ASPHALT CEMENT VISCOSITIES AT AMBIENT TEMPERATURES BY A RAPID METHOD

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This paper describes a method for determining the apparent viscosity and shear susceptibility of asphalt cements at 25 C and other ambient temperatures. Although it is based on another study, the present work utilizes a modified barrel and sample holder to permit improved productivity in running tests. A modified plunger is used that eliminates certain interferences. Apparent viscosity is evaluated at a selected shear rate, and shear susceptibility is measured by the complex flow index that is the exponent in the power law equation for non-Newtonian fluids. It is believed that the proposed method is adaptable for a routine testing procedure by using carefully standardized capillaries and more sensitive load cells with sophisticated temperature control. When such a test is developed by cooperative effort, it is believed it would replace the penetrometer and other empirical flow tests to provide rheological information of practical value for explaining service behavior. In fact, such information should be useful in design for applications where the rheology of the asphalt component is a critical factor.

•THERE is a demand for a simple, rapid test to measure the consistency in absolute units of asphalt cements in the ambient temperature range of 10 to 60 C. Methods have been proposed in ASTM standards (1) for this purpose, but they are complicated and generally not suitable except for research studies. The method discussed in this paper will be proposed as an alternative method for consideration by a task force of ASTM Committee D04.40. The extrusion method proposed is based on an earlier study in a companion paper by Schweyer and Busot (2), which discussed in detail certain theoretical and empirical aspects of the method.

The test is applied to asphalts sufficiently fluid that they can be extruded through an appropriate capillary without exceeding the safe loads of the apparatus. Accordingly, the limits of viscosity for the test will depend not only on the viscosity of the asphalt but also on the specific geometry (diameter and length of the capillary) that is employed for the determination. The test procedure is for use at 25 C but would also apply for other temperatures where the viscosity of the asphalt or the combination of diameter and length of the capillaries employed were such that satisfactory results would be obtained. Under these conditions, the preparation step on the samples for 25 C would necessarily have to be altered for whatever temperature was being used.

The object of the evaluations is to determine the apparent viscosity of the asphalt in terms of the ratio of the shearing force divided by the corrected rate of shear at a standard condition for rate of shear. In addition, the shear susceptibility is evaluated as the constant in the power law equation.

STUDY PROCEDURE

The procedure is similar to a previous one (2) except that the component equipment design has been changed to provide greatly increased productivity and simplicity. In

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the earlier methods, a very expensive and cumbersome barrel (into which the sample is poured) was used; it has been replaced by a simple sample tube. These inexpensive sample tubes, which carry a capillary and can be filled in multiples and then brought to temperature, are inserted into a simple barrel holder for each run. They are then removed quickly and replaced by a new sample tube and capillary containing the next sample that had previously been brought to temperature and that is ready to run.

Figure 1 shows the rheometer assembly, and Figure 2 shows the rheometer components.

STUDY RESULTS

The results of the modified sample tube method as compared with the long barrel method (2) are given in Table 1 for 25 C and in Table 2 for 15.5 C.

In general, the data for 25 C for a rheometer barrel and sample tube are in good agreement (Table 1). In Table 2, the data for 15.5 C show anomalies because the sample tube data are in good agreement, but the data for the barrel and tube do not agree. Based on recent experimental work, the explanation for the difference is in the flow of asphalt in a very thin layer in front of the 0-ring between the tube wall and the plunger. The high drag in this region apparently is accentuated for the low temperature data. The plunger has been redesigned to minimize this interference.

Comparison of Methods

A comparison of certain data obtained by using the capillary rheometer, the cone and plate (1, 3), and the sliding plate procedures (1, 4) is given in Table 3. These procedures compute the viscosity at 0.05 reciprocal sec without the power law correction for rate of shear (2). These data were developed through a joint effort with R. N. Traxler of the Texas Transportation Institute and V. T. Puzinauskas of The Asphalt Institute in connection with studies of a task force of committee ASTM D4.44 on rheological tests. The agreement over a range of data is shown in Figure 3. The solid line indicates exact agreement. The Florida method data are corrected for geometry and the Rabinowitsch correction (2). The complex flow indexes given in Table 3 were computed by the author from graphs supplied by the other investigators. For the cone and plate method, the plot of log viscosity versus log shear rate was used. A straight line was drawn from the viscosity at 0.05-sec^{-1} shear rate through the points at higher shear rates to provide an estimate of complex flow. For the sliding plate method, the reciprocal slope of log shear rate versus log shear stress was evaluated. For this method, the data are close together, and it is possible to make errors in estimating the true slope.

Shear Susceptibility

The effect of shear susceptibility on the apparent viscosity is shown in Figure 4. The complex flow index indicates that asphalt D is definitely more shear susceptible than asphalt B. At $\dot{\gamma} = 0.1\ sec^{-1}$, both asphalts have about the same consistency; at $\dot{\gamma} = 1.0\ sec^{-1}$, the D sample has only 50 percent of the viscosity of sample B. These effects are accentuated for the harder asphalts that have a low value of the complex flow index. Samples M and F are similar at 0.05 sec^{-1}, but at 1.0 sec^{-1} the M sample has only about 20 percent of the viscous resistance as the F sample. This could be of significance in service applications under stress. The data in Figure 4 at other than 0.05 and 1.0 sec^{-1} are for values at a constant power input. As shown by the data and the plot, comparative data at a constant power input occur at different rates of shear depending on the consistency of the asphalt cement and the degree of complex flow that results from the nature of the basic rheological relation. Data for Figure 4 are given in Table 4.

Because shear susceptibility is an important property in distinguishing among asphalt cements, it should be considered in more than a cursory manner. Because it affects the deformation profile under stress, shear susceptibility must be considered in the theoretical analysis of viscosity data. Current ASTM procedures do not consider these implications, but they do arbitrarily state that comparisons should be made at some

Figure 1. Rheometer assembly.

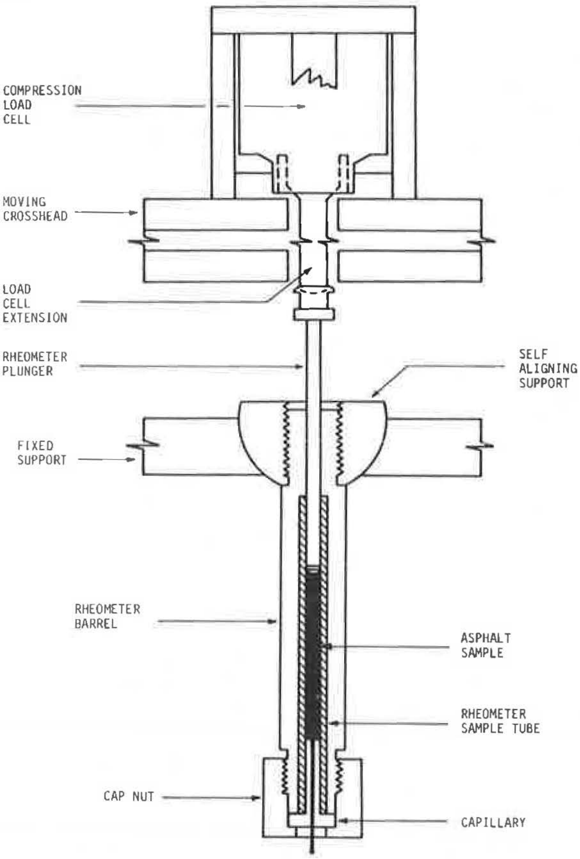

Figure 2. Rheometer components.

Table 1. Comparative data using Florida method for determination of apparent viscosity at 25 C and 180-deg entry for asphalt cements.

Asphalt	Pene-tration at 25 C	Equipment	Capillary (in.)	Sample Size (in.)	Tube Size (in.)	Apparent Viscosity (MP)	Complex Flow Index C
Smackover, S63-4	89	Barrel extrusion and conical plunger	$\frac{1}{16}$ by $1\frac{1}{4}$	$4\frac{1}{2}$	-	1.64	0.82
						1.48[a]	0.84[a]
			$\frac{3}{16}$ by 3	3	-	1.91	0.86
		Tube extrusion and conical plunger	$\frac{1}{16}$ by $1\frac{1}{4}$	$4\frac{1}{2}$	6	1.75	0.79
		Tube extrusion and blunt plunger	$\frac{1}{16}$ by $1\frac{1}{4}$	$4\frac{1}{2}$	6	1.22	0.82
			$\frac{1}{8}$ by $1\frac{1}{4}$	$4\frac{1}{2}$	6	1.78	0.80
Air-blown, S63-13	89	Barrel extrusion and conical plunger	$\frac{1}{16}$ by $1\frac{1}{4}$	$4\frac{1}{2}$	-	0.60	0.64
						0.62[a]	0.64[a]
			$\frac{3}{16}$ by 3	3	-	0.66[a]	0.78[a]
		Tube extrusion and conical plunger	$\frac{1}{16}$ by $1\frac{1}{4}$	$4\frac{1}{2}$	6	0.73	0.64
		Tube extrusion and blunt plunger	$\frac{1}{16}$ by $1\frac{1}{4}$	$4\frac{1}{2}$	6	0.84	0.64
			$\frac{1}{8}$ by $1\frac{1}{4}$	$4\frac{1}{2}$	6	0.98	0.65
Panuco, S63-19	90	Barrel extrusion and conical plunger	$\frac{1}{16}$ by $1\frac{1}{4}$	$4\frac{1}{2}$	-	1.33	0.89
						0.98[a]	0.85[a]
			$\frac{3}{16}$ by 3	3	-	1.69[a]	0.82[a]
		Tube extrusion and conical plunger	$\frac{1}{16}$ by $1\frac{1}{4}$	$4\frac{1}{2}$	6	1.28	0.84
		Tube extrusion and blunt plunger	$\frac{1}{16}$ by $1\frac{1}{4}$	$4\frac{1}{2}$	6	0.93	0.80
			$\frac{1}{8}$ by $1\frac{1}{4}$	$4\frac{1}{2}$	6	1.54	0.81
Los Angeles Basin, S63-20	89	Barrel extrusion and conical plunger	$\frac{1}{16}$ by $1\frac{1}{4}$	$4\frac{1}{2}$	-	1.20	0.98
						1.34[a]	1.02[a]
			$\frac{3}{16}$ by 3	3	-	1.52[a]	1.05[a]
		Tube extrusion and conical plunger	$\frac{1}{16}$ by $1\frac{1}{4}$	$4\frac{1}{2}$	6	1.31	0.96
		Tube extrusion and blunt plunger	$\frac{1}{16}$ by $1\frac{1}{4}$	$4\frac{1}{2}$	6	1.31	1.11
			$\frac{1}{8}$ by $1\frac{1}{4}$	$4\frac{1}{2}$	6	1.40	0.92
Kern River, S63-21	89	Barrel extrusion and conical plunger	$\frac{1}{16}$ by $1\frac{1}{4}$	$4\frac{1}{2}$	-	-	-
			$\frac{3}{16}$ by 3	3	-	-	-
		Tube extrusion and conical plunger	$\frac{1}{16}$ by $1\frac{1}{4}$	$4\frac{1}{2}$	6	-	-
		Tube extrusion and blunt plunger	$\frac{1}{16}$ by $1\frac{1}{4}$	$4\frac{1}{2}$	6	1.17	1.17
			$\frac{1}{8}$ by $1\frac{1}{4}$	$4\frac{1}{2}$	6	1.33	0.99

[a]Taken from Schweyer and Busot (2); 3-in. samples, 90-deg entry.

Figure 3. Comparative results below 4.0 MP for asphalt cements at 0.05 reciprocal sec.

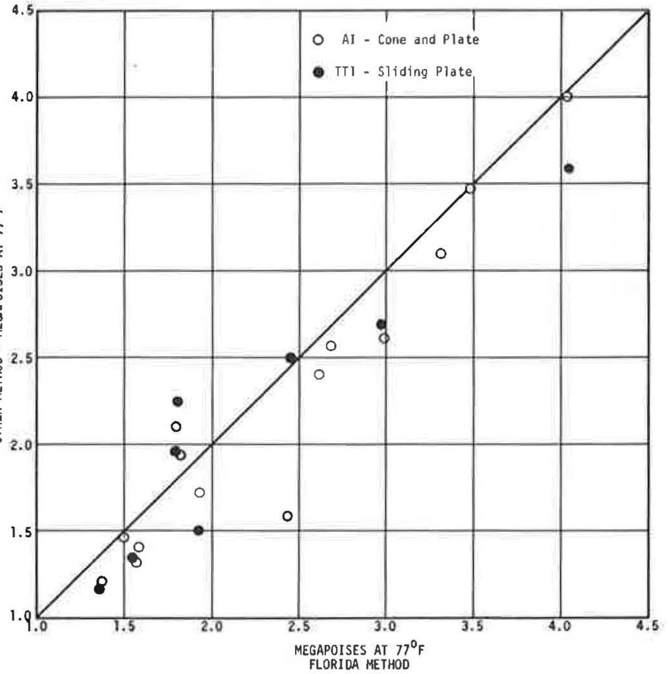

Figure 4. Shear susceptibility of various asphalts.

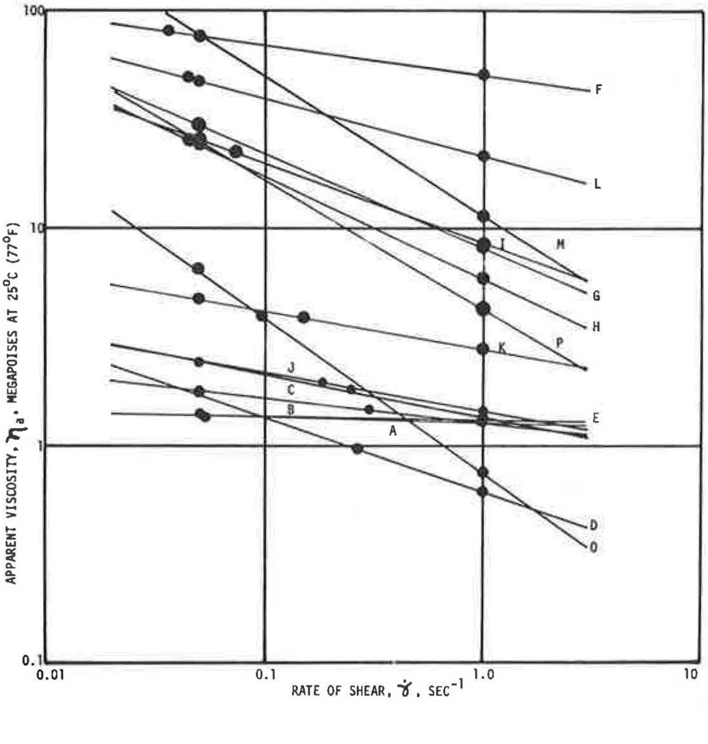

Table 2. Comparative data using Florida method for determination of apparent viscosity at 15.5 C and 180-deg entry for asphalt cements.

Asphalt	Penetration at 15.5 C	Equipment	Capillary (in.)	Sample Size (in.)	Tube Size (in.)	Apparent Viscosity (MP)	Complex Flow Index C
Smackover, S63-4	89	Barrel extrusion and conical plunger	1/16 by 1 1/4	3	-	22.3	0.78
			3/16 by 3	3	6	9.1	0.79
		Tube extrusion and conical plunger	1/8 by 1 1/4	4 1/2	6	10.5	0.84
			1/16 by 1 1/4	3	4	7.7	0.76
		Tube extrusion and blunt plunger	1/16 by 1 1/4	4 1/2	6	8.21	0.80
			3/16 by 3	4 1/2	6	8.12	0.81
			1/8 by 1 1/4	4 1/2	6	9.03	0.74
Air-blown, S63-13	89	Barrel extrusion and conical plunger	1/16 by 1 1/4	3	-	4.4[a]	0.72[a]
			3/16 by 3	3	6	4.7	0.74
		Tube extrusion and conical plunger	1/8 by 1 1/4	4 1/2	6	3.3	0.71
			1/16 by 1 1/4	3	4	3.8	0.68
		Tube extrusion and blunt plunger	1/16 by 1 1/4	4 1/2	6	4.18	0.63
			3/16 by 3	4 1/2	6	3.46	0.59
			1/8 by 1 1/4	4 1/2	6	3.73	0.56
Panuco, S63-19	90	Barrel extrusion and conical plunger	1/16 by 1 1/4	3	-	17.1[a]	0.90[a]
			3/16 by 3	3	6	8.7	0.89
		Tube extrusion and conical plunger	1/8 by 1 1/4	4 1/2	6	5.5	0.86
			1/16 by 1 1/4	3	4	8.5	0.87
		Tube extrusion and blunt plunger	1/16 by 1 1/4	4 1/2	6	4.22	0.83
			3/16 by 3	4 1/2	6	6.12	0.76
			1/8 by 1 1/4	4 1/2	6	7.62	0.70
Los Angeles Basin, S63-20	89	Barrel extrusion and conical plunger	1/16 by 1 1/4	3	-	49[a]	0.96[a]
			3/16 by 3	3	6	16.0	0.98
		Tube extrusion and conical plunger	1/8 by 1 1/4	4 1/2	6	8.1	1.03
			1/16 by 1 1/4	3	4	-[b]	-[b]
		Tube extrusion and blunt plunger	1/16 by 1 1/4	4 1/2	6	-[b]	-[b]
			3/16 by 3	4 1/2	6	6.90	1.09
			1/8 by 1 1/4	4 1/2	6	7.57	1.06
Kern River, S63-21	89	Barrel extrusion and conical plunger	1/16 by 1 1/4	3	-	-	-
			3/16 by 3	3	6	-	-
		Tube extrusion and conical plunger	1/8 by 1 1/4	4 1/2	6	-	-
			1/16 by 1 1/4	3	4	-	-
		Tube extrusion and blunt plunger	1/16 by 1 1/4	4 1/2	6	-	-
			3/16 by 3	4 1/2	6	8.34	1.03
			1/8 by 1 1/4	4 1/2	6	10.4	0.90

[a]Taken from Schweyer and Busot (2). [b]Did not reach an equilibrium value.

Table 3. Comparative data of methods used.

Sample	Penetration at 25 C	Florida Method (corrected for geometry)		Cone and Plate Method		Sliding Plate Method	
		Complex Flow Index C	Apparent Viscosity (MP)	Complex Flow Index C	Apparent Viscosity (MP)	Complex Flow Index C	Apparent Viscosity (MP)
8621	60	0.69	4.04	0.61	4.00	0.89	3.60
8693	55	0.98	2.62	0.89	2.40	-[a]	-[a]
8610	62	0.73	3.48	0.62	3.47	-[a]	-[a]
8581	59	0.85	2.99	0.87	2.60	0.91	2.70
8594	58	0.81	3.32	0.74	3.10	-[a]	-[a]
8617	90	0.81	1.56	0.74	1.32	1.07	1.44
8580	82	0.86	1.94	0.90	1.23	1.10	1.50
8590	87	0.70	1.59	0.75	1.40	-[a]	-[a]
8589	77	0.76[b]	1.50[b]	0.72	1.45	0.98	2.94[c]
8620	65	0.74	2.69	0.72	2.56	-[a]	-[a]
A (S63-20)	89	0.98	1.37	0.92	1.23	0.98	1.16
B (S63-19)	90	0.89	1.81	0.75	1.95	0.81	2.26
D (S63-13)	89	0.65	1.79	0.56	2.12	0.94	1.96
F (8757A)	20	0.86	75.8	-[a]	-[a]	1.13	57.6
G (8659A)	30	0.57	30.0	0.35	39.0	0.66	25.6
H (8665B)	13	0.57	24.1	0.37	32.0	0.83	20.0
I (S64-22)	21	0.65	25.5	0.49	19.5	0.58	23.4
J (S64-42)	65	0.82	2.45	0.84	1.60	0.99	2.50
K (S64-46)	43	0.83	4.76	0.75	4.70	0.94	7.15
L (S64-47)	19	0.74	46.6	0.56	36.0	0.61	33.6
M (S67-15)	16	0.38	74.6	0.22	52.5	-[a]	Too hard
O (S64-33)	25	0.28	6.4	-[a]	-[a]	-[a]	-[a]
P (R71-8)	23	0.41	25.2	0.27	33.3	0.20	33.0

[a]Not run.
[b]A different sample of this material gave values of C = 0.71 and a viscosity of 2.63 MP. There may have been a sample mixup.
[c]Average of four determinations.

fixed value, usually 0.05 sec^{-1}. The data given in Tables 1 and 2 are at a constant power input because previous data were available at this condition.

In the original Florida study (2), it was recommended that comparisons be made at the same power input of 100,000 ergs/(sec-cm^3). If a constant rate of shear value is to be used, it is suggested that a value of 1.0 sec^{-1} be the standard. This suggestion is based on a very simple consideration.

The fundamental relation for a power law fluid is expressed mathematically as

$$\eta = \eta_0 \left| \dot{\gamma}/\dot{\gamma}_0 \right|^{C-1} \tag{1}$$

η is the apparent viscosity, in poises, at the point where $\dot{\gamma}$ is rate of shear, and η_0 and $\dot{\gamma}_0$ are corresponding values at some standard state with C being the exponent in the power function. It will be noted that, if the standard value of $\dot{\gamma}_0$ is taken as 1.0 sec^{-1}, the standard viscosity η_0 is numerically equal to the value of the standard shearing stress τ_0 where both τ_0 and $\dot{\gamma}_0$ must be measured at the same point in the fluid. This is true because the viscosity at any $\dot{\gamma}$ is also defined for the apparent viscosity η_a:

$$\eta_a = \tau/\dot{\gamma} \tag{2}$$

and if $\dot{\gamma}$ is 1.0 sec^{-1}, the value of the viscosity η_a, in poises, is numerically the same as τ, the shearing stress (given in dynes/cm^2).

Another form of Eq. 1, which relates shear stress to rate of shear, is

$$\tau = \eta\dot{\gamma}_0^{C} \tag{3}$$

which plots as a straight line on log-log coordinates with a slope of C whenever the power law is applicable. In this form, η is a correlation coefficient (which also is the viscosity in poises when C is equal to unity).

For most asphalt cements in the range of 85 to 100 penetration, observations will give measurements in the range of rates of shear of 1.0 sec^{-1}. Some correlations, however, possibly should be made at a constant power input as was originally suggested.

It should be noted that the data given in Tables 1 and 2 for the apparent viscosity in the Florida method are corrected for complex flow (Rabinowitsch) and for geometry. However, the rates of shear are the average values as used in evaluating the slope of $C = (d\,\ell n\,\tau)/(d\,\ell n\,\dot{\gamma})$ for the rheological diagram.

Recent studies by Lodge (5) have indicated that asphalts may show a pressure susceptibility that will accentuate shear-susceptibility effects. A method for correction for pressure was proposed if it becomes desirable to make such corrections. This subject is being explored further.

The present studies, using various instruments, show acceptable agreement in general for all three methods with paving grade asphalts as indicated in Figure 4. As might be expected, special asphalts are less in agreement probably because of non-Newtonian flow phenomena. However, even with these materials, one order of magnitude agreement is shown for the apparent viscosity values. The poorest agreement is in the complex flow index, but there is no apparent trend in disagreement.

In a recent paper, Lefebvre and Robertson (6) presented comparable data, using several different instruments, which indicated that the cone method tends to give lower values for the complex flow index at 25 C than does the capillary method. These were limited data on very soft asphalts (300 penetration).

Temperature Susceptibility

Certain nonlinear temperature effects noted for low temperatures on the ASTM chart were discussed by Lefebvre and Robertson (6). They also showed for one asphalt that there was a significant break of the plots at the region from 40 to 60 C. This was the region where the apparatus they used was changed from the efflux type to the cone and plate and cone-cone types. The authors commented that the temperature susceptibility appeared to be greater in the lower temperature regions. This was not confirmed in the present study because the data plotted at the power input point show lower slopes than those at the higher temperatures. This effect appears to be accentuated with increased complex flow behavior.

The new procedure was used to develop data in the lower ambient range from 5 to 60 C (Table 5). These data, at a constant power input, 10^5 ergs/(sec-cm^3), were plotted with other high-temperature data up to 195 C as shown on a redrawn ASTM D2493 chart (log-log viscosity versus log of absolute temperature in degrees Rankine). These plots (and many others) show a good straight line for the efflux viscosities above 60 C when all are reported in poises. Below this temperature, Florida capillary method data give essentially a continuation of the high-temperature line for materials exhibiting essentially Newtonian flow as shown in Figure 5 for R70-56. However, for other asphalts such as R70-51 (Fig. 6), the line shows a definite offset from the higher temperature data. When data at different shear rates are plotted as shown in Figure 7, the best straight line appears to be at the power point. Shear-susceptible materials tend to show better agreement for the data at a constant power input, but whether this is universally true is not known. These materials also show larger viscosities at 60 C when the Florida capillary method is used than when the efflux method (Cannon-Manning) is used.

No explanation is given for the discrepancy of the data at 60 C by different methods except that possible pressure-viscosity effects, which Lodge (5) found at lower temperatures, may also be present. This is being investigated in a special study. (For temperatures substantially above and below 25 C, which was the controlled room temperature with primary environmental chamber control, special precautions were taken for ensuring that sample was at the indicated test temperature.)

COMMENTS ON PROCEDURES

The recommended procedure for the analysis of asphalt rheology given in the tables allows for the Rabinowitsch correction (2) and corrects for the sample tube geometry relative to the capillary geometry (2). This is not appreciable for a $\frac{1}{16}$- by $1\frac{1}{2}$-in. capillary until the complex flow index is 0.5 or less (at which point the observed viscosity should be reduced by about 5 percent). For a $\frac{3}{16}$- by $1\frac{1}{2}$-in. capillary, this correction is about 10 percent for a complex flow index of 1.00 and about 30 percent when C has a value of 0.5.

For analysis at 25 C, a nominal capillary of $\frac{1}{16}$- by $1\frac{1}{2}$-in. for asphalt cements of 80 to 100 penetration is suggested with expected range of results as shown at the lower values in Figure 1. The variability for values of apparent viscosities averaged about 7 percent of the mean value based on five check runs. For the complex flow index, the variability was within about 5 percent of the average value (2).

It has been found that capillaries with length-to-diameter ratios in excess of 15 are desirable for satisfactory results (2). In selecting a standard size for different ranges of viscosities at variable temperatures, several factors need to be considered. First, a small diameter uses less sample, provides good heat dissipation, and requires a shorter length to meet the length-to-diameter ratio requirement. However, small-diameter capillaries are more difficult to fabricate. Second, larger bores require longer sample tubes to accommodate greater length of capillary and require lower pressures (force per unit cross-sectional area), which minimizes certain problems of anomalous flow at high pressures. In addition, large-diameter capillaries require a geometric correction for the data depending on the sample tube diameter.

As a guide for capillary selection, the following tabulation is helpful for 85-penetration asphalt cements having an apparent viscosity of about 1 megapoise (MP) at 25 C. Softer asphalts would use the smaller diameters and harder asphalts the larger (Table 6).

In general, it is believed that shearing stresses should be less than 5×10^6 dynes/cm^2 as a maximum until further research determines that this can be raised. With this limit, certain problems of critical stress phenomena can be minimized.

Other observations of interest that have been noted are that 90-deg entry gives about the same result as does 180-deg (flat) entry. Stainless steel, brass, and amalgamated brass gave about the same results in tubes. It was also noted that heating the sample tubes showed little or no effect.

Table 4. Comparative data of asphalt cements at different shear rates at 25 C.

		Rheological Analysis			
			V25[b], Apparent Viscosity (MP)		
Asphalt[a]	Pene-tration at 25 C	Complex Flow Index C	0.05 sec^{-1}	1.0 sec^{-1}	10^5 ergs/sec-cm^3
A	89	0.98	1.37	1.27	1.36
B	90	0.89	1.81	1.28	1.48
C	89	0.80	2.44	1.32	1.78
D	89	0.65	1.79	0.62	0.98
E	89	0.99	1.37	1.31	1.33
F	20	0.86	75.8	50.3	80.1
G	30	0.57	30.0	8.07	30.8
H	13	0.53	24.1	5.90	25.3
I	21	0.65	25.5	8.6	22.4
J	65	0.82	2.45	1.46	1.93
K	43	0.83	4.76	2.82	3.93
L	19	0.74	46.6	21.3	49.4
M	16	0.38	74.6	11.4	141.0
O	25	0.28	6.4	0.75	3.90
P	23	0.41	25.2	4.22	25.6

[a]Samples A to E are paving asphalts; others are miscellaneous items including recovered paving asphalts and air-blown and roofing asphalts.
[b]V25 is used to designate absolute viscosity at 25 C.

Table 5. Comparative Florida rheometer data on asphalt cements at ambient temperatures.

Asphalt	5 C Vis-cosity (MP)	10 C Vis-cosity (MP)	15.5 C Vis-cosity (MP)	25 C Vis-cosity (MP)	40 C Vis-cosity (kP)	50 C Vis-cosity (kP)	60 C Vis-cosity (kP)
R70-50, 89 pen							
Complex flow index C	0.84	0.86	0.80	0.80	0.96	0.92	0.95
Rate of shear							
$\dot{\gamma}_{05}$, sec^{-1}	250	73.5	18.5	2.44	79	24.5	6.15
$\dot{\gamma}_{1}$, sec^{-1}	165	48.4	10.4	1.32	74	18.1	4.95
$\dot{\gamma}_{P}$, ergs/(sec-cm^3)	292	77.8	17.5	1.78	74	18.1	4.52
R70-51, 89 pen							
Complex flow index C	0.65	0.63	0.57	0.65	0.78	0.86	0.90
Rate of shear							
$\dot{\gamma}_{05}$, sec^{-1}	50.4	13.4	5.88	1.79	111	21.4	5.75
$\dot{\gamma}_{1}$, sec^{-1}	17.3	4.4	1.61	0.625	60	14.3	4.04
$\dot{\gamma}_{P}$, ergs/(sec-cm^3)	55.1	11.4	3.84	0.985	57	12.5	3.38
R70-55, 90 pen							
Comples flow index C	0.71	0.85	0.72	0.81	0.86	0.88	0.91
Rate of shear							
$\dot{\gamma}_{05}$, sec^{-1}	94.8	34.8	6.29	1.81	128	44.9	11.5
$\dot{\gamma}_{1}$, sec^{-1}	39.5	22.9	4.27	1.28	89	30.8	8.65
$\dot{\gamma}_{P}$, ergs/(sec-cm^3)	113.3	35.2	8.26	1.54	89	29.3	7.70
R70-56, 89 pen							
Complex flow index C	1.12	0.98	1.02	0.92	1.01	1.10	0.99
Rate of shear							
$\dot{\gamma}_{05}$, sec^{-1}	535	87.0	7.47	1.37	34	6.14	1.52
$\dot{\gamma}_{1}$, sec^{-1}	459	80.0	8.04	1.27	35	7.65	1.48
$\dot{\gamma}_{P}$, ergs/(sec-cm^3)	803	88.2	7.62	1.40	35	8.45	1.45

Figure 5. Temperature susceptibility of R70-56.

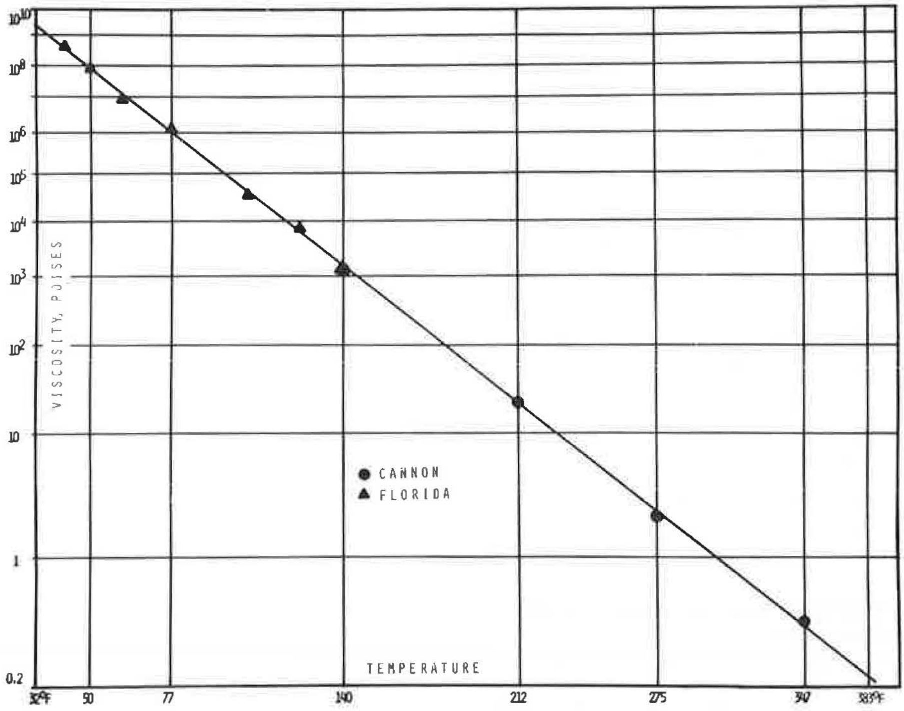

Figure 6. Temperature susceptibility of R70-51.

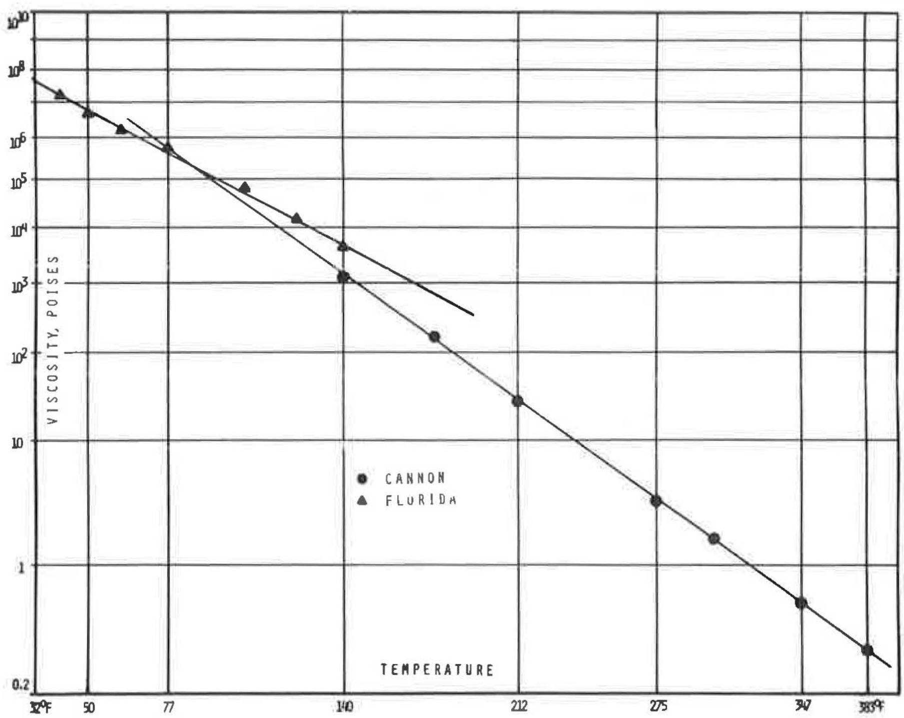

Figure 7. Low-temperature susceptibility of R70-51.

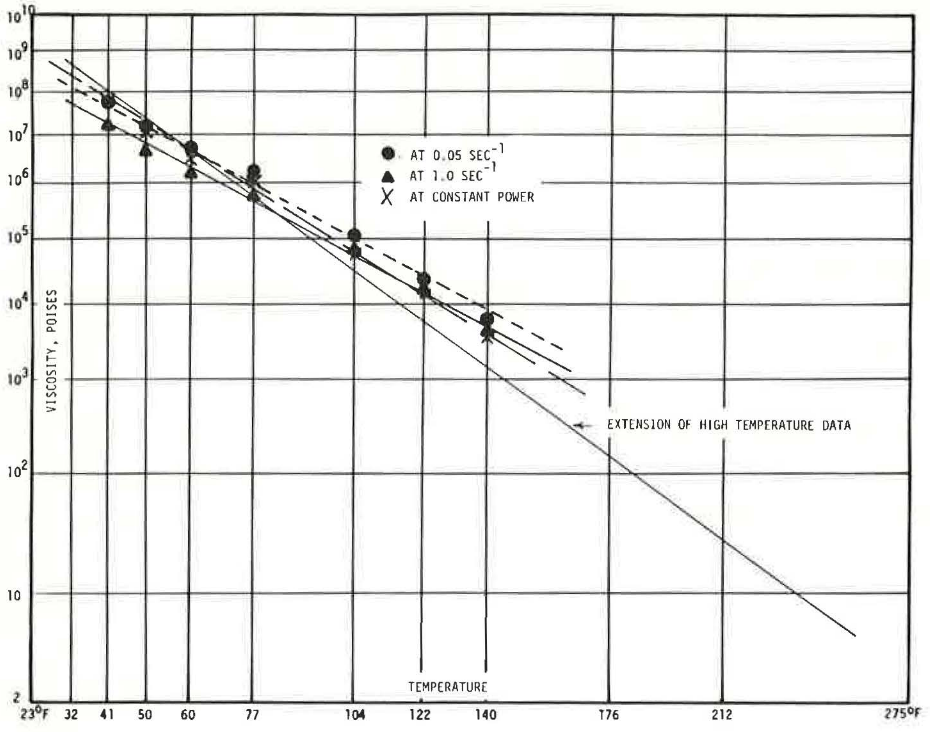

Table 6. Nominal capillary dimensions.

Temperature of Absolute Visocity (deg C)	Dimension (in.)		Temperature of Absolute Visocity (deg C)	Dimension (in.)	
	Diameter	Length		Diameter	Length
60	0.020	1.5	25	0.08	1.5
	0.030	1.5		0.120	1.5
50	0.030	1.5	15	0.120	1.5
	0.050	1.5		0.187	1.5
40	0.040	1.5	5	0.187	1.5
	0.060	1.5		0.25	1.5

In its present state of development, the Florida method can be used for general routine testing at low cost if a suitable inexpensive constant force drive or constant velocity drive apparatus is made available.

ACKNOWLEDGMENT

Certain initial work on this research was supported by the Florida Department of Transportation whose assistance is acknowledged. Also, the author is grateful for the advice of J. C. Busot in helping to develop the method used in this study.

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