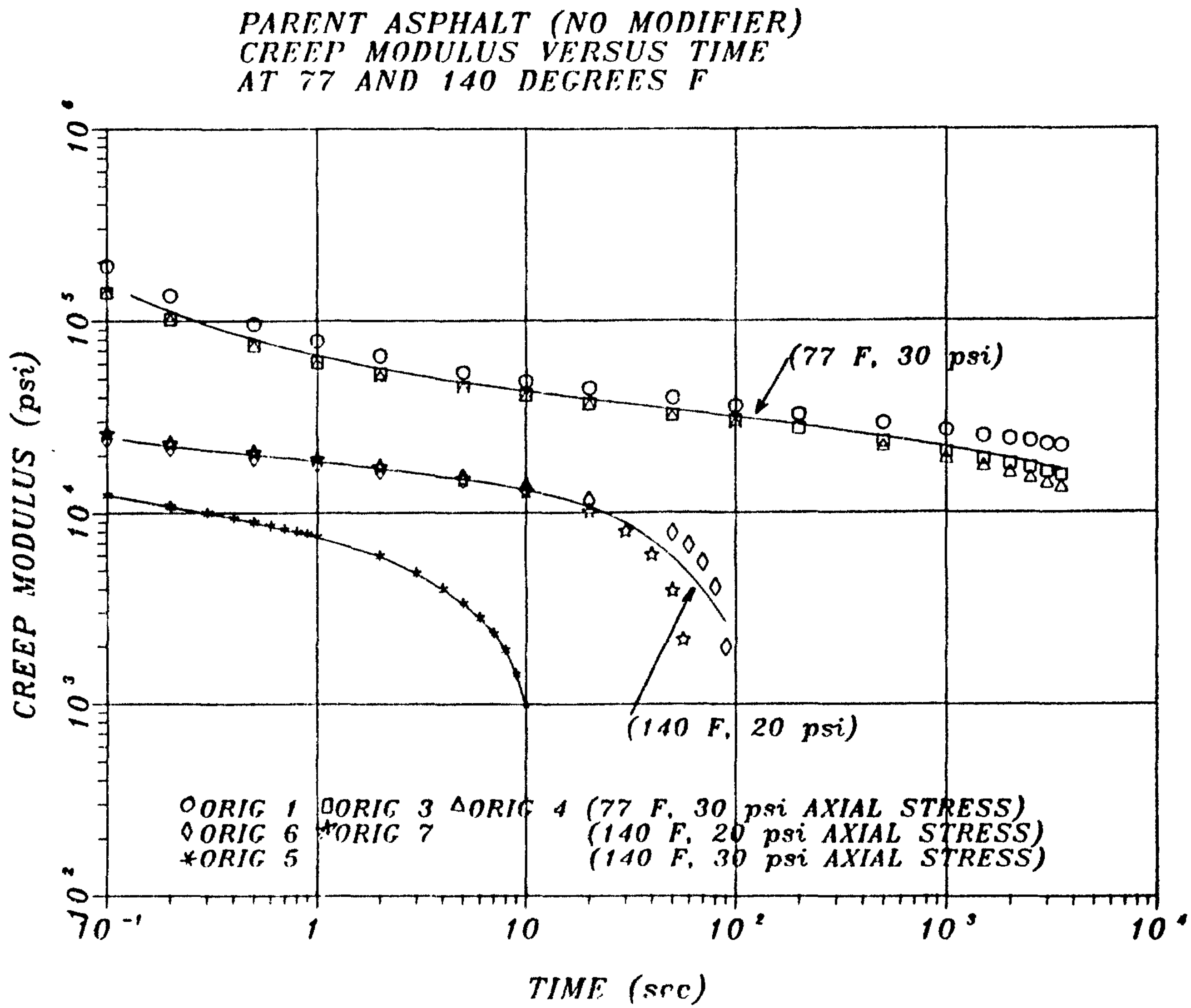

Figure C-1. Creep Modulus vs. Time, Unmodified Asphalt

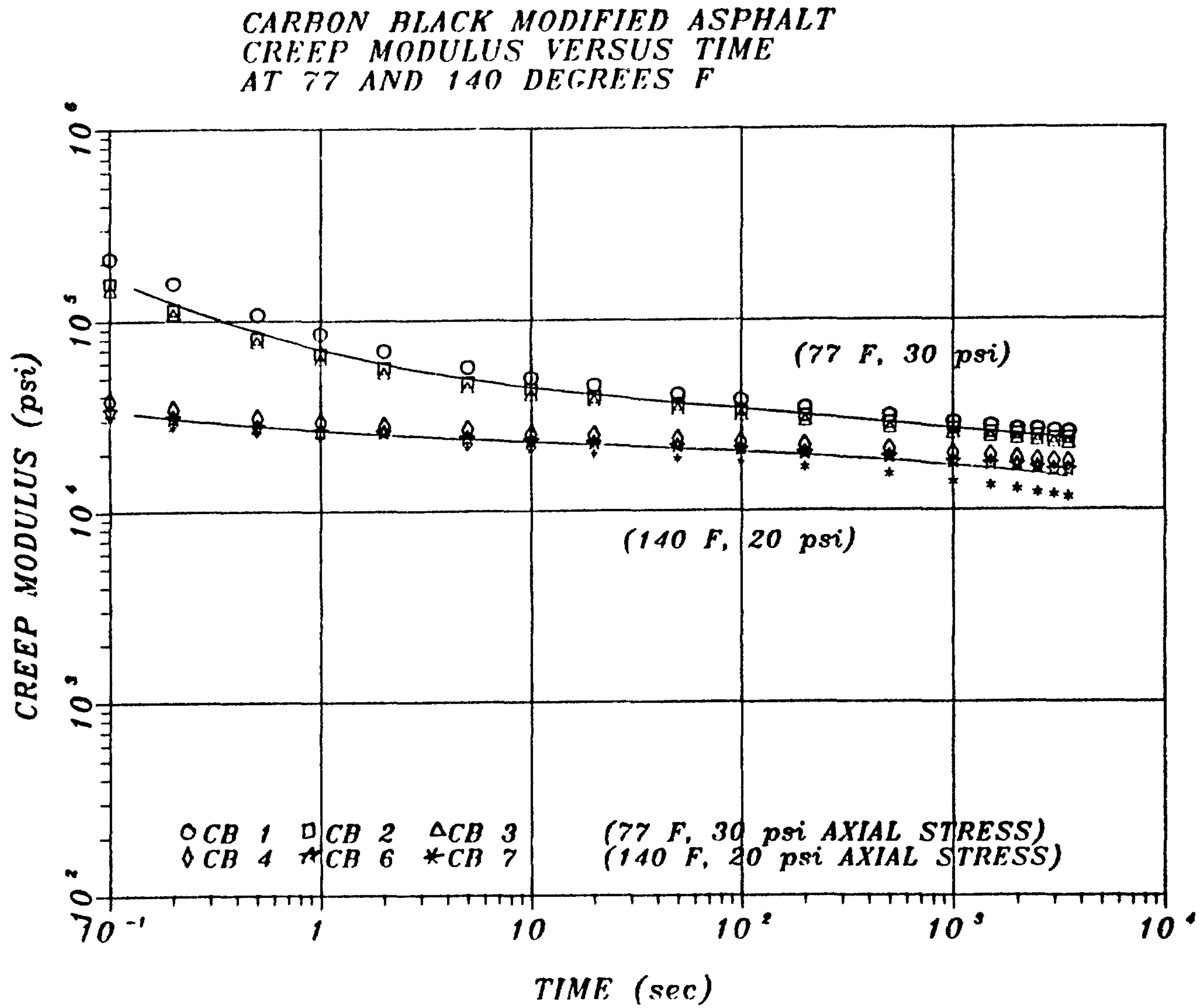

Figure C-2. Creep Modulus vs. Time, Carbon Black Modified Asphalt

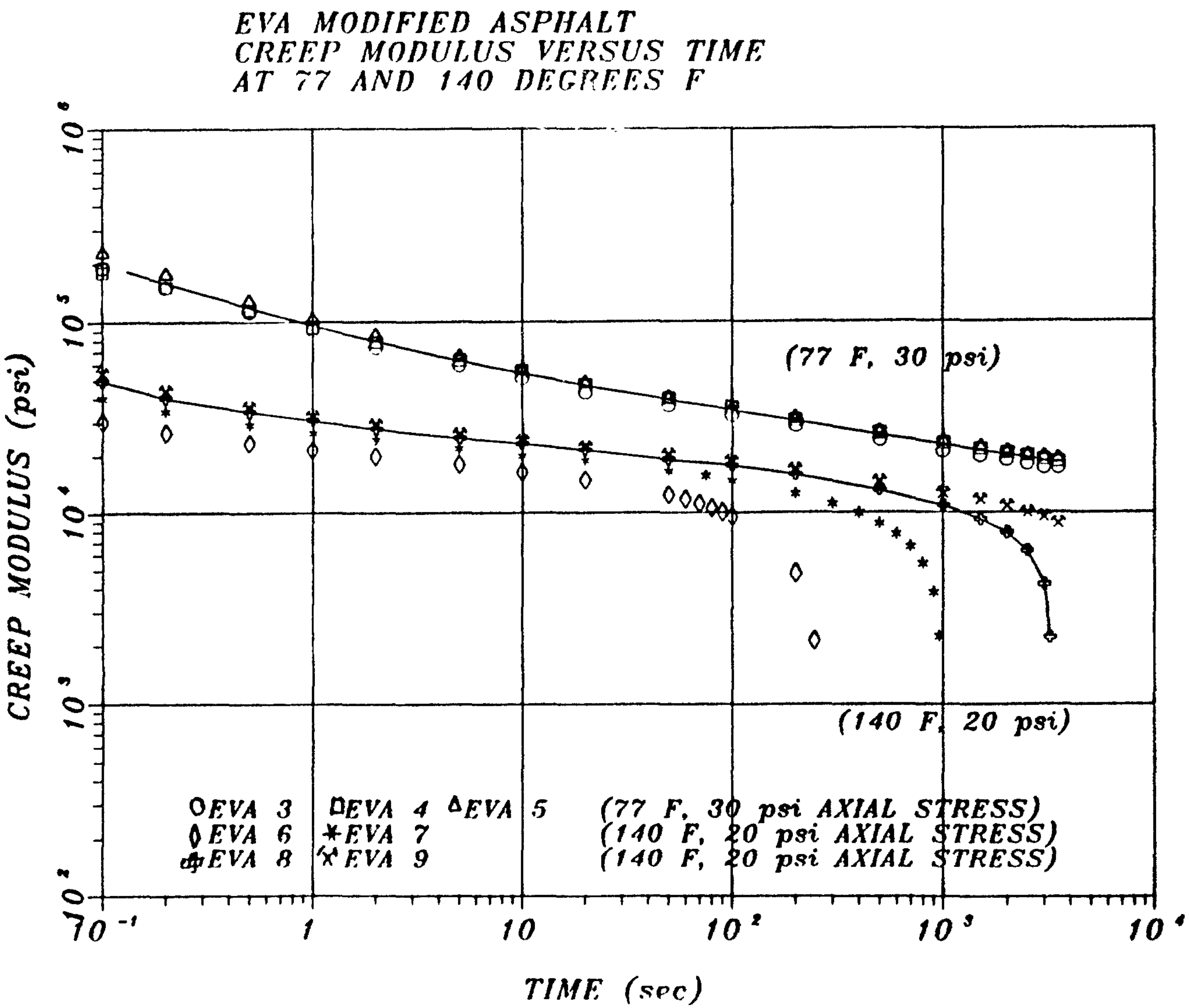

Figure C-3. Creep Modulus vs. Time, Sulfur Modified Asphalt

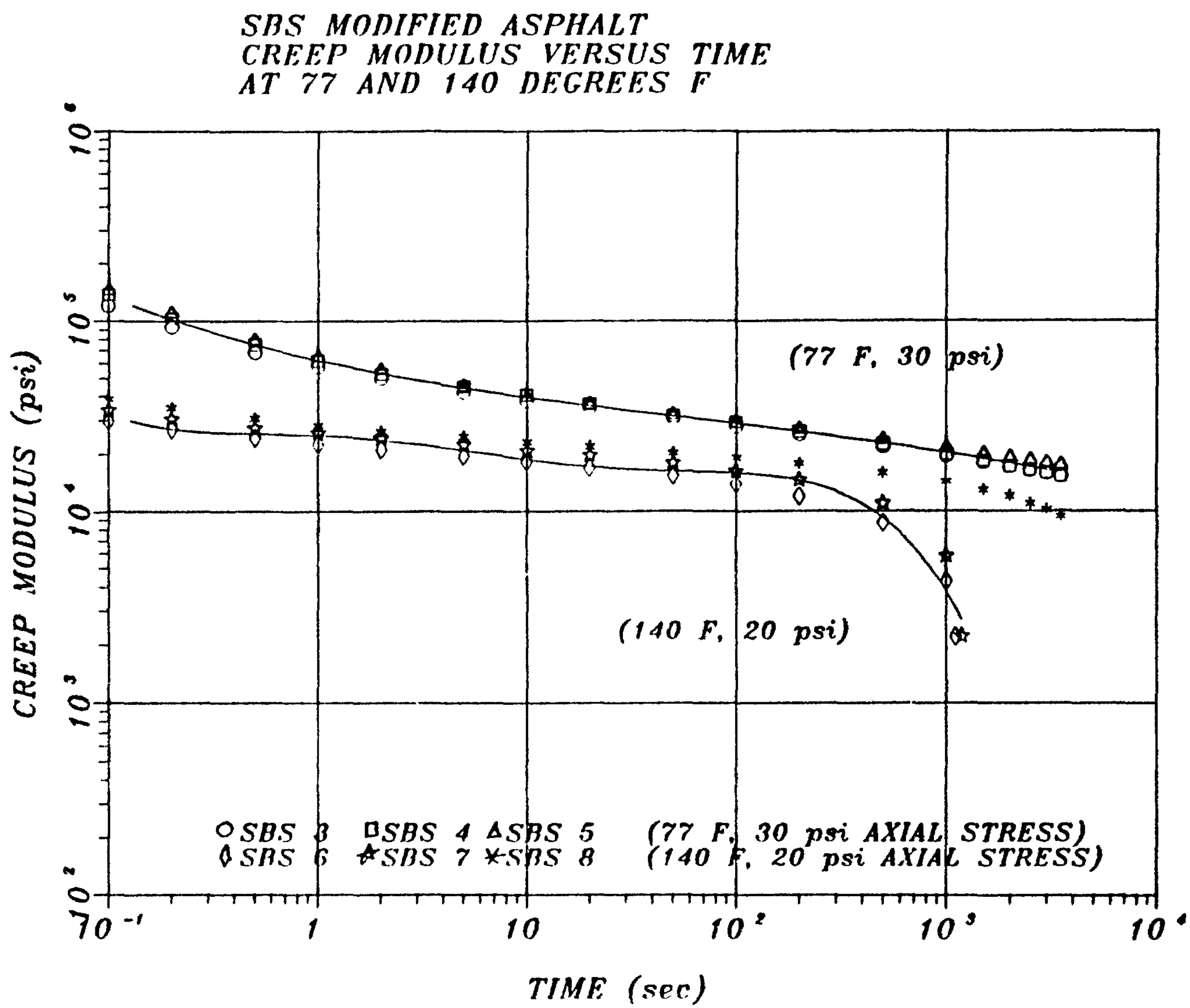

Figure C-4. Creep Modulus vs. Time, SBS Modified Asphalt

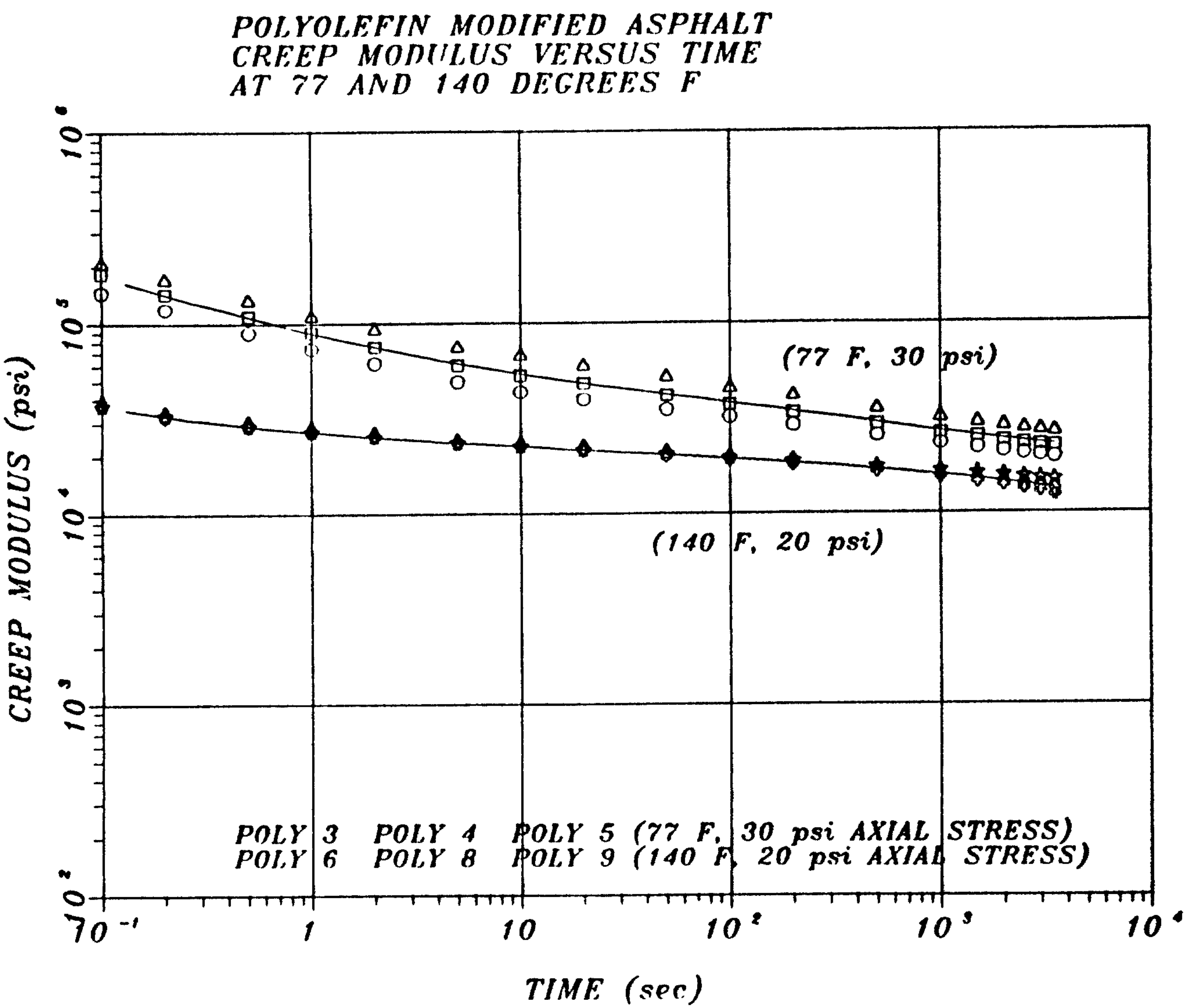

Figure C-5. Creep Modulus vs. Time, EVA Modified Asphalt

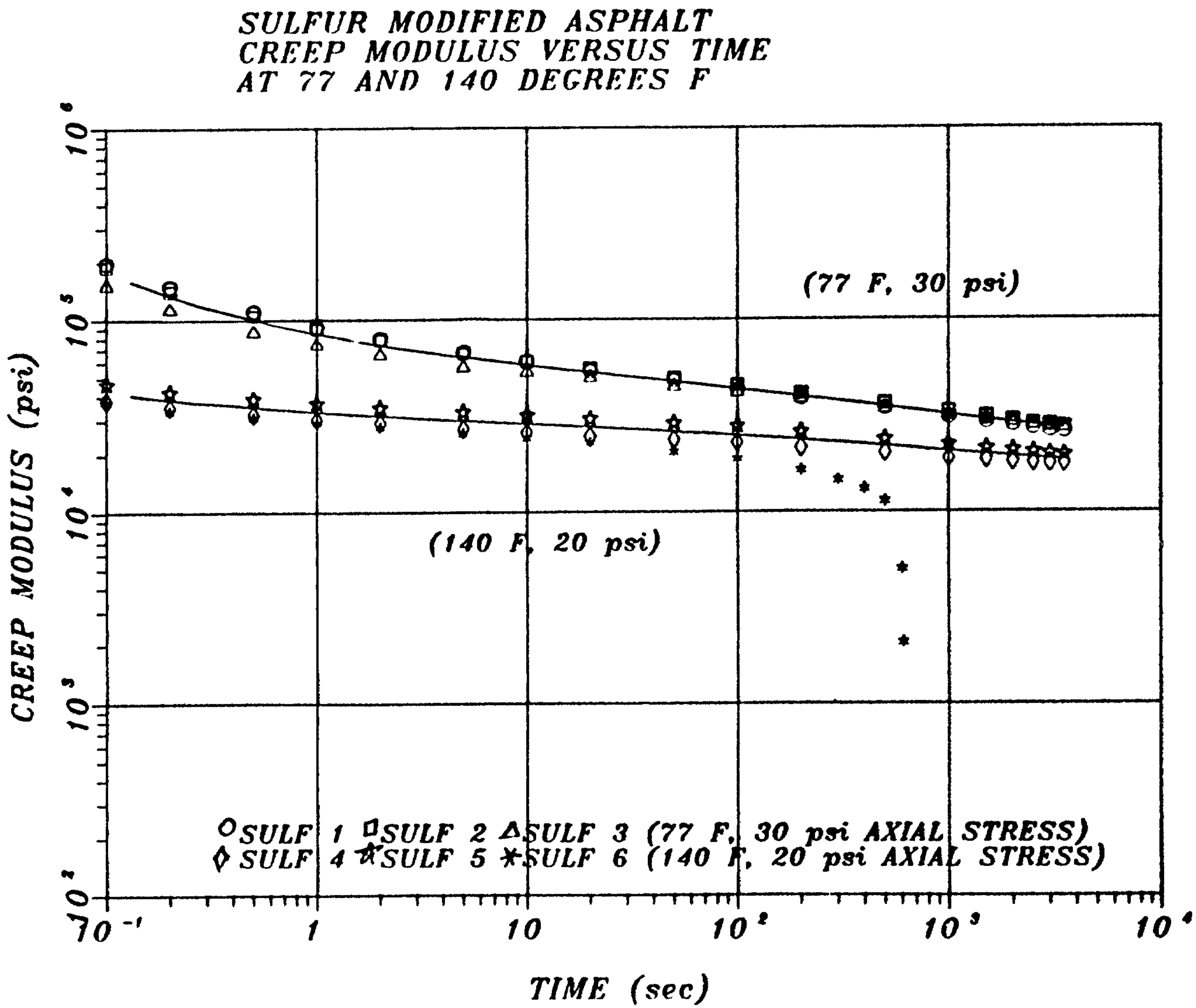

Figure C-6. Creep Modulus vs. Time, Polyolefin Modified Asphalt

TABLE C-4. CREEP MODULUS TEST DATA

PARENT ASPHALT (NO MODIFIER)

SPECIMEN #	ORIG 1		ORIG 3		ORIG 4
AXIAL STRESS	30 psi		30 psi		30 psi
TEMP. F	77		77		77
TIME (sec)	CREEP MODULUS (psi)	TIME (sec)	CREEP MODULUS (psi)	TIME (sec)	CREEP MODULUS (psi)
0.1	1.91E+05	0.1	1.39E+05	0.1	1.41E+05
0.2	1.35E+05	0.2	1.02E+05	0.2	1.02E+05
0.5	9.59E+04	0.5	7.44E+04	0.5	7.42E+04
1	7.86E+04	1	6.10E+04	1	6.04E+04
2	6.59E+04	2	5.31E+04	2	5.17E+04
5	5.39E+04	5	4.53E+04	5	4.52E+04
10	4.83E+04	10	4.13E+04	10	4.08E+04
20	4.45E+04	20	3.73E+04	20	3.68E+04
50	3.97E+04	50	3.26E+04	50	3.21E+04
100	3.62E+04	100	3.05E+04	100	2.97E+04
200	3.25E+04	200	2.76E+04	500	2.25E+04
500	2.94E+04	500	2.36E+04	1000	1.93E+04
1000	2.70E+04	1000	2.08E+04	1500	1.77E+04
1500	2.52E+04	1500	1.90E+04	2000	1.63E+04
2000	2.43E+04	2000	1.79E+04	2500	1.53E+04
2500	2.37E+04	2500	1.71E+04	3000	1.44E+04
3000	2.28E+04	3000	1.62E+04	3500	1.37E+04
3500	2.24E+04	3500	1.56E+04		

TABLE C-4. CREEP MODULUS TEST DATA (continued)

PARENT ASPHALT (NO MODIFIER)

SPECIMEN #	ORIG 5		ORIG 6		ORIG 7
AXIAL STRESS	30 psi		20 psi		20 psi
TEMP. F	140		140		140
TIME (sec)	CREEP MODULUS (psi)	TIME (sec)	CREEP MODULUS (psi)	TIME (sec)	CREEP MODULUS (psi)
0.1	1.25E+04	0.1	2.43E+04	0.1	2.62E+04
0.2	1.08E+04	0.2	2.19E+04	0.2	2.31E+04
0.3	9.99E+03	0.5	1.95E+04	0.5	2.07E+04
0.4	9.41E+03	1	1.80E+04	1	1.92E+04
0.5	8.95E+03	2	1.66E+04	2	1.74E+04
0.6	8.56E+03	5	1.51E+04	5	1.50E+04
0.7	8.21E+03	10	1.34E+04	10	1.30E+04
0.8	7.94E+03	20	1.16E+04	20	1.02E+04
0.9	7.73E+03	50	7.85E+03	30	8.07E+03
1	7.53E+03	60	6.74E+03	40	6.05E+03
2	5.93E+03	70	5.48E+03	50	3.93E+03
3	4.81E+03	80	4.07E+03	56	2.18E+03
4	4.00E+03	90	1.98E+03		
5	3.33E+03				
6	2.81E+03				
7	2.34E+03				
8	1.91E+03				
9	1.42E+03				
10	9.69E+02				

TABLE C-4. CREEP MODULUS TEST DATA (continued)

CARBON BLACK MODIFIED ASPHALT

SPECIMEN #	CB 1		CB 2		CB 3
AXIAL STRESS	30 psi		30 psi		30 psi
TEMP. F	77		77		77

TIME (sec)	CREEP MODULUS (psi)	TIME (sec)	CREEP MODULUS (psi)	TIME (sec)	CREEP MODULUS (psi)
0.1	2.11E+05	0.1	1.57E+05	0.1	1.46E+05
0.2	1.57E+05	0.2	1.14E+05	0.2	1.09E+05
0.5	1.08E+05	0.5	8.09E+04	0.5	7.77E+04
1	8.53E+04	1	6.65E+04	1	6.27E+04
2	6.90E+04	2	5.61E+04	2	5.30E+04
5	5.64E+04	5	4.71E+04	5	4.44E+04
10	4.95E+04	10	4.31E+04	10	4.02E+04
20	4.51E+04	20	3.90E+04	20	3.76E+04
50	4.03E+04	50	3.57E+04	50	3.41E+04
100	3.76E+04	100	3.34E+04	100	3.17E+04
200	3.41E+04	200	3.13E+04	200	2.96E+04
500	3.10E+04	500	2.87E+04	500	2.71E+04
1000	2.88E+04	1000	2.67E+04	1000	2.54E+04
1500	2.75E+04	1500	2.55E+04	1500	2.43E+04
2000	2.64E+04	2000	2.50E+04	2000	2.37E+04
2500	2.63E+04	2500	2.44E+04	2500	2.32E+04
3000	2.58E+04	3000	2.38E+04	3000	2.26E+04
3500	2.55E+04	3500	2.37E+04	3500	2.23E+04

TABLE C-4. CREEP MODULUS TEST DATA (continued)

CARBON BLACK MODIFIED ASPHALT

SPECIMEN #	CB 4		CB 6		CB 7
AXIAL STRESS	20 psi		20 psi		20 psi
TEMP. F	140		140		140
TIME (sec)	CREEP MODULUS (psi)	TIME (sec)	CREEP MODULUS (psi)	TIME	CREEP MODULUS (psi)
0.1	3.06E+04	0.1	3.76E+04	0.1	3.39E+04
0.2	2.76E+04	0.2	3.39E+04	0.2	3.12E+04
0.5	2.54E+04	0.5	3.08E+04	0.5	2.78E+04
1	2.39E+04	1	2.93E+04	1	2.64E+04
5	2.14E+04	2	2.78E+04	2	2.60E+04
10	2.06E+04	5	2.67E+04	5	2.42E+04
20	1.97E+04	10	2.50E+04	10	2.33E+04
50	1.86E+04	20	2.47E+04	20	2.27E+04
100	1.79E+04	50	2.35E+04	50	2.18E+04
200	1.68E+04	100	2.27E+04	100	2.11E+04
500	1.55E+04	200	2.18E+04	200	2.00E+04
1000	1.40E+04	500	2.08E+04	500	1.91E+04
1500	1.33E+04	1000	1.98E+04	1000	1.80E+04
2000	1.28E+04	1500	1.92E+04	1500	1.76E+04
2500	1.22E+04	2000	1.85E+04	2000	1.72E+04
3000	1.19E+04	2500	1.81E+04	2500	1.67E+04
3500	1.16E+04	3000	1.79E+04	3000	1.63E+04
		3500	1.77E+04	3500	1.62E+04

TABLE C-4. CREEP MODULUS TEST DATA (continued)

SULFUR MODIFIED ASPHALT

SPECIMEN #		SULF 1		SULF 2		SULF 3
AXIAL STRESS		30 psi		30 psi		30 psi
TEMP. F		77		77		77
	TIME (sec)	CREEP MODULUS (psi)	TIME (sec)	CREEP MODULUS (psi)	TIME (sec)	CREEP MODULUS (psi)
	0.1	1.97E+05	0.1	1.89E+05	0.1	1.54E+05
	0.2	1.49E+05	0.2	1.41E+05	0.2	1.16E+05
	0.5	1.10E+05	0.5	1.06E+05	0.5	8.81E+04
	1	9.18E+04	1	8.94E+04	1	7.60E+04
	2	7.95E+04	2	7.86E+04	2	6.73E+04
	5	6.71E+04	5	6.67E+04	5	5.76E+04
	10	6.06E+04	10	6.04E+04	10	5.45E+04
	20	5.40E+04	20	5.53E+04	20	5.10E+04
	50	4.84E+04	50	4.93E+04	50	4.57E+04
	100	4.28E+04	100	4.55E+04	100	4.24E+04
	200	3.88E+04	200	4.10E+04	200	3.95E+04
	500	3.44E+04	500	3.64E+04	500	3.48E+04
	1000	3.08E+04	1000	3.31E+04	1000	3.19E+04
	1500	2.92E+04	1500	3.11E+04	1500	3.03E+04
	2000	2.82E+04	2000	2.97E+04	2000	2.97E+04
	2500	2.70E+04	2500	2.87E+04	2500	2.86E+04
	3000	2.64E+04	3000	2.82E+04	3000	2.79E+04
	3500	2.59E+04	3500	2.76E+04	3500	2.76E+04

TABLE C-4. CREEP MODULUS TEST DATA (continued)

SULFUR MODIFIED ASPHALT

SPECIMEN #	SULF 4		SULF 5		SULF 6
AXIAL STRESS	20 psi		20 psi		20 psi
TEMP. F	140		140		140
TIME (sec)	CREEP MODULUS (psi)	TIME (sec)	CREEP MODULUS (psi)	TIME (sec)	CREEP MODULUS (psi)
0.1	3.80E+04	0.1	4.70E+04	0.1	3.76E+04
0.2	3.52E+04	0.2	4.27E+04	0.2	3.38E+04
0.5	3.22E+04	0.5	3.91E+04	0.5	3.12E+04
1	3.04E+04	1	3.72E+04	1	2.94E+04
2	2.91E+04	2	3.52E+04	2	2.77E+04
5	2.71E+04	5	3.34E+04	5	2.56E+04
10	2.59E+04	10	3.19E+04	10	2.42E+04
20	2.46E+04	20	3.06E+04	20	2.28E+04
50	2.38E+04	50	2.91E+04	50	2.06E+04
100	2.29E+04	100	2.80E+04	100	1.89E+04
200	2.15E+04	200	2.61E+04	200	1.65E+04
500	2.03E+04	500	2.39E+04	300	1.46E+04
1000	1.89E+04	1000	2.24E+04	400	1.31E+04
1500	1.87E+04	1500	2.15E+04	500	1.13E+04
2000	1.81E+04	2000	2.10E+04	600	4.98E+03
2500	1.79E+04	2500	2.05E+04	609	2.06E+03
3000	1.78E+04	3000	2.00E+04		
3500	1.78E+04	3500	1.98E+04		

TABLE C-4. CREEP MODULUS TEST DATA (continued)

SBS MODIFIED ASPHALT

SPECIMEN #	SBS 3		SBS 4		SBS 5
AXIAL STRESS	30 psi		30 psi		30 psi
TEMP. F	77		77		77

TIME (sec)	CREEP MODULUS (psi)	TIME (sec)	CREEP MODULUS (psi)	TIME (sec)	CREEP MODULUS (psi)
0.1	1.20E+05	0.1	1.37E+05	0.1	1.47E+05
0.2	9.30E+04	0.2	1.03E+05	0.2	1.12E+05
0.5	6.86E+04	0.5	7.51E+04	0.5	8.09E+04
1	5.73E+04	1	6.16E+04	1	6.61E+04
2	4.98E+04	2	5.24E+04	2	5.61E+04
5	4.22E+04	5	4.49E+04	5	4.60E+04
10	3.78E+04	10	4.08E+04	10	4.05E+04
20	3.48E+04	20	3.64E+04	20	3.70E+04
50	3.07E+04	50	3.15E+04	50	3.26E+04
100	2.76E+04	100	2.91E+04	100	2.97E+04
200	2.53E+04	200	2.60E+04	200	2.73E+04
500	2.19E+04	500	2.25E+04	500	2.41E+04
1000	1.95E+04	1000	1.98E+04	1000	2.18E+04
1500	1.81E+04	1500	1.83E+04	1500	2.04E+04
2000	1.71E+04	2000	1.71E+04	2000	1.94E+04
2500	1.64E+04	2500	1.64E+04	2500	1.88E+04
3000	1.58E+04	3000	1.59E+04	3000	1.82E+04
3500	1.52E+04	3500	1.52E+04	3500	1.78E+04

TABLE C-4. CREEP MODULUS TEST DATA (continued)

SBS MODIFIED ASPHALT

SPECIMEN #	SBS 6		SBS 7		SBS 8
AXIAL STRESS	20 psi		20 psi		20 psi
TEMP. F	140		140		140
TIME (sec)	CREEP MODULUS (psi)	TIME (sec)	CREEP MODULUS (psi)	TIME (sec)	CREEP MODULUS (psi)
0.1	2.97E+04	0.1	3.43E+04	0.1	3.89E+04
0.2	2.69E+04	0.2	3.08E+04	0.2	3.49E+04
0.5	2.42E+04	0.5	2.74E+04	0.5	3.07E+04
1	2.25E+04	1	2.59E+04	1	2.82E+04
2	2.12E+04	2	2.43E+04	2	2.62E+04
5	1.95E+04	5	2.25E+04	5	2.45E+04
10	1.81E+04	10	2.09E+04	10	2.31E+04
20	1.69E+04	20	1.99E+04	20	2.19E+04
50	1.53E+04	50	1.81E+04	50	2.0[illegible]E+04
100	1.38E+04	100	1.63E+04	100	1.91E+04
200	1.20E+04	200	1.46E+04	200	1.78E+04
500	8.69E+03	500	1.11E+04	500	1.59E+04
1000	4.26E+03	1000	5.82E+03	1000	1.43E+04
1108	2.21E+03	1186	2.23E+03	1500	1.29E+04
				2000	1.20E+04
				2500	1.10E+04
				3000	1.02E+04
				3500	9.40E+03

TABLE C-4. CREEP MODULUS TEST DATA (continued)

EVA MODIFIED ASPHALT

SPECIMEN #	EVA 3		EVA 4		EVA 5
AXIAL STRESS	30 psi		30 psi		30 psi
TEMP. F	77		77		77

TIME (sec)	CREEP MODULUS (psi)	TIME (sec)	CREEP MODULUS (psi)	TIME (sec)	CREEP MODULUS (psi)
0.1	1.92E+05	0.1	1.81E+05	0.1	2.32E+05
0.2	1.51E+05	0.2	1.51E+05	0.2	1.80E+05
0.5	1.13E+05	0.5	1.14E+05	0.5	1.29E+05
1	9.10E+04	1	9.31E+04	1	1.05E+05
2	7.38E+04	2	7.85E+04	2	8.67E+04
5	5.97E+04	5	6.31E+04	5	6.69E+04
10	5.11E+04	10	5.55E+04	10	5.71E+04
20	4.32E+04	20	4.70E+04	20	4.89E+04
50	3.69E+04	50	3.99E+04	50	4.10E+04
100	3.27E+04	100	3.60E+04	100	3.59E+04
200	2.91E+04	200	3.09E+04	200	3.20E+04
500	2.45E+04	500	2.64E+04	500	2.71E+04
1000	2.11E+04	1000	2.34E+04	1000	2.42E+04
1500	2.00E+04	1500	2.18E+04	1500	2.26E+04
2000	1.90E+04	2000	2.07E+04	2000	2.14E+04
2500	1.82E+04	2500	2.00E+04	2500	2.05E+04
3000	1.74E+04	3000	1.92E+04	3000	2.01E+04
3500	1.73E+04	3500	1.86E+04	3500	1.96E+04

TABLE C-4. CREEP MODULUS TEST DATA (continued)

EVA MODIFIED ASPHALT

SPECIMEN #	EVA 6		EVA 7
AXIAL STRESS	20 psi		20 psi
TEMP. F	140		140
TIME (sec)	CREEP MODULUS (psi)	TIME (sec)	CREEP MODULUS (psi)
0.1	3.03E+04	0.1	4.01E+04
0.2	2.66E+04	0.2	3.44E+04
0.5	2.34E+04	0.5	2.93E+04
1	2.15E+04	1	2.67E+04
2	1.99E+04	2	2.45E+04
5	1.80E+04	5	2.20E+04
10	1.64E+04	10	2.00E+04
20	1.49E+04	20	1.89E+04
50	1.24E+04	50	1.65E+04
60	1.17E+04	75	1.56E+04
70	1.11E+04	100	1.48E+04
80	1.05E+04	200	1.26E+04
90	1.00E+04	300	1.11E+04
100	9.49E+03	400	9.89E+03
200	4.82E+03	500	8.79E+03
245	2.12E+03	600	7.73E+03
		700	6.62E+03
		800	5.41E+03
		900	3815.18701
		958	2235.05688

TABLE C-4. CREEP MODULUS TEST DATA (continued)

POLYOLEFIN MODIFIED ASPHALT

SPECIMEN #	POLY 3		POLY 4		POLY 5
AXIAL STRESS	30 psi		30 psi		30 psi
TEMP. F	77		77		77
TIME (sec)	CREEP MODULUS (psi)	TIME (sec)	CREEP MODULUS (psi)	TIME (sec)	CREEP MODULUS (psi)
0.1	1.47E+05	0.1	1.84E+05	0.1	2.12E+05
0.2	1.20E+05	0.2	1.44E+05	0.2	1.74E+05
0.5	9.01E+04	0.5	1.09E+05	0.5	1.34E+05
1	7.39E+04	1	9.01E+04	1	1.10E+05
2	6.19E+04	2	7.52E+04	2	9.44E+04
5	4.96E+04	5	6.03E+04	5	7.58E+04
10	4.38E+04	10	5.31E+04	10	6.86E+04
20	3.99E+04	20	4.83E+04	20	6.06E+04
50	3.51E+04	50	4.15E+04	50	5.30E+04
100	3.22E+04	100	3.73E+04	100	4.63E+04
200	2.91E+04	200	3.37E+04	200	4.23E+04
500	2.55E+04	500	2.94E+04	500	3.59E+04
1000	2.32E+04	1000	2.64E+04	1000	3.22E+04
1500	2.19E+04	1500	2.53E+04	1500	3.03E+04
2000	2.11E+04	2000	2.40E+04	2000	2.91E+04
2500	2.05E+04	2500	2.32E+04	2500	2.83E+04
3000	2.01E+04	3000	2.28E+04	3000	2.76E+04
3500	1.96E+04	3500	2.25E+04	3500	2.71E+04

TABLE C-4. CREEP MODULUS TEST DATA (concluded)

POLYOLEFIN MODIFIED ASPHALT

SPECIMEN #	POLY 6		POLY 8		POLY 9
AXIAL STRESS	20 psi		20 psi		20 psi
TEMP. F	140		140		140
TIME (sec)	CREEP MODULUS (psi)	TIME (sec)	CREEP MODULUS (psi)	TIME (sec)	CREEP MODULUS (psi)
0.1	3.79E+04	0.1	3.75E+04	0.1	3.68E+04
0.2	3.31E+04	0.2	3.34E+04	0.2	3.23E+04
0.5	2.95E+04	0.5	2.93E+04	0.5	2.87E+04
1	2.74E+04	1	2.72E+04	1	2.66E+04
2	2.58E+04	2	2.55E+04	2	2.52E+04
5	2.35E+04	5	2.37E+04	5	2.35E+04
10	2.27E+04	10	2.25E+04	10	2.23E+04
20	2.18E+04	20	2.15E+04	20	2.13E+04
50	2.05E+04	50	2.05E+04	50	1.99E+04
100	1.94E+04	100	1.95E+04	100	1.92E+04
200	1.83E+04	200	1.88E+04	200	1.81E+04
500	1.69E+04	500	1.75E+04	500	1.66E+04
1000	1.55E+04	1000	1.67E+04	1000	1.55E+04
1500	1.48E+04	1500	1.61E+04	1500	1.45E+04
2000	1.43E+04	2000	1.58E+04	2000	1.39E+04
2500	1.39E+04	2500	1.55E+04	2500	1.32E+04
3000	1.36E+04	3000	1.52E+04	3000	1.28E+04
3500	1.32E+04	3500	1.50E+04	3500	1.23E+04