CHANGES IN ASPHALT CONCRETE MIXTURE PROPERTIES AS AFFECTED BY ABSORPTION, HARDENING, AND TEMPERATURE

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This paper provides information on the split cylinder testing of laboratory-compacted specimens and cores taken from in-service pavements. Tension test data were obtained for mixtures containing different aggregates, asphalt contents, types of asphalt, and temperatures. Relations between energy and vertical and horizontal deformations were developed from the test data. It was observed that energy decreased at lower temperatures. The horizontal and vertical deformations as measured in the split cylinder test were found to be related to the viscosity of the asphalts as influenced by hardening and temperature. This could be significant because it may provide a method to evaluate the composite effects of asphalt-aggregate interaction for use in quality control of asphalt paving mixtures. Further information is provided on penetration-viscosity relations and the properties of the materials used in the investigation.

•NUMEROUS factors can contribute to the fatigue cracking of flexible pavements. In Florida, the unexpected increase in traffic volume is considered a major contributor to early fatigue failure. The prevalence of pavement cracking in northern Florida has been of particular interest. Highly absorptive lime rock aggregates are used for pavement construction in this region. Preliminary studies of this paving material revealed that volume changes that are caused by the absorption of water or drying effects were very small and, undoubtedly, could not be a primary cause of pavement cracking.

Other investigations of pavement cracking on Interstate 10 in the northern part of Florida provided at least a partial insight into the factors affecting pavement performance (1). High air-void and low asphalt contents were generally synonymous with more extensive cracking than was observed on pavement sections with low air-void and high asphalt contents. Poor performance appeared to result from excessive hardening of the asphalt. It was observed that cracking was most prevalent when the extracted asphalt viscosity exceeded 10 megapoises (MP) at 25 C.

Further investigation of I-10 and several other pavements were directed toward the identification of the composite properties of paving materials (compacted asphalt-aggregate mixture). Laboratory-compacted specimens and cores from different pavement sections were split cylinder tested to separate good performing pavement sections from bad performing pavement sections by the tensile properties of the paving materials. The general approach to testing was similar to that of Breen and Stephens (2) in that work energy expended to failure was used as a definitive parameter.

MATERIALS

The aggregates used in this investigation were typical of those used in northern and southern Florida. Aggregate blends were selected to provide duplication of mixtures

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used in actual paving projects. The gradation, specific gravity, and absorption values for each of the 4 aggregate blends used in the study are given in Tables 1 and 2. Mixtures 1 and 2 are almost identical except for slight differences in fine aggregate blending. These mixtures are representative of the surface course used in the construction of I-10 in northern Florida. Mixtures 3 and 4 are typical of asphalt surfacing materials used in the Miami area.

The absorptive character of Florida aggregates is quite variable. Natural silica sands have absorptions of usually less than 0.80 percent whereas the lime rocks and oolitic limestones range between approximately 2.0 percent to 5.0 percent. The screened shell used in mixture 3 had a water absorption of 2.25 percent. Visual observation of asphalt mixtures that contain absorptive aggregates indicated that selective absorption may exist.

Table 3 presents a summary of properties for each of the 5 asphalts used in the study. Asphalt A was an aromatic, temperature-susceptible asphalt with a high glass transition temperature. Asphalts B and E were highly asphaltic and similar in properties except for substantial differences in glass transition temperature and flash point. Asphalts C and D were both air-blown materials derived from naphthenic base crudes.

These asphalts gave similar penetration and viscosity values for the 25 C test temperature. However, considerable differences in glass transition temperatures, degree of hardening, and viscosities at other temperatures were obtained for the asphalts. These differences appeared to be significant because of their effect on the results of split tension testing of compacted mixtures containing these asphalts.

TESTING PROCEDURES

The laboratory testing procedures included the use of the following:

1. Marshall method (ASTM D 1559-71) to determine design asphalt contents and preparing test specimens for each mixture;
2. Corps of Engineers procedure (ASTM D 854-52) to evaluate the bulk-impregnated specific gravity of the aggregate blends;
3. Rice method (ASTM D 2041-71) to obtain the virtual specific gravity and asphalt absorption of the mixtures prepared with the different asphalts;
4. Atlas weatherometer to accelerate the weathering of compacted asphalt mixture specimens; and
5. Split tension testing of unweathered (control) and weathered specimens.

In some instances it was necessary to modify the standard procedures. The specimens for processing in the weatherometer and split cylinder testing were mixed at temperatures corresponding to 1.5 P viscosity and compacted by using 6-blow Marshall compaction. This level of compaction provided densities that were slightly lower than actual pavement densities, but it was advantageous to obtain accelerated weathering of the specimens.

The standard sample size for the bulk-impregnated specific gravity test was reduced to 300 g of aggregate and 150 g of asphalt to minimize the difficulty in eliminating entrapped air and the time required for each specific gravity determination. Duplicate tests were conducted at preparation temperatures corresponding to viscosities of 10, 4, and 1.5 P for each aggregate blend and type of asphalt.

Accelerated weathering of test specimens was accomplished by using an Atlas weatherometer that contained carbon electrodes for arc light and a water spraying device. Temperatures up to 160 F were common during the heating cycle; an average temperature for each day was approximately 90 F. The 6-blow, Marshall-compacted specimens were arranged on a 2-level revolving rack in the weatherometer that continuously rotated around the light source and under the water spray bar. The specimens were revolved a quarter turn and rotated between top and bottom rack daily to obtain a uniform weathering exposure. The daily weathering schedule is given in Table 4. Specimens of mixtures 1 and 2 and mixtures 3 and 4 were exposed for a total of 864 hours and 672 hours respectively.

The tensile properties of unweathered and weathered laboratory specimens and pave-

Table 1. Aggregate gradation of test mixtures.

	Percent Passing			
Sieve Size	Mixture 1[a]	Mixture 2[b]	Mixture 3[c]	Mixture 4[d]
3/8 in.	100	100	100	100
4 in.	65.0	65.0	68.6	67.0
No. 10	42.1	42.0	45.3	41.8
No. 40	34.1	34.0	33.8	28.0
No. 80	14.9	18.9	11.6	15.7
No. 200	4.8	4.8	4.6	5.1

[a]58 percent No. 16 live oak crushed stone, 35 percent Oak Ridge silica sand, and 7 percent crushed stone screenings.
[b]58 percent No. 16 live oak crushed stone, 31.5 percent Oak Ridge silica sand, and 10.5 percent crushed stone screenings.
[c]56 percent No. 16 Dade County crushed stone, 8.1 percent crushed stone screenings, 32.4 percent Palm Beach screened shell, and 3.5 percent portland cement mineral filler.
[d]57 percent No. 16 Dade County crushed stone, 39.5 percent crushed stone screenings, and 3.5 percent portland cement mineral filler.

Table 2. Aggregate properties of test mixtures.

Asphalt	Bulk Specific Gravity	Apparent Specific Gravity	Water Absorption (percent)
Mixture 1	2.511	2.629	2.14
Mixture 2	2.506	2.630	2.27
Mixture 3	2.454	2.623	2.51
Mixture 4	2.461	2.615	2.40

Table 3. Asphalt properties.

	Type of Asphalt				
Properties	A	B	C	D	E
Penetration at 25 C	91	85	84	88	87
Specific gravity at 25 C	1.012	1.032	1.002	0.997	1.032
Flash point, deg C	257	215	324	313	294
Solubility in trichloroethylene, percent	99.96	99.95	99.95	99.96	99.59
Ductility at 25 C, cm	150+	150+	150+	150+	146
Viscosity					
V135 at 135 C, P	1.64	5.88	2.93	3.17	6.15
V60 at 60 C, kP	0.930	3.07	1.22	1.72	2.11
V25 at 25 C, MP[a]	0.875[b]	1.11[b]	1.25[b]	1.05[b]	0.99[b]
V25 complex flow, C	1.02[b]	0.80[b]	0.87[b]	0.78[b]	0.76[b]
V5 at 5 C, MP[a]	996[bc]	132[b]	275[b]	122[b]	134[b]
V5 complex flow, C	1.15[b]	0.80[b]	0.76[b]	0.66[b]	0.54[b]
Glass transition, isobaric method, 1 C/min					
1 atmosphere, deg C[d]	1.0	-4.5	-2.0	-7.0	-9.0
500 atmosphere, deg C[d]	16.5	12	12.5	8.0	7.0
Pressure sensitivity, m	0.033	0.031	0.028	0.029	0.030
Penetration method, deg C[e]	3.7	-0.2	4.8	1.2	-1.8
TFOT residues					
Penetration at 25 C	52	36	58	61	53
Penetration, percent of original	57	42	69	69	61
Loss, percent	0.26	1.53	—	—	0.34
Gain, percent	—	—	0.06	0.07	—
V60, kP	1.91	22.1	2.39	3.11	7.05
Viscosity ratio	2.05	7.20	1.96	0.98	3.34
V25, MP[a]	3.21	6.61	2.57	1.98	3.43
V25 complex flow, C	1.11	0.73	0.81	0.75	0.70
Ductility at 25 C, cm	150+	58	150+	150+	45

[a]Florida capillary method at constant shear rate for power input of 10^5 erg/cm^2 sec (4).
[b]Average of 2 tests.
[c]This material exhibits "glassy" phenomena at 5 C.
[d]By interpolation or extrapolation of data.
[e]Shoor, Majidzadeh, and Schweyer method (5).

Table 4. Daily weathering schedule.

Time	Water Spray	Arc Lamp
0700	Off	Off
0900	On	Off
1030	Off	On
1830	Off	Off
1900	On	Off
2300	Off	On

Note: Total water spray time: 5.5 hours. Total arc lamp time: 16 hours. Total time off: 2.5 hours.

ment cores were evaluated by using a split cylinder test. This test was selected because of its simplicity and potential to evaluate those physical properties of compacted asphalt mixtures that relate to flexibility, fatigue resistance, or resistance to cracking.

The test mechanism consisted of two 0.5-in.-wide parallel steel contact plates, one mounted on a load cell and the other mounted directly below the platen of the test machine. The screw-driven testing machine was limited to a single speed that provided a constant vertical deformation rate of 2.68 in./min. Instrumentation consisted of a 10,000-lb load cell and a linear variable differential transformer (LVDT) connected to a strip chart recorder. Horizontal deformation was measured across the 4-in.-wide specimens by using a LVDT.

Figure 1 shows typical data output from the split cylinder tests. Data curves for mixture 4 using asphalt A and asphalt D illustrate the extremes in response obtained for the different asphalt mixtures tested at 5 C. Energy and strain ratios were computed from the data in the following manner.

1. Initial deformation that was due to seating of the steel contact plates on the 4-in.-diameter asphalt concrete specimens was eliminated from the analysis by projecting the linear portion of the curve to the abscissa.

2. Vertical deformation corresponding to the point where the rate of horizontal deformation increased rapidly was used to calculate initial energy (E_I) as illustrated in the following computation for asphalt D shown in Figure 1:

$$E_I = \begin{pmatrix}\text{avg}\\ \text{load}\end{pmatrix} + \begin{pmatrix}\text{vertical}\\ \text{deformation}\end{pmatrix} = \left[\frac{3{,}000}{2}(0.1)\right] + \left[\frac{3{,}000 + 4{,}500}{2}(0.084)\right] = 465 \text{ in.-lb} \quad (1)$$

3. The horizontal/vertical strain ratio (ϵ_H/ϵ_V) was computed by using a horizontal deformation increment of 0.04 in. measured from the point at which the horizontal deformation rate increased. The vertical deformation increment was determined from the data plot by using the previously defined horizontal deformations. An example of this calculation using asphalt D data is

$$\frac{\epsilon_H}{\epsilon_V} = \frac{0.04}{0.0617} = 0.65 \quad (2)$$

4. Additional vertical energy was computed by using the vertical deformation as determined in Eq. 2. The following example illustrates this computation for asphalt D:

$$E_A = \begin{pmatrix}\text{avg}\\ \text{load}\end{pmatrix}\begin{pmatrix}\text{vertical deformation for}\\ \text{0.04-in. horizontal deformation}\end{pmatrix} = (3{,}800)(0.0617) = 234 \text{ in.-lb} \quad (3)$$

5. The computation for total energy is as follows:

$$E_T = E_I + E_A = 465 + 234 = 699 \text{ in.-lb} \quad (4)$$

The energy values presented in this report have been corrected for specimen diameter and thickness so that the energy corresponds to a standard specimen 4 in. in diameter and 2.5 in. in thickness.

Viscosity tests on asphalts recovered by the Abson method (ASTM D1856-69) from laboratory samples and field cores were obtained to evaluate hardening that had occurred in mixing and in weathering. Viscosity tests were performed at 25 C although it would have been desirable to have low temperature viscosity data.

RESULTS

The Marshall mixture design results for the different mixtures using asphalt E are given in Table 5. The air-void content for the mixtures at the design asphalt content may appear low, which is common for these mixtures because the density and stability values do not change appreciably at different asphalt contents. The optimum asphalt contents were used as a guide in selecting asphalt contents for preparation of the tension

Figure 1. Analysis of split cylinder test data.

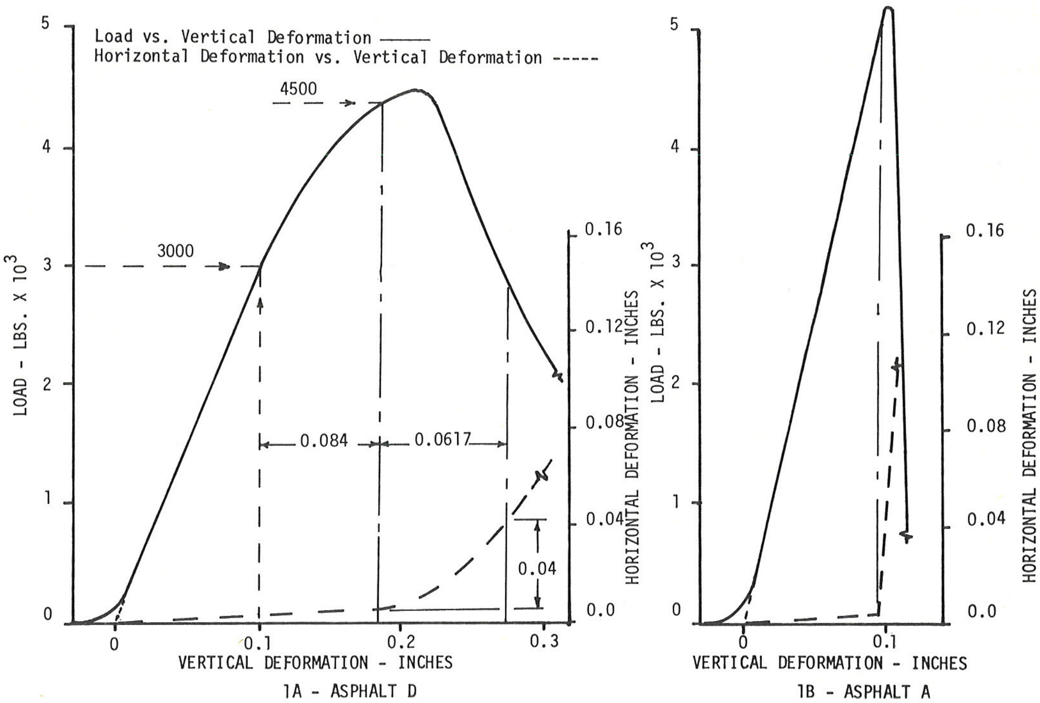


Table 5. Marshall mixture design results.

Mixture	Unit Weight (pcf)	Stability (lb)	Flow (0.01 in.)	VMA (percent)	Air Voids (percent)	Optimum AC (percent)
1	142.80	1,265	8.5	14.0	2.4	6.10
2	141.90	1,360	9.6	14.2	3.2	6.30
3	140.5	2,010	10.7	13.8	4.0	6.0
4	141.0	2,780	12.2	14.3	2.9	6.6

Note: 1 pcf = 16.01 kg/m^3. 1 lb = 4.45 N. 1 in. = 25.4 mm.

Table 6. Compaction data for tensile test specimens.

Mixture	AC (percent)	Compaction Blows per Side	Unit Weight (pcf)	Marshall Compaction (percent)
1	5	6	135.36	95
	6	6	137.50	96.5
2	5	6	134.71	95
	6	6	136.60	96.3
3	5	6	131.27	93.5
	6	6	132.51	94.4
4	5.5	6	130.16	92.4
	6.8	6	132.45	94.0

Note: 1 pcf = 16.01 kg/m^3.

test specimens. The compaction data for the 6-blow, split cylinder test specimens are given in Table 6.

The bulk-impregnated specific gravity test results are given in Table 7. Data for the 10.0 P test temperature have been deleted because it was found that removal of entrapped air was difficult to achieve at this higher viscosity. The test values for asphalt E were essentially the same as values obtained on mixtures tested by the Rice method as given in Table 8.

The results of the 5 C split cylinder tests on mixtures 1 and 2 and cores from I-10 are presented in Figures 2 and 3 respectively. Mixtures 3 and 4 are not presented because the data were essentially the same as those for mixtures 1 and 2. Variation in specimen and core thickness were taken into account by adjusting all test values to a standard thickness of 2.5 in. Because the effect of weathering was substantial for mixtures containing asphalt B, it was decided to shortcut the weatherometer process and to use asphalts from the thin film oven test (TFOT) for preparation of specimens. The data for this limited study are shown in Figure 4. The dashed lines representing the data trends are exactly the same in Figures 2, 3, and 4.

Viscosity data for the extracted asphalts from laboratory specimens and I-10 cores are given in Tables 9 and 10. Also, penetration data and asphalt contents for the different sections are presented in Table 9 for comparative purposes.

DISCUSSION OF RESULTS

Preliminary analysis of the viscosity data indicated that a considerable difference exists among asphalts in their hardening properties. The summary of laboratory viscosity data for the different asphalts, as given in Table 11, shows that some hardening occurs in the heating, mixing, and preparation of test specimens. Asphalt B was the most affected by the process whereas air-blown asphalts (asphalts C and D) showed negligible hardening. Good correlation was obtained between TFOT and weatherometer viscosities. The weatherometer produced greater hardening of asphalt A than did the TFOT. This hardening had a noticeable effect on the split tension test results; this can be readily identified in Figures 2 and 3 where the energy values decrease and the strain ratio increases for the weathered specimens containing asphalt B.

All viscosity and penetration data for original asphalts, TFOT residue, and extracted asphalts were compared to the viscosity prediction curve, which is based on the following equation developed by Schweyer (3):

$$N_p = 3{,}240\ P^{-2.32} \tag{5}$$

where

N_p = viscosity in MPa·s at a constant power input of 10^5 erg/cm^2·sec and
P = penetration at 25 C.

This comparison, as shown in Figure 5, indicates reasonably good correlation between the prediction equation and the experimental values.

The effect of asphalt content on the split cylinder tests was observed by Breen and Stephens (2). At low temperatures they concluded that work appeared to be independent of asphalt content. The test results presented in Figures 3 and 4 indicate a slight increase in energy as the asphalt content is increased. However, the initial energy from the test data is directly comparable to Breen and Stephens work values and appears to justify their conclusions.

Any change in energy values with changes in asphalt content may be a result of compacted density variations. However, comparison of tension test results for 50-blow and 6-blow compacted specimens gave essentially the same energy and strain ratio values.

Breen and Stephens (2) observed the effect of increasing viscosity by lowering the temperature for the split cylinder tests. They note that with decreasing temperature the fracture load increases slowly and the work required to fracture the specimen decreases. This phenomenon was observed in tests conducted on mixture 4 by using different asphalts and test temperatures of 2, -3.3, and -8 C. As shown in Figure 6, the

Table 7. Bulk-impregnated specific gravity values.

Type of Asphalt	Mixture 1	2	3	4
4.0 P test results				
A	2.556	2.583	2.566	2.574
B	2.547	2.561	2.548	2.557
C	2.545	2.563	2.544	2.554
D	2.556	2.555	2.536	2.541
E	2.558	2.568	2.555	2.564
1.5 P test results				
A	2.564	2.577	2.562	2.574
B	2.538	2.558	2.544	2.555
C	2.545	2.560	2.546	2.558
D	2.543	2.554	2.540	2.548
E	2.551	2.556	2.544	2.553
Mean of B, C, D, E	2.548	2.559	2.545	2.545
Standard deviation of B, C, D, E	0.0078	0.0071	0.0073	0.0083
Difference between asphalt A and mean	+0.016	+0.018	+0.017	+0.020

Table 8. Comparison of bulk-impregnated and Rice method specific gravity methods, 4.0 P test results.

Mixture	Bulk-Impregnated Method, Asphalt E	Rice Method, Asphalt E	Asphalt Absorption (percent)
1	2.558	2.572	1.12
2	2.568	2.570	1.38
3	2.555	2.549	1.65
4	2.564	2.558	1.67

Figure 2. Energy-strain ratio relationship for laboratory test specimens.

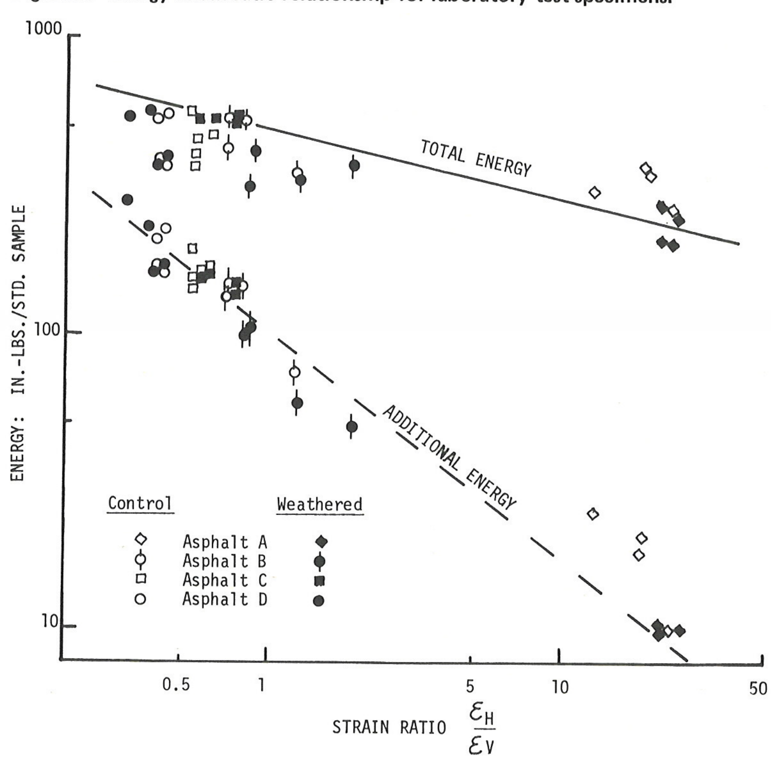


Figure 3. Energy-strain ratio relationship for I-10 cores.

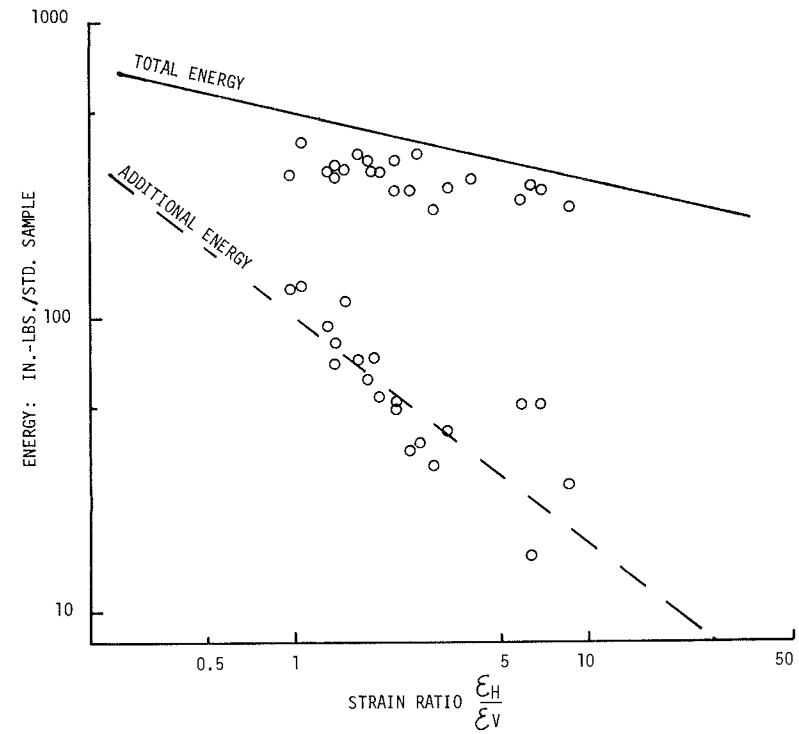


Figure 4. Energy-strain ratio relationship for laboratory test specimens containing TFOT asphalt residues.

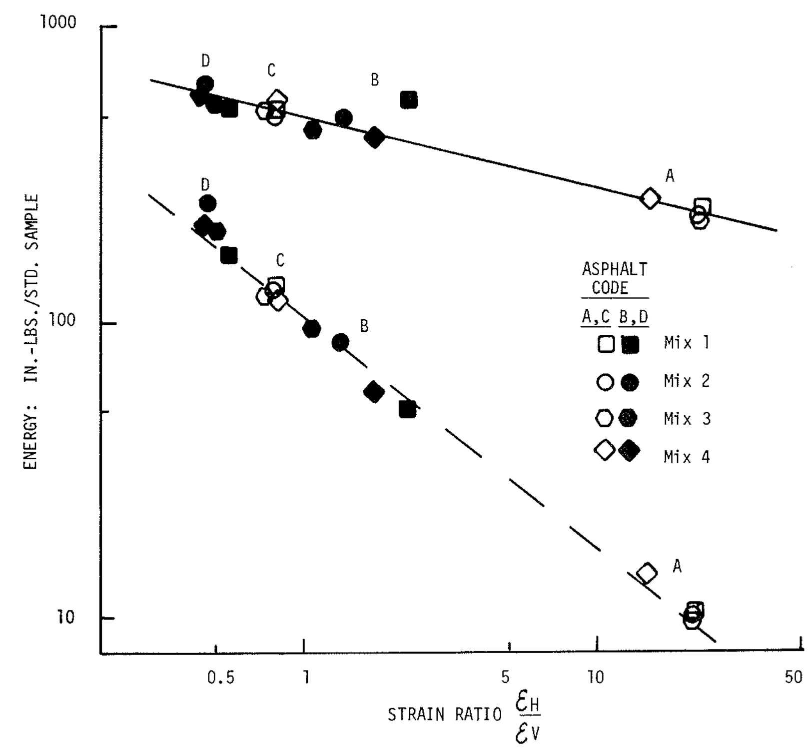


Table 9. Viscosity of asphalts extracted from test specimens.

Type	AC (percent)	Viscosity at 25 C (MP) Control Specimens	Viscosity at 25 C (MP) Weatherometer Specimens	Type	AC (percent)	Viscosity at 25 C (MP) Control Specimens	Viscosity at 25 C (MP) Weatherometer Specimens
Asphalt A				Asphalt C			
Mix 1	5.0	1.30	4.90	Mix 1	5.0	1.57	2.17
	6.0	1.41	5.83		6.0	1.22	2.37
Mix 2	5.0	1.99	5.48	Mix 2	5.0	0.86	3.02
	6.0	1.71	5.03		6.0	1.49	3.47
Mix 3	5.0	1.35	4.48	Mix 3	5.0	1.37	2.21
	6.0	1.75	4.14		6.0	1.55	2.26
Mix 4	5.5	2.11	5.03	Mix 4	5.5	1.66	2.32
	6.8	1.71	4.96		6.8	1.53	2.12
Asphalt B				Asphalt D			
Mix 1	5.0	2.24	10.3	Mix 1	5.0	1.46	1.88
	6.0	1.41	6.76		6.0	1.14	1.35
Mix 2	5.0	2.25	7.29	Mix 2	5.0	1.13	1.96
	6.0	3.97	4.67		6.0	0.93	1.91
Mix 3	5.0	1.83	6.58	Mix 3	5.0	1.12	1.72
	6.0	2.27	5.80		6.0	1.18	1.91
Mix 4	5.5	1.98	5.19	Mix 4	5.5	1.14	2.00
	6.8	2.19	5.02		6.8	1.24	2.18

Table 10. Penetration and viscosity data for recovered asphalts from I-10 cores.

Section Number	Penetration at 25 C	Viscosity at 25 C (MP)	AC (percent)
7	26	15.6	–
8, 9	18	42.0	–
10	25	18.0	–
11	25	20.8 to 23.0	–
15	22	31.1	–
16	24	25.4	5.3 to 5.6
21	41	–	6.2 to 6.5
21	37	–	6.5
22	43	13.9	–
23	37	8.09	6.3
25	23	21.0	–
26	25	19.1	5.4
27	25	–	5.5 to 5.9
28, 29	27	19.6	5.2 to 6.1
30	21	–	–

Table 11. Comparison of viscosity data.

Type of Asphalt	Average Viscosity Values at 25 C (MP) Original Asphalt	Extracted From Control Specimens	TFOT Residue	Extracted From Weatherometer Specimens
A	0.875	1.67	3.21	4.98
B	1.11	2.27	6.61	6.48
C	1.25	1.41	2.57	2.49
D	1.05	1.17	1.98	1.86
E	0.99	–	3.43	–

Figure 5. Penetration-viscosity relations.

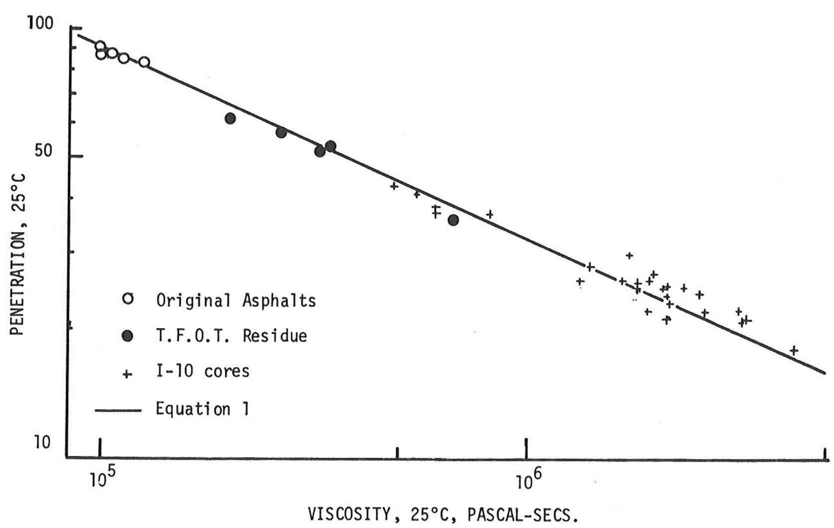


Figure 6. Energy-strain ratio relationship for certain asphalts at different temperatures.

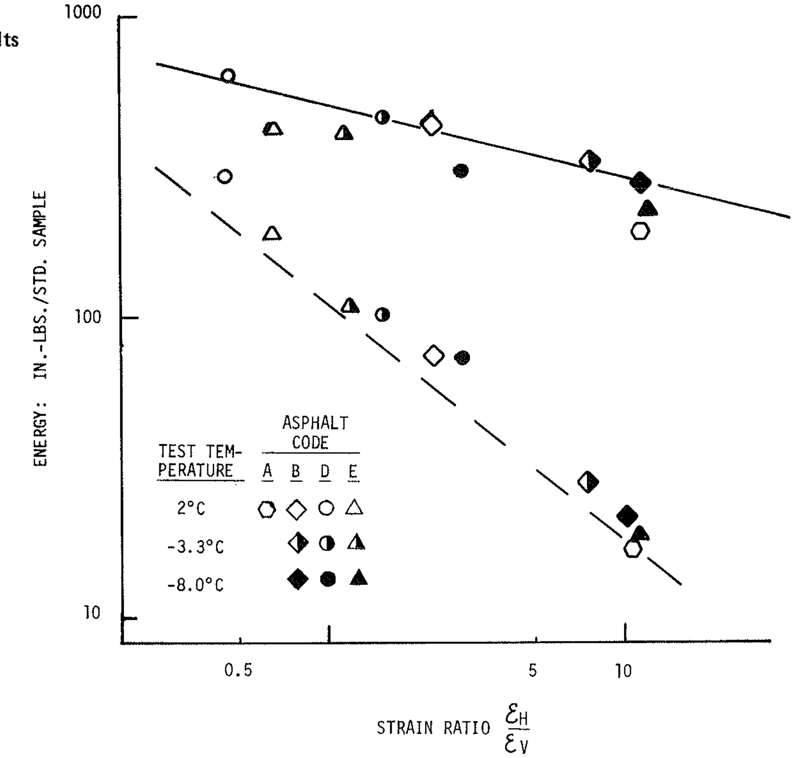
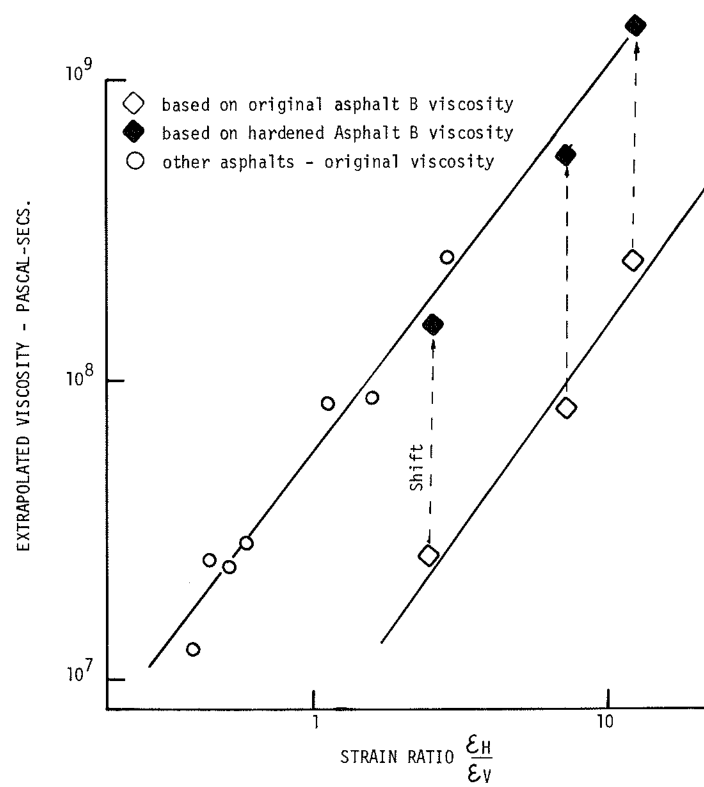


Figure 7. Deformation-energy-viscosity relations.



energy decreases and the strain ratio increases as the temperature is lowered. This effect was directly related to viscosity changes and brittle fracture as experienced with asphalt A mixtures, which occurred near or at the glass transition temperature.

The split cylinder test, in particular the strain ratio, evaluates the composite effects of selective absorption or surface tension and viscosity or glass transition temperature as influenced by asphalt hardening. The pressure exerted on asphalt films between aggregate particles by loads on a pavement conceivably could increase the glass transition temperature. The pressure sensitivity given in Table 3 implies that glass transition temperature would increase about 1 C for each pressure increase of 450 psi. The combined influence of pressure and the greater absorption of asphalt A, as given in Table 6, would justify the glassy, brittle fracture obtained in the split tension test at 5 C.

The relationship between asphalt viscosity and the strain ratio is illustrated in Figure 7. The viscosity data was based on extrapolation of the viscosity trend by using viscosity curves for the original asphalt that included 5 C data. Viscosity values for hardening that is caused by mixing or weatherometer processing were determined by shifting the original viscosity curve to the viscosity corresponding to the measured values at 25 C. Asphalts C, D, and E show the same general relationship for different test temperatures (viscosity). The curve depicting asphalt B was based on the original viscosity curve. However, if the hardening caused by mixing is taken into account by using the shifted viscosity curve, the data come close to superimposing over the viscosity-strain ratio curve for the other asphalts. This same technique appeared to be valid for asphalt A although it was difficult to evaluate because of the brittle nature and high viscosity of this asphalt at all test temperatures. A few test temperatures above 5 C would have improved the range in values and hopefully the accuracy of the relationship.

CONCLUSIONS

The ability of an asphalt concrete pavement to resist cracking depends on the strains induced by vehicular loading and the ability of the paving materials to accommodate cumulative tensile strains without fracture at low temperatures. Conventional specifications for bituminous materials cannot evaluate totally the adequacy of an asphalt as it interacts with different types of aggregates. The split cylinder test is relatively simple and provides a direct evaluation of the tensile properties for paving materials.

It is envisioned that tensile testing methods could be devised to either control the quality of asphalts as influenced by hardening and absorption by aggregates or use the test parameters in pavement design by testing the actual materials to be used in construction. Although additional research is needed, a pavement design approach may be developed that incorporates the ratio of pavement tensile strain to fracture tensile strain. In this approach the maximum pavement surface tensile strain is the sum of load-induced strain and thermal strains that occur at some critical temperature. This temperature depends on the pavement temperature gradient and the low temperature properties of the asphalt such as fracture strain and nonrelaxed thermal tensile strains.

These are the specific conclusions obtained from the research.

1. Strain energy of asphalt concrete subjected to tensile stress decreases as the temperature decreases or as the asphalt viscosity increases. Viscosity changes may be attributed to temperature, hardening, or absorption.
2. Asphalt viscosity appears to be an indirect measure of the strain ratio as obtained in the split cylinder test. At viscosities of 1,000 MP or more the material approaches a brittle condition or the glass transition temperature. At these higher viscosities a strain ratio in excess of 2.0 was obtained.
3. Asphalt content and density do not have any appreciable influence on the energy or strain ratio.

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