# MECHANISTIC EVALUATION OF SELECTED ASPHALT ADDITIVES

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# INTRODUCTION

Highway engineering is a field which requires the judicious use of materials manufactured by nature. Naturally occurring soils serve as the foundation for highway pavements. Some serve faithfully and well. Others cause problems at every opportunity. Nature's products are used in pavement bases and asphalt mixtures, often with relatively minor refinements. Many of these products are remarkably well suited to meet our needs. It is the duty and responsibility of paving engineers to optimize the use of these materials to the maximum benefit of the taxpayers and the driving public. A host of man-made products are now available which can be used to improve the rheological and/or adhesive properties of nature's own asphalt cement. The laboratory evaluation of five of these asphalt additives is the subject of this report.

The primary objective was to evaluate performance of materials added to asphalt concrete mixtures for the purpose of reducing the pavement cracking and/or rutting potential. The laboratory test program was designed to examine stiffness, brittleness and flexibility at low temperatures and high loading rates and evaluate the resistance to fatigue-type tensile loads such as those caused by vehicular loading and thermal variations. Increases in flexibility must not, however, be gained at the expense of structural stability.

The research (1,2) consisted of a systematic identification of promising types of asphalt additives designed to reduce plastic deformation and cracking in asphalt concrete pavements. Asphalt cements with and without additives were tested in the laboratory to determine chemical, rheological, elastic, fracture and thermal properties as well as sensitivity to heat and oxidation and compatibility between asphalts and additives. Asphalt concrete mixtures were tested to determine stability, compactibility and water susceptibility as well as stiffness, tensile, fatigue and creep/permanent deformation properties as functions of temperature.

# DESCRIPTION OF MATERIALS

## ASPHALT ADDITIVES

Initially, all known asphalt additives were considered for inclusion in the study. Funding and time constraints permitted testing of only five additives. The interest lay primarily in products that would, immediately, upon addition to asphalt concrete, alter the mechanical properties. The products finally selected for evaluation in the study include:

1. Latex (emulsified styrene-butadiene-rubber),
2. Block Copolymer Rubber (styrene-butadiene-styrene),
3. Ethylene Vinylacetate,
4. Finely dispersed Polyethylene, and
5. Carbon Black

Only one carbon black preparation was evaluated since there is presently only one product produced particularly for asphalt modification, Microfil-8, supplied by Cabot Corporation. Microfil-8 is a mixture of approximately 92 percent high-structure HAF grade carbon black plus approximately 8 percent oil similar to the maltenes portion of asphalts, formed into soft pellets dispersible in asphalt.

Styrene-butadiene latexes are available in a wide variety of monomer proportions, molecular weight ranges, emulsifier types and other variables. Two products specifically recommended for use in hot-mixed asphalt concrete were included in the investigation, Latex XUS 40052.00 from Dow Chemical USA and Ultra Pave 70 from Textile Rubber and Chemical Co. Both are anionic and contain about 70 percent solids.

Thermoplastic block copolymer rubber was obtained from Shell Development Company. Kraton TR60-8774 (a blend of equal parts Kraton D-1101 3-block styrene-butadiene-styrene polymer and Kraton DX-1118 2-block styrene-butadiene polymer) was supplied as dry crumbs.

Information on the Novophalt process indicated that almost any polyolefin was satisfactory for processing. Dispersions containing six polyethylene resins which varied in density, molecular weight and melt index were prepared. Dow 526 was selected for use in most of the study.

Two EVA resins differing in monomer ratio, solubility, softening point and melt index were studied. These included Elvax 150 from DuPont Company and EX 042 from Exxon Chemical Americas. Elvax 150 was used in the mixture study.

## ASPHALT CEMENTS

Asphalts for this study were obtained from two sources known to produce asphalt of substantially different composition and temperature susceptibility. Three grades of paving asphalt were obtained from each source: AC-5, AC-10 and AC-20 grades from a Texas Coastal refinery and AR-1000, AR-2000 and AR-4000 grades from a California refinery which processes crude oil originating in the San Joaquin Valley.

Component composition of the Texas Coastal AC-5 and AC-10 and San Joaquin Valley AR-1000 and AR-2000 grade asphalts is shown in Table 1. The San Joaquin Valley asphalts have a relatively low asphaltenes content and a high content of nitrogen bases; the latter component is a solvent for asphaltenes and makes asphaltenes compatible with the other maltenes fractions. These properties of the asphalt are related to the relative

TABLE 1

COMPONENT COMPOSITION OF ASPHALTS

| Property | Texas Coastal Asphalts | | | San Joaquin Valley Asphalts | | |
|---|---|---|---|---|---|---|
| | AC-5 | AC-10 | AC-20 | AR-1000 | AR-2000 | AR-4000 |
| Corbett Analysis[a] | | | | | | |
| Asphaltenes, % | 14.6 | - | 14.8 | 5.0 | - | 6.0 |
| Saturates, % | 13.4 | - | 10.1 | 13.7 | - | 10.0 |
| Napthene Aromatics, % | 41.5 | - | 30.3 | 36.1 | - | 33.5 |
| Polar Aromatics, % | 30.5 | - | 44.8 | 45.1 | - | 50.6 |
| Rostler Analysis[b] | | | | | | |
| Asphaltenes, % | 19.1 | 22.4 | - | 9.2 | 10.3 | - |
| Nitrogen Bases, % | 21.0 | 18.6 | - | 37.7 | 42.0 | - |
| First Acidaffins, % | 22.0 | 14.1 | - | 16.8 | 9.0 | - |
| Second Acidaffins, % | 25.0 | 33.5 | - | 22.2 | 28.3 | - |
| Paraffins, % | 12.9 | 11.4 | - | 14.1 | 10.4 | - |
| Refractive Index of Paraffins, $n_D^{25}$ | 1.4812 | 1.4820 | - | 1.4862 | 1.4907 | - |
| Durability Rating[c] $(N+A_1)/(P+A_2)$ | 1.13 | 0.73 | - | 1.50 | 1.32 | - |
| Sulphur, % | - | 5.08 | - | - | 1.34 | - |

[a]ASTM D4124 (Precipitates asphaltenes using n-heptane)

[b]ASTM D2006 (Discontinued) (Precipitates asphaltenes using n-pentane)

[c]Durability decreases with increasing parameter value; 0.4 - 1.0 = Group I, "superior" durability; 1.0 - 1.2 = Group II, "good" durability; 1.2 - 1.5 = Group III; "satisfactory" durability (3)

compatibility with, or solvent power for polymers such as the rubbers and resins suggested as additives.

## RESULTS OF TESTS ON BINDERS

### BLENDING OF ASPHALTS AND ADDITIVES

Dispersions of the additives and the asphalts were prepared using methods described in Reference 1. Standard rheological tests were performed on the blends. Results are given in Tables 2 and 3. All five additives demonstrate the ability to decrease temperature susceptibility of both asphalts. Since the additives are much more effective at increasing high-temperature viscosity than in decreasing low-temperature penetration, they were incorporated in the soft asphalts for evaluation in the mixture study. Generally, the additives increase the high-temperature viscosity to resist rutting, while not appreciably affecting the cracking resistance of the low-viscosity base asphalts at low temperatures.

### FORCE DUCTILITY

The force ductility test is a modification of the asphalt ductility test. The test has been described (4,5,6) as a means to measure tensile load-deformation characteristics of asphalt and asphalt-rubber binders.

Examples of a typical stress-strain curves are shown in Figure 1. The initial slope of the stress-strain curve in the linear region under primary loading is referred to as the "asphalt modulus" (6). A second slope or loading was observed for certain blends. Athough the data are limited, the stress-strain curves may be indicating compatibility between the additives

TABLE 2

SUMMARY OF BINDER DATA FOR UNMODIFIED AND MODIFIED TEXAS COASTAL ASPHALTS

| Test Value | AC-20 | AC-5 | AC-5 + 15% Microfil-8 | AC-5 + 5% Dow Latex | AC-5 + 3% Dow Latex | AC-5 + 5% Kraton | AC-5 + 5% Elvax 150 | AC-5 + 5% Polyethylene |
|---|---|---|---|---|---|---|---|---|
| Penetration@25°C(77°F) 100g, 5 sec[1] | 75 | 194 | 152 | 114 | 140 | 103 | 176 | 105 |
| Penetration@4°C(39°F) 100g, 5 sec | 8 | 20 | 21 | 14 | 15 | 14 | 17 | 13 |
| Penetration@4°C(39°F) 200g, 60 sec | 28 | 63 | 66 | 54 | 57 | 49 | 54 | 49 |
| Viscosity@60°C(140°F)[2] | 2040 | 506 | 1850 | 5480 | 1960 | 6720 | 1160 | 2200 |
| Viscosity@135°C(275°F)[3] | 398 | 224 | 740 | 2780 | 1020 | 870 | 618 | 840 |
| R&B Soft Point°C(°F)[4] | - | 41(107) | - | 63(145) | 52(125) | 59(138) | 49(120) | 52(126) |
| Ductility 4°C/25°C[5] | - | 150+/150+ | -/11 | 150+/150+ | 150+/150+ | 69/98 | 24/45 | -/35 |
| Viscosity Temp. Suscep.[6] (60°C-135°C) | 3.52 | 3.42 | 2.99 | 2.52 | 2.78 | 2.44 | 2.94 | 2.98 |
| Pen-Vis Number (PVN)[7] | 0.6 | -0.3 | 1.4 | 3.0 | 1.8 | 1.0 | 1.3 | 1.0 |
| Pen Index[8] | -0.9 | -1.0 | -0.2 | -0.5 | -0.9 | -0.2 | 1.2 | -0.5 |
| Penetration Ratio[9] | 37 | 32 | 43 | 47 | 41 | 48 | 31 | 47 |

[1]AASHTO T53.

[2]AASHTO T202.

[3]AASHTO T201.

[4]AASHTO T49.

[5]AASHTO T51, 5 cm/min.

[6]Temperature susceptibility = $(\log\log \eta_2 - \log\log \eta_1)/(\log T_2 - \log T_1)$, where $\eta$ = viscosity in cP, T = absolute temperature.

[7]Determined from penetration at 77°F and viscosity at 275°F (McLeod, 1976).

[8]$P.I. = (20 - 500\alpha)/(1 + 50\alpha)$: $\alpha = [\log(pen_2) - \log(pen_1)]/(T_2 - T_1)$ or $[\log 800 - \log(pen_{25°C})]/T_{SP} - 25)$, where T = temperature, °C.

[9]100(Pen 39.2°F, 200 g, 60 s)/(Pen 77°F, 100 g, 5 s).

TABLE 3

SUMMARY OF BINDER DATA FOR UNMODIFIED AND MODIFIED SAN JOAQUIN ASPHALTS

| Test Value | AR-4000 | AR-1000 | AR-1000+15% Microfil-8 | AR-1000+5% Dow Latex | AR-1000+3% Dow Latex | AR-1000+5% Kraton | AR-1000+5% Elvax 150 | AR-1000+5% Polyethylene |
|---|---|---|---|---|---|---|---|---|
| Penetration@25°C(77°F) 100g, 5 sec[1] | 57 | 146 | 109 | 72 | 83 | 134 | 161 | 98 |
| Penetration@4°C(39°F) 100g, 5 sec | 4 | 10 | 10 | 6 | 6 | 11 | 12 | 8 |
| Penetration@4°C(39°F) 200g, 60 sec | 16 | 46 | 43 | 29 | 28 | 43 | 50 | 41 |
| Viscosity@60°C(140°F)[2] | 2170 | 498 | 1640 | 10,100 | 4020 | 1720 | 1180 | 1295 |
| Viscosity@135°C(275°F)[3] | 256 | 128 | 398 | 3600 | 1190 | 431 | 434 | 399 |
| R&B Soft Point°C(°F)[4] | - | 41(106) | - | 67(152) | 54(130) | 52/(126) | 45(113) | 47(117) |
| Ductility 4°C/25°C[5] | - | 150+/130+ | -/7 | 150+/144 | 36/131 | 141/83 | - | -/26 |
| Viscosity Temp. Suscep.(60-135°C)[6] | 3.92 | 3.94 | 3.43 | 2.58 | 2.96 | 3.38 | 3.22 | 3.33 |
| Pen-Vis Number[7] | -1.4 | -1.6 | -0.1 | 2.5 | 1.2 | 0.3 | 0.5 | -0.2 |
| Pen Index[8] | -2.0 | -2.0 | -1.4 | -1.6 | -1.9 | -1.6 | -1.9 | -1.6 |
| Penetration Ratio[9] | 28 | 32 | 39 | 40 | 34 | 32 | 31 | 37 |

[1] AASHTO T53.

[2] AASHTO T202.

[3] AASHTO T201.

[4] AASHTO T49.

[5] AASHTO T51, $5^{cm}$/min.

[6] Temperature susceptibility = $(\log \log \eta_2 - \log \log \eta_1)/(\log T_2 - \log T_1)$, where $\eta$ = viscosity in cP, T = absolute temperature.

[7] Determined from penetration at 77°F and viscosity at 275°F (McLeod, 1976).

[8] $P.I. = (20 - 500\alpha)/(1 + 50\alpha)$: $\alpha = [\log(pen_2) - \log(pen_1)]/(T_2 - T_1)$ or $[\log 800 - \log (pen_{25°C})] / T_{SP} - 25)$, where T = temperature, °C.

[9] 100(Pen 39.2°F, 200 g, 60 s)/(Pen 77°F, 100 g, 5 s).

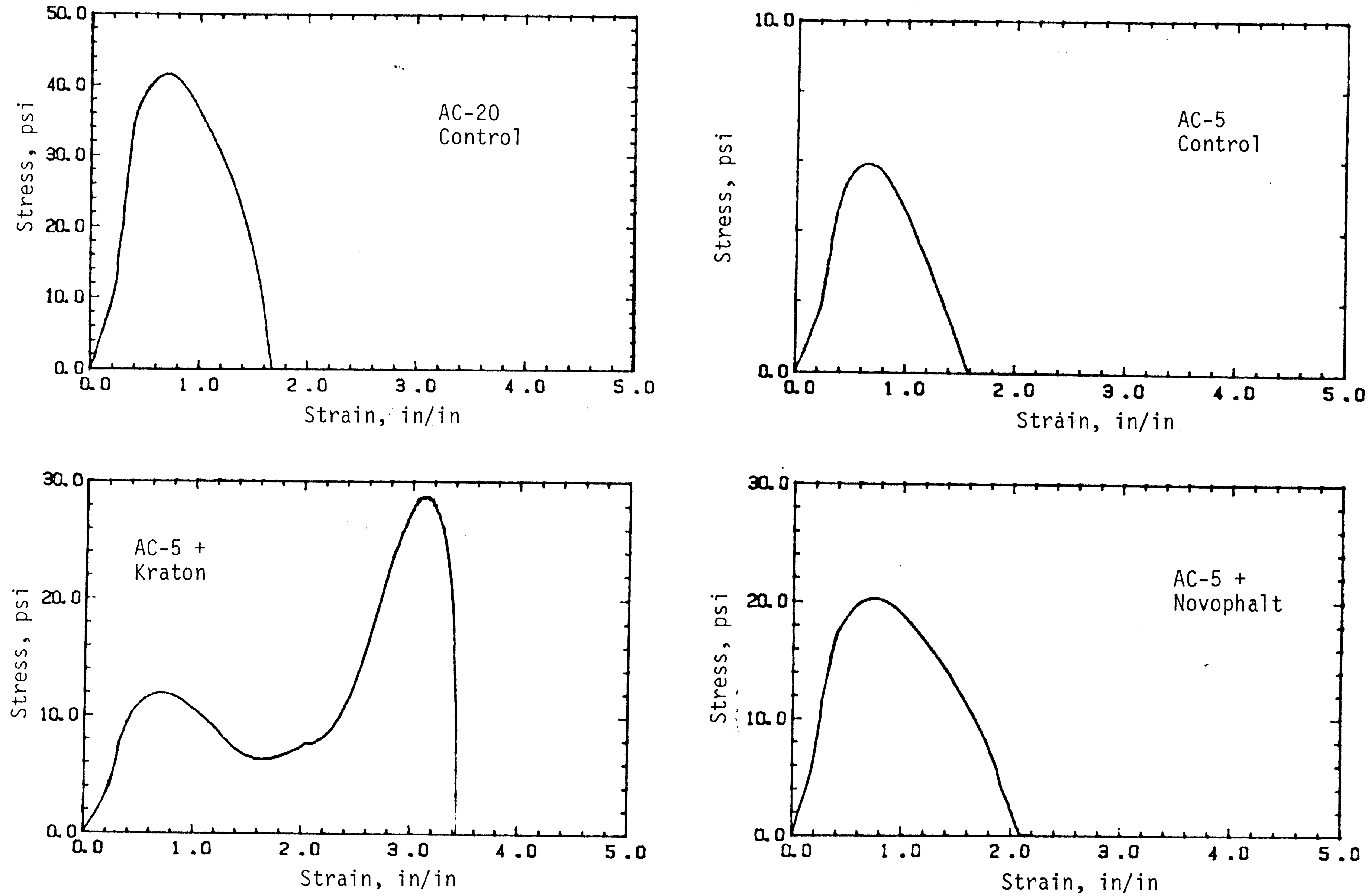


FIGURE 1 - TYPICAL STRESS-STRAIN CURVES FROM FORCE DUCTILITY TESTS AT 30.2°F AND 5 CM/MIN FOR UNMODIFIED AND MODIFIED TEXAS COASTAL ASPHALTS

and the asphalts. The polymeric additives have been shown to be more compatible in the San Joaquin Valley asphalt than in the Texas Coastal asphalt (1). Those polymers that are compatible, i.e., "dissolved" in the asphalt or develop a continuous network of microscopic strands, are characterized by a secondary loading which exhibits significantly more stress than the unmodified asphalt. In the Texaco asphalt, only Kraton exhibited the second peak. In the San Joaquin Valley asphalt, Kraton, latex and Elvax exhibited the second peak. Carbon black and polyethylene (Novophalt) do not "dissolve" in any asphalt, but exist as a discontinuous dispersion in the continuous asphalt phase, and did not show the second peak in either asphalt.

Area under the stress-strain curve could be considered total work or energy required to produce failure. AC-5 and AR-1000 containing an additive exhibited marked increases in energy required to produce failure. The data also indicated that the changes in stress-strain properties imparted by these additives are highly dependent upon the properties of the base asphalt.

Figure 2 shows that a relationship exists between maximum stress of the binders and tensile strength of corresponding paving mixtures. (Indirect tension test results are discussed later). It appears that the force ductility test may be useful in predicting changes in mixture tensile strength when asphalt additives are employed.

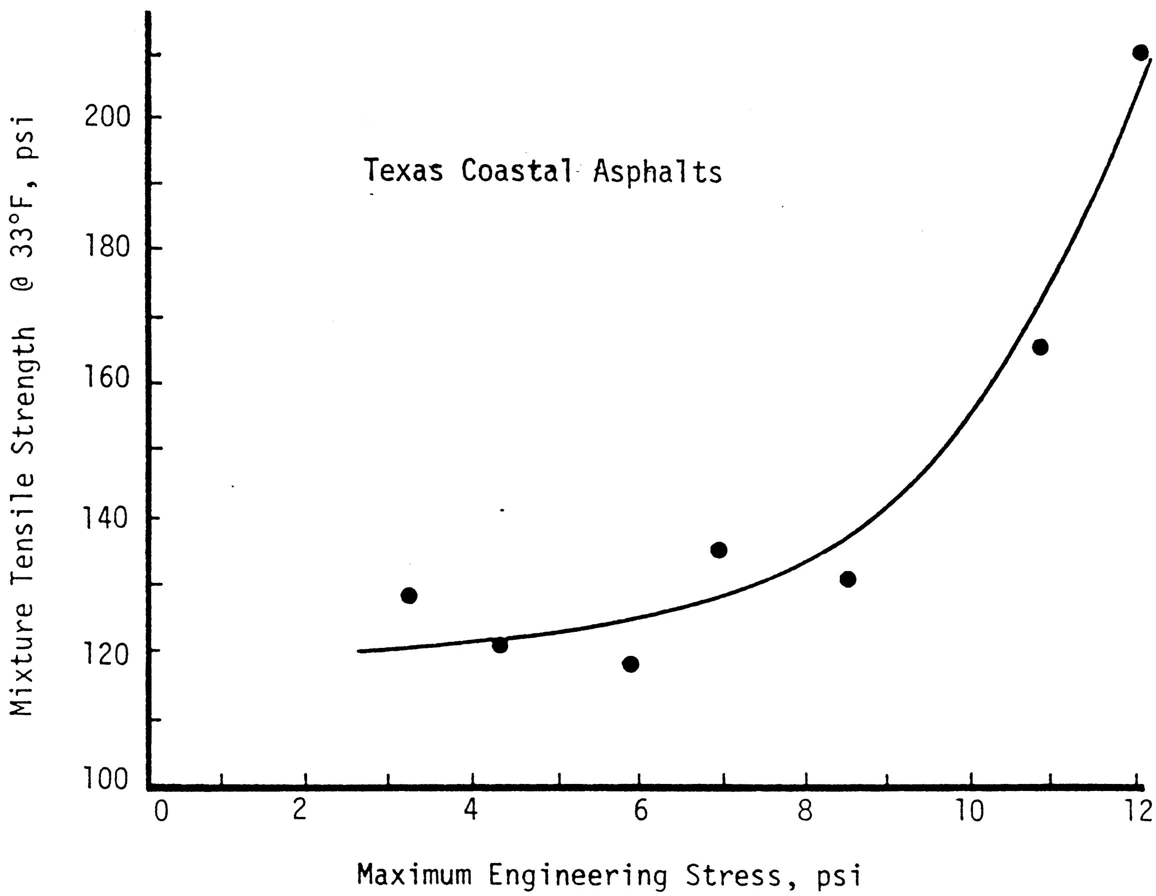


FIGURE 2 - MIXTURE TENSILE STRENGTH AS A FUNCTION OF MAXIMUM ENGINEERING STRESS. (MIXTURE TENSILE STRENGTH WAS MEASURED AT 33°F and 2 IN/MIN USING INDIRECT TENSION TEST. FORCE DUCTILITY DATA AT 4°C AFTER RTFOT WERE USED)

# TEST RESULTS ON ASPHALT CONCRETE MIXTURES

## MIXTURE PREPARATION

The aggregate used in the mixture tests consisted of subrounded, silicious river gravel and a similar sand with limestone crusher fines added to improve stability. This aggregate was selected because it produces a relatively binder-sensitive mixture which accentuates the properties of the binders more than a high-stability mix.

The asphalts used in this segment of the study include Texas Coastal and San Joaquin (California) Valley products. Texas Coastal AC-20 in the control mixtures and Texas Coastal AC-5 modified with the five additives discussed previously were the primary binders for the mixtures. San Joaquin Valley AR-4000 in control mixtures and AR-1000 modified with additives comprise the secondary binders. The additives were incorporated into the mixtures using methods which simulate field conditions as closely as possible. For example, latex and carbon black were added to the hot asphalt-aggregate mixture and stirred for an extra one minute period during mixing; whereas, the other three additives were preblended in the asphalt cement before combining with the aggregate.

Optimum binder content was determined using the Marshall Method with emphasis on uniform air void content (density). The Marshall method was selected because it is much more sensitive to binder properties than the Hveem method. Optimum binder content for most of the mixtures was about 4.5 percent. Mixtures containing carbon black require a slightly higher binder content (4.75 percent). The primary reason for this is that the carbon black modified binder has a significantly higher specific gravity.

All mixtures were mixed and compacted at constant binder viscosities. That is, binder viscosity upon mixing was 170+20 cSt and upon compacting was 280+30 cSt. This was an attempt to produce specimens with approximately equivalent air void contents.

## BASIC MIXTURE PROPERTIES

Marshall and Hveem stability (Table 4), resilient modulus (Figure 3) and indirect tension (Table 5) tests were performed on unmodified and modified mixtures composed of river gravel with two asphalts. No single additive demonstrated the ability to produce mixtures with consistently higher values of stability, stiffness or strength.

After collection of significant data, it was surmised that the design asphalt content selected for the latex modified mixture with Texas Coastal asphalt was slightly higher than it should have been. As a result, the latex mixture probably exhibited lower air void content, stability and stiffness than it should have.

## MOISTURE RESISTANCE

The modified accelerated Lottman (7) moisture treatment procedure was utilized on mixtures containing both asphalts. It appeared that, generally, the additives have little effect on moisture susceptibility of the mixtures made using the materials included in this study.

## EXTRACTION AND RECOVERY WITH ADDITIVES

Asphalt concrete containing the asphalts and additives studied herein were extracted and the binders were recovered. There were differences in the

TABLE 4

STABILITY OF MIXTURES CONTAINING RIVER GRAVEL

| Type Mixture | Asphalt Content, percent | Air Void Content, percent | Hveem Stability | Marshall Test Stability | Marshall Test Flow |
|---|---|---|---|---|---|
| Texas Coastal Asphalts | | | | | |
| Control: AC-20 | 4.5 | 5.0 | 43 | 1600 | 8 |
| Control: AC-5 | 4.6 | 4.3 | 43 | 900 | 9 |
| AC-5+15% Microfil-8 | 4.8 | 5.5 | 42 | 900 | 8 |
| AC-5+5% Elvax 150 | 4.5 | 4.9 | 46 | 1100 | 9 |
| AC-5+5% Kraton D | 4.5 | 4.6 | 47 | 1300 | 7 |
| AC-5+5% Latex* | 5.0 | 4.1 | 41 | 1000 | 10 |
| AC-5+5% Novophalt | 4.6 | 5.5 | 51 | 1300 | 8 |
| San Joaquin Valley | | | | | |
| Control: AR-4000 | 4.6 | 4.4 | 49 | 1200 | 7 |
| Control: AR-1000 | 4.5 | 4.1 | 48 | 700 | 6 |
| AR-1000+15% Microfil-8 | 4.7 | 5.0 | 50 | 1200 | 7 |
| AR-1000+5% Elvax 150 | 4.5 | 5.2 | 44 | 600 | 7 |
| AR-1000+5% Kraton D | 4.5 | 4.8 | 46 | 900 | 6 |
| AR-1000+5% Latex* | 4.5 | 5.1 | 48 | 800 | 6 |
| AR-1000+5% Novophalt | 4.5 | 5.3 | 46 | 950 | 5 |

*Latex is 30% water or 70% solids; therefore, 3.5% solids by weight of asphalt were used throughout the study.

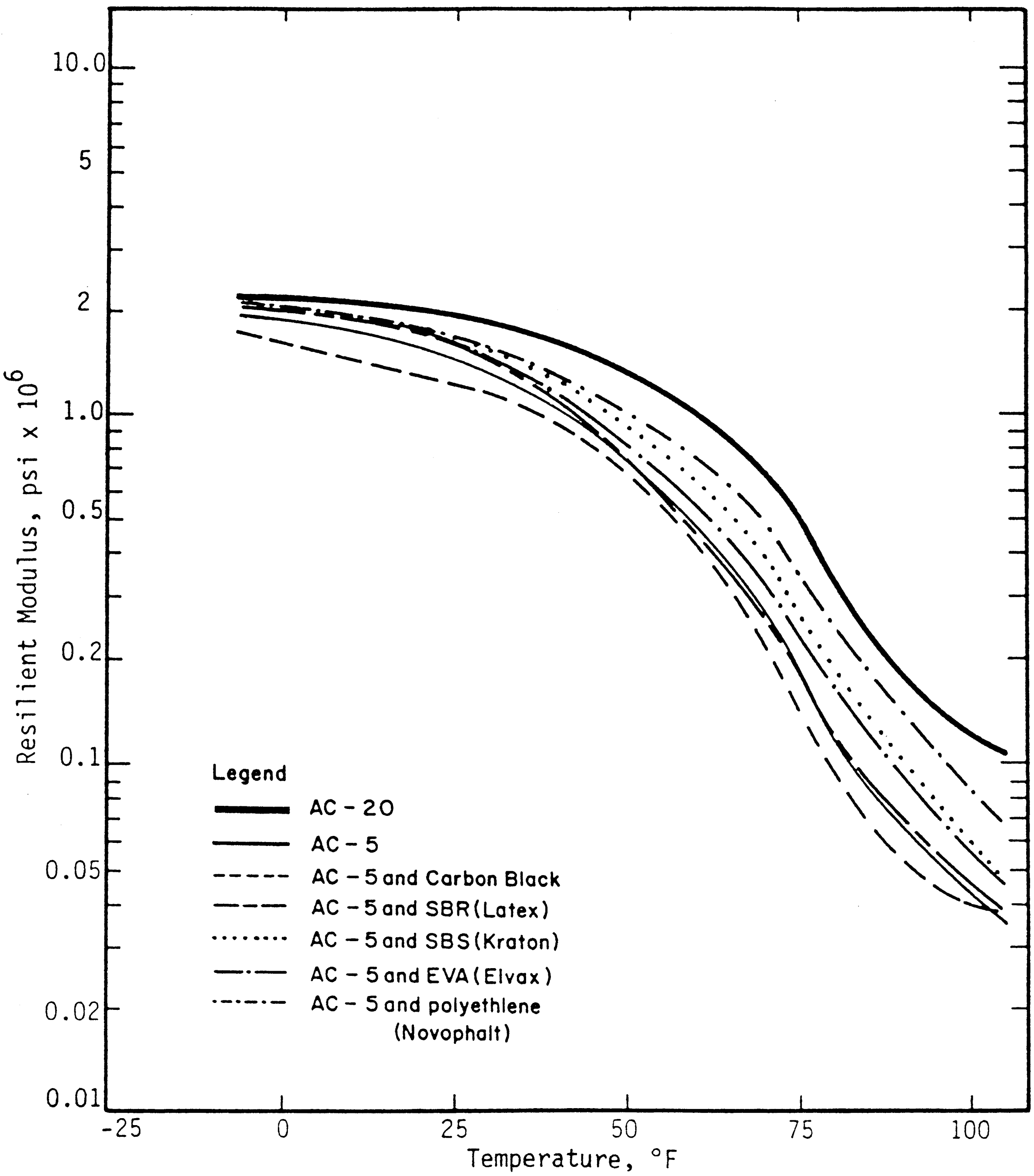


FIGURE 3 - RESILIENT MODULUS AS A FUNCTION OF TEMPERATURE FOR RIVER GRAVEL MIXTURES CONTAINING TEXAS ASPHALTS WITH AND WITHOUT ADDITIVES

TABLE 5

TENSILE STRENGTH OF MIXTURES MADE USING TEXAS ASPHALT AND RIVER GRAVEL

| Type Mixture | Tensile Strength, psi | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 0.02 in/min | | | 0.2 in/min | | | 2.0 in/min | | |
| | 25°C (77°F) | 1°C (33°F) | -15°C (-26°F) | 25°C (77°F) | 1°C (33°F) | -15°C (-26°F) | 25°C (77°F) | 1°C (33°F) | -15°C (-26°F) |
| Control: AC-20 | 45 | 211 | 413 | 83 | 342 | 395 | 121 | 369 | 374 |
| Control: AC-5 | 16 | 128 | 327 | 28 | 244 | 440 | 63 | 376 | 522 |
| AC-5 + 15% Microfil-8 | 15 | 132 | 319 | 33 | 217 | 424 | 64 | 360 | 450 |
| AC-5 + 5% Elvax 150 | 22 | 119 | 381 | 48 | 241 | 512 | 87 | 444 | 425 |
| AC-5 + 5% Kraton D | 27 | 136 | 404 | 54 | 300 | 472 | 112 | 428 | 502 |
| AC-5 + 5% Latex | 15 | 121 | 348 | 31 | 239 | 352 | 74 | 399 | 437 |
| AC-5 + 5% Novophalt | 28 | 167 | 393 | 58 | 329 | 444 | 119 | 436 | 387 |

relative effectiveness of the hot (reflux) and cold (centrifugal) extraction methods. Some of the results with the San Joaquin Valley asphalts were contrary to those found for the Texas Coastal asphalts. The limited number of tests did not establish whether the differences in extractability of the additives were specific to the asphalt used, or were due to other factors in the preparation and history of the asphalt concrete.

Since conventional extraction methods do not remove all of an additive, data obtained for the quantity of extracted binder and for properties of the recovered binders should be used only with the realization that a substantial fraction of the additive may remain in the extracted aggregate.

## EVALUATION OF FATIGUE CRACKING POTENTIAL

The potential of mixtures of asphalt concrete modified by asphalt additives to crack due to cyclic fatigue was evaluated using two approaches: (1) the phenomenological flexural fatigue approach and (2) a fracture mechanics-based controlled longitudinal displacement approach.

Generally, the phenomenological approach, which is a controlled-stress flexural fatigue test, provides a reasonably simple approach to simulate traffic-induced loads which has been almost universally adopted. However, it bears the limitation that it cannot account for both crack initiation and propagation. Such distinctions may be very important in establishing the fatigue life of a new material expected to be used for a wide range of applications. It seems reasonable that a stiff but brittle material may perform well in a controlled stress laboratory test, but fail rapidly due to immediate crack propagation if the material is used where controlled strain is the mode of cyclic applications.

The fracture mechanics-based approach employs a device which applies a controlled displacement to an asphalt concrete beam. The device was developed at Texas A&M (8) and is called the overlay tester as it was initially used to simulate the controlled displacement opening and closing of a crack beneath an asphalt concrete overlay. Fracture mechanics techniques are used to evaluate the energy required to propagate the crack through the material.

Beams 7.6x7.6x38 cm (3x3x15-in) were prepared using the Cox kneading compactor. The target air void contents were achieved for all mixtures except those containing carbon black. For these beams, it was much more difficult to compact the specimens to the 6-percent air void level. Even when twice the compactive effort was applied, the air void content could only be reduced to about 7-percent. This difference in compaction is largely due to the higher mass viscosity of the carbon black modified mixture.

## Controlled Stress Flexural Fatigue Test Results

Three beams were tested at each of three stress levels (low, intermediate and high). The logarithm of the strain, $\varepsilon_t$, induced at the 200th repetition of the applied stress level was plotted versus the logarithm of the number of load cycles to failure, $N_f$. The 20$^oC$ (68$^oF$) data are plotted in Figure 4 and the 0$^oC$ (32$^oF$) data are plotted in Figure 5. Based on the log $\varepsilon_t$ versus log $N_f$ plots the following trends are apparent:

1. At 20$^oC$ (68$^oF$), each additive blend with AC-5 produced a mixture which has statistically superior fatigue properties compared to the control mixture using AC-20 asphalt as the binder. Although the plots from mixtures

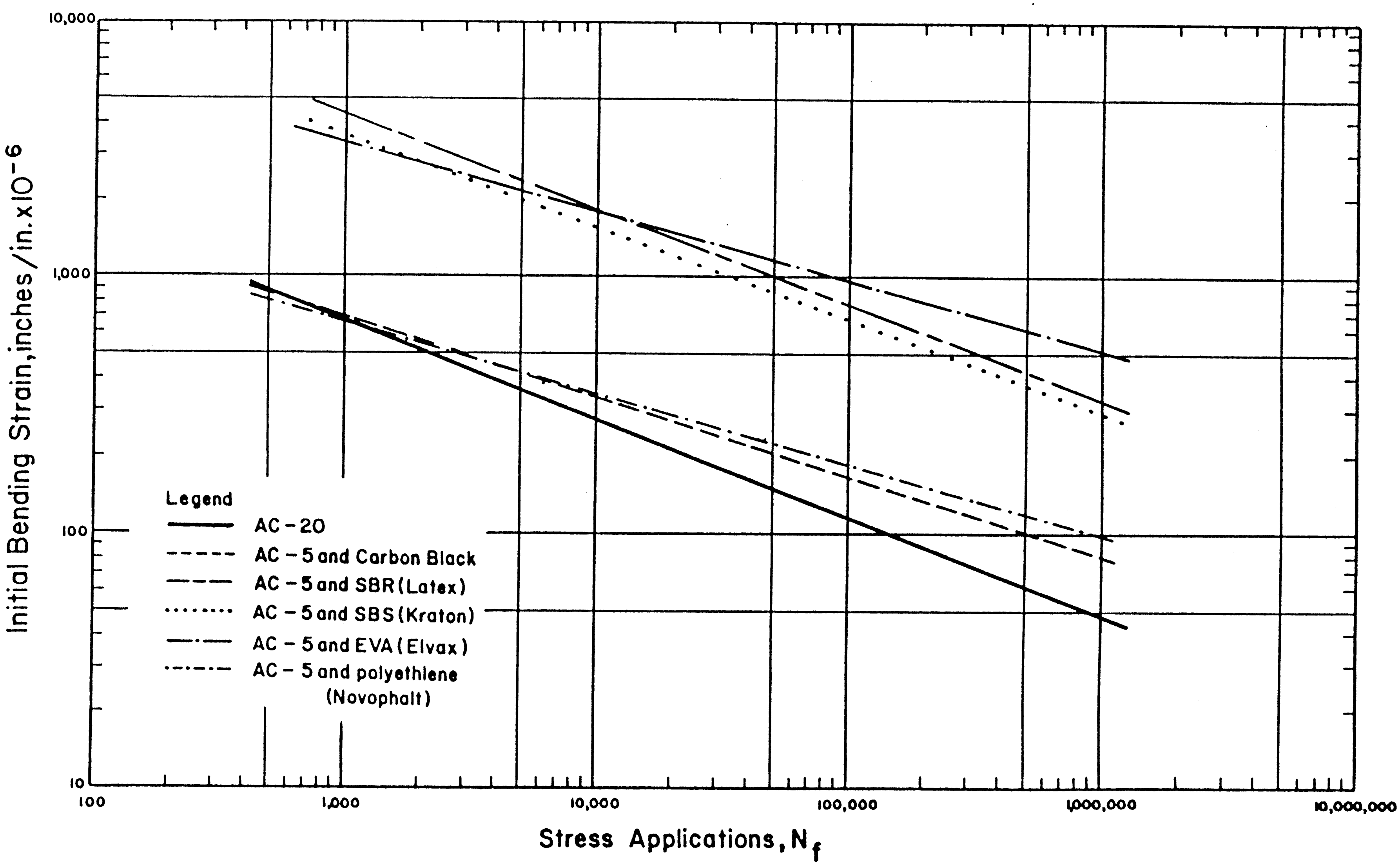


FIGURE 4 - CONTROLLED STRESS FLEXURAL BEAM FATIGUE RESULTS AT 20°C (68°F)

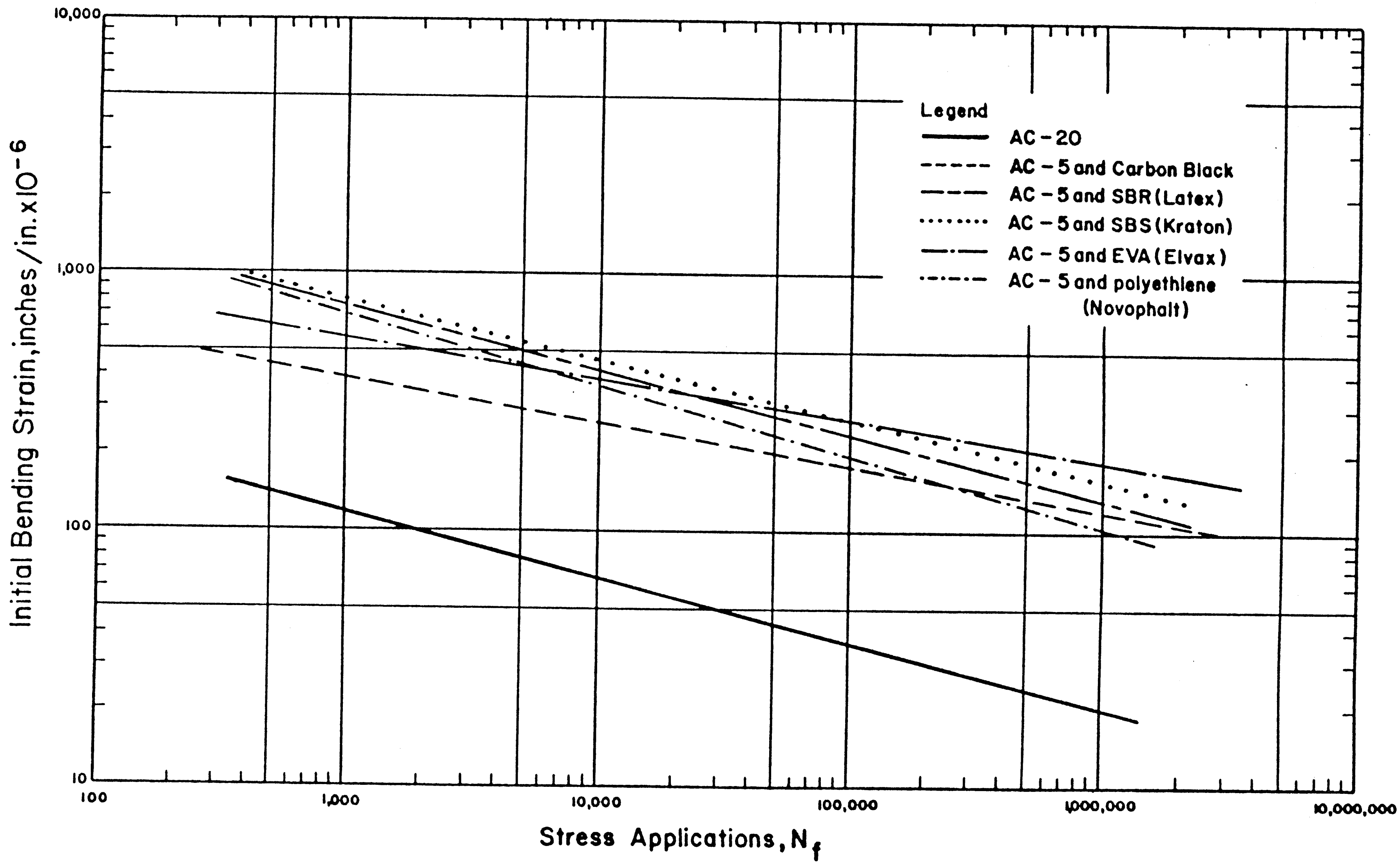


FIGURE 5 - CONTROLLED STRESS FLEXURAL BEAM FATIGUE RESULTS AT 0°C (32°F)

containing AC-20, Novophalt and carbon black are closely grouped, they are statistically different ($\alpha = 0.05$). Statistical difference is defined as when either the intercept or slope are different.

2. At 20$^{o}$C (68$^{o}$F), the mixtures containing EVA (Elvax), SBR (Latex) and SBS (Kraton) performed the same for practical purposes; however, the fatigue plots are statistically different ($\alpha = 0.05$). These mixtures showed significantly superior fatigue responses to the mixtures containing either Microfil-8 or polyethylene (Novophalt).

3. At 0$^{o}$C (32$^{o}$F), the modified AC-5 asphalt blends once again provided a response superior to the control. Fatigue results among mixtures containing polyethylene (Novophalt), SBS (Kraton), SBR (Latex) and EVA (Elvax) were not significantly different.

4. Although the mixtures containing AC-5 blends with latex, SBS and EVA exhibit superior fatigue performance at 20$^{o}$C (68$^{o}$F) based on the $N_f$ versus $\varepsilon_t$ (at 200th load cycle) criterion, the mixtures containing AC-5 blends with polyethylene and carbon black possess sufficient stiffness such that stress levels higher than for AC-20 are required to induce the critical strains. Based on the total analysis of fatigue data, the mixture containing AC-5 and polyethylene exhibited attractive fatigue properties as the mixture combined good fatigue resistance, higher values of stiffness than other AC-5 and additive blends at 20$^{o}$C (68$^{o}$F) and similar values of stiffness and a similar $N_f$ versus $\varepsilon_t$ (200th load cycle) relationship at 0$^{o}$C (32$^{o}$F).

## Controlled Displacement Fatigue Testing

General. A mechanistic approach proposed by several researchers (4,9 and 10) considers fatigue as a process of cumulative damage and utilizes fracture mechanics to investigate this property. In this approach, fatigue life, under a given stress state, is defined as the period of time during which damage increases according to a crack propagation law from an initial state to a critical or final level. The method accounts for the changes in state of stress due to cracking, geometry and boundary conditions, material characteristics and variability. Fatigue life can be obtained from both controlled stress and controlled strain tests. The method is independent of the mode of testing.

Little, et al (1), applied this approach using controlled displacement tensile testing to evaluate the mixtures discussed previously. A detailed discussion of the theory and mechanics of the test is given in Reference 1.

The fabrication procedure for the beam specimens used in this test is identical to that used in beam fatigue testing. This relatively large specimen size allows the use of typical paving mixtures. The overlay tester was calibrated to apply a maximum ram displacement of 1.14 mm (0.045-in) for specimens tested at 25$^{o}$C (77$^{o}$F). The oscillating horizontal movement was designed to simulate the opening and closing of pavement cracks due to thermal contraction and expansion of pavement materials.

A loading rate of 6 cycles per minute was used throughout the test program. The load and displacement values were monitored and recorded on an X-Y plotter. The change in crack length with each loading cycle was visually measured. Areas within the plotted load-displacement loops were used to measure the energy required to cause crack propagation during certain load cycles and thus to compute the J-integral. The J-integral ($J^*$) is in essence an energy term which defines the energy per unit area of crack length required to cause the predetermined magnitude of crack tip opening displacement.

**Method of Evaluation Using Fracture Mechanics.** The primary objective of controlled displacement, fracture mechanics-based testing is to evaluate the potential of modified asphalt concrete mixtures to resist fracture due to thermal cycling or other contraction induced displacement.

In the application of $J^*$ parameter, the interpretation of the fatigue-fracture behavior cannot be made solely on the basis of either the intercept, $A^*$, or the slope, $n^*$, of the Paris equation:

$$\log da/dN = \log A^* + n^* \log J^* \qquad \text{Equation 1}$$

where da/dN is the crack growth rate.

A combined form of parameters A and n, in Paris' law accounts for the effects of both parameters in fatigue-fracture behavior. In this approach, the term ($n^* + \log A^*$) is defined to be a measure of resistance to crack growth. It is the logarithmic value of crack speed (log da/dN) when the numerical value of $J^*$ is equal to 10. Log da/dN will always be negative; the more negative it is, the more crack resistant the material is.

Typically a regression plot of da/dN versus $J^*$ is constructed. An upward shift in this line represents a material possessing more brittle behavior and, of course, a more ductile material will plot lower on the graph. In the displacement control mode, the slope of the regression line indicates how sensitive the material is to crack growth. A steep slope is an indication of rapid reduction in crack growth rate, da/dN, as the test continues.

**Discussion of Test Results.** Based on the results of controlled displacement testing, Table 6 and Figure 6 show the following trends are noted:

1. At 1°C (33°F), all additive-soft asphalt blends demonstrated significantly superior resistance to crack propagation compared to the control mixtures which were bound with a harder asphalt without an additive. The improvement was equally dramatic for both asphalts (San Joaquin Valley and Texas Coastal).

2. At 1°C (33°F), the EVA AR-1000 blend gave the best results among the additives and San Joaquin Valley asphalts, while the latex (Ultrapave 70)-AC-5 blend gave the best results among blends of additives and Texas Coastal asphalt. Apparently, synergistic interactions affect performance.

3. Considering the performance of additives from both asphalt sources at 1°C (33°F), the SBS (Kraton)-asphalt blends produced the most consistently superior results.

4. At 1°C (33°F), the additives blended with Texas Coastal AC-5 demonstrated superior performance when compared to San Joaquin Valley AR-1000 blends. This can be partially explained by the higher penetrations of the AC-5-additive blend at 4°C (39.2°F) as compared to the AR-1000 blends at 4°C (39.2°F). Note also that the Texas Coastal AC-20 asphalt performed

TABLE 6

SUMMARY OF CONTROLLED DISPLACEMENT FATIGUE RESULTS[a]

| Base Asphalt | Mixture Type | 1°C (33°F) Air Voids, Percent | 1°C (33°F) No. Cycles to Failure | 25°C (77°F) Air Voids, Percent | 25°C (77°F) No. Cycles to Failure |
|---|---|---|---|---|---|
| Texas Coastal | AC-20 | 5.9 | 6 | 5.9 | 250 |
| | AC-5 + Car. Blk. | 7.0 | 590 | 6.7 | 530 |
| | AC-5 + Elvax | 5.9 | 390 | 6.0 | 7[b] |
| | AC-5 + Kraton | 5.6 | 860 | 5.8 | 350 |
| | AC-5 + Latex | 6.0 | 1190 | 6.2 | 740 |
| | AC-5 + Novophalt | 6.0 | 1230[b] | 6.5 | 190 |
| San Joaquin Valley | AR-4000 | 6.3 | 1 | 6.0 | 110 |
| | AR-1000 + Car. Blk. | 7.1 | 250[b] | 6.5 | 490 |
| | AR-1000 + Elvax | 6.9 | 740 | 6.5 | >2000 |
| | AR-1000 + Kraton | 6.3 | 370 | 6.8 | >2000 |
| | AR-1000 + Latex | 6.5 | 90 | 6.6 | >2000 |
| | AR-1000 + Novophalt | 6.7 | 180 | 6.4 | 782 |

[a]Each value represents an average of at least two values.

[b]These values represent an average of three values.

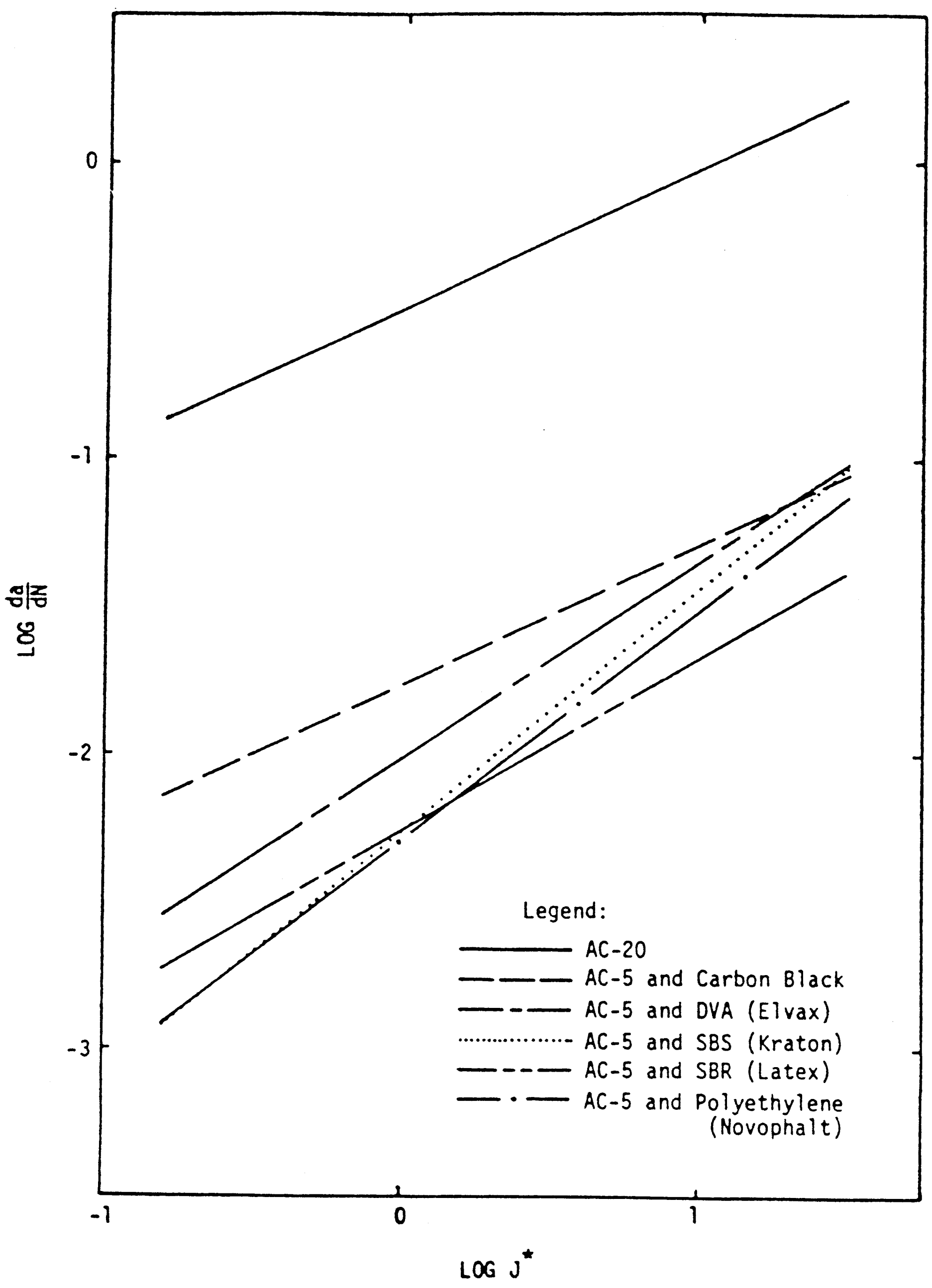


FIGURE 6 - LOG-LOG PLOT OF CRACK SPEED VERSUS J-INTEGRAL AT 1°C (33°F) FOR TEXAS ASPHALTS

slightly better than did the San Joaquin Valley AR-4000 at 1°C (33°F) (see Table 6).

5. At 25°C (77°F), the additive blends with the San Joaquin Valley AR-1000 asphalt generally outperformed the blends of additives and the Texas Coastal AC-5 asphalt. Perhaps this is due to the better compatibility between the additives and the San Joaquin Valley asphalt than between the additive and the Texas Coastal asphalt. Furthermore, the base asphalt penetrations are very similar at 25°C (77°F) so that compatibility may well be the predominant effect. On the otherhand, at 1°C (33°F), the significant difference in penetration seems to predominate over relative compatibility.

6. At 25°C, samples fabricated with EVA (Elvax), SBS (Kraton) and latex (Ultrapave 70) blends with AR-1000 demonstrated multiple cracking or "crack branching". This branching of hairline cracks distributes the tensile stresses from the original crack tip and slows the progression of cracks through the sample. As a result, cycles to failure for these samples were often greater than 2000.

7. Mixtures fabricated with carbon black-asphalt blends generally demonstrated the poorest controlled displacement fatigue performance at 25°C.

## HEALING STUDY

Without question, laboratory phenomenological fatigue data under-predicts the field fatigue performance of asphalt mixtures. The controlled stress laboratory flexural fatigue tests do not account for healing of the pavement between stress applications, residual stresses, the length of rest periods between load applications and variability of the position of the wheel load.

Little, et al (11) showed that in the controlled displacement fatigue mode the energy required to initiate crack propagation is affected by rest periods as follows:

$$\Delta u = e^{h \log t} \qquad \text{Equation 2}$$

The term $\Delta u$ is the increase in energy required to initiate a selected magnitude of crack opening displacement between loading cycles N and N + 1, where a rest period, t, intervenes. The term h represents a constant equal to 0.45.

Since asphalt additives have been shown to substantially affect the creep and relaxation properties of asphalt mixtures, it was assumed that additives could dramatically affect the healing characteristics of asphalt mixtures as reflected by $\Delta u$. The purpose of this study was to evaluate the relative effect on healing of the five additives studied in this research by comparing the relative effects of the additives on healing.

All beams used in the healing experiments were fabricated identically to the beams used in the flexural beam fatigue and controlled displacement fatigue (overlay simulation) testing. The specimens were subjected to controlled displacement cycling using the overlay tester as previously explained. All testing was accomplished at 25°C (77°F). The experiment was performed identically to previous controlled displacement experiments at

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$25^{o}C$ except that 45 minute rest periods were introduced after 3, 6, 10, 20, 30, 50, 100 and 200 cycles. Healing energies were calculated as follows:

$$\Delta u = u' - u_0 \qquad \text{Equation 3}$$

where $\Delta u$ is the healing energy, $u'$ is the energy required to induce the prescribed displacement following a 45 minute rest period, and $u_0$ is the energy required to induce the prescribed displacement prior t[illegible]est period. Normalized healing energies are plotted in Figure 7.

## CREEP/PERMANENT DEFORMATION TESTING

Asphalt concrete cylinders 8-in high and 4-in in diameter were fabricated using the standard California kneading compactor for the direct compression testing program. Two replicate specimens for each condition were fabricated. Every effort was made to keep the air voids in the cylinders between six and seven percent. Also, care was taken that the ai[illegible]should be distributed equally in the cylinders to avoid a vertical density gradient.

All creep tests were performed on a Material Test [illegible] closed-loop, feedback control hydraulic tester with controlled-environment chamber. The creep tests were performed [illegible] accordance with the Alternate Procedure II described in the VESYS Users Manual (12). Tests on two specimens each at temperatures of 4, 21 and $38^{o}C$ ($40^{o}F$, $70^{o}F$, $100^{o}F$) were performed. Permanent deformation properties were

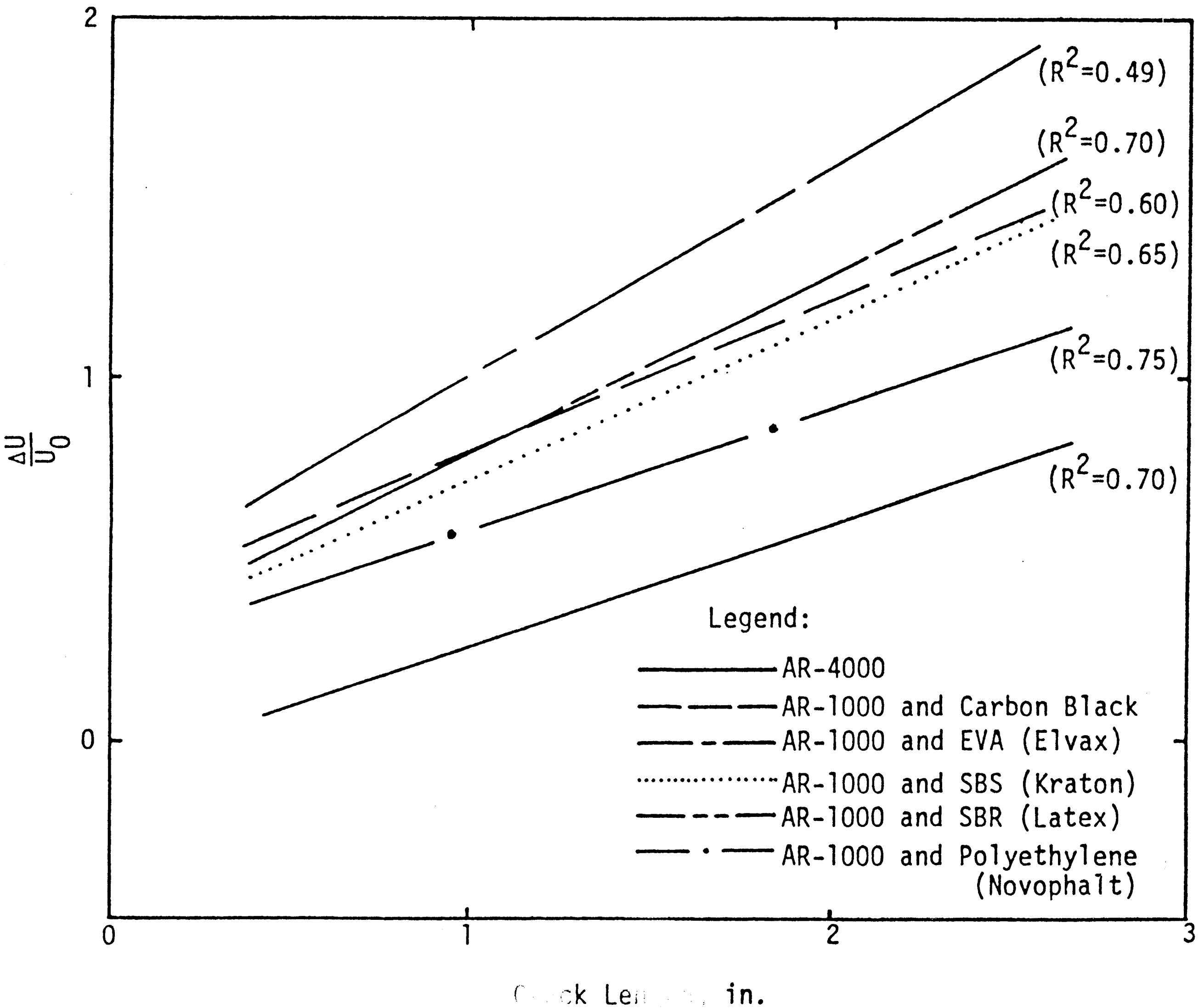


FIGURE 7 - EFFECTS OF ADDITIVES ON HEALING ENERGY

calculated from the incremental static loading and the creep compliance properties from the 1,000 second response curve for each specimen.

## Results from Creep Compliance Tests

The 1,000 second response curve was used to calculate the creep compliance at the loading times of 0.03, 0.1, 0.3, 1.3, 10, 30, 100, 300 and 1,000 seconds. Creep compliance, D(t), is defined as:

$$D(t) = \frac{\text{Total strain observed (function of time)}}{\text{Applied stress}} \qquad \text{Equation 4}$$

Figure 8 presents the results of creep compliance testing at 4 and 38°C (40 and 100°F) for mixtures bound with blends of Texas Coastal AC-5 with additives and the AC-20 control mixture.

From the compliance testing results, the following trends were observed:

1. Polyethylene in AC-5 exhibited compliance characteristics which were statistically the same as the AC-20 control. Although the resistance of the AC-5 to high temperature deformation is greatly improved by adding polyethylene, the low temperature compliance is also reduced giving essentially the same fracture susceptibility as the AC-20 control.

2. Blends of AC-5 with SBR (Latex), EVA, SBS and carbon black all respond with a higher compliance than the AC-20 control at the low temperature. The more compliant nature of these blends indicates mixtures which are better suited to relieve stresses induced at lower temperatures and thus better resist temperature cracking.

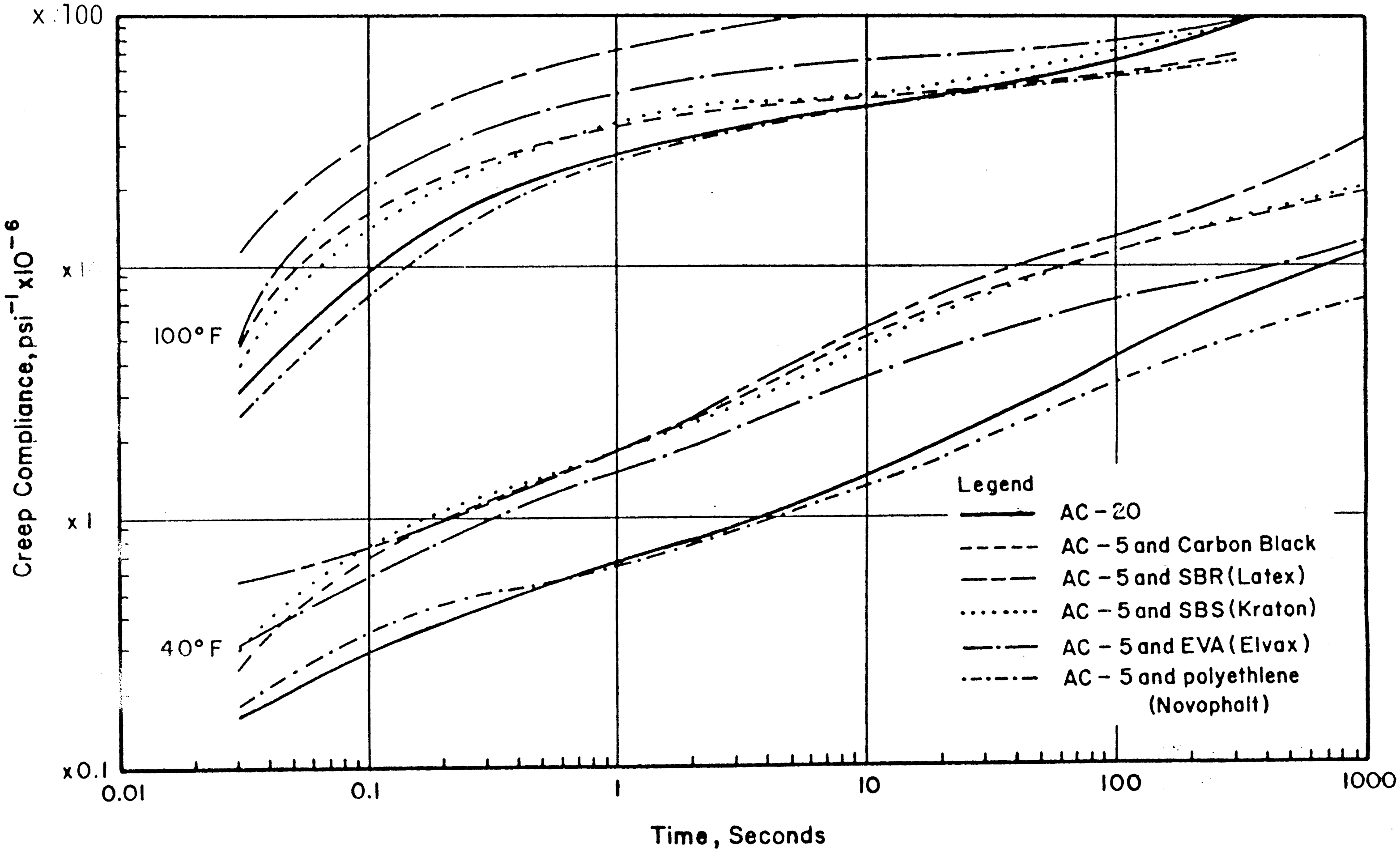


FIGURE 8 - CREEP COMPLIANCE CURVES AT 4°C (40°F) and 38°C (100°F) FOR MIXTURES CONTAINING TEXAS COASTAL ASPHALTS

3. SBS and carbon black blends respond acceptably at 38°C (100°F). Although their compliances at 100°F are significantly higher than those of the control at relatively short load durations (less than 10 seconds), the compliances approach those of the control at long load durations, approaching 1000 seconds.

4. The compliances of the AC-5 with SBR (Latex) or EVA at 38°C (100°F) are significantly higher than those of the control mixture. This is particularly true of the SBR (Latex) blend. From these data, one would expect a reduced potential for load spreading capabilities and excessive permanent deformation at high pavement service temperatures. Repeated tests at 21°C (70°F) with 4.5 percent binder instead of 5.0 percent in the latex mixture resulted in statistically lower compliances but it still ranked as the most susceptible to deformation.

5. Based upon Figure 8, at the longer load durations, it may be stated that, generally, EVA (Elvax), SBS (Kraton), SBR (Latex) and carbon black provide reduced temperature susceptibility. This occurs [illegible] compliances of the additive mixtures are significantly higher than the AC-20 control at 4°C (40°F) and converge toward the AC-20 at the 38°C [illegible] test temperature. The practical significance of this observation is [illegible] response is expected of additives which reduce rutting potential at higher temperatures and maintain a compliant (fracture resistant) nature at lower temperatures.

6. Although not shown herein, test results on modified San Joaquin Valley asphalt mixtures were substantially different from the Texas Coastal

asphalt mixtures indicating synergistic effects probably related to asphalt-additive compatibility.

## Results from Permanent Deformation Tests

The total permanent strain at the end of each rest period was plotted on log-log paper as a function of the incremental loading times: 0.1, 1, 10, 100, and 1000 second. The permanent deformation plots from incremental static loading tests at 4 and 38°C (40 and 100°F) are shown in Figure 9.

An analysis of the plots reveals the following:

1. Mixtures containing SBR (latex) exhibited large deformations during pre-loading (exceeding 2500 micro-strain units) at 21°C (70°F) and at 38°C (100°F), and, in accordance with the VESYS Manual (12), the level of applied stress was reduced in these cases. Even at the lower level of applied stress, the latex specimens showed the greatest permanent deformation relative to the AC-20 control and the other additives tested.

2. At 4°C (40°F), the mixture containing the latex blend [illegible]ted significantly higher deformation than the other five mixtures. Perhaps a reduction in binder content within the mixture or an increase in the amount of latex used in the blend is warranted to improve the creep and de[illegible]n responses.

3. Polyethylene (Novophalt) exhibited a greater resistance to permanent deformation at 4°C (40°F) and at 21°C (70°F) than any other mixtures, including the AC-20 control. At 38°C (100°F), the carbon black blend yielded the [illegible]st permanent deformation followed closely by Novophalt. However, the slope of the permanent deformation versus time of loading p[illegible]t

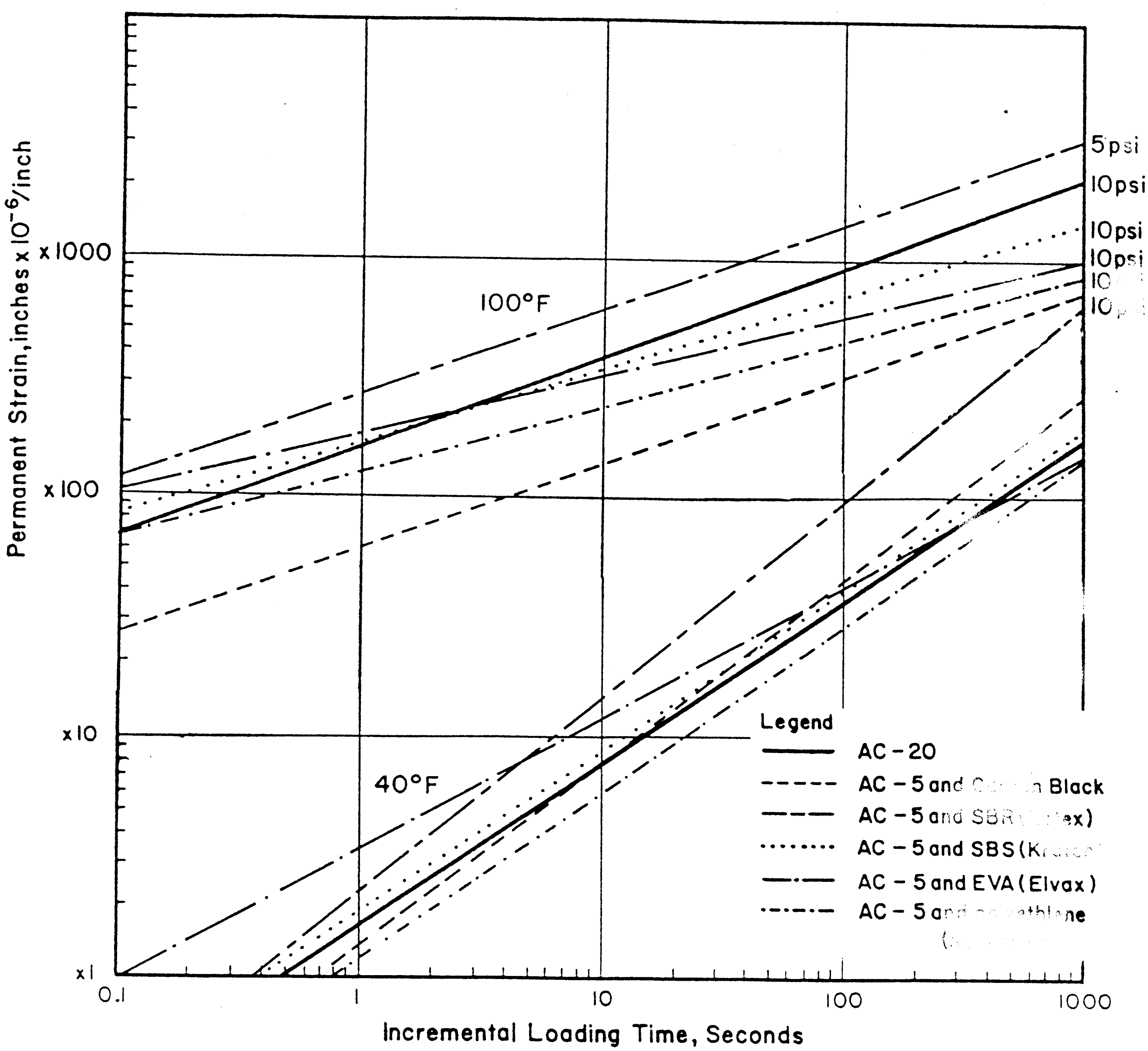


FIGURE 9 - PERMANENT STRAIN FROM INCREMENTAL STATIC LOADING TESTS AT 4°C (40°F) AND 38°C (100°F) FOR MIXTURES CONTAINING TEXAS ASPHALTS

for the Novophalt mixture was statistically smaller than slopes for the other mixtures. This fact coupled with the relative position of the plot indicates a greater resistance overall for Novophalt in resisting permanent deformation.

4. It is surmised that the relative positions of the permanent strain versus incremental loading time plots are influenced greatly by the preconditioning procedure. This procedure may not adequately account for material property peculiarities of polymer-modified asphalts. This hypothesis will require further study for evaluation.

5. Mixtures containing EVA and SBS showed permanent deformation responses similar to the AC-20 control.

6. Tests were performed using San Joaquin Valley asphalts (1,2) but are not shown herein. Although the results are somewhat different from the Texas Coastal asphalts, the relative behavior of the additives are similar. At 10,000 loading cycles, the order of resistance to permanent deformation is as follows: (1) Polyethylene, (2) EVA, (3) Carbon black, (4) SBS, (5) AC-20 and (6) SBR (latex). The mixtures were so soft at 100°F (probably due to the high temperature susceptibility of the base asphalt) that a loading stress of only 5 psi could be used during the test.

## SUMMARY OF CONCLUSIONS

Additives were sought out that showed potential to reduce cracking in asphalt concrete pavements without adversely affecting rutting. It appeared that, for best results, a softer than usual asphalt should be used with an additive capable of lowering the the temperature susceptibility of the binder. The soft asphalt provides flexibility to reduce cracking at the lower temperatures and the additive increases the viscosity at higher temperatures to reduce the potential for permanent deformation. Five additives were selected and evaluated in a comprehesive laboratory program including tests on binders and paving mixtures (1,2). Based on results of laboratory tests and review of the current literature on asphalt additives, the following conclusions appear warranted.

1. Traditional mixture design procedures including the Marshall and Hveem methods appear acceptable for determining optimum binder contents for additive-modified asphalt mixtures.

2. Although certain binder and mixture properties appeared to be sensitive to compatibility between the asphalt and the additives, overall, the mixture properties demonstrated an ability for each additive to alter mixture temperature susceptibility in a generally favorable manner. The degree of alteration is highly dependent upon the chemical composition and/or physical properties of the asphalt cement.

3. Hveem stability of mixtures was not significantly altered by the additives. Although Hveem stability is quite sensitive to changes in binder quantity, it is not very sensitive to changes in rheological properties of the binder properties.

4. The additives increased Marshall stability of mixtures when added to AC-5 or AR-1000 but not up to that of mixtures containing AC-20 or AR-4000 with no additive. This should not discourage the use of these additives with asphalts softer than the usual paving grade, particularly where low temperature cracking is a concern.

5. At low temperatures (less than $0^{o}C$ or $32^{o}F$), the additives had little effect on consistency of the asphalt cements. This was reflected in the diametral resilient moduli (stiffness) of the mixtures. Resilient moduli of AC-5 (or AR-1000) mixtures above $16^{o}C$ ($60^{o}F$) were generally increased by the additives but not up to that of the AC-20 (or AR-4000) mixtures without additives. Although the load spreading ability of asphalt concrete containing a soft asphalt is increased when these additives are employed, the pavement thickness should not be reduced.

6. Indirect tension test results showed that, at the lower temperatures and higher loading rates, the additives increased mixture tensile strength over that of the control mixtures. Strain (deformation) at failure was generally increased by the additives. At the higher temperatures and lower loading rates, the additives did not appreciably affect the mixture tensile properties.

7. The additives had little effect on moisture susceptibility of the mixtures made using the materials included in this study.

8. Flexural fatigue responses of mixtures containing AC-5 plus additive at $20^{o}C$ ($68^{o}F$) and particularly at $0^{o}C$ ($32^{o}F$) were superior to control mixture which contained AC-20 with no additive.

9. Creep/permanent deformation testing showed that, at high temperatures, all the additives except latex produced equal or better performance than the AC-20 control mixture. (The binder content of the latex mixture was apparently in excess of the true optimum which adversely affected creep/permanent deformation.) At low temperatures, all the additives in AC-5 except polyethylene produced equal or better creep compliance than the AC-20 control mixture.

10. Controlled displacement fatigue testing (overlay tester) at $1^{o}C$ ($33^{o}F$) demonstrated that mixtures containing AC-5 plus an additive gave greater resistance to crack propagation than control mixtures containing AC-20. The "dissolved" additives, EVA, SBR and SBS, showed evidence of improving the distribution of tensile stresses within the mixture. Practically, this could result in retarding crack propagation which should be manifested by resistance to cracking in asphalt concrete overlays.

11. In a limited study of crack healing, the mixtures containing the soft asphalt (AC-5) plus an additive gave better responses than those containing the control asphalt (AC-20). The practical significance of this could be substantially improved flexural fatigue lives of asphalt concrete pavements.

12. Standard asphalt extraction methods to determine binder content of paving mixtures are unsuitable when polymers or carbon black are used as these materials are insoluble or only partly soluble in standard solvents.

13. Each additive proved to be successful to some degree in improving properties on at least one end of the performance spectrum. However, no additive proved to be a panacea. To rank the additives according to relative

capabilities is a difficult task, as sensitivity to the base asphalt played a significant role.

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