Laboratory Performance Comparisons of Polymer-Modified and Unmodified Asphalt Concrete Mixtures

S. H. CARPENTER AND TOM VANDAM

The use of additives to improve the performance of asphalt cement and asphalt concrete mixtures has increased in recent years. Polymeric additives have been proposed as a potential source of specific improvements to asphalt cements. The major use has been in surface dressings; work in asphalt concrete has only recently been conducted. Presented in this paper are the results of a comprehensive series of laboratory tests on a series of polymer additives to establish test data that can serve as performance indicators for the mixes. Five polymer blends were manufactured from a base AC-5 asphalt cement. Three standard grades of asphalt cement, the base AC-5, an AC-10, and an AC-20, were used for control. A crushed limestone was used to prepare dense-graded mixtures that met the Illinois Interstate overlay mixture criteria. Testing included the diametral resilient modulus test at three temperature levels, indirect tensile testing at temperatures ranging from 72°F to −20°F, permanent deformation testing at 72°F and 100°F, and Lottman moisture susceptibility testing. The testing indicated that the polymer additives reduced stiffness at low temperatures yet maintained adequate stiffness at elevated temperatures. Low-temperature performance was greatly improved over that of untreated asphalt cements of all grades. The permanent deformation characteristics were greatly improved at elevated temperatures. No moisture sensitivity was noted in any of the samples. In general, the polymeric additives improved the base asphalt characteristics to those of the next stiffer grade at normal temperatures; made them better than the base asphalt at low temperatures; and made them better than an AC-20, two grades stiffer than the base asphalt, at elevated temperatures. Long-term fatigue characteristics will require further testing before the influence of the modifiers can be evaluated.

A major reason for using polymer-modified asphalt cements is to increase the level of field performance of the asphalt concrete pavement. To be successful in the marketplace, this increased performance should offset any increased expenditures associated with incorporating the polymer in the asphalt cement. The areas of performance critical to the long-term performance of flexible pavements are

- Stiffness and stiffness-temperature relationships,
- Fatigue resistance,
- Permanent deformation resistance,
- Low-temperature cracking resistance, and
- Strength characteristics.

Although all of these properties can be presented independently, it is obvious that they are all interrelated. It is difficult to present data for one property without discussing overall performance. As an example, the tensile strength of a mixture is useful in categorizing fatigue performance at 72°F, and at extremely low temperatures it, along with stiffness, also indicates resistance to low-temperature cracking.

Presented in this paper are the results of laboratory testing to characterize performance differences among five different polymer blends and three unmodified asphalts. The base asphalt is an AC-5 that was used in all polymer blends. The remaining unmodified asphalts are an AC-10 and an AC-20. The polymers used were various amounts and types of Kraton®, a proprietary polymer from Shell Development Company, Houston, Texas.

PREPARATION OF SAMPLES

The asphalts prepared for use in this study were made from an AC-5 modified with the following polymers:

1. 3 percent Kraton® D-1101,
2. 6 percent Kraton® D-1101,
3. 3 percent Kraton® D-1650,
4. Experimental polymer, and
5. 2.85 percent Kraton® D-1116 with 1.14 percent Kraton® D-1107.

The three grades of asphalt cement used for control purposes were

6. AC-5 (base asphalt cement used in all polymer blends),
7. AC-10, and
8. AC-20.

The properties of the asphalt cements formed with these polymer combinations are given in Table 1. Marshall mix design was performed to determine optimum properties for 4 percent air voids. The optimum values used in this study *(1)* are given in Table 2. The aggregate was a crushed limestone blended to the dense gradation required by the Illinois Department of Transportation for new Interstate overlay mixes as shown in Figure 1. This mix design was used for both the 50- and the 75-blow Marshall test. The 50-blow Marshall test was used for the main laboratory testing program because this is the standard mix design procedure used in Illinois.

Marshall samples (4 in. diameter and 2.5 in. high) were compacted at both 75 and 50 blows at optimum asphalt content and at asphalt levels 0.5 percent above and below optimum.

Civil Engineering Department, University of Illinois, Urbana, Ill. 61801.

TABLE 1 PROPERTIES OF ASPHALT CEMENTS EVALUATED IN THIS STUDY

	Modified Exxon AC-5 Base Asphalt with Treatment					Unmodified		
Property	1[a]	2[b]	3[c]	4[d]	5[e]	Exxon AC-5 with Treatment 6	Shell AC-10 with Treatment 7	Shell AC-20 with Treatment 8
Penetration at 25°C (dmm)	100	78	104	103	97	128	84	59
Viscosity at 80°C (poises)	560	–	200	282	628	78	131	207
Viscosity at 135°C (cPs)	570	1675	525	660	905	250	365	480
Ductility, 4°C, 5 cm/min (cm)	98	91	23	34	104	31	3	0
Softening point, ring and ball (°F)	121	193	118	120	130	112	118	123
Penetration index	+0.5	+6.8	+0.2	+0.5	+1.0	−0.9	−0.6	−0.7
Pen-vis no.	+0.2	+1.0	+0.2	+0.5	+1.0	−0.9	−0.6	−0.5
Toughness (in./lb)	85	171	85	177	144	17	42	73
Tenacity (in./lb)	67	141	20	147	126	10	11	12

[a]3 percent Kraton® D-1101.
[b]6 percent Kraton® D-1101.
[c]3 percent Kraton® G-1650.
[d]Experimental polymer.
[e]2.86 percent Kraton® D-116 with 1.14 percent Kraton® D-1107, 4 percent polymer content.

TABLE 2 MIX DESIGN PROPERTIES OF SAMPLES TESTED

Treatment	Asphalt Content (%)	G_{mm}[a]	G_{mb}[b]	Air Voids (%)
1	5.75	2.457	2.384	2.97
2	5.75	2.457	2.388	2.77
3	6.5	2.431	2.407	1.02
4	6.2	2.442	2.399	2.09
5	6.25	2.440	2.399	1.68
6	6.0	2.448	2.379	2.80
7	6.25	2.450	2.392	2.37
8	6.5	2.432	2.400	1.32

[a]G_{mm} = maximum theoretical density or specific gravity of an asphalt mixture.
[b]G_{mb} = density or bulk specific gravity of an asphalt mixture.

This was done to determine any relative influence of asphalt content and compaction on performance in the indirect tensile strength determinations.

The creep compliance and permanent deformation testing required cylindrical samples 4 in. in diameter and 7 in. tall. The California kneading compactor was used to compact these cylinders. This type of compaction has been shown by other investigators *(2)* to produce a sample that better approximates a field-compacted material for use in determining permanent deformation characteristics. The kneading compactor was calibrated with an AC-10 asphalt cement to establish operating characteristics that would produce compacted samples with the same density as produced by 50-blow Marshall compaction. On average, the densities were higher with the kneading com-

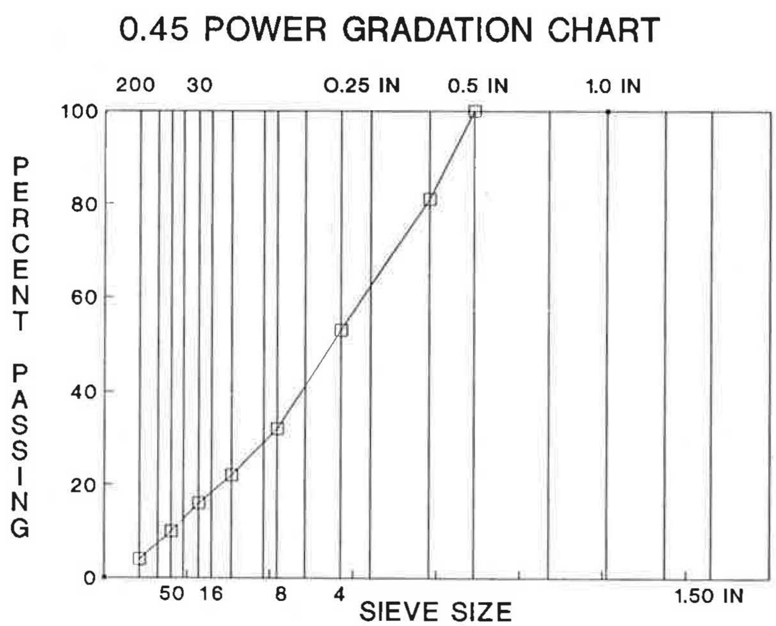

FIGURE 1 Gradation of Illinois dense-graded Interstate concrete overlay mixture.

pactor, and the air voids were lower than anticipated (Table 2). All asphalt contents were chosen to provide 4 percent air voids. This increase in density illustrates an interesting point about polymer-modified asphalt cements: at large strain levels, the resistance of the modified cement to deformation is significantly less than that of a normal asphalt cement of the same grade consistency compacted at the same temperatures *(3)*. In comparison with the Marshall hammer method of compaction, the kneading compactor is a large-strain device.

The cylindrical samples were trimmed using a concrete saw to provide parallel, polished ends for creep and permanent deformation testing. This produced a sample with a minimum length of 6 in. Samples not used for creep and permanent deformation testing were prepared for use as thermal contraction bars and samples for low-temperature indirect tensile strength determinations by cutting them into samples 4 in. in diameter with heights of approximately 2 in. The use of these samples for indirect tensile testing was significant because it showed that the influence of the kneading compactor extends to strains measured in the indirect tensile test as well as in the permanent deformation test.

TESTS

Stiffness

Stiffness determinations were performed using the diametral resilient modulus device. A 0.1-sec pulse load is applied along the vertical diameter of the sample, and the horizontal deformation is recorded.

The test is performed on two diameters of the sample, 90 degrees apart, and averaged. Testing was performed at three temperatures, 40°F, 72°F, and 100°F, to cover the values normally found in typical pavement structures in the United States that would be used as yearly design temperatures. These temperatures cover the range for high-temperature stability. Low-temperature cracking requires testing at lower temperatures and does not involve the diametral resilient modulus device.

Tensile Strength

The tensile strength of compacted asphalt concrete specimens is typically determined by the indirect tensile test or the Brazilian split test. This test is conceptually similar to the diametral resilient modulus test, except that the load is applied at a constant rate and is increased until failure occurs. The load and deformation applied to the vertical diameter are recorded along with the deformations along the horizontal axis. Indirect tensile strength, stiffness, tensile strain, compressive strain, Poisson's ratio, and vertical deformation at failure can be calculated from formulas given elsewhere *(4)*. The coefficients for the equations will vary with sample diameter. All samples tested in this study were standard Marshall size with a diameter of 4 in.

Testing was performed at 72°F with a rate of deformation of 2.0 in./min. Testing under these conditions evaluates the quality of the mixture and can provide an indication of the fatigue resistance of mixtures compared with that of normal asphalt cements. There is some question about whether polymer-modified asphalt cements tested in indirect tension provide accurate fatigue data as will be seen later. Subsequent testing was conducted at 40°F, 20°F, 0°F, and –20°F at a deformation rate of 0.05 in./min to provide an indication of the low-temperature performance of the mixtures.

Permanent Deformation

The permanent deformation or rutting resistance of a mixture must be evaluated using cylindrical samples. Loads are applied to the vertical axis of the cylinder, and the total deformation under the load is recorded by a noncontacting sensor. The test equipment used can perform a standard creep compliance test and a continual repeated load test. The procedure used in this study to develop permanent deformation characteristics was the FHWA incremental-static procedure, which defines the VESYS *ALPHA* and *GNU* parameters *(5)*.

The VESYS incremental-static test sequence consists of a series of load applications and measurement of the deformation remaining after a specified period of rest with no load applied. Permanent deformation versus loading time on logarithmic scales furnishes an indication of the relative resistance to permanent deformation of the mixture. Previous studies have clearly shown that the time of loading in a creep test is directly related to the accumulation of permanent deformation under repeated loadings *(6)*. The calculations for *ALPHA* and *GNU* are shown in Figure 2.

Thermal Coefficient of Expansion

Determination of the coefficient of expansion or contraction is an integral part of the analysis of the thermal behavior of mixes. The cylindrical samples formed with kneading compaction for use in the creep and permanent deformation study were used to determine the thermal coefficient of contraction. Samples not used in creep testing were cut into quarters. Set points were epoxied into the ends of two of the quartered bars. The length of the bars was monitored with a 0.0001-in. dial gauge. The asphalt concrete bars were placed in an environmental chamber for 24 hr at each temperature, and the length of the bar was recorded after the 24-hr temperature cycle. Temperature levels investigated included 72°F, 40°F, 20°F, 0°F, and –20°F. Readings were taken during both the cooling and the heating cycle for comparison.

TEST RESULTS

Diametral Resilient Modulus

The plots of stiffness as a function of temperature are shown in Figure 3. The relationship of stiffness and temperature for each type of asphalt is not unexpected when the temperature susceptibility parameters of the asphalt cements are considered. In particular, the pen-vis number (PVN) and the penetration index (PI) values indicate that the polymer-modified asphalt cements (Table 1) are less temperature susceptible than are the unmodified cements. Although the use of PI or PVN for modified asphalts is of questionable accuracy, these values show that the

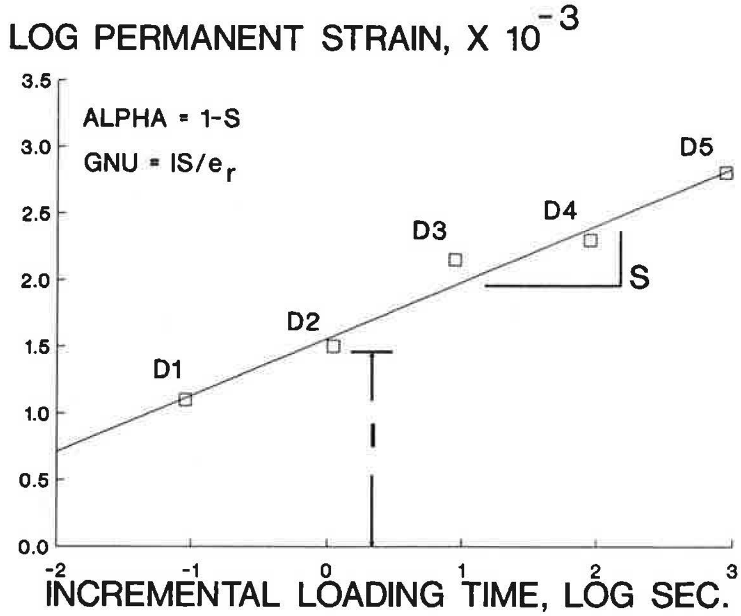

FIGURE 2 Schematic results of VESYS incremental-static analysis.

polymer-modified asphalt cements have the potential to provide an asphalt concrete that is stiffer at high temperatures and less stiff at low temperatures than are mixes made with asphalt cements that are a stiffer grade than the base asphalt used to formulate the polymer-modified asphalt cement. This has the potential to provide an asphalt concrete capable of resisting rutting at high temperatures and thermal cracking at low temperatures.

The influence of the polymers on the stiffness of the mixes is readily apparent, and the following comparisons between them and the three control asphalt cements can be made. The polymer-modified mixes are stiffer than the base AC-5 until the temperature drops below approximately 20°F. Below this temperature the polymer mixes are softer than the AC-5. The modified mixes show stiffnesses intermediate between those of the AC-5 and the AC-20 at elevated temperatures. Treatment 2 produced stiffness values similar to those of the AC-20 at 72°F. Extrapolating the data below 40°F indicates that the blends will remain more flexible than the AC-10 and AC-20, and below 20°F the polymer blends are more flexible than the base asphalt.

These mixtures were all compacted at the optimum asphalt content determined for each particular asphalt blend from the Marshall procedure. In general, a stiffer asphalt cement will

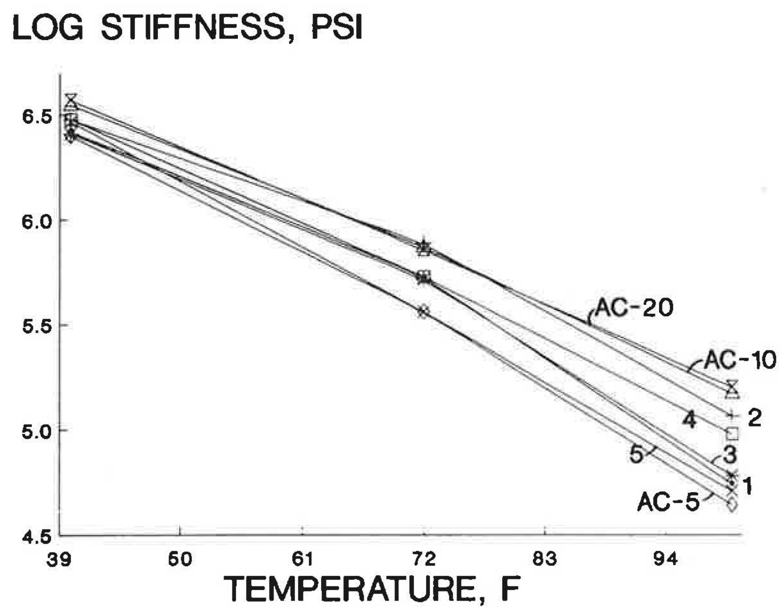

FIGURE 3 Stiffness versus temperature for treated and untreated samples.

TABLE 3 TENSILE STRENGTH RESULTS

Asphalt	Blows	Tensile Strength (psi)	Strain
1	50	105	0.00547
	75	132	0.00670
2	50	139	0.00654
	75	123	0.00812
3	50	110	0.00806
	75	136	0.00535
4	50	135	0.00609
	75	155	0.00569
5	50	124	0.00871
	75	128	0.00622
6	50	95	0.00791
	75	95	0.00846
7	50	164	0.00663
	75	152	0.00546
8	50	228	0.00561
	75	214	0.00507

require from 0.25 to 0.50 percent more asphalt cement in a mixture compacted at optimum *(1)*. A higher asphalt content typically produces lower stiffness, which may not be totally offset by a stiffer asphalt cement. The influence of the polymers is apparent in the overlapping stiffness curves (Figure 3). The mixtures are stiffer at normal or slightly above normal temperatures and significantly softer at low temperatures compared with the AC-5. Treatment 2 produced a very stiff mix at normal temperatures but was significantly softer at the extremes compared with the AC-10 and the AC-20.

Because of the limited number of data points, the stiffness values of each mixture at asphalt contents above and below optimum are not shown. In general, increasing asphalt content produced a decrease in stiffness. Sometimes, however, this trend was not easily discerned, and a maximum stiffness was indicated at the optimum asphalt content. These trends are typical of asphalt concrete samples with a dense gradation. All stiffness measurements were made on Marshall-compacted samples.

TABLE 4 STIFFNESS AND TENSILE STRENGTH DATA FOR MARSHALL COMPACTED SAMPLES

Treatment	Compaction Level					
	50			75		
	AC %	S_{it}	Stiffness	AC %	Sit	Stiffness
	5.75	110.6	554600	5.75	130	470200
1	5.75	105.2	517800	5.75	132.9	647000
	5.25	128.5	821250	5.25	148.8	700850
2	5.75	134.8	785950	5.75	121	546950
	5.75	143.2	759950	5.75	124.7	662150
	6.25	136.1	693400	6.25	138	651550
	6.00	124	560000	5.25	130.3	752100
3	6.00	98.1	484400	5.75	137.9	754050
	6.50	124	511350	5.75	133.3	801500
	6.50	119.6	592700	6.50	124	757750
	5.75	147.6	702300	5.25	163.6	870100
4	5.75	140.5	539800	5.25	146.7	875150
	6.25	129.6	527300			
	5.75	120.2	484400	5.00	145	754350
5	6.25	132.3	535200	5.50	121.3	500900
	6.25	115.5	458200	5.50	134.4	607000
	6.75	118.9	510850	6.00	133.6	555350
	5.5	92.2	267150	5.50	88.4	467600
6	6.00	93.2	338700	6.00	101.8	369000
	6.00	96.9	390150	6.00	88.9	359350
	6.50	84.6	270100	6.50	94.8	281550
	5.75	162.2	729850	5.00	155.8	773100
7	6.25	170.8	743100	5.50	151.9	732100
	6.25	156.4	738900	5.50	151.9	603300
	6.75	143.1	723300	6.00	166.6	817550
	6.50	202.8	743000	4.75	221.8	1083350
8	6.50	226.2	692050	5.25	230.4	873700
	7.00	185	699150	5.25	226.7	1288500
				5.75	225.9	977050

Indirect Tensile Strength

Indirect tensile strengths were determined at 72°F with a loading rate of 2.0 in./min. Additional testing at 40°F, 20°F, 0°F, and −20°F was done with a loading rate of 0.05 in./min. The 72°F test can be used to indicate fatigue resistance of a mixture prepared with unmodified asphalt cements. The lower temperatures are necessary for characterization of the low-temperature performance of the mixes.

Results at 72°F

The 72°F tensile test results are given in Table 3 for the eight mixes. Tests at these levels were conducted only on Marshall-compacted samples at both compaction levels and several asphalt contents. The results of the stiffness measurements at 72°F, given earlier, are mirrored by the tensile strengths. The data in Table 4 can be used to establish a relationship between indirect tensile strength and dynamic modulus, which has been proposed by others. The data have been plotted in Figure 4 to indicate the relationship. The relationship for this particular gradation, using the different asphalt cements, asphalt contents, and compaction efforts at 72°F, is

$$MR = 35{,}632 + 4{,}446(S_{it}) \quad (1)$$

where S_{it} is the indirect tensile strength (psi) and MR is the diametral resilient modulus (psi). The R^2 coefficient for this relationship was 0.85. This equation included only Marshall samples, compacted at 50 and 75 blows, below, at, and above optimum asphalt content in 0.5 percent increments.

At 72°F the polymer modifiers clearly increased the tensile strength of the mixes above the levels provided by the base AC-5 asphalt cement but not above that provided by an AC-10 asphalt cement. The tensile strain at failure for the polymer treatments was generally greater than that for the AC-10 and AC-20 mixtures. Increased strain at failure indicates that more strain energy is required to fail the specimen of that mixture, which is sometimes interpreted as a "tougher" mixture. The improvement at 72°F, however, is minimal in terms of increased performance.

Results at Low Temperatures

The tensile strengths and strains from the low-temperature tests are given in Table 5. The tests at the lower temperatures were conducted only on the samples compacted by the kneading compactor.

Tensile strength as a function of temperature is shown in Figure 5 for the untreated asphalts and polymer-modified blends. These curves are typical of dense-graded asphalt concrete mixtures *(4)*. The AC-20 mixture developed its peak strength at approximately 0°F whereas the AC-10 and the AC-5 developed peak strength at approximately −15°F. Typically, the softer grade of asphalt cement provides better resistance to low-temperature cracking by lowering the temperature at which failure occurs as well as increasing the tensile strength at failure.

The polymer-modified mixes demonstrate distinct differences from the untreated asphalt mixes. At approximately 10°F all mixes possess the strength of the AC-20 mixture. Below 10°F, even at very low temperatures, all polymer mixes maintain a higher strength than does the AC-20 mixture. It is thought that the peak strengths of several of the polymer blends may not have been reached because of temperature equipment control limitations that precluded going below −20°F. Improvement in the strength-temperature relationship has a significant impact on resistance to low-temperature thermal cracking in the field.

Tensile strain as a function of temperature is shown in

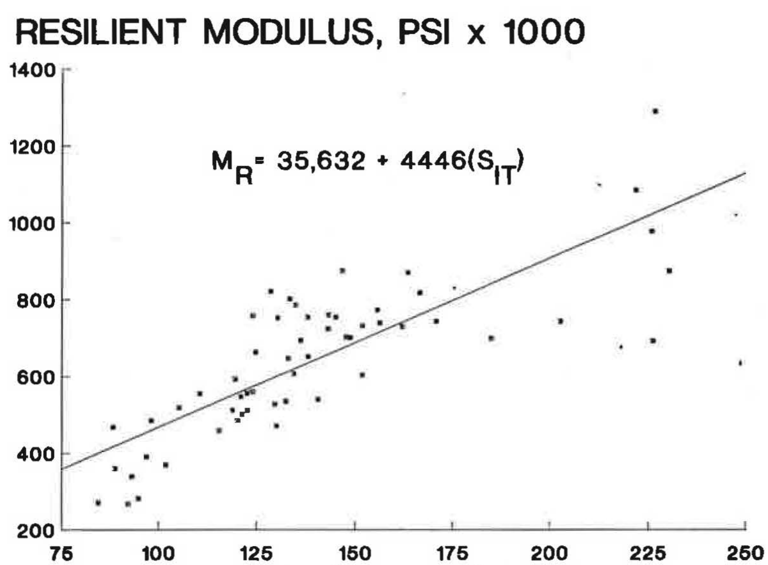

FIGURE 4 Resilient modulus as a function of indirect tensile strength at 72°F.

TABLE 5 TENSILE TEST RESULTS AT VARIOUS TEMPERATURES

Asphalt No.	40 °F Strength, psi	40 °F Strain in/in	10 °F Strength, psi	10 °F Strain in/in	-10 °F Strength, psi	-10 °F Strain in/in	-20 °F Strength, psi	-20 °F Strain in/in
1	-	-	398	0.0048	512	0.0030	476	0.0024
2	162	0.0091	417	0.0051	499	0.0036	479	0.0039
3	155	0.0073	460	0.0011	459	0.0026	492	0.0032
4	170	0.0068	450	0.0023	530	0.0014	559	0.0031
5	159	0.0066	436	0.0031	515	0.0030	510	0.0022
6	139	0.0070	299	0.0018	497	0.0013	432	0.0008
7	199	0.0070	299	0.0018	388	0.0009	450	0.0016
8	-	-	453	0.0012	400	0.0009	372	0.0019

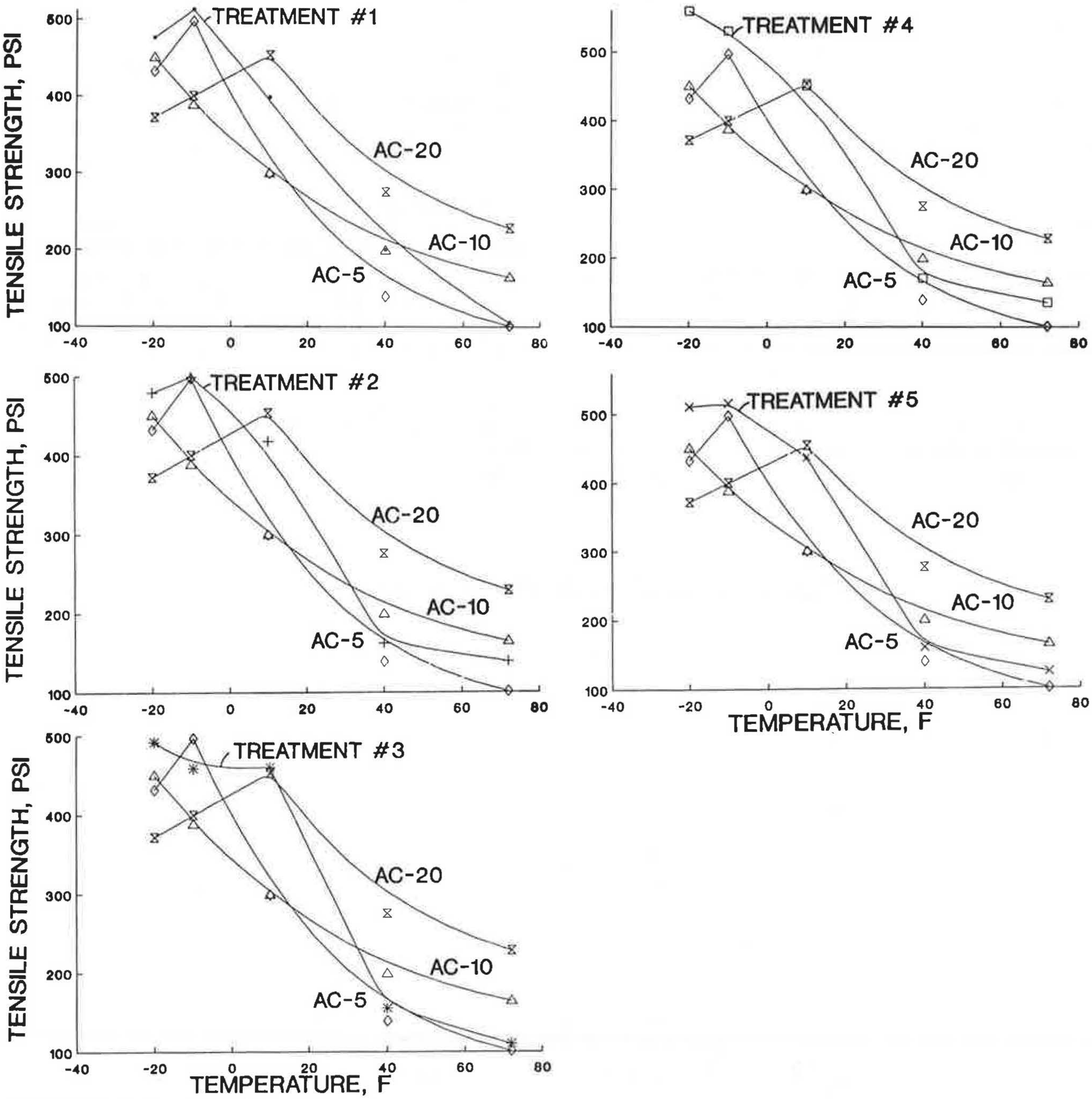

FIGURE 5 Indirect tensile strength as a function of temperature.

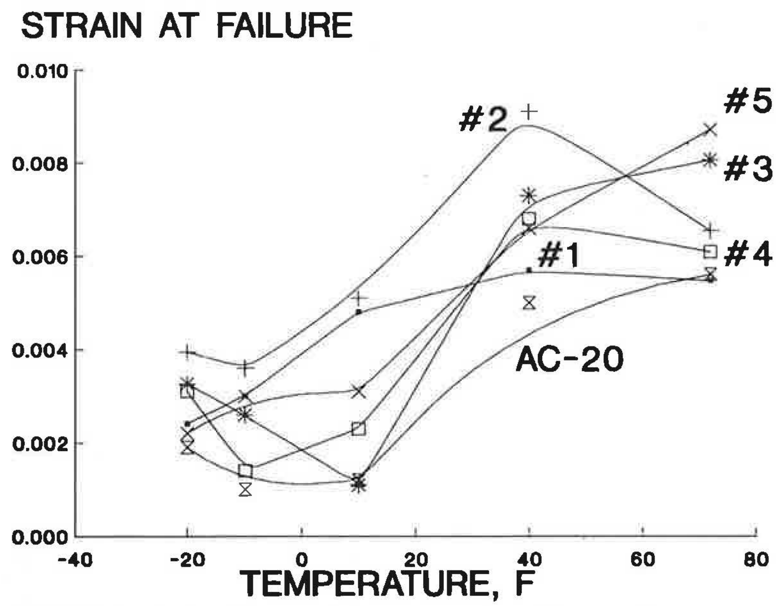

FIGURE 6 Indirect tensile strain as a function of temperature (AC-20).

Figures 6–8 for the untreated and polymer-modified blends. Each figure shows the untreated asphalt cement results superimposed on the results from the treated mixes. The strain at failure in the normal asphalt mixes rapidly decreases to a minimum value, even at moderate temperature levels, and remains at this level to extremely low temperatures. The polymer-modified blends, however, show a significantly different relationship. As shown in these figures, the tensile strain at failure for the polymer-modified blends remains much higher than those of the normal asphalt cements. Most significantly, at −20°F the failure strain in the polymer mixes is two to three times greater than those of the normal asphalt cements. This corresponds to the lower resilient modulus stiffness values indicated for these mixes at low temperatures. From these data, it would appear that Mixture 2 provides the best strain at failure and that Mixtures 1 and 3 perform quite well. It is evident that the polymers significantly modify the low-temperature performance of the mixes. This modification is not possible with normal asphalts even if they are of very different grades.

Fatigue Characteristics

Maupin *(7)* has developed statistically valid relationships between the indirect tensile strength and the fatigue characteristics of a dense-graded asphalt concrete mixture compacted by

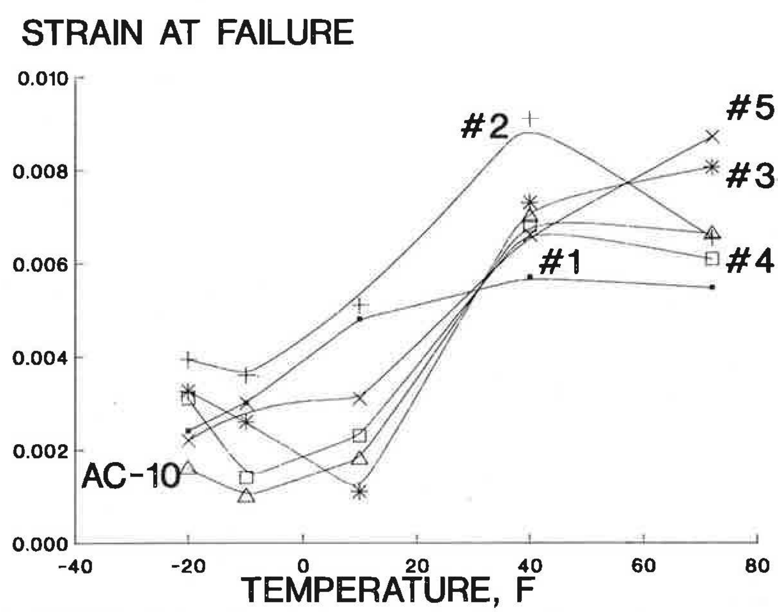

FIGURE 7 Indirect tensile strain as a function of temperature (AC-10).

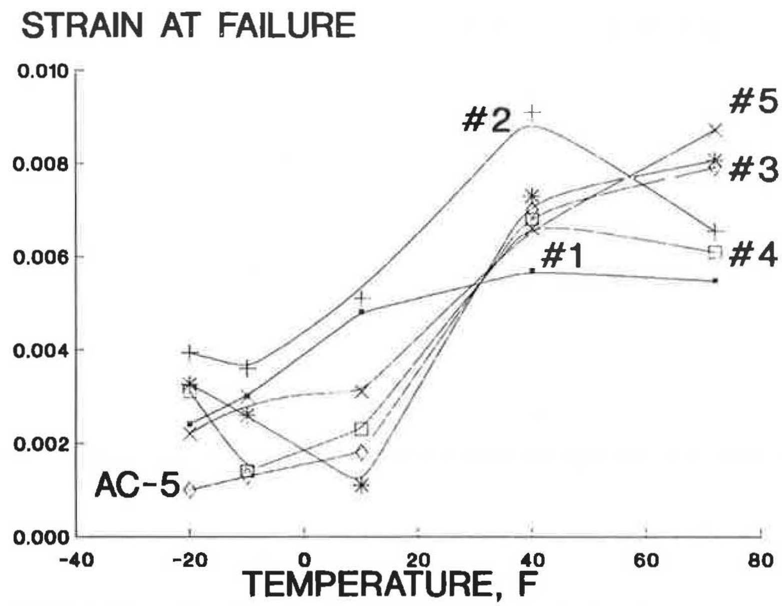

FIGURE 8 Indirect tensile strain as a function of temperature (AC-5).

the Marshall device and tested at 72°F at a rate of 2.0 in./min. These relationships are for the constant strain and constant stress mode of fatigue testing. The relationship for constant strain is

$$N_f = K_2(1/e)^n \quad (2)$$

where

N_f = number of loadings required to reduce the dynamic stiffness modulus by one-third,
e = radial tensile strain in the asphalt concrete layer,
K_2 = $10^{(7.92 - 0.0122 S_{it})}$,
n = $0.0374 S_{it} - 0.744$, and
S_{it} = indirect tensile strength (psi).

The constant strain representation of fatigue data is most widely used for normal fatigue testing because of the ease of testing.

The indirect tensile strength data presented in the previous section are all typical of high-quality dense-graded mixes similar to those tested in the development of Maupin's relationships. However, the Illinois gradation and the use of crushed stone and nonstandard asphalts produce mixes with significantly higher tensile strengths than those tested by Maupin. The mixes used in this study may provide a fatigue life that is significantly different from that of a more normal mix that contains natural gravels or sands instead of the crushed limestone. The relative effects of the addition of the polymer asphalts should remain similar to those reported here. The actual use of this relationship for predicting fatigue life for polymer-modified mixes cannot be recommended at present because of the use of different asphalts and the problems inherent in using regression relationships that place limitations on the data used to develop the equation.

As was noted earlier, a problem with polymer-modified asphalt cements is the influence on strain-related performance, particularly strains at large magnitudes, which appears to radically alter the performance of the asphalt cement. Thus it could be expected that actual fatigue testing would show different results than were seen in the indirect tensile strength tests that have not been validated for modified binders. It is expected that the polymeric properties would provide increased fatigue resistance, but this parameter requires further testing in an appropriate fatigue testing configuration.

Permanent Deformation

The *ALPHA* and *GNU* parameters calculated from the static-incremental creep test are given in Table 6. Static-incremental data furnish input parameters for the equation

$$F_{(N)} = GNU*(N)^{-ALPHA} \quad (3)$$

where

N = cumulative load applications;

TABLE 6 *GNU* AND *ALPHA* PERMANENT DEFORMATION PARAMETERS AT TWO TEMPERATURE LEVELS

	72°F		100°F	
Asphalt	*GNU*	*ALPHA*	*GNU*	*ALPHA*
1	0.1770	0.5562	0.1114	0.5521
2	0.1516	0.3731	0.1483	0.5759
3	0.2352	0.5298	0.1136	0.4838
4	0.2713	0.4282	0.1948	0.6622
5	0.5303	0.5626	0.0533	0.5311
6	0.2100	0.4746	0.1193	0.5197
7	0.2984	0.5243	0.1271	0.5855
8	0.2625	0.4775	0.1358	0.4557

GNU	= IS/e_r;
I	= intercept at Log t = 0;
S	= slope, as shown in Figure 5;
e_r	= resilient strain in the sample under the stress used in the test;
ALPHA	= 1.0 − *S*; and
$F_{(N)}$	= percentage of the resilient strain occurring in the asphalt layer under load *N* that will become permanent.

It can be seen from Equation 3 that as *GNU* increases permanent deformation increases and that as *ALPHA* decreases permanent deformation increases. However, this increase is only in the percentage of the total deformation under a load that becomes permanent and thus calculation of the actual magnitude of permanent deformation is dependent on the stiffness of the mixture. Any one mixture may have *ALPHA* and *GNU* parameters that allow a higher percentage of the strain to become permanent, but, if the mixture has a very high stiffness, the total strain occurring under one wheel load will be small, and the accumulation of permanent deformation will develop at a much slower rate than in another sample with different (better) parameters but a low stiffness.

To show the true relative amount of permanent deformation that develops in each of the mixtures tested, a computer program was prepared to use the *ALPHA* and *GNU* parameters and perform the accumulation of the $F_{(N)}$ percentage in a 15-year period with Interstate levels of traffic. A 3-in. asphalt concrete layer and an 80-psi vertical stress were used. The diametral resilient modulus of each mixture as determined from the 50-blow Marshall sample was used to calculate the strain occurring in a 3-in. layer under the 80-psi stress. Equal traffic levels were applied to all samples. The accumulation of rutting for the untreated asphalt samples is shown in Figure 9 for the 72°F test sequence. Rutting is given in a relative unit for comparison only because the calculated rut depths are for comparison of mixture quality only and are not indicative of actual rut depths that would develop in a complete pavement structure. It is interesting that the AC-10 showed less rutting potential than the AC-20. This may be because the asphalt content of the AC-10 is less than that of the AC-20 from the mix design (6.25 versus 6.5) and because the AC-20 was compacted in the kneading compactor, which produced a denser mix with low air voids of 1.3 percent that increase the rutting potential. The dramatic influence of the soft AC-5 binder is clear even though these samples were constructed with an asphalt content of 6.0 percent.

The rutting curves for the polymer-modified asphalt cements are shown in Figure 10 for the 72°F test sequence. Asphalt 4 showed a much higher potential for permanent deformation than even the AC-5, and all of the other polymer treatments, particularly Treatments 1 and 3, showed less rutting potential than did the AC-5. The low amount of rutting for Treatment 3 is significant because the samples for Treatment 3 were compacted to air voids in the range of 1 percent. This low amount of air voids should produce a mixture that is highly susceptible to rutting, as was shown with the AC-20 mixture. The low amount of rutting potential indicates that the polymer treatment improves the integrity of the mixture.

The rutting curves for the asphalt concretes at 100°F are given in Figures 11 and 12 for the untreated and treated samples, respectively. This temperature level is important because this is where the asphalt cement plays a greater role in resisting rutting than does gradation variation. The untreated asphalt samples show a dramatic increase in the potential for rutting, as would be expected. In particular, the AC-5 shows an almost complete loss of stability at this temperature. The polymer-treated asphalts also show an increase in rutting potential, but the increase is not nearly as dramatic as it is for the untreated samples. This is particularly true for Asphalt 4 that did not change its potential for rutting at all, which demonstrates a very stable temperature influence. Treatments 1 and 3 showed the largest increase in rutting potential, but they still performed better than the AC-10 and nearly as well as the AC-20 at similar asphalt contents. Treatment 5 also showed no change, and Treatment 2 actually showed a decrease in rutting.

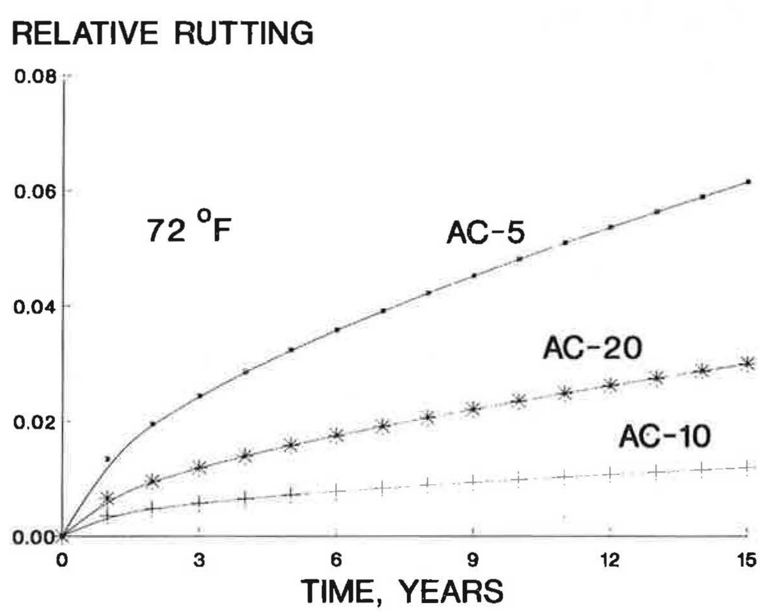

FIGURE 9 Development of rutting in untreated samples at 72°F.

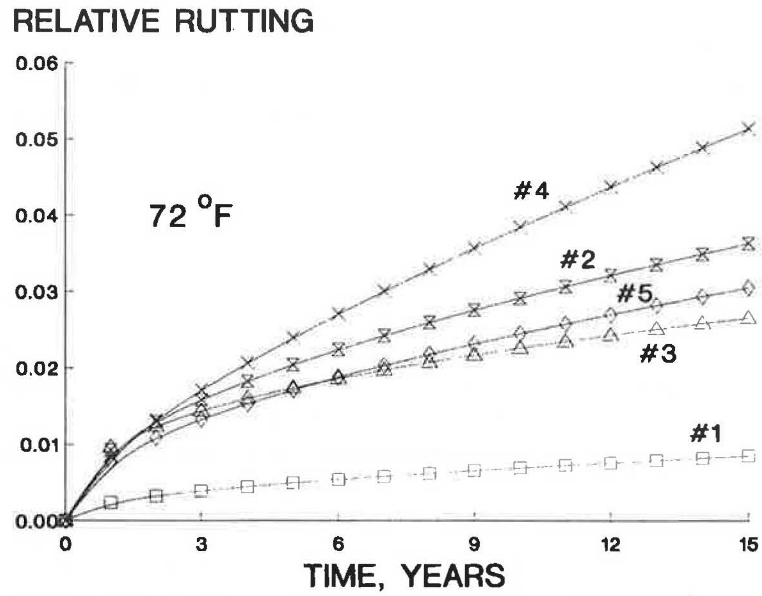

FIGURE 10 Development of rutting in treated samples at 72°F.

Coefficient of Thermal Contraction

The coefficients of thermal contraction are given in Table 7 for each of the temperature ranges examined. These coefficients are typical of any dense-graded mixture and do not appear to be affected by the asphalt grade used or the type of polymer treatment. The polymer-treated mixtures did show a difference from the untreated asphalt cements in that the coefficients did not show the same linear relationship with temperature. The polymer-treated mixes exhibited a nonlinear relationship in the 40°F temperature range. Although this does not cause any significant difference in performance, it may be indicative of the polymer's influence.

Moisture Sensitivity

Cores cut from the cylindrical samples (kneading compaction) were prepared and run through the Lottman vacuum saturation freeze-thaw procedure to induce stripping *(8)*. This procedure relies on the indirect tensile strength before and after conditioning to indicate the potential for stripping to develop in the mixture in service. A 50 percent loss in tensile strength in laboratory-prepared samples indicates severe moisture sensitivity of the mixture; such sensitivity has been correlated to stripping in field samples. The strength values of the mixtures evaluated in this program are given in Table 8. The combination of virgin asphalt and limestone aggregate used in this study

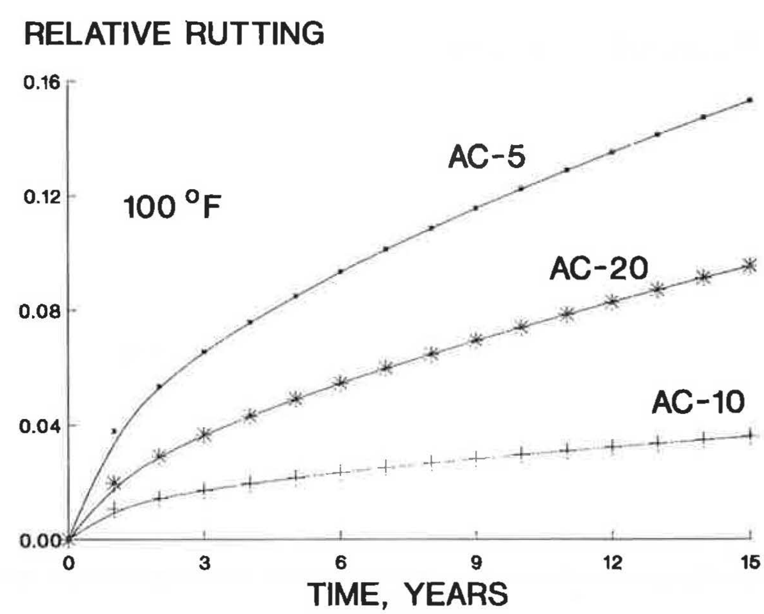

FIGURE 11 Development of rutting in untreated samples at 100°F.

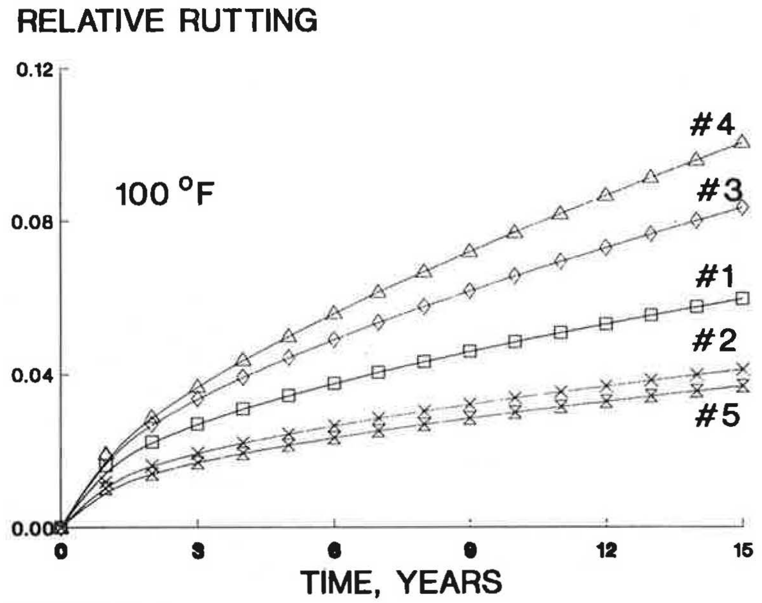

FIGURE 12 Development of rutting in treated samples at 100°F.

was apparently not moisture sensitive. Therefore any potential of the modified blends for improving resistance to stripping cannot be investigated with these mixtures. It is just as important to note that the modified asphalt cements did not increase the potential for moisture sensitivity in these mixes. Further research on moisture susceptible mixtures should be performed to evaluate any improvements in resistance to stripping that may be achieved through the use of polymer-modified binders.

CONCLUSIONS

It must be emphasized that, even for the same mixture, merely selecting one grade of asphalt cement over another does not guarantee better performance. Different grades of asphalt cement are selected to provide resistance to specific types of distress that are related to the environment of a specific area. Low-stiffness AC-5 cements are selected in northern climates to enhance resistance to thermal cracking; stiffer AC-20 cements are selected in warmer climates where rutting is the major problem. The function of the polymer treatment is to improve performance-related material properties of an asphalt cement. Thus relative comparisons of the test data are made against a soft and a stiff asphalt cement to demonstrate how the properties of an asphalt cement can be modified to change its performance at extremes of temperature.

The study presented here was designed to illustrate differences in performance of several different polymer blends, not to recommend any one of the blends as better than another. The data presented here represent the scope of information a state materials engineer should expect to see on any polymer additives blended with his specific asphalt cements. Less information would not allow for an adequate investigation of material differences. Further testing for aging and fatigue characteristics may also be advisable and recommended.

The laboratory test data developed in this study clearly illustrate that polymer modification of an asphalt cement produces a mixture that is quite different from the normal asphalt cement. Beginning with a base AC-5 asphalt, performance can be enhanced to a level expected of an AC-10, and in some

TABLE 7 THERMAL COEFFICIENTS OF CONTRACTION (× 10^{-5}/°F) IN TEMPERATURE RANGES

	Temperature Range (°F)			
Asphalt	72 to 40	40 to 20	20 to 0	0 to −20
1	1.06	1.10	1.22	1.10
2	0.99	1.24	1.22	1.14
3	1.04	1.24	1.40	1.16
4	0.92	1.08	1.33	1.25
5	0.96	1.29	1.49	1.23
6	–	1.51	1.33	1.10
7	1.37	1.32	1.41	1.21
8	1.42	1.66	1.33	1.22

TABLE 8 CHANGE IN INDIRECT TENSILE STRENGTH AFTER LOTTMAN PROCEDURE

	Tensile Strength (psi)		
Asphalt	Dry	After Conditioning	Tensile Strength Ratio
1	105	91	0.87
2	139	116	0.83
3	110	107	0.97
4	135	105	0.77
5	124	110	0.89
6	95	82	0.86
7	164	126	0.77
8	228	175	0.77

instances to that found in an AC-20 depending on which distress mechanism is being evaluated. At temperatures around 72°F, the performance of the polymer-modified asphalts is better than that of the untreated asphalt cements with similar consistencies (penetration at 77°F). The performance of these asphalts is most similar to that of an AC-10. At low temperatures, the performance of the modified asphalts approaches and surpasses that of an AC-5, and, at higher temperatures, the performance of the modified asphalt can meet or exceed that of an AC-20 in the permanent deformation test.

The different polymer blends and amounts used in the mix design all provide a different level of performance modification. Some blends were more beneficial than others, and some blends provided improvement in one area and not in another. In certain instances, the performance of the original asphalt was better.

The following conclusion can be drawn from the laboratory study of the polymer blends investigated here.

1. The dynamic resilient modulus–temperature relationship of the base asphalt can be enhanced to provide a stiffer asphalt at elevated temperatures yet maintain a stiffness below that of the base asphalt at low temperatures. This alteration becomes most significant when evaluated in the static mode of testing.
2. The fatigue resistance of a mixture is improved slightly with a polymer-modified asphalt cement, particularly at high temperatures where the elevated stiffness values produce lower radial tensile strains. Further laboratory testing is required to validate this trend thoroughly.
3. The potential for low-temperature thermal cracking is significantly reduced by use of a polymer-modified asphalt cement. Significantly higher tensile strengths are provided while a lower stiffness, which provides increased resistance to thermal cracking at temperatures in the range of from −20°F to 0°F, is maintained. The tensile strengths at extremely low temperatures are above those of an untreated asphalt concrete sample and they maintain this relationship to significantly lower temperatures than were possible in these tests.
4. A significant improvement in low-temperature performance properties is seen in the dramatic increase in the tensile strain at failure at low temperatures. This is the most important factor in polymer modification for low-temperature performance of asphalt concrete mixtures. With increased strains at failure, the polymer-modified mixes are not as brittle as unmodified mixes at low temperatures and provide improved resistance to thermal cracking.
5. Polymer modification provides a significant improvement in rutting resistance in comparison with the mixture prepared with the base asphalt. The performance of the modified blends is similar to, but not significantly better than, that of an AC-10 or an AC-20 at 72°F. The improvement provided by the polymer modification is seen when rutting at 100°F is compared. At these elevated temperatures, the improvement provided by the polymer treatment over the untreated AC-5 is quite dramatic. Several of the polymer blends actually showed no increase in rutting at the elevated temperature. One even had a lower potential for rutting at the elevated temperature; this may be due to mix design variability rather than polymer effect. At the elevated temperature, the performance of the polymer-modified blends was substantially equal to that of the untreated AC-10 and AC-20 mixtures.

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