ASPHALT PROPERTIES IN RELATION TO PAVEMENT PERFORMANCE

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Six asphalt cements from different sources were used during 1964 in the construction of the pavements studied and reported in this paper. These asphalt cements ranged in viscosity at 140 F (60 C) from 966 to 2,649 poises (96.6 to 265 Pa·s) and in penetration from 62 to 149 units. Tests have been conducted to determine the properties of the original asphalts, as well as the asphalts recovered from time to time from the pavements in service. The performance of these test pavements was evaluated in 1974 by a team of eight evaluators. Changes in the asphalt properties have been observed to be a hyperbolic function of time. According to this study, viscosity or shear susceptibility of the aging asphalt alone does not, necessarily, indicate the pavement performance. The rate of gain in shear susceptibility relative to increase in viscosity at 77 F (25 C) seems to be one of the major factors affecting pavement performance. Asphalt ductility values, determined at 39.2 F (4 C) before and after pug mill mixing, seem to be consistent with the pavement performance observed so far. Higher ductility values are associated with better pavement performance.

•THE ability of a bituminous pavement structure to support traffic-induced stresses and strains as well as adverse effects of climatic conditions during its service life depends on the rheological properties of the pavement system. These properties in turn are related to the properties of the constituents of the bituminous mixture. Most durability studies in the past have been confined to analyzing the properties of aging asphaltic binder since it is this main constituent that contributes to the cohesiveness and adhesiveness of the mixture and thus affects pavement performance. In this study, effort has been directed toward evaluating and characterizing those physical properties that are associated with aging and their relationship to pavement performance.

DETAILS OF TEST PAVEMENTS

The six test pavements, totalling 3.67 miles (5.3 km) in length, are located in Clinton County on LR 219 (US-220) between Mill Hall and Beech Creek, Pennsylvania. The original pavement consisted of 18 to 20 ft (5.5 to 6.1 m) in width of 8-in. (203-mm) reinforced concrete, which was constructed in 1929 and 1934. This pavement was resurfaced with 2 in. (51 mm) of ID-2 binder and 1 in. (25 mm) of ID-2 wearing course during October 1964. This study is limited to an evaluation of six experimental sections of dense-graded ID-2 bituminous wearing course surfaces, each containing a different asphalt. An asphalt of 70 to 85 penetration grade was used in the binder course throughout the entire project. Average daily traffic on this road is 4,200 vehicles.

Properties of the six asphalts used in the project are given in Table 1. Excellent control was maintained throughout the project to ensure uniform construction of these six pavements. Limestone aggregate gradation and asphalt content (6.4 percent optimum) were held consistent. Details of design and construction of these pavements are given elsewhere (1). In this closely controlled research project, the only significant

Table 1. Asphalt test properties.

Property	Asphalt 1	2	3	4	5	6
Before Pug Mill Mixing						
Viscosity, poises						
At 140 F	1613	1544	1447	966	2200	2649
At 275 F[a]	339.6	343.0	475.4	318.5	509.4	556.7
At 39.2 F at 0.05 sec^{-1}	1.19×10^9	2.65×10^8	4.22×10^7	9.50×10^7	1.68×10^8	2.57×10^8
At 77 F at 0.05 sec^{-1}	3.05×10^6	1.06×10^6	4.83×10^5	9.15×10^5	1.32×10^6	1.85×10^6
At 115 F at 0.05 sec^{-1}	2.09×10^4	1.54×10^4	1.15×10^4	1.15×10^6	2.19×10^4	2.80×10^4
Shear susceptibility						
At 39.2 F	0.20	0.20	0.35	0.45	0.32	0.32
At 77 F	0.05	0.02	0.11	0.06	0.12	0.09
At 115 F	0.02	0.03	0.04	0.03	0.04	0.02
Penetration						
At 39.2 F, 200 g, 5 sec	9	11	28	19	15	12
At 77 F, 100 g, 5 sec	62	92	149	114	94	80
After Pug Mill Mixing						
Penetration at 77 F, 100 g, 5 sec	36	69	98	66	69	60
Penetration, percentage retained	58	76	67	58	73	76
Viscosity at 140 F, poises	3645	2505	2971	2078	3463	4770
Viscosity ratio at 140 F	2.27	1.62	2.06	2.16	1.57	1.80
Aging index[b] after mixing based on viscosity at 77 F, 0.05 sec^{-1} shear rate	3.3	1.9	2.5	3.3	2.1	1.9
Viscosity at 77 F, 0.05 sec^{-1} determined from aging indexes, poises	1.01×10^7	2.01×10^6	1.21×10^6	3.02×10^6	2.77×10^6	3.52×10^6

Note: 1 poise = 0.1 Pa·s; 1 F = 1.8 C + 32.

[a]In centistokes.

[b]No test data available. These were determined from Fig. 4 of the paper by Halstead and Zenewitz (ASTM, STP. 309, 1962), which gives relation between percent of original penetration and viscosity aging index for thin film test.

Table 2. Pavement condition after 113 months.

Item Observed	Asphalt 1	2	3	4	5	6
Riding quality	Good	Good	Good	Good	Good	Good
Raveling (loss of aggregate larger than ¼ in.)	Moderate	Slight	Slight	Slight to moderate	Slight	Slight to moderate
Spalling	Slight	None	None	None to slight	None to slight	None to slight
Loss of matrix (loss of fines)	Moderate	Slight	Slight	Slight	Slight	Slight
Rutting (in.)	0.20	0.18	0.20	0.19	0.21	0.21
Transverse cracking	Slight	None to slight	None	None to slight	None to slight	None to slight
Longitudinal cracking	Slight to moderate	None	None	None	None	None
Alligator cracking	None	None	None	None	None	None
Surface texture	Average	Closed	Closed	Closed	Closed	Closed to average

Note: 1 in. = 25 mm.

variable is the asphalt type.

Since construction of these six pavements, core samples have been obtained periodically to determine the percentage of air voids in the pavements and rheological properties of the aged asphalts. The last core sampling was done in March 1974, 113 months after construction.

PERFORMANCE OF TEST PAVEMENTS

No differences in texture or color tones of the asphalts were observed when the pavements were visually inspected just after construction and after 1 year of service. Visual evaluation during April 1967 (after 30 months of service) indicated that the road surface was good except for the asphalt 1 section, which showed some raveling.

A rating method suggested by Olsen, Welborn, and Vallerga (2) to evaluate the effect of asphalt aging on pavement condition was used as a guideline in the visual survey of pavement condition. Visual evaluation included riding quality, raveling, spalling, loss of matrix, rutting, cracking (transverse, longitudinal, and alligator), and surface texture. A team of five engineers evaluated these sections during 1971 after 80 months of service (1, 3). For comparison, it should be pointed out that the designations of asphalts 2 and 3, as reported in earlier references, have been interchanged in this report. A performance evaluation was made most recently in 1974 (after 113 months of service) by eight evaluators. Because the differences between some asphalts were relatively small, the rating form was revised to include intermediate levels of observed distress such as none to slight and slight to moderate. The overall ratings obtained on individual pavements were as follows:

Asphalt	Rating
1	51.1
6	59.8
4	60.1
2	60.4
5	61.2
3	61.5

An ideal pavement according to this performance evaluation would rate 72. Brief details of the pavement condition after 113 months in service are given in Table 2. Reflection cracks due to the underlying portland cement concrete pavement were not considered in the evaluation.

ANALYSIS OF RESEARCH DATA

Data on percentage of air voids in the test pavements and rheological properties of the recovered asphalts have been gathered since construction. Changes in the percentage of air voids, viscosity at 77 and 140 F (25 and 60 C), and shear susceptibility at 77 F (25 C) were found to follow the hyperbolic model suggested by Brown, Sparks, and Larsen (4) and confirmed by Lee (5). According to this theory, the changes in these physical properties are a hyperbolic function of time and approach a definite limit with time. Brown and coworkers suggested the following equations to express the hardening of asphalts in the field:

$$\Delta Y = \frac{T}{a + bT} \quad (1)$$

Figure 1. T versus T/ΔY plots for changing asphalt properties.

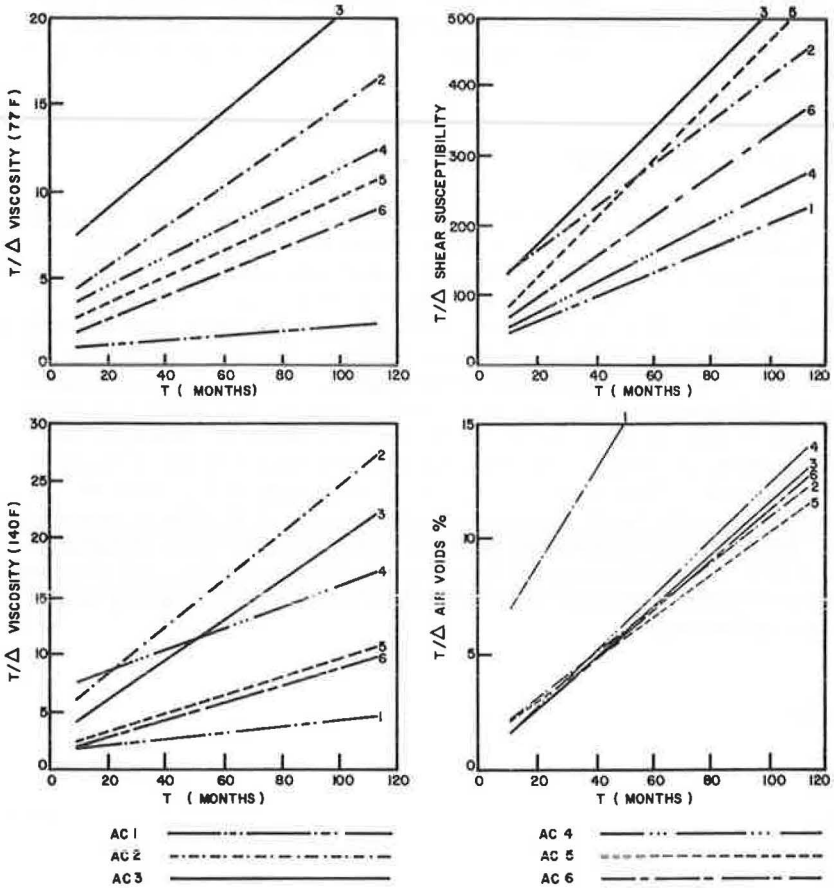


Table 3. Linear regression data (T versus T/ΔY).

Test Property Y	Asphalt 1	2	3	4	5	6
Viscosity at 77 F						
r	0.970	0.950	0.834	0.987	0.968	0.950
a	0.495	3.233	5.965	2.740	1.717	0.961
b	0.017	0.116	0.141	0.086	0.061	0.071
Viscosity at 140 F						
r	0.975	0.941	0.974	0.935	0.982	0.961
a	1.531	4.144	2.756	3.447	1.399	1.834
b	0.029	0.207	0.122	0.118	0.081	0.071
Shear susceptibility						
r	0.991	0.929	0.998	0.998	0.993	0.999
a	27.523	104.914	86.351	34.407	45.151	42.243
b	1.740	2.993	4.225	2.197	4.171	2.890
Percentage of air voids						
r	0.982	0.998	0.999	0.999	0.999	0.999
a	5.155	1.178	0.328	0.389	1.080	0.599
b	0.207	0.099	0.117	0.123	0.095	0.111

Note: 1 F = 1.8 C + 32.

or

$$\frac{T}{\Delta Y} = a + bT \qquad (2)$$

where

ΔY = change in test property (such as viscosity, penetration, shear susceptibility) with time T or the difference between the zero-life value and the value for any subsequent year,
T = time,
a = intercept of the equation 2 line on the ordinate,
b = slope of the equation 2 line, and
1/b = ultimate change (limiting value of change) of the property at infinite time.

The terms a and b are constants: a is primarily a measure of the rate of change or degree of curving of the hyperbola, and b is the measure of the ultimate magnitude of the variable at infinite time. $T/\Delta Y$ is the reciprocal of the overall average rate of change of the inspection value over the life period T. In this form, equation 2 is recognized as linear in $T/\Delta Y$ versus T.

Experimental data on viscosity, shear susceptibility, and percentage of air voids were fitted to equation 2 by the least squares linear regression method (Figure 1). Almost without exception, the fit, as indicated by correlation coefficient r, was excellent. The values of a, b, and r are given in Table 3. Change in percentage of air voids has been regarded as positive for plotting, even though percentage of air voids decreases with age of the pavement.

Inasmuch as equations 1 and 2 have only two constants, the mathematical solution depends on determination of Y at zero life and at any two known later T-values. Hence, inspection test values both at time zero, or immediately after compacting, and after the first and second years of aging suffice to determine the course of the whole hyperbolic relationship between inspection test values and time, including the limiting value to be approached after extreme aging. Thus, instead of analyzing a few samplings each year for a prolonged period, sampling during the early life of the pavement should be increased. By doing so, the early life values will be statistically more valid, and, from these, the changes to be experienced over later years can possibly be calculated without waiting out the time (4).

However, it has been observed that core samples must be obtained from the test pavements during the same time of the year. Most core samples in this study were obtained during the spring. The data from core samples obtained during fall in a few instances did not fit equation 1 or 2. No explanation can be given for this. It has also been observed by Gotolski and Roberts (6) on several experimental projects.

Figure 2 shows the percentage of air voids in the test pavements versus time. The curves in this and later figures showing change of properties with time were plotted based on data from the straight-line relationship ($T/\Delta Y$ versus T) shown in Figure 1. The following equation was used in conjunction with equation 1 or 2:

$$Y_T = Y_0 + \Delta Y$$

where

Y_T = value of property after time T,
Y_0 = value of property at zero time, and
ΔY = change in test property in time T determined from equation 1 or 2 by using constants a and b.

Figure 2. Air voids versus time in months.

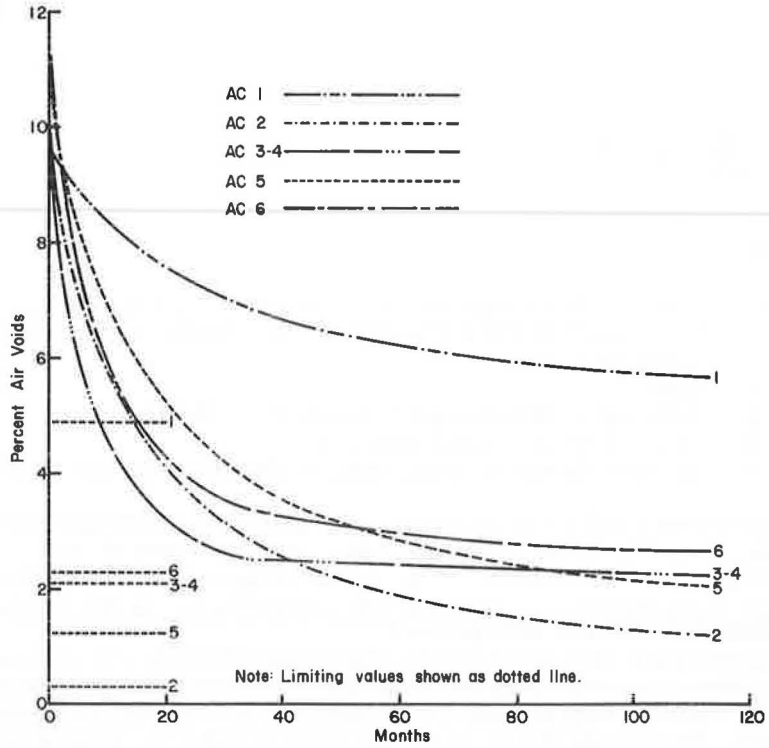
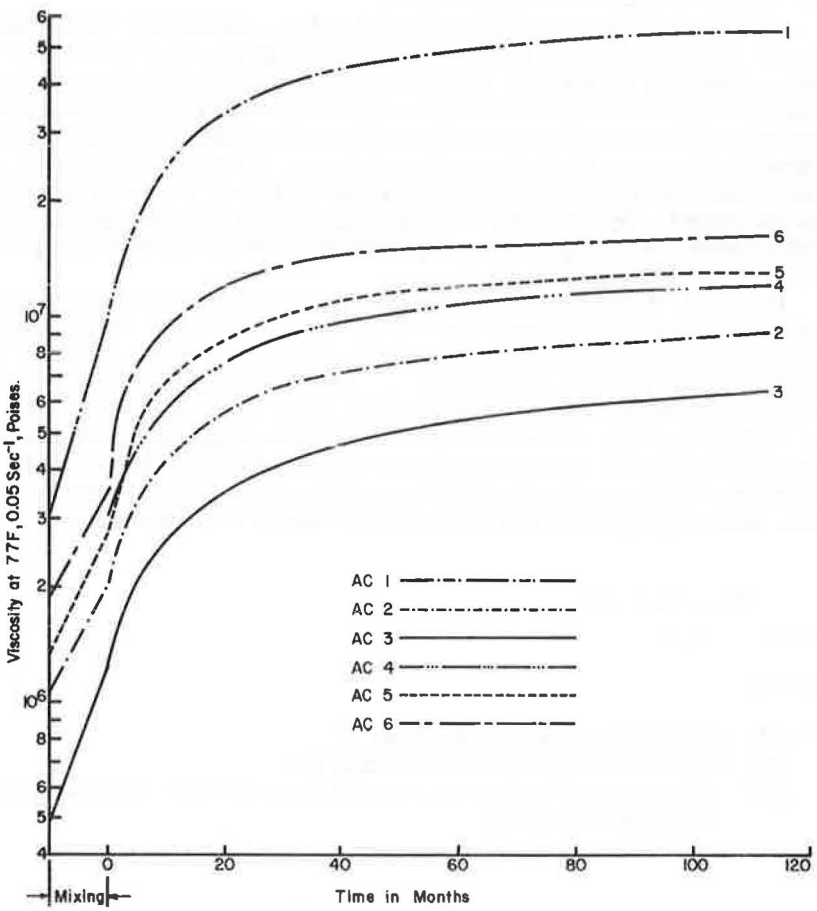


Figure 3. Viscosity at 77 F, 0.05 sec^{-1} versus time.



RHEOLOGICAL PROPERTIES OF ASPHALTS

Viscosity at 77 F (25 C)

Viscosity at 77 F (25 C) was determined for shear rates of 0.05 and 0.001 sec^{-1} by using the sliding plate microviscometer designed by Shell Oil Company. Both glass and stainless steel plates were used. A plot of viscosity at 77 F (shear rate of 0.05 sec^{-1}) versus time is shown in Figure 3.

Viscosity at 140 F (60 C)

Viscosity at 140 F (60 C) was determined by using the Cannon-Manning Vacuum Viscometer. A plot of viscosity at 140 F versus time is given in Figure 4.

Shear Susceptibility at 77 F (25 C)

The shear susceptibility (or shear index) value as used in this study is the tangent of the angle of log shear rate versus log viscosity determined with the microviscometer. Shear susceptibility values were determined for the six asphalts after increasing periods of aging. Results are shown graphically in Figure 5. The relationship between shear susceptibility and viscosity at 77 F is shown in Figure 6.

Aging Index

Considering the changes in viscosity at 77 F (0.05 sec^{-1} shear rate), aging indexes were determined from the following:

$$\text{Aging index} = \frac{\text{viscosity after aging}}{\text{viscosity before aging}}$$

Use of the aging index tends to eliminate the variability caused by differences in the viscosities of the original asphalts and gives a clearer picture of the hardening rate.

Figure 7 shows the relationship between shear susceptibility and aging index of the aged asphalts.

DISCUSSION OF RESULTS

Pavement Performance in Relation to Its Physical Properties

Initial air voids in the six pavements, when constructed, were within the permissible range in terms of Marshall design and control criteria. According to these criteria, the pavements are expected to compact under traffic during the first 1 to 2 years to less than 5 percent air voids. For these six test pavements, the type and gradation of aggregate, asphalt content, asphalt-filler ratio, traffic, and climate were identical. However, the asphalt 1 pavement offered maximum resistance to compaction under traffic. After 9½ years in service it still has more than 5 percent air voids (Figure 2). Asphalt 6 is second to asphalt 1 in offering resistance to densification by traffic. However, pavements using asphalts 2 through 6 were compacted under traffic below 5 percent air voids during the first 2 years.

Examination of the viscosities of the asphalts (after mixing in the pug mill) at 77 and 140 F (25 and 60 C) shows that the viscosity at 77 F affects, to a larger extent, the

Figure 4. Viscosity at 140 F versus time.

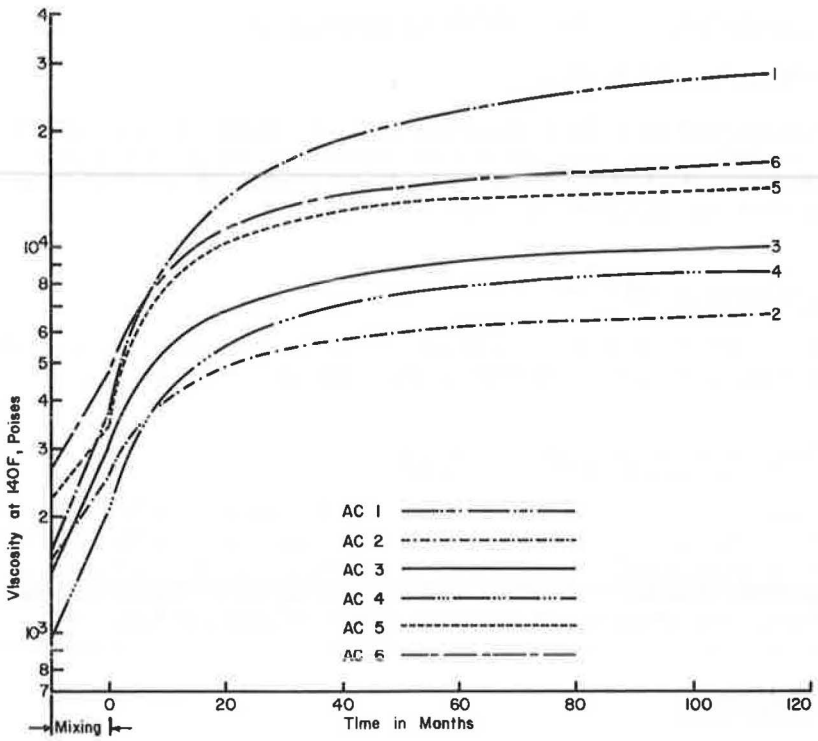


Figure 5. Shear susceptibility at 77 F versus time.

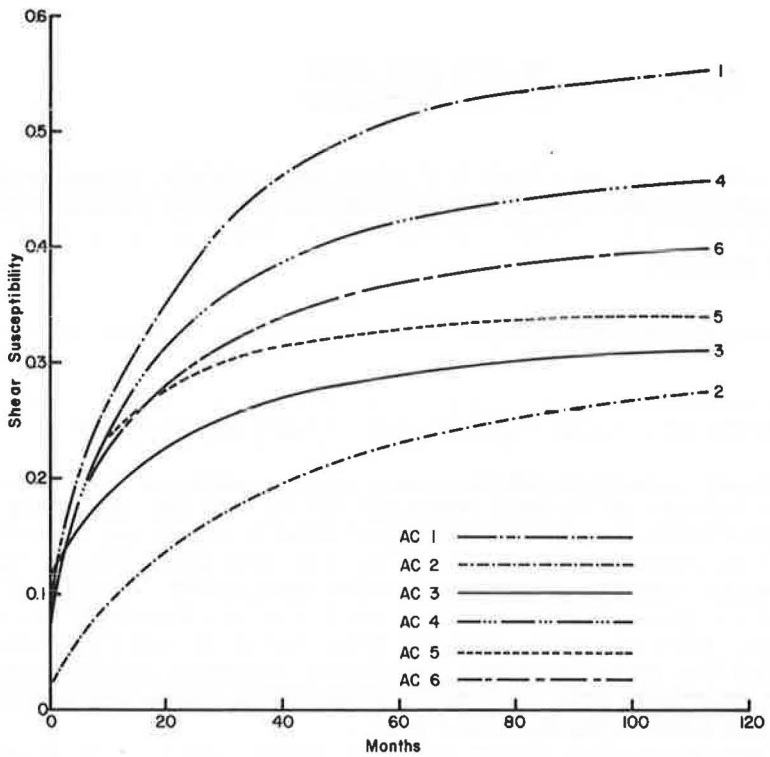


Figure 6. Shear susceptibility versus viscosity at 77 F.

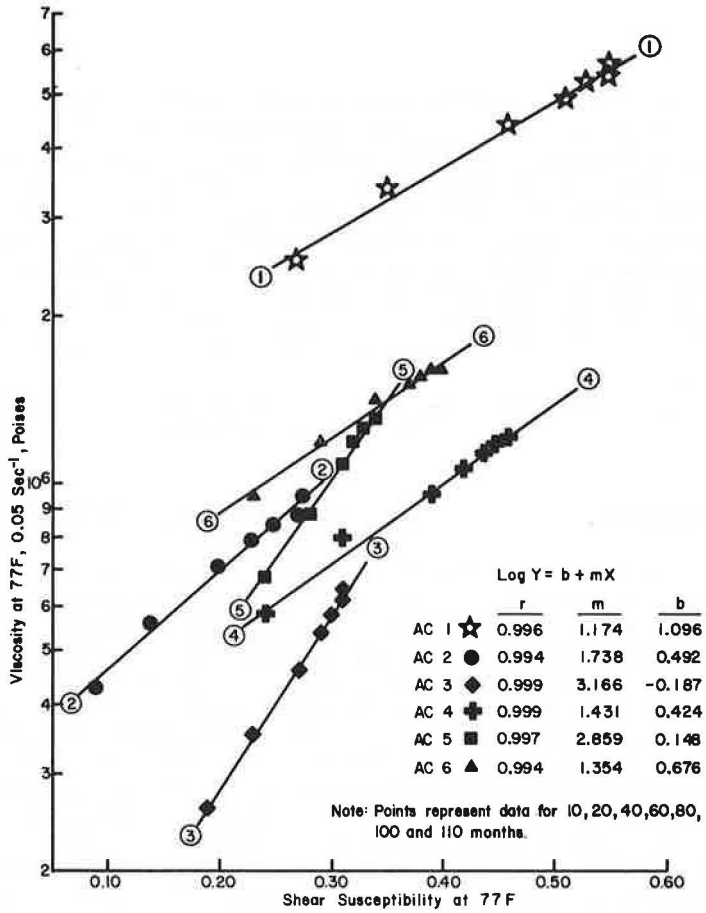
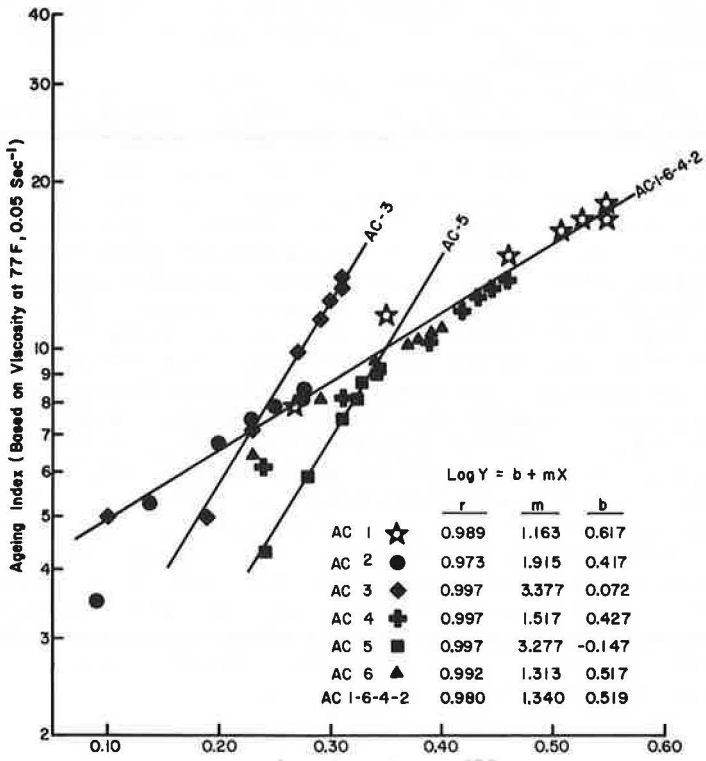


Figure 7. Shear susceptibility versus aging index (77 F).



ability of the pavements to compact under traffic. Asphalt 1, with the highest viscosity of 10.1 megapoises (1.01 MPa·s) after mixing, offered the most resistance to such compaction, followed by asphalt 6, which is second highest in viscosity and in resistance to compaction. Viscosity at 140 F does not indicate this trend.

Comparison of pavement evaluation ratings with the percentage of air voids after 113 months indicates the general trend established by many researchers that durability of the asphalts is affected by the air voids in the pavement. However, as has been pointed out (7), the air voids should be considered a secondary control factor since they are affected by other primary parameters, one of which is asphalt consistency after pug mill mixing. If the viscosity is too high, the design percentage of air voids may not be met.

Pavements containing asphalts 2 through 6 had air voids within a narrow range of 3.0 to 4.7 percent (Figure 2) after 2 years in service.

Pavement Performance in Relation to Rheological Properties

Viscosities at 77 and 140 F (25 and 60 C) and shear susceptibility at 77 F of the aging asphalts in the test pavements versus age of the pavements are plotted in Figures 3, 4, and 5 to examine their relation to pavement performance. The ranking order of these values relative to pavement performance after 9½ years of service is given in Table 4.

It can be seen that the viscosity or shear susceptibility of the aged asphalt alone does not affect pavement performance. In earlier studies (3), the aging index-shear susceptibility relationship seemed to determine the pavement durability and performance. Shear susceptibility versus viscosity at 77 F and shear susceptibility versus aging index were plotted to examine this relationship (Figures 6 and 7). On semi-log plot, the data representing 10, 20, 40, 60, 80, 100, and 110 months of pavement life have a straight linear relationship for individual test pavements. In Figure 6 the slope m of these straight lines indicates the rate of change of shear susceptibility relative to change in viscosity or vice versa. Higher values of slope m would mean relatively lower gain in shear susceptibility with the corresponding increase in viscosity and are associated with better pavement performance. The displacement of the lines, one from another, is due to the differences in asphalt viscosity after construction. The ranking of slope m for the six test pavements (Figure 6) is consistent with the pavement performance (Table 5).

To eliminate the relative displacement of straight lines as seen in Figure 6, semi-log plots were made of shear susceptibility versus aging index (Figure 7). Two general groups of asphalts are clearly evident. Asphalts 1, 6, 4, and 2 (group 1) have essentially the same shear susceptibility-aging index relationship. Asphalts 3 and 5 (group 2) tend to gain shear susceptibility at a lower rate than group 1 on aging. At the present time, differences in the pavement conditions of asphalts 6, 4, and 2 are relatively small. The performance rating numbers, which are averages of observations made by eight evaluators, also indicate negligible differences.

Asphalt 1 exhibits raveling and loss of fines more than the other test pavements. Raveling was first observed in this test pavement after 30 months when the aging index and shear susceptibility values exceeded 12 and 0.40 respectively. At the present time this test pavement can be considered to have failed and needs resurfacing. The failure was probably caused by extremely high viscosity [more than 50 megapoises (5.0 MPa·s) at 77 F (25 C) and 25 kilopoises (2.5 kPa·s) at 140 F (60 C)] in spite of the fact that the aging index-shear susceptibility relationship of asphalt 1 is similar to that of asphalts 6, 4, and 2. It is not possible simply to set an upper limit of viscosity beyond which failure under traffic will occur because the deflection of the road determines the magnitude of tensile stress developed, which in turn leads to failure (8). Because these test pavements were built on an existing concrete road, they might show some distress but no real failures in spite of the high viscosities of asphalt because of the low pavement deflections involved. It is hoped that the remaining five asphalt pavements will weather in different ways and present different forms of pavement failure, resulting in larger differences in the future.

Table 4. Relationship of viscosity and shear susceptibility to pavement performance.

Performance Rating	Viscosity at 77 F, 0.05 sec^{-1}	Viscosity at 140 F	Shear Susceptibility
1 (poorest)	1 (highest)	1 (highest)	1 (highest)
6	6	6	4
4	5	5	6
2	4	3	5
5	2	4	3
3 (best)	3 (lowest)	2 (lowest)	2 (lowest)

Note: 1 F = 1.8 C + 32.

Table 5. Relationship of slope m (from Figure 6) to pavement performance.

Test Pavement	Performance Rating (113 months)	Slope m
1 (poorest)	51.1	1.174
6	59.8	1.354
4	60.1	1.431
2	60.4	1.738
5	61.2	2.859
3 (best)	61.5	3.166

Table 6. Ductility data.

Asphalt	Pavement Performance Rating	Ductility (cm)		
		39.2 F, 1 cm/min		60 F, 5 cm/min
		Original	After Mixing	After 113 Months[a]
1 (poorest)	51.1	14	4.1	0
6	59.8	21.9	7.3	8
4	60.1	23.5	7.5	7
2	60.4	53.3	11.9	19
5	61.2	68.3	24.3	19
3 (best)	61.5	101.0	42.2	49

Note: 1 F = 1.8 C + 32.

[a]Based on one test only.

Ductility

The significance of ductility requirements in the paving asphalt specifications has been the subject of debate. Some asphalt technologists believe that ductility, under the present standard method, is of little value as an indicator of asphalt quality. Others believe that the ductile properties of asphalt give an asphalt pavement its quality of flexibility. Regardless of the merits of the various arguments, a number of studies (9, 10) have related ductility to pavement performance. Although the ductility of asphalts recovered from these test pavements has not been measured periodically, some initial data are available and might be of some interest to the researchers. The ductility at 60 F (15.5 C), 5 cm/min, of these asphalts, recovered from most recent core samples, has been determined. These data together with performance ratings are given in Table 6.

Surprisingly, in spite of the empirical nature of the test, ductility test values of the asphalts at 39.2 F (4 C), before and after pug mill mixing, are consistent with the pavement performance ratings. Higher ductility values are associated with better pavement performance. Asphalt 1 with the lowest ductility shows the poorest performance. It is most likely, as pointed out by Halstead (10), that the ability of the asphalt to undergo elongation is not the primary characteristic affecting durability; rather, the ductility test result is an indication of an internal phase relationship of the asphaltic constituents, which in turn have an important bearing on the serviceability factors of the asphalt. It is also possible that the ductility test result obtained at 39.2 or 60 F (4 or 15.5 C) reflects indirectly the viscosity-shear susceptibility relationship at these temperatures. When additional ductility data are available in future, they will be analyzed further.

Because these test pavements were constructed on existing cement concrete surface, transverse reflection cracks are visible on all the test sections. However, it is interesting to note that the asphalts with higher ductility values, such as asphalts 5 and 3, tend to have narrower reflection cracks. Reflection cracks in low-ductility asphalts have developed secondary cracks, resulting in spalling at places.

CONCLUSIONS

Based on the rheological properties of the six asphalts studied and the preceding discussion, the following conclusions are drawn.

1. Changes in percentage of air voids and asphalt properties such as viscosity and shear susceptibility are a hyperbolic function of time and approach a definite limit with time. If the changing asphalt properties are determined during the early life of the pavement (2 or 3 years), the changes to be experienced over later years can possibly be calculated.
2. Pavement performance is affected significantly by the extent of air voids in a pavement. The rate of hardening of asphalts is checked considerably if the pavements can compact under traffic during the first 1½ to 2 years, to air voids of less than 5 percent.
3. After optimum compaction during construction, the apparent viscosity at 77 F (25 C) after pug mill mixing seems to control the ability of the pavements to compact further under traffic at ambient temperatures, all other factors affecting compaction being the same. Air voids should, therefore, be considered a secondary control factor since they are affected by other primary parameters including the apparent viscosity at 77 F after mixing.
4. Viscosity or shear susceptibility of the aging asphalt alone does not, necessarily, indicate the pavement performance. The rate of gain in shear susceptibility relative to increases in viscosity at 77 F seems to be one of the major factors affecting pavement performance. Relatively lower gain in shear susceptibility with the corresponding increase in viscosity is associated with better pavement performance in this study.
5. Asphalt ductility values determined at 39.2 F (4 C) before and after pug mill mixing seem to be consistent with the pavement performance observed so far. Higher ductility values after pug mill mixing indicate better pavement performance.

The significance of some of the rheological properties of asphalts indicated by the fundamental viscosity measurements will perhaps be more clear with the continual evaluation of the remaining five test pavements until failure. It is believed that the asphalts weather in different ways and may present different forms of pavement failure.

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