Evaluation of Six AC-20 Asphalt Cements by Use of the Indirect Tensile Test

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In a 1976 research project on pavement durability in northern Pennsylvania, six AC-20 asphalt cements from different sources were used in the construction of test pavements. Two test pavements developed extensive low-temperature-associated shrinkage cracking during the first winter. The indirect tensile test is used to characterize asphaltic concrete mixes that contain the six asphalt cements. Basic mix properties, such as stiffness modulus, Poisson's ratio, tensile strength, and tensile strain at failure, are determined. The effect of temperature and asphalt rheology on these measured mix properties is evaluated. Within the temperature range used in the study [4°C to 60°C (39.2°F to 140°F)], both temperature and asphalt penetration correlate very well with mix tensile strength and stiffness modulus. Mix tensile strength and stiffness modulus increase as temperature or penetration decreases. The two cracked test pavements have much higher stiffness moduli than the other test pavements, as indicated by measurements at 25°C (77°F) or lower temperatures. The stiffness moduli of the asphaltic concrete, which are computed by two indirect methods (Heukelom and McLeod modifications of the van der Poel method), compare reasonably well with the measured values in the 4°C to 25°C temperature range.

Six test pavements were constructed on US-219 in Elk County, Pennsylvania, in September 1976. AC-20 asphalt cements from different sources were used. Penetration of the AC-20 asphalt cements ranged from 42 to 80. The research project consisted of 38-mm (1.5-in) thick, dense-graded asphaltic concrete resurfacing of the existing structurally sound pavement so that the performance of each test pavement could be studied on a comparative basis. Mix composition and compaction levels were held reasonably consistent. The only significant variable is the type or source of asphalt.

Visual observation of the six test pavements after the severe winter of 1976 and 1977 revealed that two pavements had developed extensive, low-temperature-associated transverse (shrinkage) cracking. A pavement temperature as low as -23°C (-10°F) was recorded during that winter. The stiffness moduli of the asphalts and asphaltic concrete were indirectly determined at low temperatures by using modified van der Poel charts and taking into consideration the temperature susceptibility of the asphalts used in the research project. The higher stiffness moduli of the asphaltic concrete (at low service temperatures) that contained the two asphalts were determined to be the primary cause of the non-load-associated transverse cracking. Complete details of this research project and test data are given elsewhere (1).

It was desired to determine the stiffness moduli of the asphaltic concrete by using the same six asphalts and by taking direct measurements in the laboratory. The indirect tensile test has been used to characterize asphalt paving mixtures by obtaining basic properties such as stiffness modulus, Poisson's ratio, and tensile strength (2, 3). Stiffness modulus, as used in this paper, is the relation between stress and strain as a function of time of loading and temperature. In many applications of asphaltic concrete, the stiffness characteristics of the material must be known not only to assess the behavior of the mix itself but also to evaluate the performance of an engineering structure of which the mix is a part, such as a highway pavement (4). At very short times of loading and/or low temperatures, the behavior of asphaltic concrete is almost elastic in the classical sense, and stiffness S_F is analogous to an elastic modulus E.

TEST PROCEDURE AND CALCULATIONS

The indirect tensile test involves loading a cylindrical specimen with compressive loads that act parallel to and along the vertical diametrical plane. Marshall specimens 101.6 mm (4 in) in diameter and 63.5 mm (2.5 in) in height were used in this study. To distribute the load and maintain a constant loading area, the compressive load was applied through a 12.7-mm (0.5-in) wide steel loading strip that was curved at the interface with the specimen and had a radius equal to that of the specimen.

This loading configuration develops a relatively uniform tensile stress perpendicular to the direction of the applied load and along the vertical diametrical plane that ultimately causes the specimen to fail by splitting or rupturing along the vertical diameter. By measuring the applied load at failure and by continuously monitoring the loads and the horizontal and vertical deformations of the specimens, one can estimate mix tensile strength S_T, Poisson's ratio ν, and stiffness modulus S_F. The equipment and test procedure are described elsewhere (5). A relatively high deformation rate of 0.84 mm/s (2 in/min) was used.

The theoretical relations used in calculating S_T, ν, and S_F are complex and require integration of various mathematical functions. However, by assuming a specimen diameter, one can make the required integrations and simplify the relations (3, 5). These simplified relations for calculating S_T, ν, S_F, and total tensile strain at failure ϵ_T for a 10.2-cm (4-in) diameter specimen with a 1.3-cm (0.5-in) wide curved loading strip are as follows (since the equations are formulated in U.S. customary units of measurement, no SI equivalents are given):

$$S_T = 0.156\,(P_{fail}/h) \quad (1)$$

$$\nu = (0.0673\,DR - 0.8954)/(-0.2494\,DR - 0.0156) \quad (2)$$

$$S_F = (SH/h)\,(0.9976\nu + 0.2692) \quad (3)$$

$$\epsilon_T = X_{TF}\,(0.1185\nu + 0.038\,96)/(0.2494\nu + 0.0673) \quad (4)$$

where S_T and S_F are given in pounds force per square inch and

P_{fail} = total load at failure (lb),
h = height of specimen (in),
DR = deformation ratio (Y_T/X_T) = slope of the line of best fit between vertical deformation Y_T and the corresponding horizontal deformation X_T

in the linear portion only,

S_H = horizontal tangent modulus (P/X_T) = slope of the line of best fit between load P and X_T in the linear portion only, and

X_{TF} = total horizontal deformation at failure.

The line of best fit was determined by the least-squares method. It was felt that a stiffness value obtained from the linear portion of the stress-strain relation would be more meaningful than the failure stiffness. Typical load-deformation curves are shown in Figure 1.

Figure 1. Typical load-deformation curves.

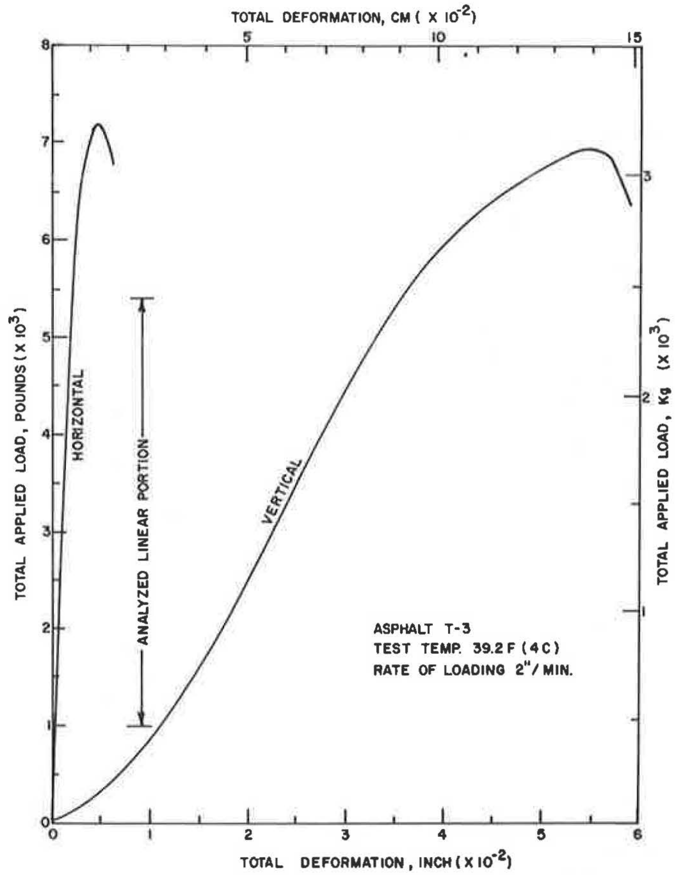


Table 1. Sources of crude and methods of refining.

Asphalt	Source	Method of Refining
T-1	49 percent Sahara, 21 percent West Texas, 21 percent Montana, 9 percent Kansas	Vacuum distillation and propane deasphalting
T-2	66.6 percent Texas Mid-Continent, 33.3 percent Arabian	Steam distillation
T-3	85 percent Light Arabian, 15 percent Bachaquero	Vacuum distillation
T-4	75 percent West Texas Sour, 25 percent Texas and Louisiana Sour	Vacuum distillation
T-5	49 percent Sahara, 21 percent West Texas, 21 percent Montana, 9 percent Kansas	Vacuum distillation and propane deasphalting
T-6	Blend of Heavy Venezuelan and Middle East crude	Vacuum distillation

Table 2. Properties of original AC-20 asphalt cements.

	Asphalt					
Test	T-1	T-2	T-3	T-4	T-5	T-6
Penetration (100 g, 5 s)						
At 4°C	2.0	7.4	6.2	6.7	3.4	7.5
At 15.6°C	11.2	25.0	24.5	23.0	16.0	29.0
At 25°C	42	64	72	65	54	80
Dynamic viscosity at 60°C (Pa·s)	270	228.4	176.4	170.5	175.9	198.2
Kinematic viscosity at 135°C (cm^2/s)	4.2	4.02	3.93	3.55	3.56	4.06
Penetration index	-2.77	-0.71	-1.51	-1.05	-2.23	-1.29
Penetration-viscosity number	-1.04	-0.70	-0.61	-0.86	-1.03	-0.45
Thin film oven residue						
Penetration at 25°C (100 g, 5 s)	26	38	45	38	37	44
Dynamic viscosity at 60°C (Pa·s)	550.1	683.5	398.2	469.4	324.8	572.1
Kinematic viscosity at 135°C (cm^2/s)	5.63	5.69	5.56	5.27	4.64	5.75
Ductility (cm)						
At 4°C, 1 cm/min	3.5	3.5	4.6	5.2	8.6	12.4
At 15.6°C, 5 cm/min	11.6	7.0	95.2	12.8	90.6	33.0

Note: $t°C = (t°F - 32)/1.8$; 1 Pa·s = 10 poises; 1 cm^2/s = 100 centistokes; 1 cm = 0.39 in.

Since the asphalt properties were determined at 4°C, 15.6°C, 25°C, and 60°C (39.2°F, 60°F, 77°F, and 140°F), these temperatures were used to conduct the indirect tensile test on the Marshall specimens. All reported test data are based on an average of three specimens.

MIX COMPOSITION AND ASPHALT PROPERTIES

The mix consisted of gravel coarse aggregate and natural sand. Mix composition data are given below (1 mm = 0.039 in):

Sieve Size (mm)	Percentage Passing
12.5	100
9.5	93
4.75	62
2.36	45
1.18	33
0.6	22
0.3	12
0.15	9
0.075	5

Asphalt content by weight of mix was 7.5 percent. The Marshall design data for the mix were as follows: theoretical maximum specific gravity (ASTM D 2041) = 2.326, specimen specific gravity = 2.278, percentage voids in mineral aggregate = 18.8, percentage air voids = 2.1, stability = 943 kg (2075 lb), and flow = 3.3 mm (0.13 in). This mix was also used on the Elk County project.

AC-20 asphalt cements were supplied by five refineries. Asphalts T-1 and T-5 came from the same refinery. Details of crude sources and methods of refining are given in Table 1.

The properties of original AC-20 asphalt cements are given in Table 2. Asphalts were recovered from the road cores taken from the six test sections just after construction. The properties of these asphalts are given in Table 3. Asphalts were also recovered from the Marshall specimens used in the indirect tensile test. The properties of these asphalts are given in Table 4. It can be observed that the asphalts (except T-1) generally hardened more on the roadway than in the laboratory. In evaluating the indirect tensile test data, only the properties of asphalts recovered from the Marshall specimens are used.

INDIRECT TENSILE TEST DATA

Tables 5 and 6 give mix test data on tensile strength, total tensile failure strain, and stiffness modulus for the six asphalts at four temperatures. In reviewing the test data, it should be kept in mind that pavements T-1 and T-5 developed excessive transverse shrinkage

Table 3. Properties of recovered AC-20 asphalt cements (roadway).

	Asphalt					
Test	T-1	T-2	T-3	T-4	T-5	T-6
Penetration (100 g, 5 s)						
At 4°C	1.5	4.5	4.5	4.0	2.0	5.8
At 15.6°C	7	17	16	13	9	20
At 25°C	24	40	43	34	29	49
Dynamic viscosity at 60°C (Pa·s)	552.6	572.9	378.9	382.9	401.9	461.1
Kinematic viscosity at 135°C (cm²/s)	5.65	5.69	5.26	4.87	4.88	5.76
Ductility (cm)						
At 4°C, 1 cm/min	0.2	4.6	13.9	5.9	0.6	14.9
At 15.6°C, 5 cm/min	8.3	7.2	48.5	10.0	15.5	34
At 25°C, 5 cm/min	≥150	80	≥150	≥150	≥150	≥150
Penetration index	-2.24	-0.80	-0.99	-0.65	-2.03	-0.64
Penetration-viscosity number	-1.13	-0.68	-0.72	-1.03	-1.16	-0.47

Note: t°C = (t°F - 32)/1.8; 1 Pa·s = 10 poises; 1 cm²/s = 100 centistokes; 1 cm = 0.39 in.

Table 4. Properties of recovered AC-20 asphalt cements (Marshall specimens).

	Asphalt					
Test	T-1	T-2	T-3	T-4	T-5	T-6
Penetration (100 g, 5 s)						
At 4°C	2.2	6.9	5.0	5.0	3.6	7.2
At 15.6°C	6.2	21.4	20.7	19.7	9.8	25.7
At 25°C	22	48.2	56	49	30.4	59.3
Dynamic viscosity at 60°C (Pa·s)	659.7	349.1	266.7	268.9	401.1	281.8
Kinematic viscosity at 135°C (cm²/s)	5.90	4.64	4.67	4.22	4.72	4.69
Ductility (cm)						
At 4°C, 1 cm/min	0	17.3	31	28	0	12.3
At 15.6°C, 5 cm/min	3.5	13.0	144.3	20.3	3.2	120.3
Penetration index	-1.08	+0.14	-1.44	-1.11	-0.54	-0.61
Penetration-viscosity number	-1.16	-0.81	-0.63	-0.89	-1.16	-0.57

Note: t°C = (t°F - 32)/1.8; 1 Pa·s = 10 poises; 1 cm²/s = 100 centistokes; 1 cm = 0.39 in.

Table 5. Tensile strength S_T and total tensile failure strain ϵ_T.

	S_T (kPa)				ϵ_T (mm)			
Asphalt	4°C	15.6°C	25°C	60°C	4°C	15.6°C	25°C	60°C
T-1	3847	2923	1193	139	0.0234	0.1173	0.1814	0.2428
T-2	2875	1269	641	114	0.0752	0.1994	0.2624	0.3708
T-3	3061	1455	690	118	0.0579	0.1821	0.2545	0.3693
T-4	3075	1420	627	117	0.0607	0.1661	0.2624	0.3589
T-5	3882	2124	1145	114	0.0279	0.1661	0.2098	0.3378
T-6	2999	1282	655	125	0.0881	0.1880	0.2350	0.3589

Note: 1 kPa = 0.145 lbf/in²; t°C = (t°F - 32)/1.8; 1 mm = 0.039 in.

cracking during the first winter. The modified cracking indexes (1) for pavements T-1 and T-5 were determined to be 51 and 38, respectively. The remaining four pavements have not developed such cracking so far.

Tensile Strength

The tensile strength of the asphaltic concrete increased as the test temperature was decreased from 60°C to 4°C (140°F to 39.2°F). Excellent correlation was found between temperature T and log S_T for all asphalts, as indicated below:

Asphalt	Correlation Coefficient	Relation
T-1	-0.992	$\log S_T = 3.408 - 0.0149\,T$
T-2	-0.995	$\log S_T = 3.095 - 0.0136\,T$
T-3	-0.995	$\log S_T = 3.149 - 0.0138\,T$
T-4	-0.992	$\log S_T = 3.135 - 0.0138\,T$
T-5	-0.999	$\log S_T = 3.386 - 0.0153\,T$
T-6	-0.993	$\log S_T = 3.092 - 0.0133\,T$

As shown in Figure 2, the rate of increase of tensile strength with decreasing temperatures is higher for asphalts T-1 and T-5 than for the other four asphalts. The penetration and viscosity of these two asphalts show that they are highly susceptible to temperature.

Figure 3 shows the effect of penetration of recovered asphalt on mix tensile strength. The regression analysis of log penetration and log tensile strength gives a correlation coefficient of -0.981. As penetration is decreased, tensile strength increases at a faster-than-linear rate. Ninety-six percent of the tensile strength values are attributable to the change in penetration as measured by the coefficient of determination (r^2).

Poisson's Ratio

The data indicate that the average Poisson's ratio is temperature dependent and increases as the temperature increases [t°C = (t°F - 32)/1.8]:

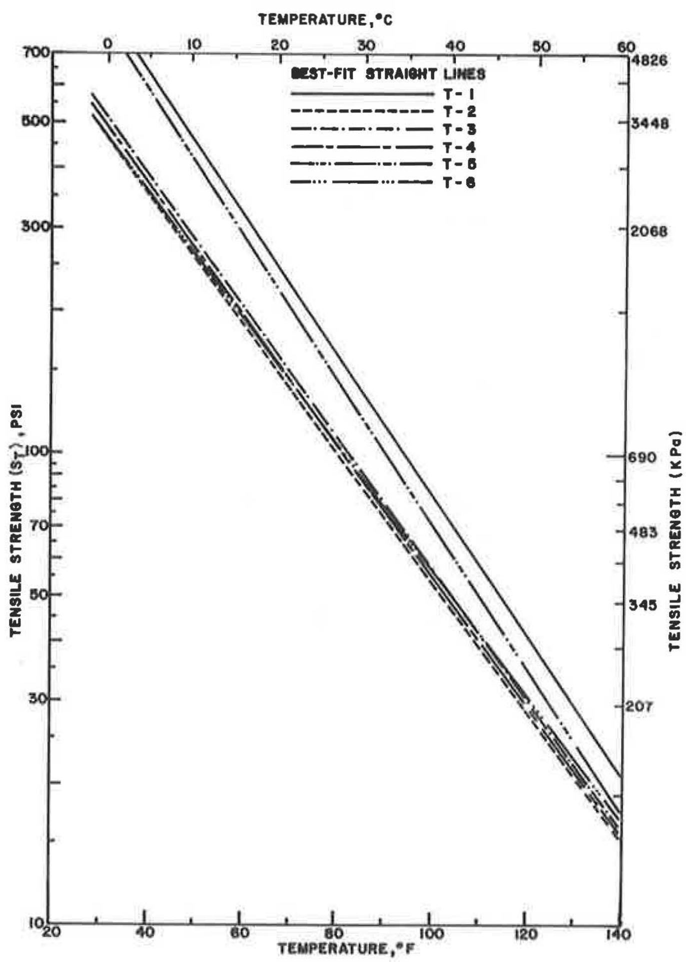
Test Temperature (°C)	Average Poisson's Ratio for All Asphalts
4	0.10
15.6	0.31
25	0.41
60	0.92

Table 6. Stiffness modulus (tensile test).

Asphalt	Stiffness Modulus (MPa) 4°C	15.6°C	25°C	60°C
T-1	7517	1172	579	80
T-2	1793	558	255	63
T-3	2690	814	248	63
T-4	2138	841	248	65
T-5	7172	1000	552	48
T-6	2207	648	227	86

Note: t°C = (t°F - 32)/1.8; 1 MPa = 145 lbf/in².

Figure 2. Temperature versus mix tensile strength.



At 60°C (140° F), the specimen begins to develop hairline cracks well before total failure, and these tension cracks cause an apparent increase in volume that explains the value greater than 0.5. Vila and Terrel (6) chose to use the term "strain ratio" rather than Poisson's ratio, which seems appropriate at higher temperatures.

Tensile Strain at Failure

Figure 4 shows the plot of temperature versus tensile

Figure 3. Penetration versus mix tensile strength.

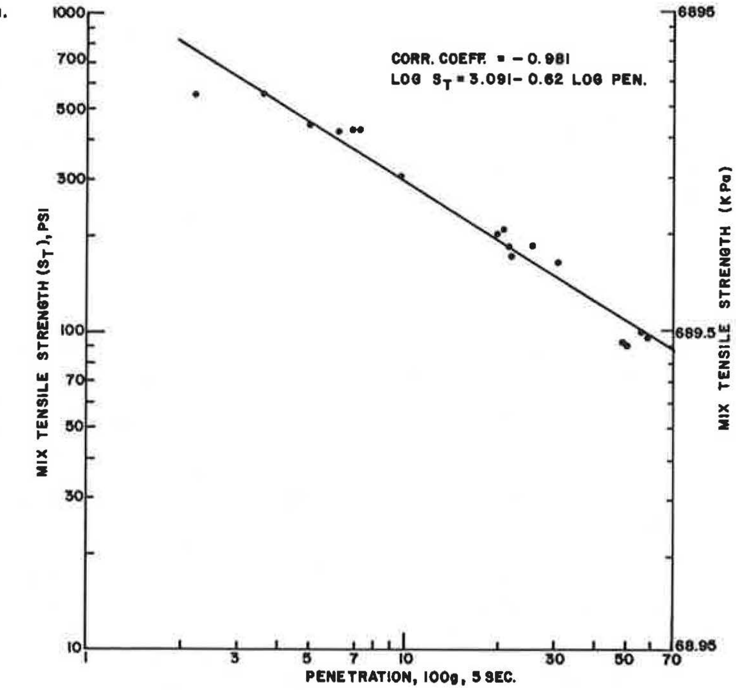
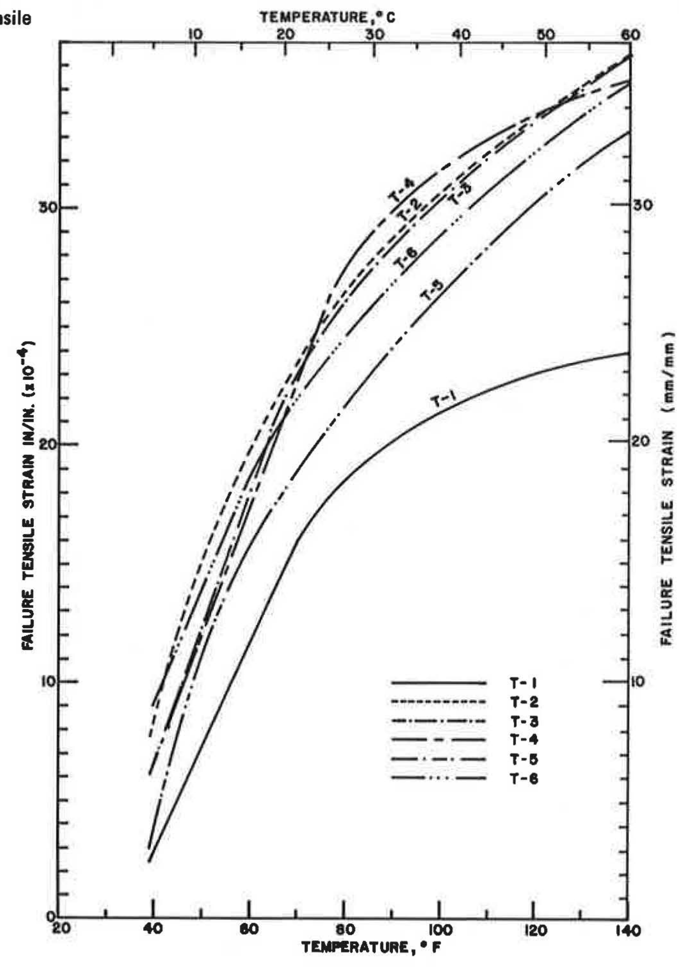


Figure 4. Temperature versus failure tensile strain.



strain at failure. At all temperatures, asphalts T-1 and T-5 failed at tensile strains lower than those for the remaining four asphalts. This trend should continue at temperatures lower than 4°C (39.2°F). Anderson and Hahn (7) consider failure strain the most significant parameter. The occurrence of cracking was found to increase as failure strain decreased.

Stiffness Modulus

As would be expected, the stiffness modulus of the asphaltic concrete increased as the temperature was decreased from 60°C to 4°C (140°F to 39.2°F). Excellent correlation was found between temperature T and log S_F for all asphalts in the temperature range 4°C to 25°C (39.2°F to 77°F), as given below:

Asphalt	Correlation Coefficient	Relation
T-1	-0.981	$\log S_F = 3.147 - 0.0297\,T$
T-2	-0.998	$\log S_F = 2.284 - 0.0224\,T$
T-3	-0.998	$\log S_F = 2.686 - 0.0272\,T$
T-4	-0.991	$\log S_F = 2.486 - 0.0245\,T$
T-5	-0.971	$\log S_F = 3.116 - 0.0298\,T$
T-6	-0.999	$\log S_F = 2.531 - 0.0260\,T$

Figure 5 shows that asphalts T-1 and T-5 have much higher stiffness moduli than the other asphalts. The greater the stiffness modulus, the greater is the thermal stress developed in the pavement by temperature change (8). This explains the low-temperature-associated shrinkage cracking in pavements T-1 and T-5.

Figure 6 shows the influence of recovered asphalt penetration on the stiffness modulus of the mix. As the penetration is lowered, the stiffness modulus increases at a faster-than-linear rate. Ninety-four percent of the stiffness moduli values show this trend, as measured by r^2.

Comparison with Past Use of Indirect Methods

Indirect methods of estimating the stiffness moduli of asphalt and asphaltic concrete have been used in the past. Two methods that are modifications of the original van der Poel method (9) were used in this study:

1. The Heukelom method (10) uses penetration at two or three temperatures, "corrected" softening point T_{800} penetration, and penetration index. The original van der Poel nomograph is used for determining the asphalt stiffness modulus.
2. The McLeod method (11) uses penetration at 25°C (77°F), viscosity at 135°C (275°F), base temperature, and penetration-viscosity number.

The stiffness modulus of a paving mixture can be determined from the stiffness modulus of asphalt and C_v^1, a factor for volume concentration of aggregate, by using the chart developed by van der Poel (12). The stiffness moduli of Marshall specimens were determined by these indirect methods at 4°C, 15.6°C, and 25°C (39.2°F, 60°F, and 77°F). A loading time of 2 s was used to correspond with the average loading time of the indirect tensile test. Based on the Marshall density data, C_v^1 was determined to be 0.84.

Figure 7 indicates that the stiffness moduli values computed by the indirect methods compare reasonably well with the measured values. It should be noted that 80 percent of these values are within the accuracy that van der Poel attributes to the nomograph for stiffness determinations on the asphalts—that is, a factor of two (shown by the dotted lines in Figure 7).

At 60°C (140°F), the stiffness moduli computed by indirect methods were considerably lower than the measured values.

Figure 5. Temperature versus mix stiffness modulus.

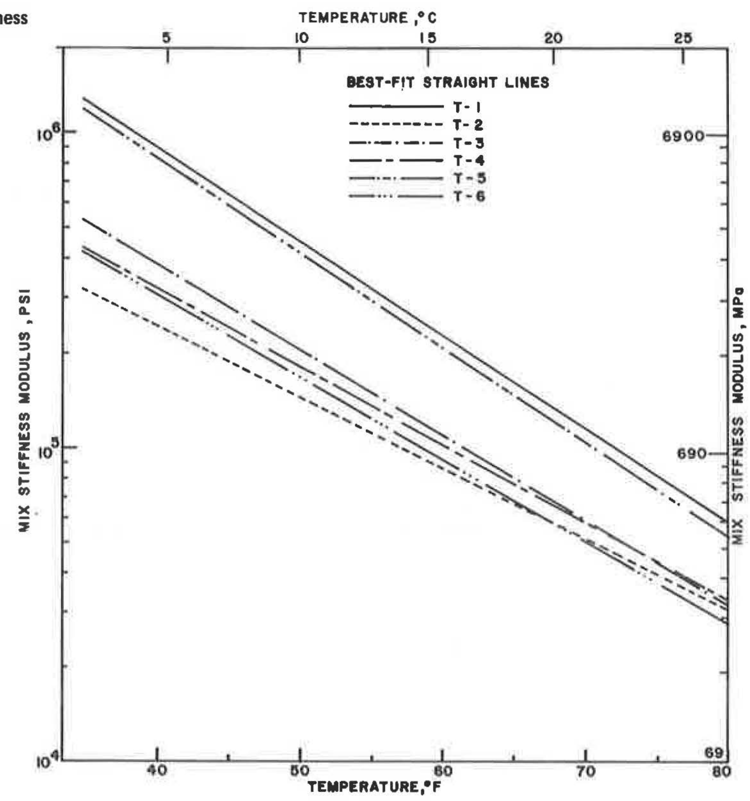


Figure 6. Penetration versus mix stiffness modulus.

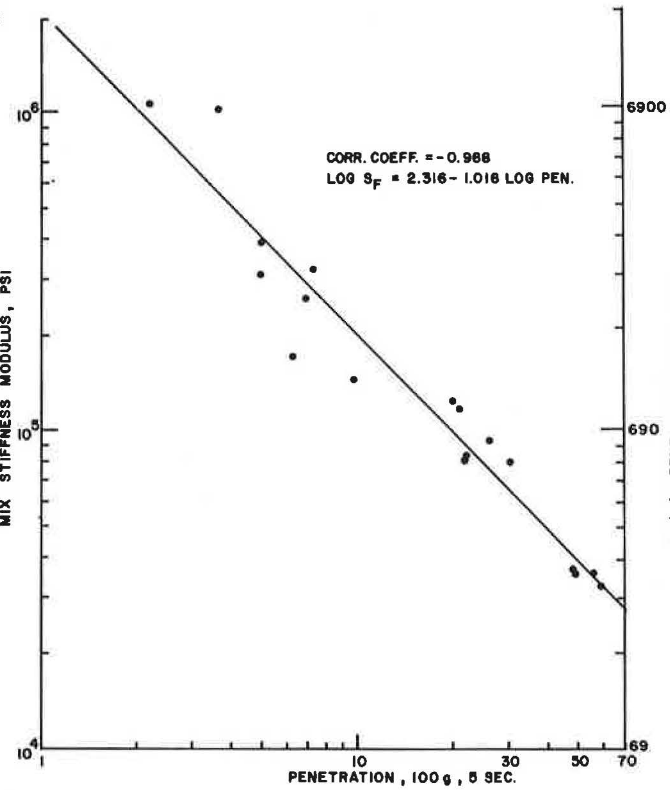
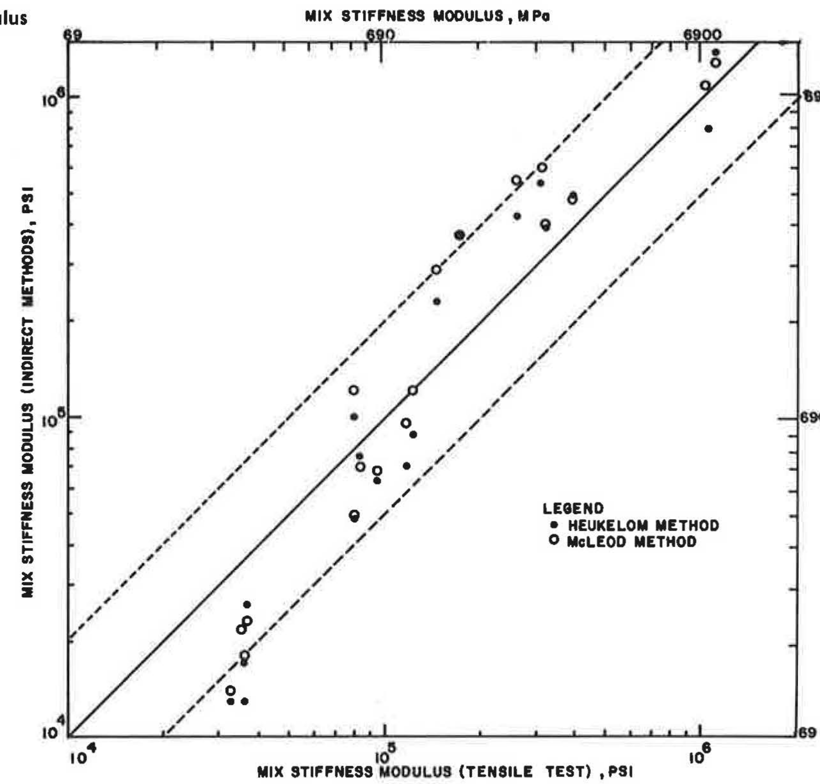


Figure 7. Measured mix stiffness modulus versus results from indirect methods.



SUMMARY AND CONCLUSIONS

This study was limited to one mix composition, six asphalt cements, and a temperature range from 4°C to 60°C (39.2°F to 140°F). The following conclusions can be drawn:

1. The indirect tensile test can be used to determine the tensile strength, Poisson's ratio, tensile strain at failure, and stiffness modulus of asphaltic concrete. These data can be used (a) to design the pavement structure and (b) to indicate the potential of low-temperature shrinkage cracking.
2. The reported test data are of major significance

since the same six AC-20 asphalt cements and the same mix composition were used on the Elk County research project, which has been evaluated periodically since September 1976. Two of the six test sections developed low-temperature-associated shrinkage cracking during the first winter. It should be realized, however, that the 0.84-mm/s (2-in/min) rate of loading that was used is much higher than the rate of loading at which such cracking actually takes place.

3. Within the temperature range used in this study, both temperature and recovered asphalt penetration showed excellent correlation with mix tensile strength. Mix tensile strength increased as temperature or penetration decreased.

4. Both temperature and asphalt penetration correlated very well with mix stiffness modulus. Mix stiffness modulus increased as temperature or penetration decreased.

5. The asphaltic concrete stiffness moduli computed by the two indirect methods (the Heukelom and McLeod modifications of the van der Poel method) compare reasonably well with the measured values in the temperature range from 4°C to 25°C (39.2°F to 77°F).

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Implementation of Stripping Test for Asphaltic Concrete

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Laboratory data were gathered by using a stripping test that is being developed and evaluated under NCHRP Project 4-8(3)/1 and is expected to be adopted for use in the state of Virginia. The testing program included a determination of the significant influences of different brands of asphalt cement and antistripping additives on the susceptibility to stripping of asphaltic concrete. Aggregates from eight sources, three asphalt cements, and two antistripping additives were used in various combinations. The results indicate that the new test method measured no significant differences in the stripping susceptibility of mixes with different asphalts. In one of the three mixes in which the effect of the type of additive was determined, a significant difference was found. Results of supplementary tests with a modified version of the test method indicate a good correlation with those obtained by use of the original method. It is concluded that the new method can probably be simplified to allow the use of equipment now available in district materials laboratories in Virginia.

A means of accurately predicting the stripping susceptibility of an asphaltic concrete has been sought for many