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16. Abstract

This report outlines the results of varying the design of HMAC by changing the gradation and the size of the coarse aggregate fraction and by using polymer-modified asphalt to provide mixtures of greater stability for use at intersections.

17. Key Words
mixtures, hot mix asphalt concrete (HMAC), coarse aggregate, gradation, size, polymer-modified asphalt, cores, rutting, shoving, intersections, design

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DISTRICT 14 PAVEMENT INTERSECTION INSTABILITY STUDY

by

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Research Report Number 960-1F

Research Project 3-14D-88-960

District 14 Pavement Intersection Instability Study

conducted for the

Texas State Department of Highways and Public Transportation

by the

CENTER FOR TRANSPORTATION RESEARCH

Bureau of Engineering Research

THE UNIVERSITY OF TEXAS AT AUSTIN

June 1991

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PREFACE

This report results from problems encountered with the rutting and shoving of asphalt concrete pavements in the Austin District of the State Department of Highways and Public Transportation. It provides information and guidelines for improving the stability of paving mixtures at intersections.

Special appreciation is extended to Messrs. James N. Anagnos, Eugene Betts, and Richard Ryle for their assistance in the testing program. In addition, the assistance of Oscar Rodriguez and his personnel from the Austin District of the State Department of Highways and Public Transportation is greatly appreciated. Appreciation is also extended to the Center for Transportation Research staff who assisted in the preparation of the report.

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William E. Elmore

ABSTRACT

This report outlines the results of varying the design of HMAC by changing the gradation and the size of the coarse aggregate fraction and by using polymer-modified asphalt to provide mixtures of greater stability for use at intersections.

SUMMARY

This report provides both design and laboratory test data to support modifications to the standard State Department of Highways and Public Transportation design procedures for hot mix asphalt concrete mixtures. The modifications are specifically for use at intersections to control or eliminate shoving or rutting of the pavement. Actual core data were too limited within the confines of the research to provide support data.

IMPLEMENTATION STATEMENT

It is recommended that the SDHPT, particularly its Austin District, utilize the reported variations for placing test pavements so that the procedures can be modified based on performance data. Successful confirmation of the recommended modifications to the procedures will allow the Department to utilize these modifications statewide where conditions warrant.

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CHAPTER 1. INTRODUCTION

The instability of asphaltic concrete pavements at intersections has been a continuing problem throughout the state. Plastic deformation is particularly prevalent where there is a combination of high temperatures, high traffic volumes, and rapid deceleration and acceleration such as that encountered at stop signs or traffic lights.

Standard mixture design procedures and selection of materials may perform adequately through the major portion of a roadway and become distressed only under the conditions listed above. This project was directed toward developing the information necessary to solve the problems encountered in one highway district and, at the same time, to provide guidelines statewide.

CHAPTER 2. EXPERIMENTAL DESIGN

The primary objective of this study is to evaluate materials which improve stability and decrease susceptibility to permanent deformation, particularly at intersections. To achieve this objective, two laboratory testing programs were carried out. In the first testing program, the basic approach was to compare engineering properties of mixtures containing various percentages of fine aggregate, maximum aggregate size, and asphalt content. In the second testing program, the effect of two polymers on the engineering properties of mixtures was evaluated. This chapter describes the materials, aggregate gradations, and test methods used in this investigation.

Materials

Aggregates

Three aggregate combinations, Weir Pit Type DF, Weir Pit Screenings, and Berdoll Sand, were used to create the various gradations used in this study. Six different gradations, 1, A, B, C, D, and E, were used to evaluate the effect of both gradation and maximum size aggregate on engineering properties. These gradations (1, A, B, C, D, and E) are shown in Table 2.1 and plotted in Figures 2.1 through 2.6. Mix 1 included 51 percent coarse

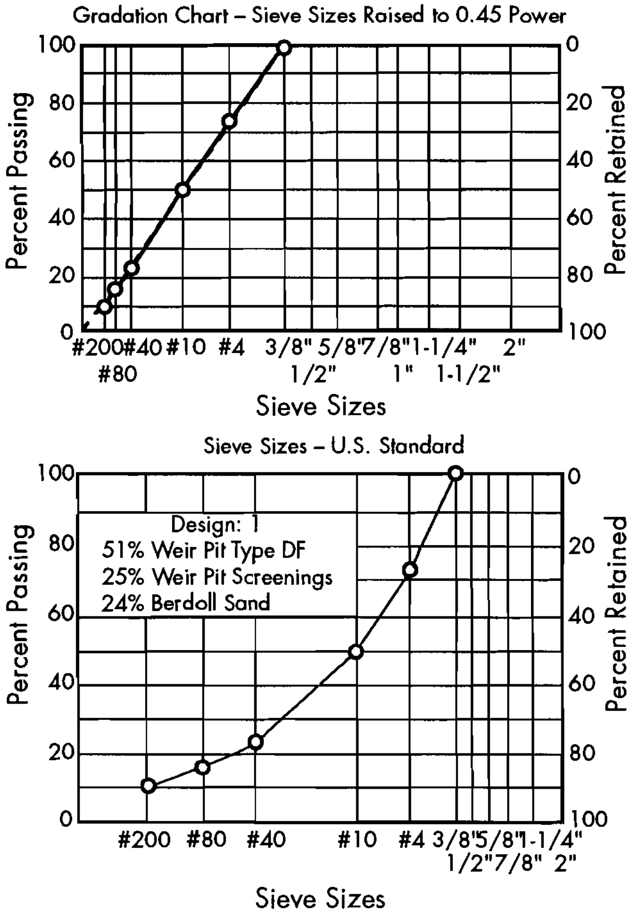


Figure 2.1 Aggregate gradation for mix 1

Table 2.1 Aggregate gradation for mixes 1, A, B, C, D, and E

	Mix 1	Mix A	Mix B	Mix C	Mix D	Mix E	SDHPT Specification Type D	SDHPT Specification Type C
Plus 5/8 in.	0.0	0.0	0.0	0.0	0.0	0.0	0	0 – 5
5/8 to 1/2 in.	0.0	0.0	0.0	0.0	9.0	10.0	0	8 – 29
1/2 to 3/8 in.	0.0	0.0	0.0	12.0	14.0	15.0	0 – 15	10 – 42
3/8 in. to No. 4	22.0	27.0	34.0	27.0	17.0	20.0	21 – 53	11 – 37
No. 4 to No. 10	22.0	24.0	25.0	23.0	20.0	20.0	11 – 32	11 – 32
Plus No. 10	44.0	51.0	59.0	62.0	60.0	65.0	54 – 74	54 – 74
No. 10 to No. 40	28.0	26.0	22.9	18.0	20.0	15.0	6 – 32	6 – 32
No. 40 to No. 80	8.0	7.0	6.0	8.0	8.0	10.0	4 – 27	4 – 27
No. 80 to No. 200	6.0	6.0	4.1	7.0	7.0	7.0	3 – 27	3 – 27
Minus No. 200	14.0	10.0	8.0	5.0	5.0	3.0	1 – 8	1 – 8
Total	100.0	100.0	100.0	100.0	100.0	100.0		

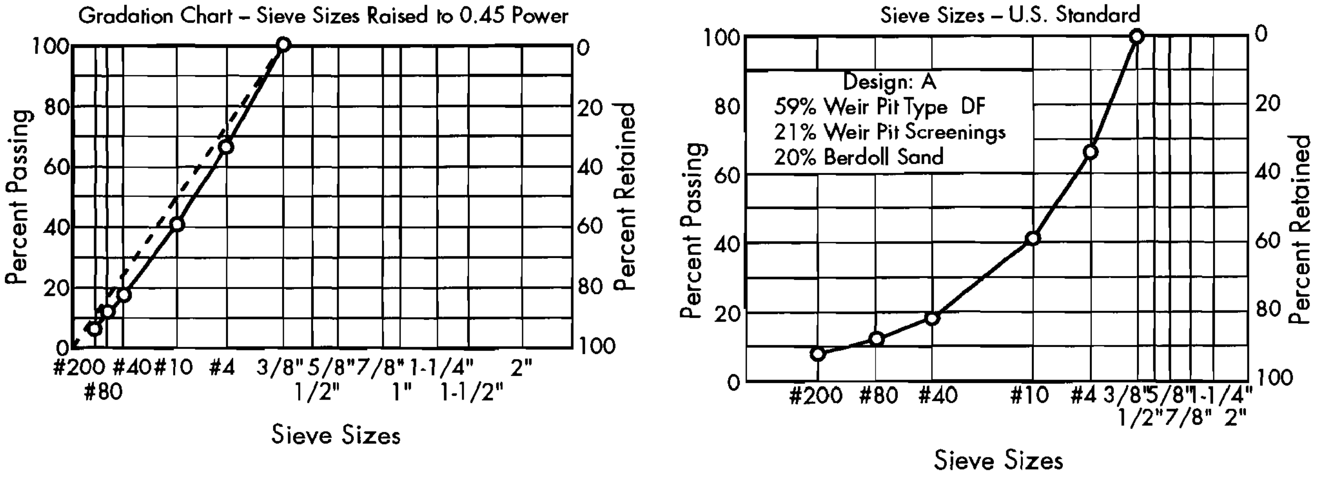


Figure 2.2 Aggregate gradation for mix A

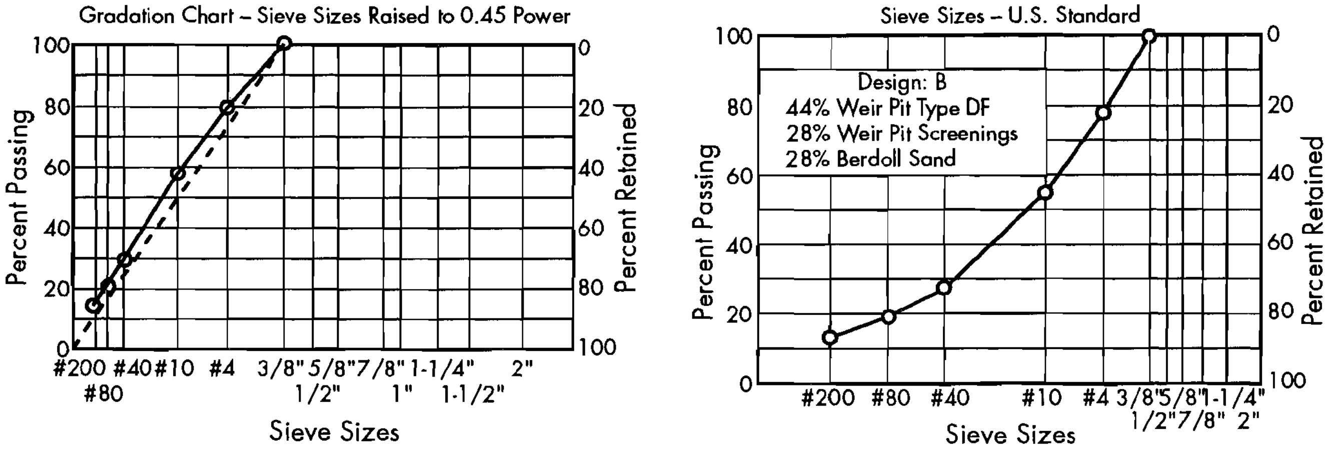


Figure 2.3 Aggregate gradation for mix B

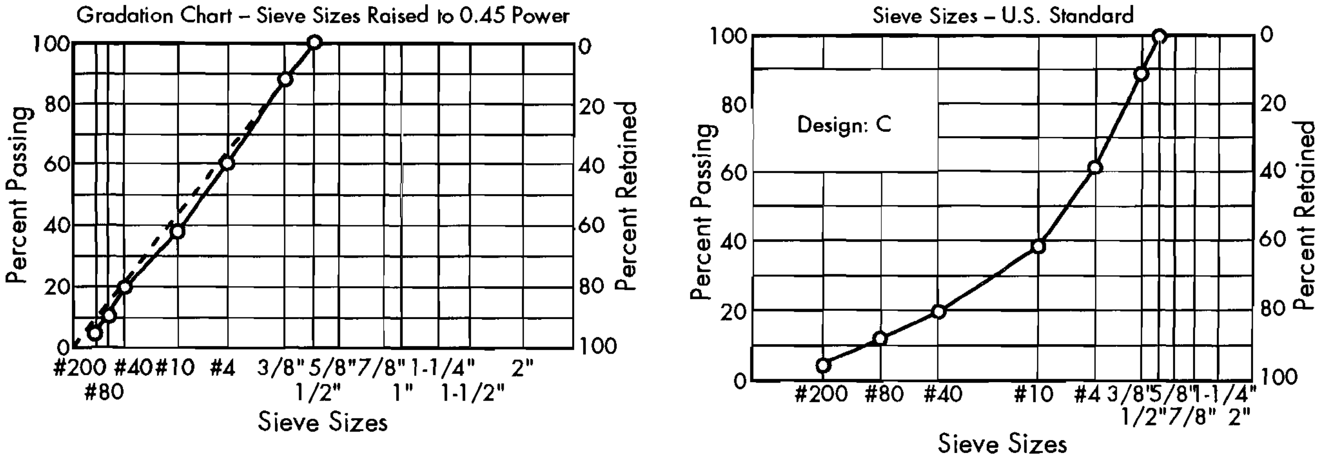


Figure 2.4 Aggregate gradation for mix C

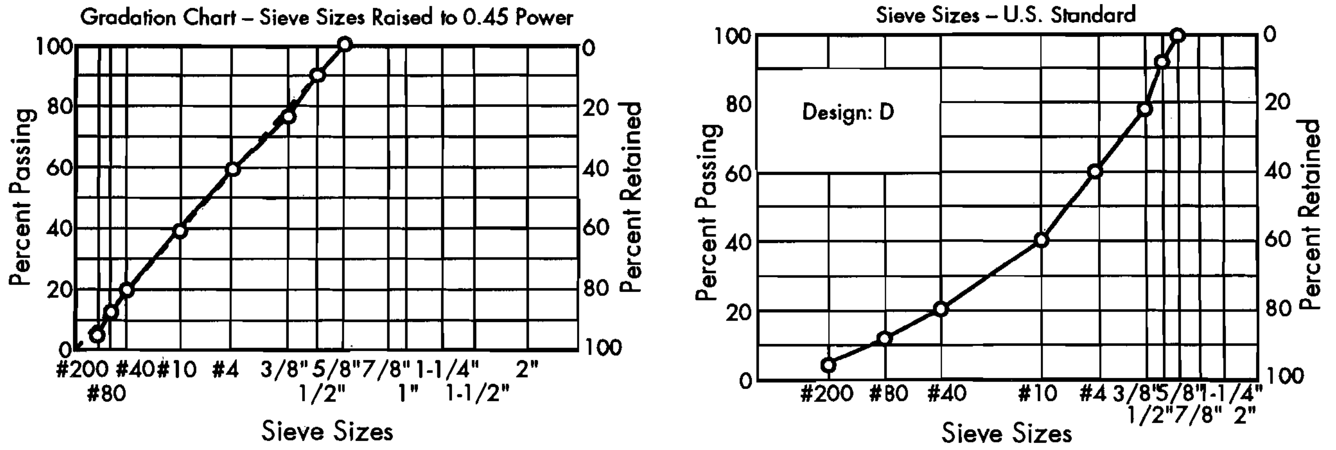


Figure 2.5 **Aggregate gradation for mix D**

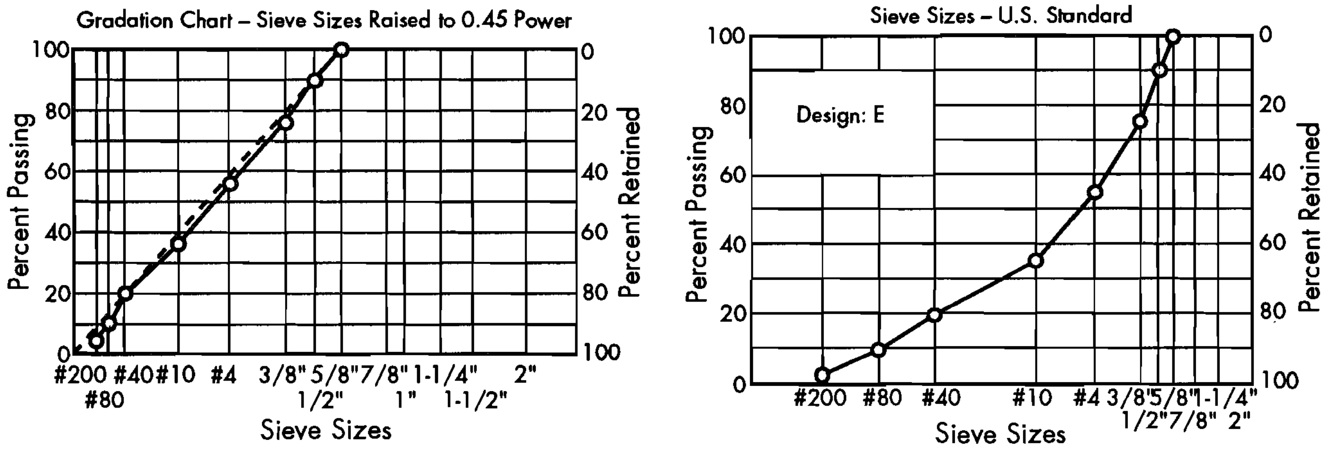


Figure 2.6 **Aggregate gradation for mix E**

aggregate retained on the No. 10 sieve combined with 49 percent fine aggregate to produce a maximum density grading curve. Mixes A and B were essentially the same as mix 1, except that the percent of coarse aggregate (retained on the No. 10 mesh sieve) was different. The maximum aggregate size of mixes C, D, and E was greater than that of mixes 1, A, and B. In addition, the percentages of coarse aggregate for mixes C, D, and E were different. An additional gradation, F, which was used for polymer-modified mixtures, is shown in Table 2.2 and plotted in Figure 2.7.

Asphalt Cement

The asphalt cements used in this study were Exxon AC-20, produced by the Exxon Oil Refinery, and TFA AC-20, produced by Texas Fuel Asphalt. The Exxon AC-20 was used in mixes 1 and A through E. TFA AC-20 was used for polymer-modified mixtures. The properties of these asphalt cements (as determined by the Texas State Department of Highways and Public Transportation) are summarized in Table 2.3.

Polymer

Two polymers included in this study consisted of an Ethylene Vinyl Acetate (EVA) and a combination of SBR Latex and Functionalized Polyolefin. Sources of these polymers and designations used for this study are shown below.

Source	*Type*	*Designation*
Exxon	EVA	Polybilt 103
Dow	SBR/Polyolefin	Dow

Polybilt 103, a copolymer of Ethylene Vinyl Acetate (EVA), had a permanent polarity which was associated with the acetate group. The modified binder contained 97 percent TFA AC-20 and 3 percent Polybilt 103. Dow polymer, which was a combination of SBR and polyolefin, was supplied by Dow Chemical Co. The Dow-modified binder contained 5 percent polymer (2 percent polyolefin and 3 percent SBR solids) and 95 percent TFA AC-20.

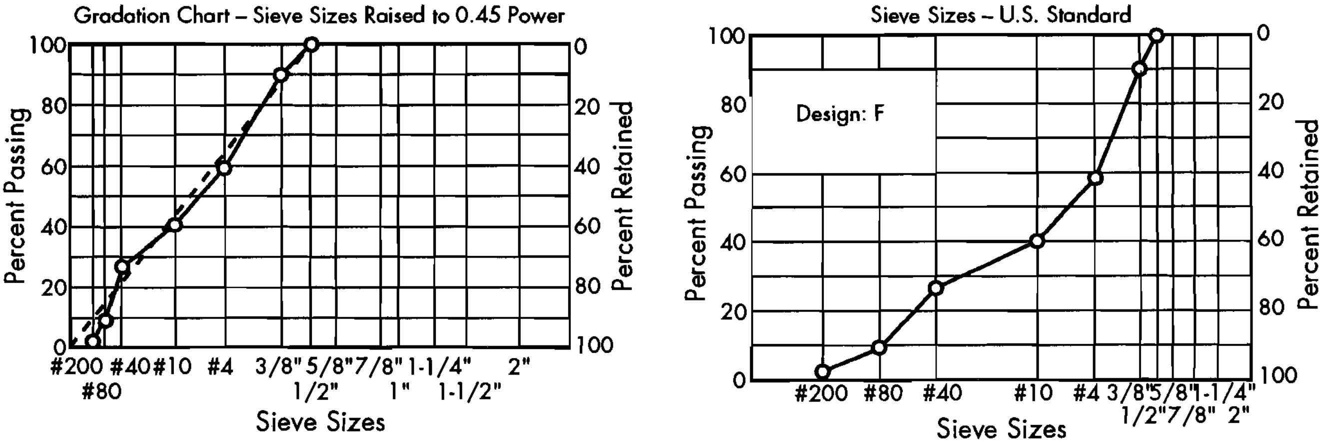


Figure 2.7 Aggregate gradation for mix F

Table 2.2 Aggregate gradation for polymer-modified mixtures

	Sandstone		Limestone		Limestone Screenings		Field Sand			
	Sieve Analysis	31%	Sieve Analysis	27%	Sieve Analysis	19%	Sieve Analysis	23%	Combined Gradation	SDHPT Specification
Plus 1/2 in.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
1/2 to 3/8 in.	33.0	10.2	0.0	0.0	0.0	0.0	0.0	0.0	10.2	0 – 15
3/8 in. to No. 4	57.1	17.7	50.5	13.6	0.0	0.0	0.0	0.0	31.3	21 – 53
No. 4 to No. 10	7.5	2.3	47.1	12.7	18.3	3.5	0.1	0.0	18.5	11 – 32
Plus No. 10									60.1	54 – 74
No. 10 to No. 40	0.5	0.2	1.3	0.4	54.4	10.3	12.2	2.8	13.6	6 – 32
No. 40 to No. 80	0.1	0.0	0.1	0.0	16.5	3.1	62.6	14.4	17.6	4 – 27
No. 80 to No. 200	0.3	0.1	0.5	0.1	7.6	1.4	21.4	4.9	6.6	3 – 27
Minus No. 200	1.5	0.5	0.5	0.1	3.2	0.6	3.7	0.9	2.1	1 – 8
Total	100.0	31.0	100.0	27.0	100.0	19.0	100.0	23.0	100.0	

Table 2.3 Properties of TFA AC-20 and Exxon AC-20 asphalt cements

Asphalt Type	TFA AC–20	Exxon AC–20
Viscosity at 275° F (stokes)	3.70 – 4.20	3.60 – 4.20
Viscosity at 140° F (poises)	1,764 – 2,008	1,735 – 2,163
Penetration at 77° F	56 – 80	57 – 100
Specific gravity at 77° F	1.012 – 1.026	1.010 – 1.033

Mixture Design

The mixture design was established using the design procedure used by the Texas State Department of Highways and Public Transportation (Ref 1). This procedure defines the asphalt which will produce e percent air voids and satisfy a Hveem stability requirement of 35 percent. The resulting asphalt contents for mixes 1 and A through F are shown in Figures 3.1 through 3.7, respectively (pages 19-20).

Specimen Preparation

The aggregate was batched by dry weight to meet a specified gradation for each mix design. Dry aggregate was preheated to a specified mixing temperature of 275 ± 5°F. The binder was heated to 275 ± 5°F and then the specified amount was added to the heated aggregates. The combined mixture was placed in the oven to raise the temperature to 275 ± 5°F and 300 ± 5°F for unmodified and modified mixtures, respectively. The mixture was then mixed for approximately 3 minutes in an automatic 12-quart-capacity Hobart mixer. The mixtures were then placed in preheated ovens and brought to the compaction temperature of 250 ± 5°F and 270 ± 5°F for unmodified and modified mixtures, respectively. Mixtures were compacted using the Texas gyratory shear compactor.

Two compaction procedures, described as standard and modified compactions, were utilized. The standard compaction procedure specified by the State Department of Highways and Public

Transportation would normally produce 3 percent air voids in the design mixture containing optimum asphalt content. Since 3 percent air voids is generally not obtained in the construction process, a modified compaction procedure was also used for certain specimens. For the modified compaction process, the compactive effort was reduced to produce an air void content of approximately 7 percent. No correction to compaction procedure was made for mixtures containing polymers.

After compaction, all specimens were cured at room temperature for 7 days. The specimens were then placed in an environmental chamber for 15 hours to attain the desired testing temperatures.

Test Methods

Several tests were performed on mixtures to measure their engineering properties. The following engineering properties were measured:

- Marshall Stability Test (ASTM D1559)
  - Marshall Stability
- Hveem Stability Test (Tex-208-F)
  - Hveem Stability
- Indirect Tensile Strength Test (Tex-226-F)
  - Indirect Tensile Strength
  - Tensile Strain at Failure
  - Secant Modulus
- Indirect Tension Test for Resilient Modulus (ASTM D1423)
  - Resilient Modulus
- Indirect Tensile Creep Test
  - Tensile Creep Compliance

In addition, the air voids and VMA (Voids in Mineral Aggregate) of certain specimens were measured.

Marshall Stability Test

Marshall stabilities were determined using a Marshall loading apparatus as described in ASTM D1559. The compacted specimens were loaded at 140°F at a constant deformation rate at 2 inches per minute, and the load and corresponding vertical deformation were recorded on an X-Y plotter. The maximum load is the Marshall stability, and the vertical deformation corresponding to the maximum, expressed in units of 0.01 inches, is the flow value. Marshall stability and flow can be measures of the resistance to plastic flow.

Hveem Stability

Hveem stabilities were determined using the Hveem stabilometer as described in Tex-208-F. The compacted asphalt mixture specimens were loaded at 140°F at a constant deformation rate of 0.05 inches per minute to a vertical load of 5,000 pounds. The resultant horizontal force at 5,000 pounds was measured as the pressure on the stabilometer wall and was used to calculate the Hveem stability as follows:

$$\frac{22.2}{PhD_2 \, (P_v - P_h) + 0.222}$$

where

S = Hveem stability, percent;
P_v = applied vertical pressure, psi;
P_h = transmitted horizontal pressure, psi; and
D_2 = displacement of the stabilometer fluid to increase the horizontal pressure from 5 to 100 psi measured in revolutions of a calibrated pump handle. Hveem stability is a measure of mixture's resistance to plastic flow.

Indirect Tensile Test

The indirect tensile test was performed by loading a cylindrical specimen with a single or repeated compressive load which acts parallel to and

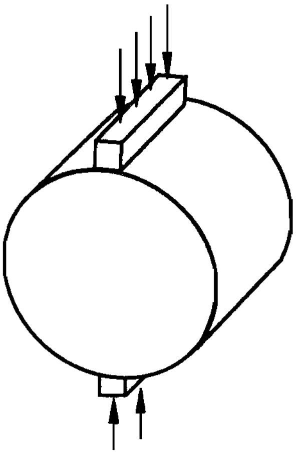


Figure 2.8a Compressive load being applied

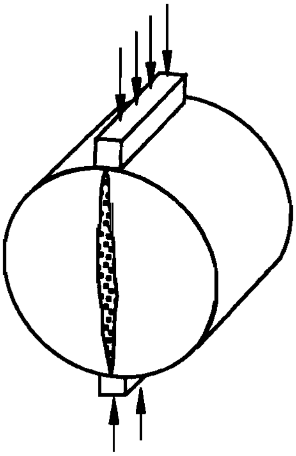


Figure 2.8b Specimen failing in tension

Figure 2.8 Indirect tensile loading and failure

along the vertical diametral plane (Figure 2.8a). The load, which was distributed through 0.5-inch-wide steel loading strips curved to fit the specimen, produced a fairly uniform tensile stress perpendicular to the plane of the applied load. The specimen ultimately failed by splitting along the vertical diameter (Figure 2.8b).

The test equipment included a loading frame, loading head, and an MTS closed-loop electrohydraulic system to apply load and control deformation rate. The loading head was a modified commercially-available die set with the lower platen fixed and the upper platen constrained so that both platens remained parallel. The curved stainless steel loading strips were attached to both the upper and lower platens.

Indirect Tensile Strength

Indirect tensile strength was measured in accordance with Tex-226-F. Although only one test temperature is specified (77°F) in the test method Tex-226-F, additional test temperatures were used to determine the effect of temperature on the tensile strength of the mixtures. Tensile strength was calculated using the following equation for 4-inch-diameter specimens:

$$S_t = 0.156 \frac{P_{max}}{t}$$

where

S_t = tensile strength, psi;
P_{max} = total applied load at failure, pounds; and
t = thickness of specimen, inches.

Tensile Strain at Failure

The tensile strain at failure was calculated using the following equation (Refs 2, 3) for 4-inch-diameter specimens:

$$E_f = \frac{\Delta H 0.1185 \upsilon + 0.03896}{0.02494 \upsilon + 0.0673}$$

where

E_f = strain at failure.
ΔH = horizontal deformation at failure or deformation at maximum load, inches; and
ν = Poisson's ratio.

Secant Modulus

The secant modulus is a measure of the stiffness of the mixture and of specimens under a single load applied to failure. The secant modulus was calculated using the following equation:

$$E_s = \frac{P_{max}}{t\Delta H}(0.27 + \upsilon)$$

where

E_s = secant modulus, psi;
P_{max} = maximum applied load, pounds;
ΔH = horizontal deformation at maximum applied load, inches;
t = specimen thickness, inches; and
ν = Poisson's ratio.

Resilient Modulus

Resilient modulus was determined using the repeated-load indirect tensile test as described in ASTM D1423. A small preload was applied to the specimen to prevent impact of loading and to minimize the effect of seating of the loading strip. Then the repeated load (which was approximately 20 percent of the static failure load) was applied at a frequency of one cycle per second (1 Hz) with a 0.1-second load duration and a 0.9-second rest period. The load, as well as vertical and horizontal deformations, was recorded on a pair of X-Y plotters. A typical load pulse and resulting deformation relationships are shown in Figure 2.9. The resilient modulus was calculated using the resilient, or instantaneously recoverable, horizontal and vertical deformations after approximately 200 load cycles. The equation used to calculate the resilient modulus was

$$E_R = \frac{P_R}{tH_R}(0.27 + \upsilon_R)$$

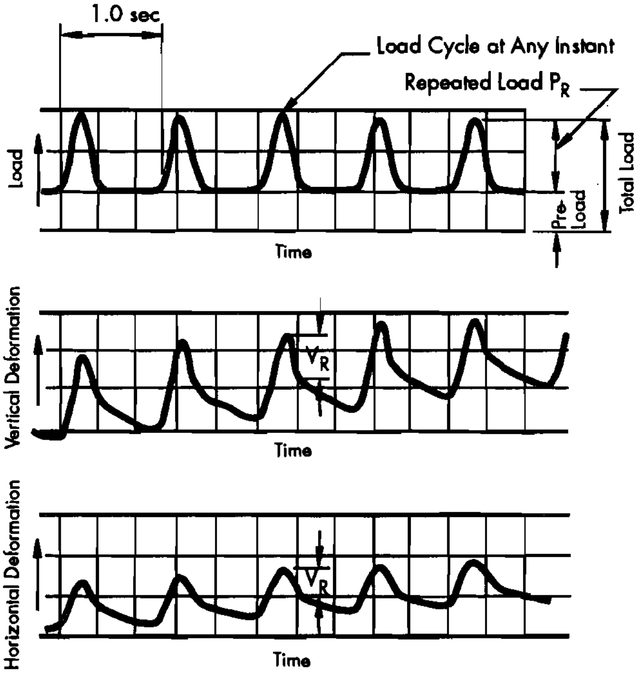


Figure 2.9 Typical load pulse and deformation-time relationships for the repeated-load indirect tensile test

where

E_R = resilient modulus, psi;
P_R = applied repeated load, pounds (Figure 3.16);
t = specimen thickness, inches;
H_R = horizontal resilient deformation, inches; and
v_R = resilient Poisson's ratio.

Creep Test

Normally a creep test is conducted by applying a constant uniaxial stress to a cylindrical specimen and measuring the line-dependent deformation which occurs. Creep compliance Dt is then calculated by dividing the strain by the applied stress as follows:

$Dt = \frac{Et}{\sigma}$ at any test temperature T,
E_t = strain at time t, and
σ = applied stress.

Since the indirect tensile test configuration was used to measure creep compliance of HMAC mixtures, the above equation cannot be used. The state of stress in indirect tensile tests is not uniaxial. Therefore, the creep compliance equation recently developed during the course of CTR Project 492 was used.

Experimental Testing Program

The variables included in this study were asphalt content, test temperature, maximum aggregate size, and aggregate gradation. These variables were studied according to the testing program outlined in Table 2.4. In addition, the effect of polymer on the engineering properties of mixtures was evaluated. This variable (polymer) was studied according to the testing program outlined in Table 2.5.

Table 2.4 Experimental testing program for laboratory mixtures containing different aggregate gradations

Type of Test	Asphalt Content (%)	Test Temperature (°F)	Mix 1	Mix A	Mix B	Mix C	Mix D	Mix E
Hveem stability	4	140	3	3	3	3	3	3
	5	140	3	3	3	3	3	3
	6	140	3	3	3	3	3	3
	7	140	3	3	3	3	3	3
	8	140	3	3	3	3	3	3
Indirect Tensile	Optimum	39	3	3	3	3	3	3
		77	3	3	3	3	3	3
		140	3	3	3	3	3	3
Resilient modulus	4	77	3	3	3	-	-	-
	5	77	3	3	3	-	-	-
	6	77	3	3	3	-	-	-
	7	77	3	3	3	-	-	-
	8	77	3	3	3	-	-	-
Indirect Tensile	4	77	3	3	3	-	-	-
	5	77	3	3	3	-	-	-
	6	77	3	3	3	-	-	-
	7	77	3	3	3	-	-	-
	8	77	3	3	3	-	-	-
	4	140	3	3	3	-	-	-
	5	140	3	3	3	-	-	-
	6	140	3	3	3	-	-	-
	7	140	3	3	3	-	-	-
	8	140	3	3	3	-	-	-

Table 2.5 **Experimental testing program for polymer-modified mixtures**

Type of Test	Asphalt Content (%)	Test Temperature (°F)	Mix F TFA AC–20	TFA AC – 20 with 3% Polybilt	TFA AC – 20 with 5% Dow
Hveem stability	4	140	3	–	–
	5	140	3	–	–
	6	140	3	–	–
	7	140	3	–	–
	8	140	3	–	–
Hveem stability	Optimum	140	3	3	3
		140	3	3	3
		140	3	3	3
Marshall stability	Optimum	140	3	3	3
		140	3	3	3
		140	3	3	3
Indirect tensile	Optimum	39	3	3	3
		77	3	3	3
		104	3	3	3
Resilient modulus	Optimum	39	3	3	3
		77	3	3	3
		104	3	3	3
Creep compliance	Optimum	60	3	3	3
		77	3	3	3
		90	3	3	3

CHAPTER 3. DISCUSSION OF TEST RESULTS

Results of laboratory tests conducted on the mixtures (mixes 1, A, B, C, D, E, and F and the polymer-modified mixtures) are listed in Tables 3.1 through 3.7 and plotted in Figures 3.1 through 3.7. Analysis of variance (ANOVA) techniques were utilized to determine whether significant differences exist between mixture types for each test parameter where appropriate. In each case when a significant difference was indicated, the Newman-Keul multiple range test was used to determine which means were significantly different.

Optimum Asphalt Content

The results of optimum asphalt content for mixes 1, A, B, C, D, E, and F are shown in Table 3.1 and plotted in Figures 3.1 through 3.7. As shown in Figures 3.1 through 3.3, the optimum asphalt content of mix A (59% + No. 10) was less than the optimum asphalt contents of mixes 1 and B. This indicates that the optimum asphalt content decreased when increasing the percent of plus No. 10 sieve. Figures 3.4 through 3.6 show that use of larger-size aggregate also reduces the optimum asphalt content. It should be noted that use of excessive binder or fine aggregates (material passing the No. 200 sieve) manifests itself in low air voids, causing a loss of mechanical friction and higher permanent deformation.

Hveem Stability

The results of Hveem stability are shown in Tables 3.2 and 3.3 and plotted in Figures 3.1 through 3.8. These figures contain the average Hveem stability obtained from three replicate tests conducted for each mix at a given asphalt content. The results show that the Hveem stability of mix A was significantly greater than the Hveem stability of mixes 1 and B at optimum asphalt content. In addition, mixes C, D, and E showed higher values of Hveem stability than mix 1. This indicates that use of a larger maximum aggregate size or use of a higher percent of plus No. 10 sieve may increase the Hveem stability of the mix. Figures 3.1 through 3.7 also reveal that the Hveem stability was increased by decreasing the amount of optimum asphalt content up to a certain point.

The effect of polymers on Hveem stability is shown in Figure 3.8. As shown in this figure, the Hveem stability of the polymer-modified mixtures (Dow and Polybilt 103) was significantly higher than that of the control mixture (TFA AC-20). It appears that addition of the polymers to TFA asphalt cement increased Hveem stability. The effect of Dow was more pronounced than the effect of Polybilt 103 on Hveem stability.

Marshall Stability

Results of the Marshall stability test are shown in Table 3.3 and plotted in Figure 3.9. This figure shows the effect of the polymers on Marshall stability. In a manner similar to that for Hveem stability, polymer-modified mixtures exhibited significantly higher Marshall stability than the control mixture (TFA AC-20). The Polybilt 103 showed more improvement than the Dow.

Voids in Mineral Aggregate (VMA)

Voids in mineral aggregate (VMA) is a measure of the amount of void space available in the aggregate of a compacted HMAC. This void space consists of the space available for asphalt, which gives durability and cohesiveness to the mixture, and that for air voids, which is insurance against asphalt migration and subsequent instability of the pavement. The VMA is a function of aggregate characteristics, asphalt characteristics, the proportion of asphalt and aggregate in the mixture, and compaction. Table 3.2 and Figure 3.10 show VMA values of mixes 1, A, B, C, D, and E at different asphalt contents. Based on this figure, the following trends were apparent.

(1) For a given aggregate, gradation, and compaction method, VMA values normally decreased with increasing asphalt content to a minimum value and then increased as the increased asphalt content prevented aggregate particles from achieving their most intimate contact.

(2) Optimum asphalt content based on the SDHPT mix design procedure normally resulted in an

Table 3.1 **Density test results for mixtures 1, A, B, C, D, E and F**

Mixture	AC (%)	Density (C-14) (%)	Density (Rice) (%)	AC (%)	Density (C-14) (%)	Density (Rice) (%)	AC (%)	Density (C-14) (%)	Density (Rice) (%)	AC (%)	Density (C-14) (%)	Density (Rice) (%)	AC (%)	Density (C-14) (%)	Density (Rice) (%)
Mix 1	4.0	90.4	90.0	5.0	92.7	92.4	6.0	95.2	94.7	7.0	97.5	96.8	8.0	–	–
		90.4	89.6		92.8	92.1		94.8	94.2		97.1	96.6		–	–
		90.5	89.5		93.1	92.0		94.9	94.4		97.8	96.9		–	–
	Average	90.4	89.7	Average	92.9	92.2	Average	95.0	94.4	Average	97.5	96.8	Average	–	–
Mix A	4.0	91.7	90.6	5.0	93.8	92.5	6.0	96.8	95.7	7.0	98.9	98.0	8.0	100.0	99.2
		91.2	90.1		93.5	92.4		96.5	95.4		98.7	97.8		100.0	99.1
		91.1	89.8		93.3	92.4		96.6	95.3		98.8	97.4		100.0	98.8
	Average	91.3	90.2	Average	93.5	92.4	Average	96.6	95.5	Average	98.8	97.7	Average	100.0	99.0
Mix B	4.0	88.8	88.0	5.0	90.9	90.7	6.0	94.3	93.6	7.0	96.3	96.0	8.0	98.8	98.0
		88.4	87.9		91.0	90.6		94.0	93.4		96.5	96.0		98.4	97.8
		89.0	88.4		91.4	90.2		93.8	93.1		96.6	95.8		98.1	97.5
	Average	88.7	88.1	Average	91.1	90.5	Average	94.0	93.4	Average	96.5	95.9	Average	98.4	97.8
Mix C	3.7	92.4	92.3	4.6	95.4	94.7	5.5	98.0	97.0	6.4	99.0	98.5	7.3	100.0	99.5
		92.5	91.8		95.6	95.0		97.5	97.3		99.2	98.6		100.0	99.5
		92.7	91.9		95.2	94.6		97.6	97.0		98.9	98.2		100.0	99.3
	Average	92.5	92.0	Average	95.4	94.8	Average	97.7	97.1	Average	99.0	98.4	Average	100.0	99.4
Mix D	4.0	93.3	92.6	5.0	95.9	95.2	6.0	98.5	97.4	7.0	99.0	98.4	8.0	100.0	99.5
		93.1	92.4		96.3	95.7		98.1	97.7		99.3	98.6		100.0	99.1
		93.6	92.4		96.0	95.3		98.4	97.6		99.2	98.4		100.0	99.4
	Average	93.3	92.5	Average	96.1	95.4	Average	98.3	97.6	Average	99.2	98.5	Average	100.0	99.3
Mix E	4.0	94.5	94.0	5.0	97.1	97.0	6.0	98.5	97.9	7.0	99.1	98.9	8.0	100.0	99.6
		94.2	94.2		97.4	97.1		98.4	97.8		99.4	99.1		100.0	99.3
		94.3	93.9		97.3	97.1		98.1	98.2		99.2	98.8		100.0	99.5
	Average	94.3	94.0	Average	97.3	97.1	Average	98.3	98.0	Average	99.2	98.9	Average	100.0	99.5
Mix F	4.0	94.5	94.2	5.0	97.5	97.0	6.0	98.5	97.8	7.0	99.6	99.0	8.0	100.0	99.5
		94.7	93.7		97.3	96.6		98.6	98.0		99.4	99.1		100.0	99.4
		94.7	94.1		97.3	96.7		98.5	98.1		99.4	98.7		100.0	99.7
	Average	94.6	94.0	Average	97.4	96.8	Average	98.5	98.0	Average	99.5	98.9	Average	100.0	99.5

Table 3.2 VMA and Hveem stability test results for mixtures 1, A, B, C, C, D, E, and F at different asphalt contents

Mixture	AC (%)	VMA (%)	Hveem Stability (%)	AC (%)	VMA (%)	Hveem Stability (%)	AC (%)	VMA (%)	Hveem Stability (%)	AC (%)	VMA (%)	Hveem Stability (%)	AC (%)	VMA (%)	Hveem Stability (%)
Mix 1	4.0	17.50	50.0	5.0	17.18	56.0	6.0	17.50	45.0	7.0	17.32	41.0	8.0	–	–
		17.58	50.0		17.22	55.0		17.35	42.0		17.27	42.0		–	–
		17.53	47.5		17.31	54.5		17.39	44.0		17.35	40.3		–	–
	Average	17.54	49.2	Average	17.24	55.2	Average	17.41	43.7	Average	17.31	41.1	Average	–	–
Mix A	4.0	16.60	45.0	5.0	16.58	46.0	6.0	16.00	46.0	7.0	16.25	41.0	8.0	17.10	27.0
		16.65	41.0		16.50	46.5		15.98	48.0		16.20	42.0		17.20	25.0
		16.64	45.0		16.47	45.0		16.15	48.0		16.17	39.8		17.24	26.3
	Average	16.63	43.7	Average	16.52	45.8	Average	16.04	47.3	Average	16.21	40.9	Average	17.18	26.1
Mix B	4.0	19.15	41.0	5.0	18.85	48.0	6.0	18.32	44.0	7.0	18.24	45.0	8.0	18.65	41.0
		19.11	40.0		18.98	46.0		18.39	42.3		18.22	44.0		18.59	45.0
		19.08	43.0		18.91	46.0		18.39	39.0		18.20	42.0		18.56	44.0
	Average	19.11	41.3	Average	18.91	46.7	Average	18.37	41.8	Average	18.22	43.7	Average	18.60	43.3
Mix C	3.7	15.54	58.0	4.6	14.80	63.0	5.5	14.52	51.0	6.4	14.57	32.0	7.3	16.48	18.0
		15.52	56.0		14.82	60.0		14.48	47.0		14.53	32.0		16.60	15.0
		15.51	57.0		14.86	64.0		14.52	49.0		14.52	35.0		16.45	18.0
	Average	15.52	57.0	Average	14.83	62.3	Average	14.51	49.0	Average	14.54	33.0	Average	16.51	17.0
Mix D	4.0	15.50	67.0	5.0	15.04	59.0	6.0	15.26	41.0	7.0	16.51	20.0	8.0	18.00	11.0
		15.60	63.0		15.06	58.0		15.24	43.0		16.49	18.0		17.88	10.0
		15.59	65.0		15.10	54.0		15.19	39.0		16.58	22.0		17.90	9.0
	Average	15.56	65.0	Average	15.07	57.0	Average	15.23	41.0	Average	16.53	20.0	Average	17.93	10.0
Mix E	4.0	14.66	56.0	5.0	14.10	43.0	6.0	15.30	27.0	7.0	16.63	14.0	8.0	18.02	9.0
		14.70	59.0		14.05	48.0		15.31	27.0		16.58	11.0		18.04	9.0
		14.70	59.0		14.07	44.0		15.37	27.0		16.67	14.0		17.90	7.0
	Average	14.69	58.0	Average	14.07	45.0	Average	15.33	27.0	Average	16.63	13.0	Average	17.99	8.3
Mix F	4.0	–	46.0	5.0	–	43.0	6.0	–	34.0	7.0	–	25.0	8.0	–	18.0
		–	44.0		–	41.0		–	30.0		–	25.0		–	19.0
		–	46.0		–	43.0		–	33.0		–	24.0		–	17.0
	Average	–	45.3	Average	–	42.3	Average	–	32.3	Average	–	24.7	Average	–	18.0

Table 3.3 **Marshall and Hveem test results for polymer-modified mixtures**

Mixture		Air Voids (%)	HVEEM Stability (%)	Air Voids (%)	Marshall Stability (lbs)
Control: TFA AC–20		3.7	42	3.4	2,129
		4.2	42	3.8	1,995
		3.7	44	3.7	1,830
	Average	3.9	43	3.6	1,985
TFA AC–20 + 3% Polybilt 103		3.8	49	3.5	2,920
		3.6	50	3.3	2,675
		3.6	42	3.8	2,656
	Average	3.7	47	3.5	2,750
TFA AC–20 + 5% Dow		2.6	50	2.8	2,423
		2.9	51	2.3	2,364
		3.3	51	2.9	2,451
	Average	2.9	51	2.6	2,412

Table 3.4 **Tensile strength test results for mixtures 1, A, B, C, D, and E at optimum asphalt content**

Mixture		Air Voids (%)	Tensile Strength at 39°F	Air Voids (%)	Tensile Strength at 77°F	Air Voids (%)	Tensile Strength at 140°F
Mix 1		3.8	550	3.5	128	3.5	12
		3.9	536	3.9	120	3.9	13
		3.6	589	3.8	117	3.8	13
	Average	3.8	558.3	3.7	121.7	3.7	12.7
Mix A		3.8	598	3.6	105	3.6	11
		3.7	553	3.4	109	3.4	10
		3.6	620	3.9	111	3.9	11
	Average	3.7	590.3	3.6	108.3	3.6	10.7
Mix B		3.8	625	3.4	128	3.6	11
		3.4	635	3.8	123	3.9	12
		3.6	586	3.6	120	3.7	11
	Average	3.6	615.3	3.8	123.7	3.7	11.3
Mix C		3.9	563	3.7	265	4.0	25
		3.5	580	3.6	270	3.7	24
		3.7	526	3.8	249	3.8	24
	Average	3.7	556.3	3.7	261.3	3.8	24.3
Mix D		3.9	627	3.9	298	3.6	24
		4.2	629	3.8	270	3.8	22
		3.6	600	3.7	280	3.8	22
	Average	3.9	618.7	3.8	282.7	3.7	22.7
Mix E		3.8	650	3.5	265	3.5	20
		3.5	594	3.6	268	3.4	21
		3.4	597	3.3	295	3.8	23
	Average	3.6	613.7	3.5	276.0	3.5	21.3

Table 3.5 Tensile strength and resilient modulus of mixtures 1, A, and B at different asphalt contents

		Tensile Strength at 77°F (psi)					Tensile Strength at 140°F (psi)					Resilient Modulus at 77°F (ksi)				
Mixture		4% AC	5% AC	6% AC	7% AC	8% AC	4% AC	5% AC	6% AC	7% AC	8% AC	4% AC	5% AC	6% AC	7% AC	8% AC
Mix 1		84.0	121.0	124.0	124.0	76.0	8.0	14.0	10.0	12.0	–	1,651	2,592	3,120	1,903	–
		75.0	104.0	120.0	137.0	78.0	8.0	11.0	11.0	15.0	–	3,521	4,616	1,690	1,966	–
		79.0	124.0	110.0	127.0	86.0	7.0	13.0	9.0	13.0	–	2,120	2,113	2,446	3,150	–
	Average	79.3	116.3	118.0	129.3	80.0	7.7	12.7	10.0	13.3	–	2,431	3,107	2,419	2,340	–
Mix A		85.0	102.0	111.0	106.0	90.0	7.0	7.0	10.0	13.0	10.0	1,675	2,247	2,820	2,492	2,105
		77.0	113.0	109.0	121.0	86.0	6.0	9.0	11.0	10.0	12.0	2,196	2,531	2,120	1,686	1,520
		79.0	104.0	100.0	119.0	84.0	7.0	9.0	10.0	12.0	12.0	2,679	3,200	2,569	2,950	1,658
	Average	80.3	106.3	106.7	115.3	86.7	6.7	8.3	10.3	11.7	11.3	2,183	2,659	2,503	2,376	1,761
Mix B		75.0	99.0	101.0	131.0	98.0	6.0	9.0	7.0	11.0	14.0	1,925	2,200	1,920	2,105	1,734
		82.0	112.0	105.0	136.0	104.0	6.0	10.0	6.0	11.0	14.0	1,795	1,862	3,050	2,698	1,953
		71.0	97.0	103.0	121.0	102.0	8.0	9.0	6.0	10.0	12.0	2,749	2,280	2,065	2,036	2,815
	Average	76.0	102.7	103.0	129.3	101.3	6.7	9.3	6.3	10.7	13.3	2,156	2,114	2,345	2,280	2,167

Table 3.6 Indirect tensile test results for polymer-modified mixtures

Mixture	Test Temperature (°F)		Air Voids (%)	Indirect Tensile Strength (psi)	Strain at Failure (%)	Secant Modulus (ksi)	Air Voids (%)	Resilient Modulus (ksi)
Control: TFA AC–20	39		4.0	461	0.12	770	3.8	1,925
			4.0	472	0.09	1,007	3.9	2,625
			3.9	459	0.10	928	3.7	1,812
		Average	4.0	464	0.10	902	3.8	2,121
TFA AC–20 + 3% Polybilt	39		3.7	436	0.23	380	3.8	2,080
			3.9	447	0.20	440	3.8	1,606
			3.5	435	0.19	464	3.6	1,267
		Average	3.7	439	0.21	428	3.7	1,651
TFA AC–20 + 5% Dow	39		3.0	480	0.18	542	3.2	1,225
			2.8	482	0.21	463	2.8	711
			2.5	499	0.18	564	2.8	1,293
		Average	2.8	487	0.19	523	2.9	1,076
Control: TFA AC–20	77		3.8	126	0.62	40.2	3.7	495
			3.7	125	0.65	38.4	3.8	580
			4.1	132	0.63	41.6	3.9	576
		Average	3.9	128	0.64	40.1	3.8	550
TFA AC–20 + 3% Polybilt	77		3.7	136	0.51	52.9	3.7	490
			4.2	123	0.47	52.6	3.5	576
			3.7	138	0.48	57.7	3.6	575
		Average	3.8	133	0.49	54.4	3.6	547
TFA AC–20 + 5% Dow	77		4.8	140	0.36	76.6	3.4	733
			2.9	135	0.42	64.6	3.2	566
			2.9	138	0.39	70.7	3.1	638
		Average	3.5	137	0.39	70.6	3.2	646
Control: TFA AC–20	104		3.7	53	–	–	3.7	266
			4.0	50	0.86	11.6	3.8	233
			3.9	51	0.86	12.0	3.7	217
		Average	3.8	52	0.86	11.8	3.7	239
TFA AC–20 + 3% Polybilt	104		3.8	61	0.73	16.7	3.6	184
			3.9	60	0.72	16.5	3.7	412
			3.5	62	0.69	18.0	3.5	269
		Average	3.7	61	0.71	17.1	3.6	289
TFA AC–20 + 5% Dow	104		2.5	70	0.39	36.1	3.2	241
			3.3	60	0.47	25.6	3.3	233
			3.1	61	0.49	24.9	3.3	244
		Average	3.0	64	0.45	28.9	3.0	239

Table 3.7 Creep compliance test results for polymer-modified mixtures using modified compaction

TFA AC–20
Test Temperature = 60°F, Zigma = 7.648 psi

Time (Sec)	Total Horizontal Deformation (in.)	Tensile Strain (in./in.)	Tensile Creep Compliance (in.^2/lb)
31.6	2.85E–04	1.48E–04	9.69E–06
56.2	3.90E–04	2.03E–04	1.33E–05
100.0	5.35E–04	2.78E–04	1.82E–05
177.8	7.35E–04	3.82E–04	2.50E–05
316.2	1.03E–03	5.33E–04	3.49E–05
562.3	1.43E–03	7.41E–04	4.85E–05
1,000.0	2.09E–03	1.08E–03	7.09E–05
1,778.3	2.99E–03	1.55E–03	1.01E–04
3,162.3	4.30E–03	2.24E–03	1.46E–04
3,600.0	4.60E–03	2.39E–03	1.56E–04
7,200.0	4.13E–03	2.15E–03	

TFA AC–20
Test Temperature = 60°F, Zigma = 7.648 psi

Time (Sec)	Total Horizontal Deformation (in.)	Tensile Strain (in./in.)	Tensile Creep Compliance (in.^2/lb)
31.6	3.20E–04	1.66E–04	5.66E–06
56.2	4.50E–04	2.34E–04	7.96E–06
100.0	6.10E–04	3.17E–04	1.08E–05
177.8	8.40E–04	4.37E–04	1.49E–05
316.2	1.15E–03	5.98E–04	2.03E–05
562.3	1.60E–03	8.32E–04	2.83E–05
1,000.0	2.24E–03	1.17E–03	3.96E–05
1,778.3	3.13E–03	1.63E–03	5.53E–05
3,162.3	4.40E–03	2.29E–03	7.78E–05
3,600.0	4.72E–03	2.45E–03	8.35E–05
7,200.0	4.19E–03	2.18E–03	

TFA AC–20
Test Temperature = 77°F, Zigma = 5.570 psi

Time (Sec)	Total Horizontal Deformation (in.)	Tensile Strain (in./in.)	Tensile Creep Compliance (in.^2/lb)
31.6	4.50E–04	2.34E–04	2.10E–05
56.2	6.25E–04	3.25E–04	2.92E–05
100.0	8.50E–04	4.42E–04	3.97E–05
177.8	1.18E–03	6.11E–04	5.49E–05
316.2	1.63E–03	8.45E–04	7.59E–05
562.3	2.25E–03	1.17E–03	1.05E–04
1,000.0	3.30E–03	1.72E–03	1.54E–04
1,778.3	4.95E–03	2.57E–03	2.31E–04
3,162.3	7.80E–03	4.06E–03	3.64E–04
3,600.0	8.63E–03	4.49E–03	4.03E–04
7,200.0	8.25E–03	4.29E–03	

TFA AC–20
Test Temperature = 77°F, Zigma = 3.917 psi

Time (Sec)	Total Horizontal Deformation (in.)	Tensile Strain (in./in.)	Tensile Creep Compliance (in.^2/lb)
31.6	6.50E–04	3.38E–04	4.32E–05
56.2	9.00E–04	4.68E–04	5.98E–05
100.0	1.20E–03	6.24E–04	7.97E–05
177.8	1.65E–03	8.58E–04	1.10E–04
316.2	2.15E–03	1.12E–03	1.43E–04
562.3	2.88E–03	1.50E–03	1.91E–04
1,000.0	3.95E–03	2.05E–03	2.62E–04
1,778.3	5.63E–03	2.93E–03	3.73E–04
3,162.3	8.13E–03	4.23E–03	5.39E–04
3,600.0	8.90E–03	4.63E–03	5.91E–04
7,200.0	8.83E–03	4.59E–03	

TFA AC–20
Test Temperature = 90°F, Zigma = 2.797 psi

Time (Sec)	Total Horizontal Deformation (in.)	Tensile Strain (in./in.)	Tensile Creep Compliance (in.^2/lb)
3.2	3.00E–04	1.56E–04	2.79E–05
5.6	4.75E–04	2.47E–04	4.42E–05
10.0	6.50E–04	3.38E–04	6.04E–05
17.8	1.03E–03	5.33E–04	9.53E–05
31.6	1.43E–03	7.41E–04	1.32E–04
56.2	1.98E–03	1.03E–03	1.84E–04
100.0	2.60E–03	1.35E–03	2.42E–04
177.8	3.85E–03	2.00E–03	3.58E–04
316.2	5.45E–03	2.83E–03	5.07E–04
562.3	8.50E–03	4.42E–03	7.90E–04
1,000.0	1.55E–02	8.06E–03	1.44E–03

TFA AC–20
Test Temperature = 90°F, Zigma = 1.405 psi

Time (Sec)	Total Horizontal Deformation (in.)	Tensile Strain (in./in.)	Tensile Creep Compliance (in.^2/lb)
3.2	1.40E–04	7.28E–05	2.59E–05
5.6	1.95E–04	1.01E–04	3.61E–05
10.0	2.65E–04	1.38E–04	4.90E–05
17.8	3.70E–04	1.92E–04	6.85E–05
31.6	5.10E–04	2.65E–04	9.44E–05
56.2	7.00E–04	3.64E–04	1.30E–04
100.0	9.50E–04	4.94E–04	1.76E–04
177.8	1.35E–03	7.00E–04	2.49E–04
316.2	1.95E–03	1.01E–03	3.60E–04
562.3	2.82E–03	1.47E–03	5.22E–04
1,000.0	4.26E–03	2.22E–03	7.88E–04

Table 3.7 (continued)

TFA AC-20 + 3% Polybilt 103
Test Temperature = 60°F, Zigma = 7.700 psi

Time (Sec)	Total Horizontal Deformation (in.)	Tensile Strain (in./in.)	Tensile Creep Compliance (in.^2/lb)
31.6	2.75E–04	1.43E–04	9.29E–06
56.2	3.50E–04	1.82E–04	1.18E–05
100.0	4.60E–04	2.39E–04	1.55E–05
177.8	6.15E–04	3.20E–04	2.08E–05
316.2	8.00E–04	4.16E–04	2.70E–05
562.3	1.03E–03	5.33E–04	3.46E–05
1,000.0	1.30E–03	6.76E–04	4.39E–05
1,778.3	1.67E–03	8.66E–04	5.62E–05
3,162.3	2.08E–03	1.08E–03	7.01E–05
3,600.0	2.18E–03	1.13E–03	7.35E–05
7,200.0	1.50E–03	7.80E–04	

TFA AC-20 + 3% Polybilt 103
Test Temperature = 60°F, Zigma = 7.750 psi

Time (Sec)	Total Horizontal Deformation (in.)	Tensile Strain (in./in.)	Tensile Creep Compliance (in.^2/lb)
31.6	4.30E–04	2.24E–04	7.50E–06
56.2	5.15E–04	2.68E–04	8.99E–06
100.0	6.15E–04	3.20E–04	1.07E–05
177.8	7.20E–04	3.74E–04	1.26E–05
316.2	8.30E–04	4.32E–04	1.45E–05
562.3	1.08E–03	5.62E–04	1.88E–05
1,000.0	1.38E–03	7.18E–04	2.41E–05
1,778.3	1.78E–03	9.26E–04	3.11E–05
3,162.3	2.34E–03	1.22E–03	4.08E–05
3,600.0	2.48E–03	1.29E–03	4.32E–05
7,200.0	1.77E–03	9.19E–04	

TFA AC-20 + 3% Polybilt 103
Test Temperature = 77°F, Zigma = 6.103 psi

Time (Sec)	Total Horizontal Deformation (in.)	Tensile Strain (in./in.)	Tensile Creep Compliance (in.^2/lb)
31.6	6.00E–04	3.12E–04	2.56E–05
56.2	7.85E–04	4.08E–04	3.34E–05
100.0	1.00E–03	5.20E–04	4.26E–05
177.8	1.30E–03	6.76E–04	5.54E–05
316.2	1.69E–03	8.76E–04	7.18E–05
562.3	2.25E–03	1.17E–03	9.59E–05
1,000.0	3.04E–03	1.58E–03	1.29E–04
1,778.3	4.20E–03	2.18E–03	1.79E–04
3,162.3	5.90E–03	3.07E–03	2.51E–04
3,600.0	6.40E–03	3.33E–03	2.73E–04
7,200.0	5.70E–03	2.96E–03	

TFA AC-20 + 3% Polybilt 103
Test Temperature = 77°F, Zigma = 6.061 psi

Time (Sec)	Total Horizontal Deformation (in.)	Tensile Strain (in./in.)	Tensile Creep Compliance (in.^2/lb)
31.6	5.50E–04	2.86E–04	2.36E–05
56.2	7.25E–04	3.77E–04	3.11E–05
100.0	8.90E–04	4.63E–04	3.82E–05
177.8	1.19E–03	6.19E–04	5.11E–05
316.2	1.53E–03	7.93E–04	6.54E–05
562.3	1.95E–03	1.01E–03	8.37E–05

TFA AC-20 + 3% Polybilt 103
Test Temperature = 90°F, Zigma = 3.300 psi

Time (Sec)	Total Horizontal Deformation (in.)	Tensile Strain (in./in.)	Tensile Creep Compliance (in.^2/lb)
3.2	5.05E–04	2.63E–04	3.98E–05
5.6	6.30E–04	3.28E–04	4.96E–05
10.0	7.70E–04	4.00E–04	6.07E–05
17.8	1.00E–03	5.20E–04	7.88E–05
31.6	1.28E–03	6.63E–04	1.00E–04
56.2	1.59E–03	8.27E–04	1.25E–04
100.0	2.05E–03	1.07E–03	1.62E–04
177.8	2.62E–03	1.36E–03	2.06E–04
316.2	3.34E–03	1.73E–03	2.63E–04
562.3	4.14E–03	2.15E–03	3.26E–04

Table 3.7 (continued)

TFA AC-20 + 5% Dow
Test Temperature = 60°F, Zigma = 7.333 psi

Time (Sec)	Total Horizontal Deformation (in.)	Tensile Strain (in./in.)	Tensile Creep Compliance (in.^2/lb)
31.6	1.75E–04	9.10E–05	6.21E–06
56.2	2.05E–04	1.07E–04	7.27E–06
100.0	2.40E–04	1.25E–04	8.51E–06
177.8	2.93E–04	1.52E–04	1.04E–05
316.2	3.50E–04	1.82E–04	1.24E–05
562.3	4.20E–04	2.18E–04	1.49E–05
1,000.0	5.15E–04	2.68E–04	1.83E–05
1,778.3	6.35E–04	3.30E–04	2.25E–05
3,162.3	7.85E–04	4.08E–04	2.78E–05
3,600.0	8.28E–04	4.30E–04	2.93E–05
7,200.0	3.70E–04	1.92E–04	

TFA AC-20 + 5% Dow
Test Temperature = 60°F, Zigma = 7.395 psi

Time (Sec)	Total Horizontal Deformation (in.)	Tensile Strain (in./in.)	Tensile Creep Compliance (in.^2/lb)
31.6	1.20E–04	6.24E–05	2.19E–06
56.2	1.30E–04	6.76E–05	2.38E–06
100.0	1.53E–04	7.93E–05	2.79E–06
177.8	1.73E–04	8.97E–05	3.15E–06
316.2	2.08E–04	1.08E–04	3.80E–06
562.3	2.33E–04	1.21E–04	4.25E–06
1,000.0	2.60E–04	1.35E–04	4.76E–06
1,778.3	2.98E–04	1.55E–04	5.44E–06
3,162.3	3.45E–04	1.79E–04	6.31E–06
3,600.0	3.57E–04	1.86E–04	6.53E–06
7,200.0			

TFA AC-20 + 5% Dow
Test Temperature = 77°F, Zigma = 4.690 psi

Time (Sec)	Total Horizontal Deformation (in.)	Tensile Strain (in./in.)	Tensile Creep Compliance (in.^2/lb)
31.6	1.50E–04	7.80E–05	8.32E–06
56.2	2.10E–04	1.09E–04	1.16E–05
100.0	2.75E–04	1.43E–04	1.52E–05
177.8	3.70E–04	1.92E–04	2.05E–05
316.2	4.75E–04	2.47E–04	2.63E–05
562.3	5.90E–04	3.07E–04	3.27E–05
1,000.0	7.65E–04	3.98E–04	4.24E–05
1,778.3	9.60E–04	4.99E–04	5.32E–05
3,162.3	1.21E–03	6.27E–04	6.68E–05
3,600.0	1.28E–03	6.63E–04	7.07E–05
7,200.0	9.15E–04	4.76E–04	

TFA AC-20 + 5% Dow
Test Temperature = 77°F, Zigma = 6.058 psi

Time (Sec)	Total Horizontal Deformation (in.)	Tensile Strain (in./in.)	Tensile Creep Compliance (in.^2/lb)
31.6	2.25E–04	1.17E–04	9.66E–06
56.2	2.70E–04	1.40E–04	1.16E–05
100.0	3.20E–04	1.66E–04	1.37E–05
177.8	4.10E–04	2.13E–04	1.76E–05
316.2	5.10E–04	2.65E–04	2.19E–05
562.3	6.30E–04	3.28E–04	2.70E–05
1,000.0	8.15E–04	4.24E–04	3.50E–05
1,778.3	1.05E–03	5.46E–04	4.51E–05
3,162.3	1.38E–03	7.15E–04	5.90E–05
3,600.0	1.48E–03	7.67E–04	6.33E–05
7,200.0	1.03E–03	5.33E–04	

TFA AC-20 + 5% Dow
Test Temperature = 90°F, Zigma = 3.363 psi

Time (Sec)	Total Horizontal Deformation (in.)	Tensile Strain (in./in.)	Tensile Creep Compliance (in.^2/lb)
31.6	3.60E–04	1.87E–04	2.78E–05
56.2	4.90E–04	2.55E–04	3.79E–05
100.0	6.40E–04	3.33E–04	4.95E–05
177.8	8.00E–04	4.16E–04	6.19E–05
316.2	1.00E–03	5.20E–04	7.73E–05
562.3	1.26E–03	6.55E–04	9.74E–05
1,000.0	1.65E–03	8.58E–04	1.28E–04
1,778.3	2.16E–03	1.12E–03	1.67E–04
3,162.3	2.90E–03	1.51E–03	2.24E–04
3,600.0	3.18E–03	1.65E–03	2.46E–04
7,200.0	2.83E–03	1.47E–03	

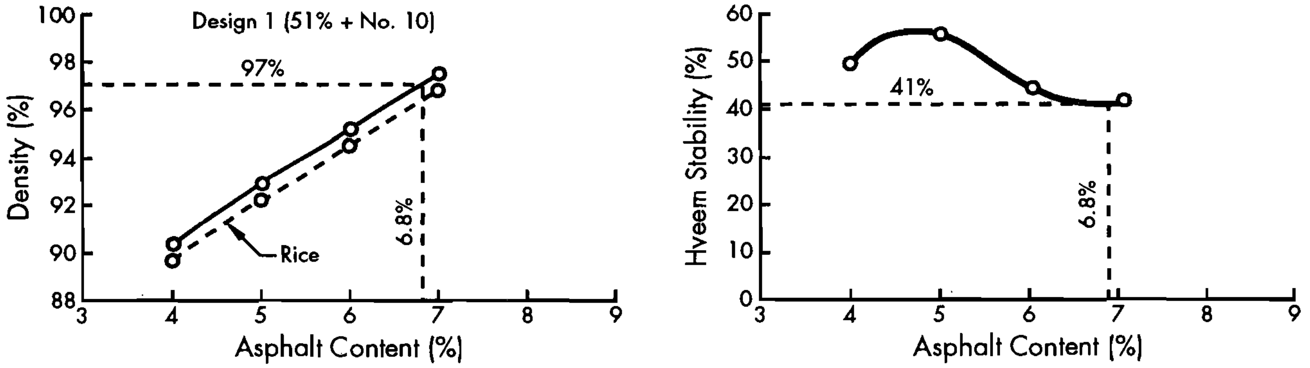


Figure 3.1 **Density and stability graphs for mixture 1**

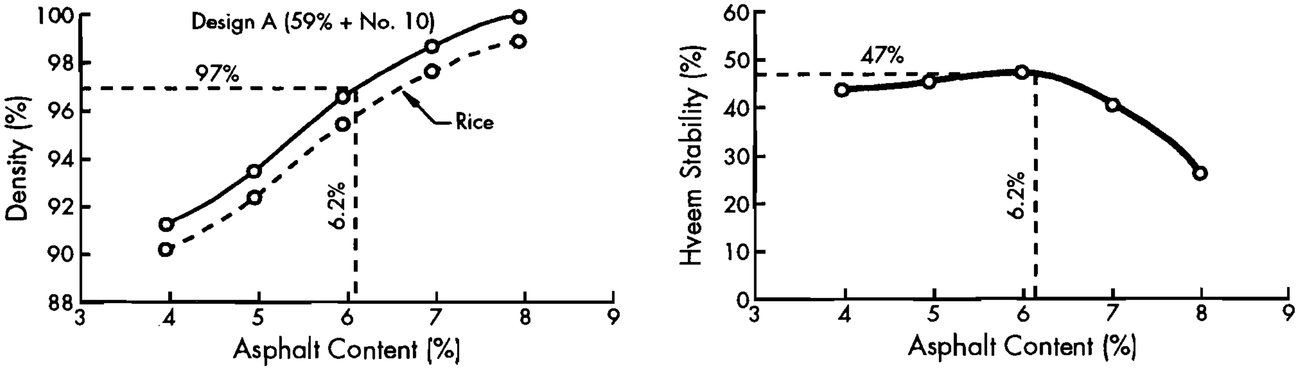


Figure 3.2 **Density and stability graphs for mixture A**

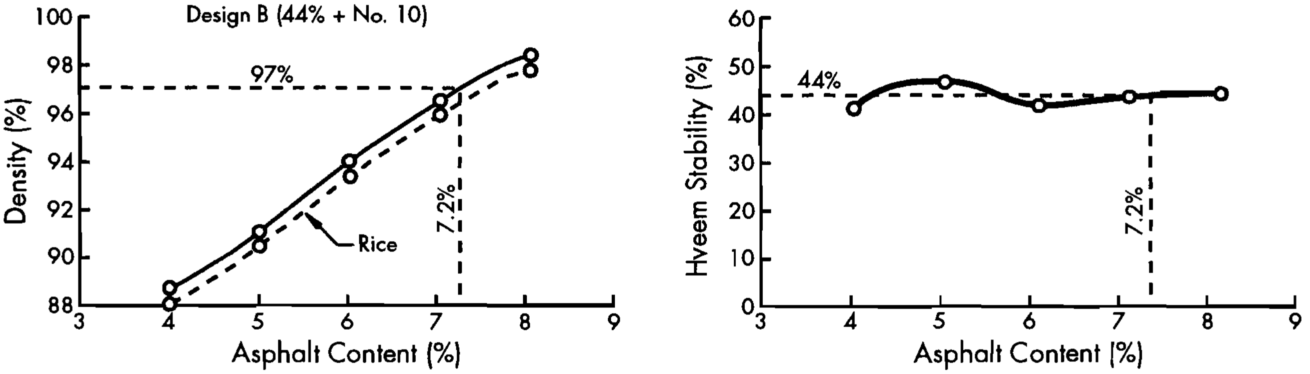


Figure 3.3 **Density and stability graphs for mixture B**

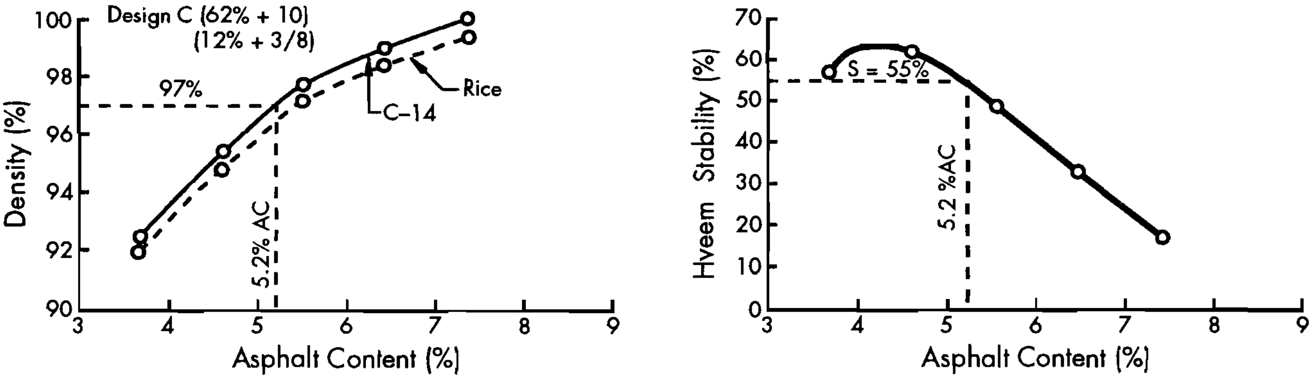


Figure 3.4 **Density and stability graphs for mixture C**

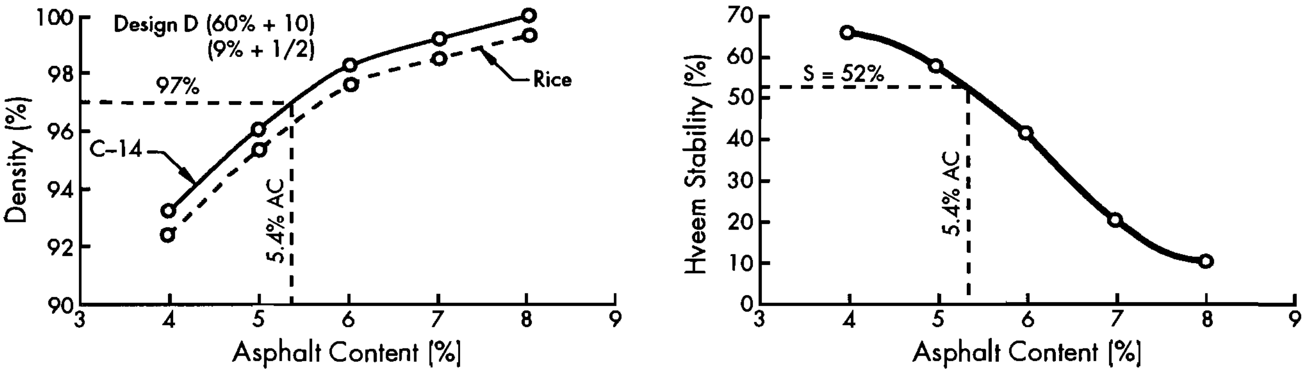


Figure 3.5 **Density and stability graphs for mixture D**

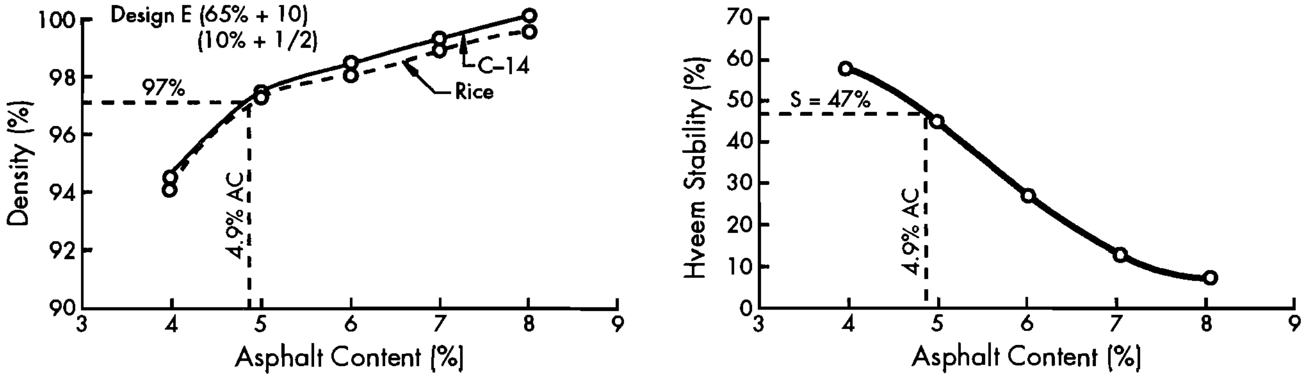


Figure 3.6 **Density and stability graphs for mixture E**

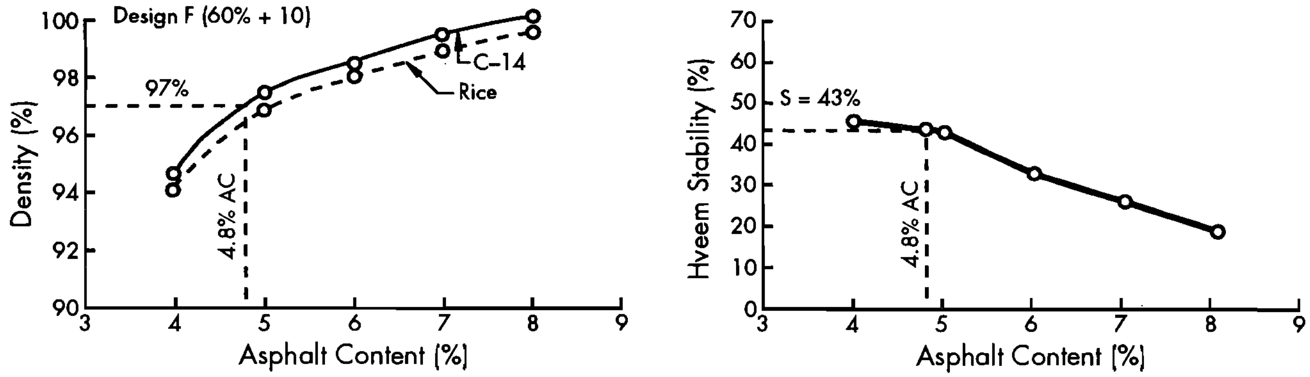


Figure 3.7 **Density and stability graphs for mixture F**

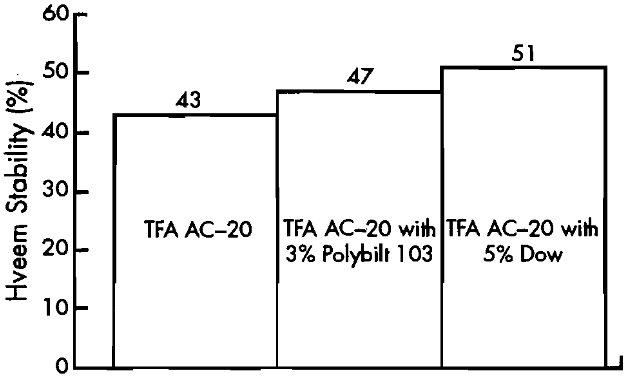


Figure 3.8 **Hveem stability of control and polymer-modified mixtures**

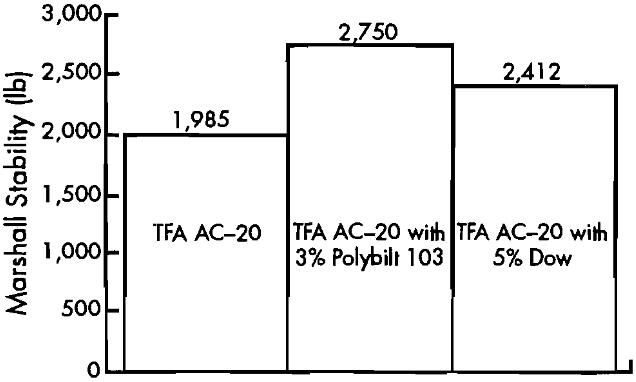


Figure 3.9 **Marshall stability of control and polymer-modified mixtures**

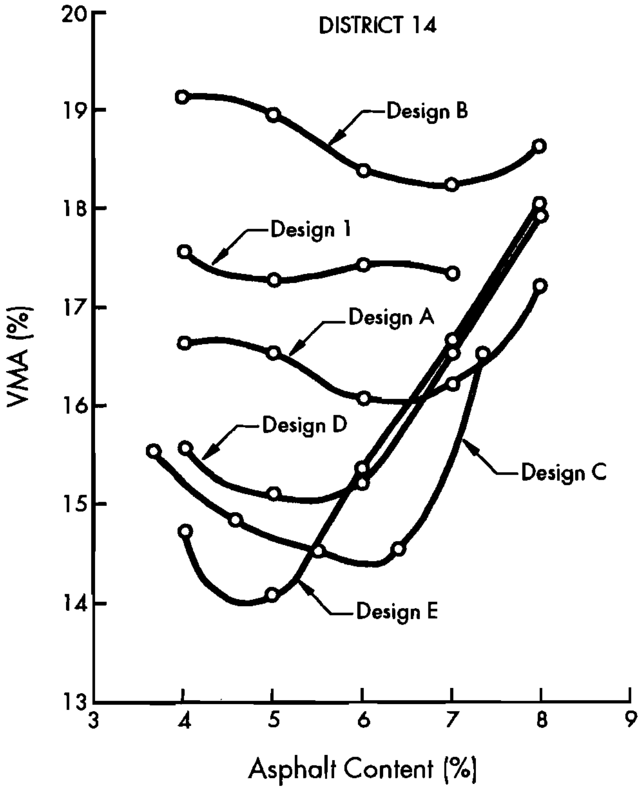


Figure 3.10 **Relationships between VMA and asphalt content for mixtures 1, A, B, C, D, and E**

asphalt content near the amount required to produce minimum VMA. Therefore, the optimum asphalt content appears to be closely related to the voids in mineral aggregate.

(3) The percent of voids in mineral aggregate can be substantially increased by decreasing the percent of plus No. 10 sieve (mix B) in dense-graded HMAC.

(4) A gradation above the 0.45 power curve increased VMA.

(5) Use of larger maximum aggregate size reduced VMA at optimum asphalt content.

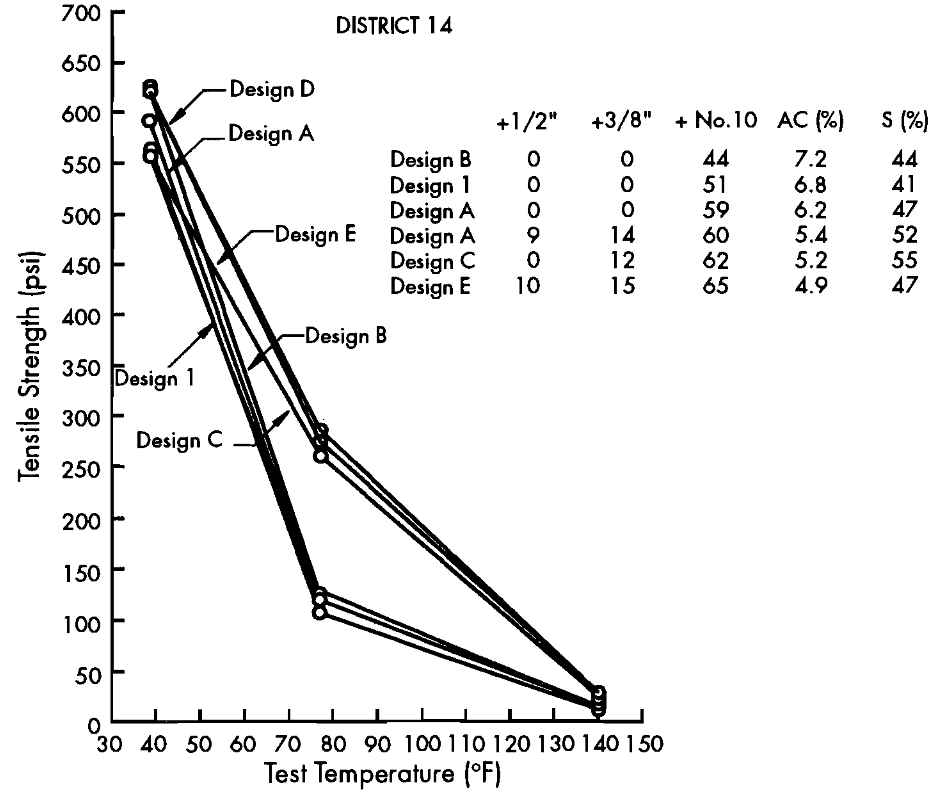
Tensile Strength

Average values of tensile strength at three different test temperatures (39°F, 77°F, and 140°F) for mixes 1, A, B, C, D, and E at the optimum asphalt content are shown in Table 3.4 and plotted in Figure 3.11.

The mixtures containing large aggregate size (mixes C, D, and E) exhibited higher tensile strength than the other mixtures. This effect was significant at higher test temperatures (77°F and 140°F). In addition, the mixtures containing 5/8-inch aggregate (mixes D and E) showed higher tensile strength than mixtures containing a maximum aggregate size of 1/2 inch at 77°F. It appears that larger aggregate size increases tensile strength, particularly at 77°F. The percent of plus No. 10 sieve did not significantly affect tensile strength. Therefore, mixes C, D, and E could be expected to reduce rutting, since, based on tensile strength, these mixtures are stiffer at high temperatures.

The relationships between tensile strength and asphalt content for mixes 1, A, and B are shown in Figure 3.12. As shown in this figure, the effect of asphalt content (which varies from 4 to 8 percent) on tensile strength at 140°F was not significant. However, the optimum asphalt content based on the SDHPT mix design procedure normally resulted in an asphalt content near or slightly higher than the amount required to produce maximum tensile strength at 77°F.

The effect of the polymers on the tensile strength of TFA mixtures is shown in Figure 3.13. The polymer-modified mixtures exhibited higher tensile strength than the control mixture at 77°F and 104°F. The Polybilt 103 showed lower tensile strength at 39°F and higher tensile strength at 104°F compared with the TFA AC-20 mixture. Therefore,



	+1/2"	+3/8"	+ No.10	AC (%)	S (%)
Design B	0	0	44	7.2	44
Design 1	0	0	51	6.8	41
Design A	0	0	59	6.2	47
Design A	9	14	60	5.4	52
Design C	0	12	62	5.2	55
Design E	10	15	65	4.9	47

Figure 3.11 **Relationships between tensile strength and test temperatures for mixtures 1, A, B, C, D, and E**

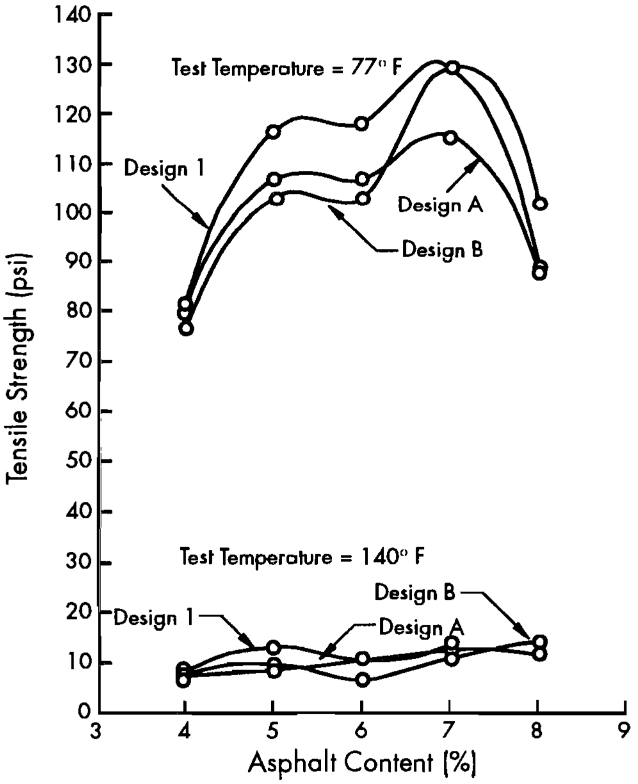


Figure 3.12 **Relationships between tensile strength and asphalt content at different temperatures for mixtures 1, A, and B**

the Polybilt 103 could be expected to reduce thermal cracking and rutting since, based on tensile strength, mixtures containing Polybilt would be more flexible (less brittle) at colder temperatures and stiffer at higher temperatures.

Tensile Strain

The effect of the polymers on tensile strain is shown in Figure 3.14. In general, addition of polymer to the TFA AC-20 mixture increased the tensile strain at 39°F and decreased it at 77°F and 104°F. This indicates that the modified mixtures are less brittle at low temperatures and stiffer at high temperatures.

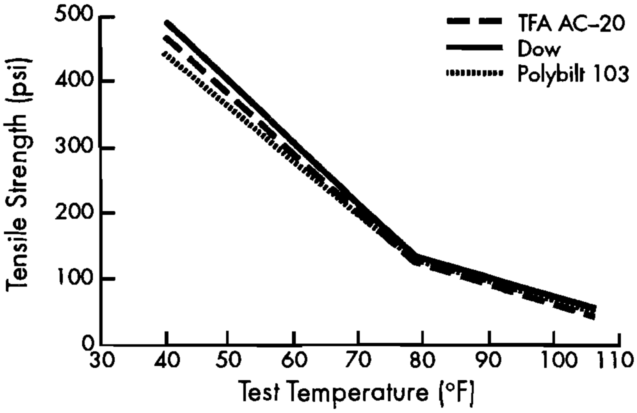


Figure 3.13 **Relationships between tensile strength and test temperature for control and modified mixtures**

Resilient Modulus

The relationships between resilient modulus and asphalt content at 77 °F for mixes 1, A, and B are shown in Figure 3.15. As shown in this figure, there is no significant difference between the resilient modulus values of these mixtures at optimum asphalt content. It appears that addition of plus No. 10 sieve did not significantly change resilient modulus of the mixture containing asphalt content near the optimum at 77°F.

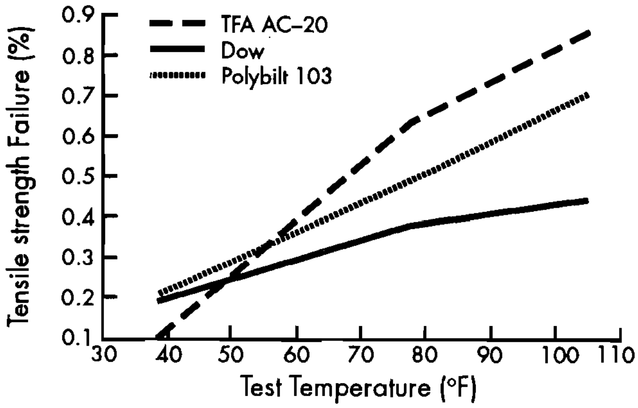


Figure 3.14 Relationships between tensile strain and test temperature for control and modified mixtures

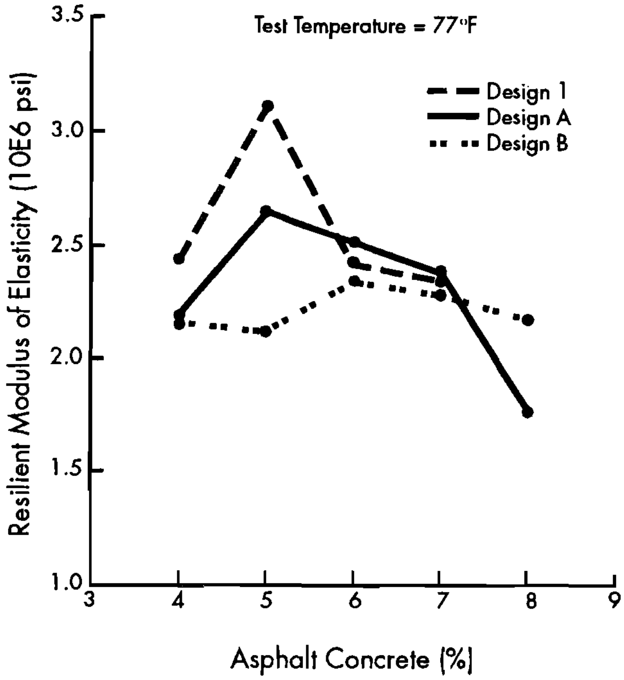


Figure 3.15 Relationships between resilient modulus and asphalt content for mixtures 1, A, and B

The effect of the polymers on resilient modulus is shown in Figure 3.16. The polymer-modified mixtures had significantly lower resilient modulus values than the TFA AC-20 mixture at 39°F and had slightly higher resilient modulus values than TFA AC-20 at 77°F, and 104°F. Ideal polymers should decrease mixture stiffness at low temperatures to improve flexibility and reduce cracking and/or to increase mixture stiffness at high temperatures in order to reduce permanent deformation.

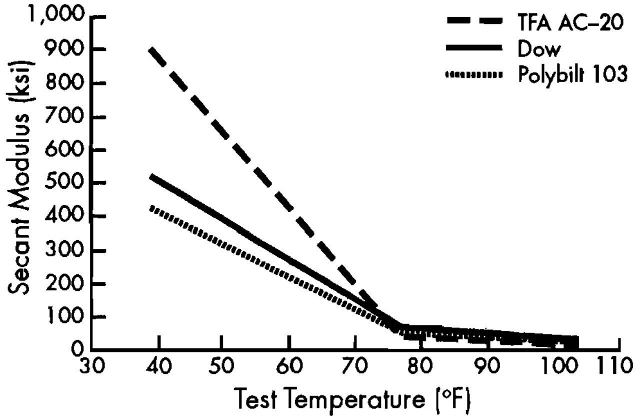


Figure 3.16 Relationships between resilient modulus and test temperature for control and modified mixtures

Secant Modulus

Results of secant modulus testing for the TFA AC-20 and polymer-modified mixtures are plotted in Figure 3.17. In a manner similar to that for resilient modulus, addition of polymers reduced secant modulus at 39°F and increased it at 77°F and 104°F. The Dow polymer showed greater improvement than the Polybilt 103.

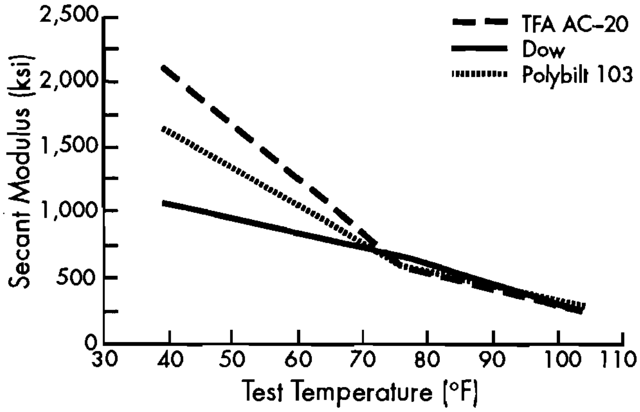


Figure 3.17 Relationships between secant modulus and test temperature for control and modified mixtures

Creep Compliance

The results of creep compliance testing for mix F (TFA AC-20) and the polymer-modified mixtures are shown in Table 3.7 and plotted in Figure 3.18. The following trends were observed from Figure 2.5, which presents the average tensile creep compliance at 60°F, 77°F, and 90°F.

(1) The modified mixtures generally responded with a higher creep compliance than that of the TFA AC-20 mixtures at all test temperatures.

(2) The Polybilt 103 mixture had a higher creep compliance than that of the Dow mixture at all test temperatures.

It appears that the addition of polymers to the TFA AC-20 improved the resistance to permanent deformation of the mixture. The effect of Dow polymer on reducing permanent deformation was more significant than the effect of the Polybilt 103.

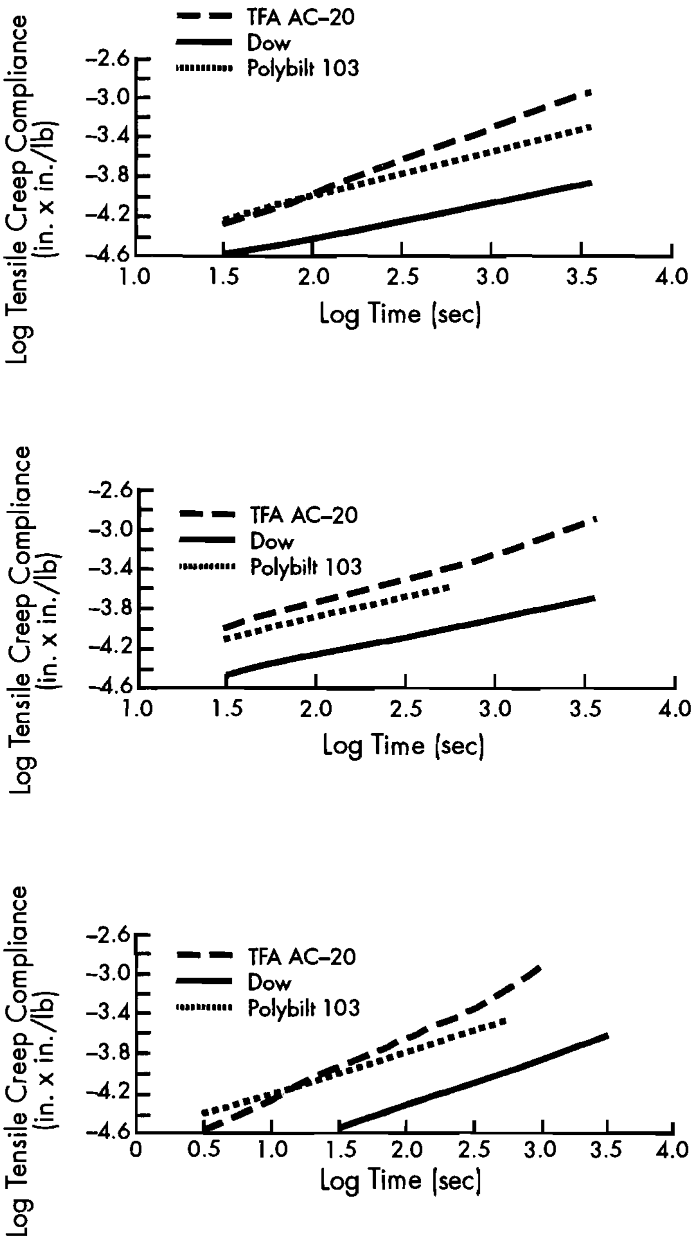


Figure 3.18 **Creep compliance curved for control and modified mixtures at different test temperatures**

CHAPTER 4. CONCLUSIONS

The investigation was designed to evaluate the effects of size and percent of coarse aggregate (plus No. 10 mesh sieve) and polymers in asphalt concrete mixtures. Conclusions applicable to the mixtures used in this study include the following.

(1) Optimum asphalt content based on the SDHPT mix design procedure can be reduced by using more coarse aggregate and larger coarse aggregate.

(2) Increasing the aggregate size produced a reduction in the voids in mineral aggregate (VMA) of the compacted mix.

(3) Mixtures containing more coarse aggregate or larger coarse aggregate exhibited higher Hveem stability.

(4) Mixtures containing larger coarse aggregate showed significantly higher tensile strength at 77°F.

(5) Optimum asphalt content obtained by the SDHPT mix design procedure normally resulted in an asphalt content near the amount required to produce minimum VMA or maximum tensile strength at 77°F.

(6) The resilient modulus of the mixtures was not sensitive to changes in the gradation of the mix.

(7) The polymers (Dow and Polybilt 103) increased Marshall stability, Hveem stability, tensile strength, and stiffness of the mixtures at high temperatures. In addition, the susceptibility to permanent deformation of the mixtures was reduced by addition of the polymers.

(8) The following steps may reduce the permanent deformation susceptibility of HMAC.

  (a) Use asphalt content which is 0.5 percent less than the optimum binder content.

  (b) Increase maximum aggregate size within limits of layer thickness.

  (c) Limit the amount of fines (passing 200 μ) to acceptable limits.

  (d) Use appropriate polymers.