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Evaluation of Filler Effect of Sulfur in Asphalt Binder

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The effectiveness of both dissolved and dispersed crystalline parts of sulfur in asphalt binders used in road-paving mixtures was evaluated. The role of sulfur as a binder extender and filler material was compared with that of conventionally used limestone filler. For this purpose, a series of viscosity measurements were performed on sulfur-extended asphalt (SEA) binders and limestone filler-extended asphalt (FEA). Ratios vary up to 50 percent by weight at a temperature range from 25°C to 140°C. Rotational and cone-plate viscometers were used in this study to evaluate the relative viscosity, temperature susceptibility, and shear susceptibility of these binders as a function of the volume concentration. The research indicates that (a) the effect of the dissolved part of sulfur in asphalt cement on the decrease in viscosity is balanced by the filler effect of a certain part of dispersed sulfur particles, which varies in its effective volume concentration according to the temperature of the SEA binder; (b) at temperatures below the softening point of asphalt cement, values of effective volume concentration for both SEA and FEA are found to be similar; and (c) the crystallization process of sulfur in terms of dynamic growth of the sulfur particles seems to be effective if the SEA is mixed with mineral aggregates and represents the major part of stiffness improvement of finished pavement with age. Increase in viscosity of SEA due to increase of effective volume

concentration of dispersed sulfur particles represents only a minor part of the stiffening effect.

During the past seven years, sulfur-extended asphalt (SEA) materials have been used to pave experimental road sections in many parts of the United States and in the Persian Gulf states in the Middle East. Investigations of the engineering properties of sulfur asphalt-paving mixtures and their structural response against both fatigue and permanent deformation have suggested that additional comprehensive evaluation of the SEA used and of its role as a binder extender as well as a filler material were warranted (1-4).

SEA is produced by high-shear-rate mixing of liquid sulfur with liquid asphalt. A part of the added sulfur by the dispersion technique ends up as dissolved sulfur. It is believed that the remainder

of the added sulfur, which is finely dispersed in a crystalline form, may have a kind of filler action that provides the observed increased strength of the paving mixtures.

Therefore, this study was aimed at the evaluation of the stiffening filler action of the added sulfur by analyzing the volume concentration of the dispersed sulfur crystals compared with limestone filler particles of equal amounts. For this purpose, a series of viscosity measurements were performed on asphalt binders extended with sulfur and limestone filler-extended asphalt (FEA) that had ratios varying up to 1:1 by weight to the asphalt. The analysis included the temperature as well as shear susceptibility of these binders and the effect of heating.

MATERIAL CHARACTERIZATION AND SAMPLE PREPARATION

The asphalt cement (AC) considered in this study is the only one produced from the local crude oil by the blowing process, graded as 60/70 penetration, and used in asphalt-paving mixtures in Kuwait. The sulfur used throughout the investigation of SEA is also a local commercial-grade product of 99.8 percent purity. The mineral filler used for comparison purposes is a locally produced limestone powder. A hydrometer analysis conducted on the filler passing sieve No. 200 (ASTM D422-63) showed that about 70 percent is finer than 10 μm and about 25 percent is finer than 1.5 μm in diameter. Photomicrographs of both elemental sulfur and limestone filler were taken with the scanning electron microscope and used to analyze particle shape and size. Sulfur and limestone agglomerates were found to be about 4 μm long on the average and the largest individual particle was about 1 μm long. These agglomerates are held together by surface forces, which cause the agglomerates to act as single particles. Grain form is found to be cubic with rounded corners for both sulfur crystals and limestone filler.

Both SEA and FEA were prepared with normal laboratory dispersing equipment operating at a constant speed of 1500 rpm. Prior to emulsification, both sulfur or filler and asphalt were proportioned by weight and preheated at about 150°C. The melted sulfur and the asphalt were added simultaneously to the receiving hopper of the mixer while it was running at its constant speed. For FEA, samples were prepared by slowly mixing the filler into the asphalt by hand and then by mixing at the same shear rate in the mixer. Shearing time was kept to 8 min for all samples, during which the mill clearance varied between 1.0 mm and 3.0 mm. To prevent coagulation and settlement of dispersed particles, a sample of the emulsified binder was used immediately after mixing for viscosity measurement. Samples were kept in the sensors of the viscometer in rotation at relatively high shear rates while viscosities were measured at temperatures above 80°C. As the binder temperature dropped below 80°C, the settling rate was found to approach zero.

TESTS AND TEST METHODS

The viscosity of SEA material was measured and compared with those of conventional AC and FEA materials used locally at a range of temperature between 25°C and 140°C, which covers operation and prevailing pavement service temperature conditions. At temperatures between 60°C and 140°C, a rotational viscometer with different measuring cylinder sensor system is used, which allows the use of different shear rates that range from 10^{-1} to 10^3 s^{-1} and the application of shear stress values up to 5×10^3 Pa. At temperatures between 25°C and

60°C, viscosities were measured by using a cone-plate viscometer that has a measuring head of 49 N-cm maximum torque and 1:100 reduction gear, which allows for determining flow behavior of the binder materials at a starting shear value of 10^{-3} s^{-1} and at shear stress values up to 10^6 Pa.

A viscosity value measured by using a given shear stress and an arbitrarily selected value of shear rate is termed "apparent" viscosity. At relatively low shear rates that induce low shear stress, the apparent viscosities appear to be constant. Such a constant, relatively shear-independent viscosity is designated as "initial" viscosity. In all relative low-temperature viscosity measurements, an attempt was made to establish such initial viscosities. To accomplish this, it was necessary to exceed the shearing time allowed in ASTM D3205 by using gradually increasing shearing loads (alternate method 1) from 10 to 20 min (5).

The temperature was maintained by circulating a light oil in a jacket outside the cup of the sensor for the rotoviscometer and underneath the plate for the cone-plate viscometer in which the sensor system is located inside a temperature-control chamber. The reading on the control thermometer is an indication of the cup or plate temperature. Before each test, the sample was kept for 30 min at the fixed temperature. The instruments allow for setting the shear rate either at 40 fixed-speed values or at a programmed steplessly variable speed setting and speed-change direction (increasing, decreasing, or constant).

Viscosity η is determined as a function of shear rate D or shear stress S . These are given by $\eta = S/D$. For the rotor-cylinder sensor used at 60°C to 140°C, the following equations hold:

$$S = (T \cdot a) / (2\pi \cdot L^* \cdot R_i^2) \quad (\text{Pa}) \quad (1)$$

$$D = [(n \cdot \pi) / 15] \cdot [R_a^2 / (R_a^2 - R_i^2)] \quad (\text{s}^{-1}) \quad (2)$$

For the cone-plate sensor used at 25°C to 60°C, the following equations hold:

$$S = (3T \cdot a) / (2\pi \cdot R_c^3) \quad (\text{Pa}) \quad (3)$$

$$D = (n \cdot \pi) / (30 \cdot \alpha) \quad (\text{s}^{-1}) \quad (4)$$

where

- T = torque (N-cm),
- a = constant correlation factor (to correlate torque applied at shaft of measuring head to indicated scale value),
- n = speed in revolutions per minute of the rotor (min^{-1}),
- L^* = corrected height of rotor sensor (cm),
- R_i = radius of rotor sensor (cm),
- R_a = radius of cup (cm),
- R_c = radius of cone (cm), and
- α = opening angle of cone (rad) ($1^\circ = \pi/180$ rad).

Viscosity measurements were carried out on freshly prepared binder samples as well as on aged ones held in the sensor of the viscometer at 25°C for 1, 24, and 72 h before viscosity measurements were run at 25°C and at different shear-rate values. These tests are supposed to study the phenomenon of the slow development of internal structure due to the formation of the crystallization process in SEA.

SEA, like other asphalt binders, during their application and use are subjected to heating for variable time periods and at a wide range of temperatures. It is well known that such heating affects properties of asphalt binders and that this

Figure 1. Relationship between viscosity at 60°C and penetration at 25°C.

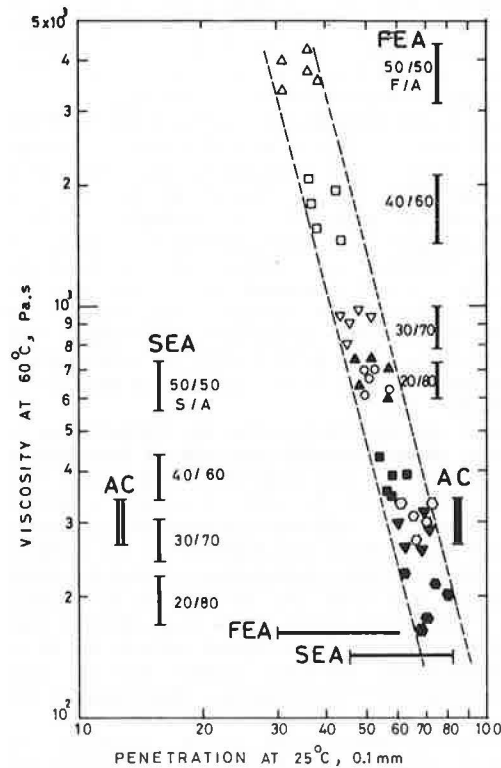
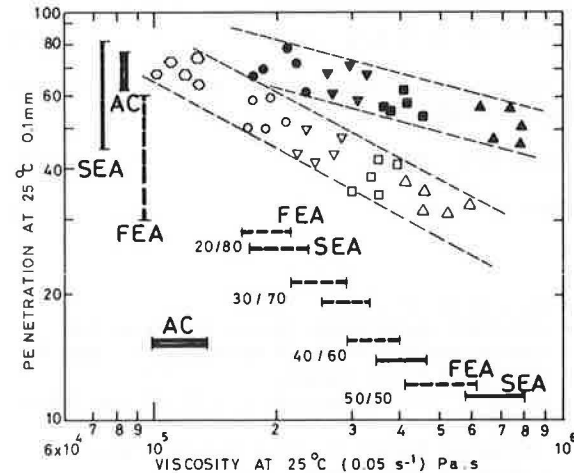


Figure 2. Relationship between viscosity at 25°C and penetration at 25°C.



in turn influences the behavior of the paving mixtures. For the evaluation of the heating effects, the thin-film oven test (TFOT) was applied on an SEA film about 3 mm thick at a temperature of 140°C for 7 h instead of 163°C for 5 h as described by AASHTO T240178. These changes were made to avoid any sulfur-asphalt chemical reaction by dehydrogenation and formation of H_2S during the process of heating the SEA. Viscosities were measured at several temperatures after heating and compared with viscosities measured for AC and FEA heated under the same testing conditions.

DISCUSSION OF RESULTS

Relationship Among Different Rheological Properties

A comparison among three properties currently used

as a basis for grading asphalt binders is given. The properties are viscosities at 25°C and 60°C, penetration at 25°C, and softening point. Figures 1 and 2 illustrate the relationship among viscosities at 25°C and 60°C of fresh prepared samples of AC, SEA, and FEA and compare such viscosities with penetration measured at 25°C. Figure 1 is a comparison of the two properties currently used as a basis for grading AC. Both viscosity and penetration ranges for AC, SEA, and FEA are indicated by bars drawn in the proximity of the appropriate axis. It may be seen readily that, through the extension of AC 60-70 penetration grade with sulfur in ratios up to 50/50 by weight, the viscosity varied between 160 and 800 Pa.s, a fivefold variation. This range of SEA viscosities that belong to a range of penetration grades varies between 80 and 45. The comparison of SEA with FEA for the same ratios up to 50/50 by weight indicates that the viscosity varied between 600 and 4000 Pa.s (about sixfold variation) and belonged to a range of penetration grades that varied between 60 and 30.

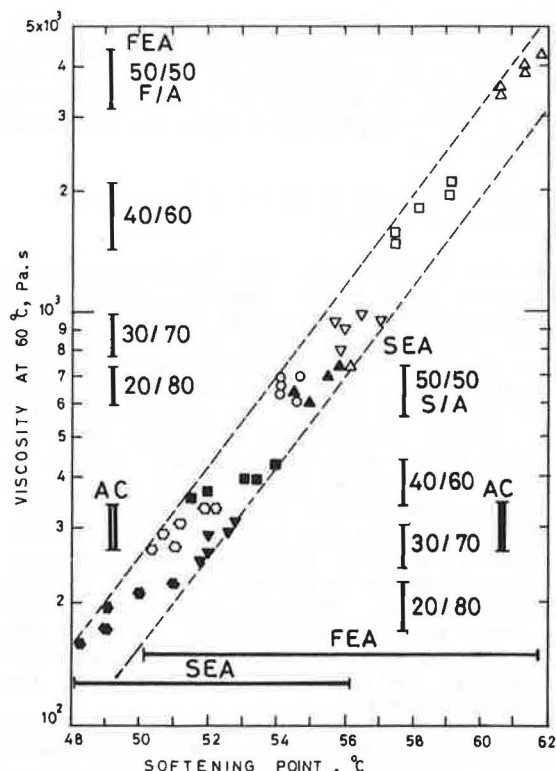
The linear relationship between log viscosity at 60°C and log penetration at 25°C illustrated in Figure 1 for both SEA and FEA indicates the relatively narrow range of penetration values compared with the wide variation of viscosities; this is a major reason for proposing viscosity grading to evaluate the behavior of these binders. It is rather obvious that two binders that belong to the same penetration grade but exhibit about threefold variation in their viscosities would behave quite differently when exposed to variable construction operation temperatures or pavement service temperatures.

The comparison of data points in Figure 1 indicates that there exists an overlap of viscosity and penetration grades for SEA with S/A ratios between 40/60 and 50/50 and FEA with F/A ratios between 20/80 and 30/70 by weight. Thus, it may be assumed that the relationship between viscosities at 60°C and penetration at 25°C is very similar for SEA and FEA with these concentration ratios.

Figure 2, which relates viscosity and penetration at 25°C, is included to provide a comparison of the low-temperature consistencies of SEA and FEA binders. Since viscosities of these binders are affected by the shear rate applied, apparent viscosities at a shear rate of 0.05 s^{-1} were used. Figure 2 indicates a general broad correlation between the two properties in question. As can be judged from the data symbols, no substantial differences can be observed between the SEA and FEA viscosity values at 25°C at each concentration value. A pronounced overlap in the viscosity grades measured for both SEA and FEA is indicated. Viscosities vary between 2×10^5 and $8 \times 10^5 \text{ Pa.s}$ for the range of concentrations considered in this analysis. This means that both sulfur and limestone filler additives within these percentages provide a similar effectiveness on the viscosity values of the binder at 25°C. Figure 2 also indicates that the relationships between viscosity at 25°C and penetration at 25°C for SEA and FEA are not similar as in the case of viscosity at 60°C and penetration at 25°C, shown in Figure 1. This could be due to the susceptibility of these binders at lower temperatures to variable shear rates applied during the penetration and viscosity tests.

The softening point of the AC 60-70 penetration grade used was found to range between 48°C and 51°C. Over the concentration range in this study of sulfur and limestone filler in both SEA and FEA, the softening point was found to change between 48°C and 62°C. A linear relationship between log viscosity at 60°C and softening point for both SEA and FEA is

Figure 3. Relationship between viscosity at 60°C and softening point.



illustrated in Figure 3. The comparison of data points in Figure 3 indicates that an overlap of viscosity and softening point exists for SEA with an S/A ratio of 50/50 by weight and for FEA with F/A ratios of 20/80 and 30/70 by weight. Thus, it may be also assumed that the relationships between viscosities at 60°C and the softening point are similar for SEA and FEA with these concentration values.

Viscosity as Function of Volume Concentration

The volume concentration of the dispersed particles is an important variable that influences the viscosity of asphalt paving materials. Since the SEA normally used has a low sulfur concentration, the effect of the shear rate may not become an overriding factor and the relationship among the relative viscosity η_{rel} , the volume concentration C_v , and the occupation ratio V_p proposed in the work of Eilers (6) and of Heukelom (7) could be applied:

$$\eta_{rel} = \left\{ 1 + [1.25C_v / (1 - V_p \cdot C_v)] \right\}^{3.6 V_p - 2.8} \quad (5)$$

where $\eta_{rel} = \eta_{SEA} / \eta_{AC}$ or η_{FEA} / η_{AC} . An infinite value of the relative viscosity was found at $C_v(\max) = 0.78$ in correspondence with an occupation ratio $V_p = 1.35$ for dispersed graded spheres.

A nearly linear relationship between $1/\eta_{rel}$ and C_v exists up to a relative viscosity of about 100. This can be demonstrated by rewriting Equation 5 as follows:

$$1/\eta_{rel} \approx 1 - 1.25C_v \quad (6)$$

By introducing constant k and m in the above equation, which accounts for the effect of shear dependence of dispersion and the shape of the dispersed

particles (mC_v is the virtual increase in concentration), respectively, Equation 6 can be written in the following more general form:

$$\begin{aligned} 1/\eta_{rel} &= 1 - [(1+k)(1+m)C_v] \\ &= 1 - (C_v/C_{\max}) \end{aligned} \quad (7)$$

where $C_{\max} = 1/[(1+k)(1+m)]$ = the value of C_v at which the viscosity tends to become infinite. For the case of fully peptized spherical particles, $m = 0$, and for low shear rates, $k = k_0 = 1/C_{\max} - 1 = 0.28$.

The results for the relative viscosity, derived from the rotor and cone-plate viscometers at a low shear rate (0.05 s^{-1}) and at temperatures that range from 25°C to 140°C, were plotted in Figures 4 and 5 for SEA and FEA, respectively. For both sulfur and limestone filler ratios that vary up to 50 percent by weight of total binder, the relative viscosity of both binders is found to be temperature dependent.

At temperatures below the softening point, relative viscosity values of both SEA and FEA are similar. Above the softening point of these binders and up to the melting point of sulfur, the stiffening effect of the sulfur additive was found to be much lower than that of the limestone filler. At 50 percent by weight of total binder, relative viscosity values measured were 1.6 and 12.5 for SEA and FEA, respectively. Above the melting point of sulfur and below the dehydrogenation temperature, relative viscosity values of SEA ranged between 0.45 and 0.55.

Figure 6 shows the relative viscosities in terms of $1/\eta_{rel}$ of both SEA and FEA as a function of volume concentration. From the resulting linear relationship shown in Figure 6, the values of C_{\max} for both SEA and FEA can be compared and used to compute the corresponding values of the correction factor $(1+m)$, introduced in Equation 7, as $(1+m) = 0.78/C_{\max}$ for the actual dispersed particles.

At 25°C, relative viscosity values of both SEA and FEA were found to be similar. As the temperature increases, the volume concentration of sulfur needed to maintain a relative viscosity equal to 1 increases. For SEA, volume concentrations at $\eta_{rel} = 1$ were found to be equal to 0.08, 0.21, 0.27, and 0.43 (equivalent to 15, 35, 43, and 61 percent by weight) at temperatures of 40, 60, 100, and 120°C, respectively. It can be assumed that at $\eta_{rel} = 1$, the effect of the dissolved part of the sulfur in asphalt cement on the decrease in viscosity has been balanced by the effect of a certain part of dispersed sulfur crystals that varies in its volume concentration according to the temperature of the SEA binder.

From the test data illustrated in Figure 6, it can be observed that values of effective volume concentration of both SEA and FEA at temperatures below the softening point are similar ($C_{\max} = 0.51$). At a temperature range above the softening point ($\approx 50^\circ\text{C}$) and below the melting point of sulfur ($\approx 116^\circ\text{C}$), the peptization state of particles in both SEA and FEA changed so that the values of effective volume concentration C_{\max} are much higher than those at temperatures below the softening point. The maximum value of volume concentration C_{\max} for both limestone filler and dispersed sulfur particles in the asphalt binder was found to be 0.37.

However, for SEA, the type of interaction between the sulfur particles and the asphalt medium changes as soon as the temperature reaches the melting point of sulfur ($\approx 116^\circ\text{C}$). At this stage, a case of quasi-complete peptization exists. However, an increase in viscosity still occurs, depending on the

forces of repulsion between the sulfur and the asphalt particles, which causes an increase in size of each particle and therefore in effective volume concentration.

Figure 4. Relative viscosity of SEA versus sulfur content.

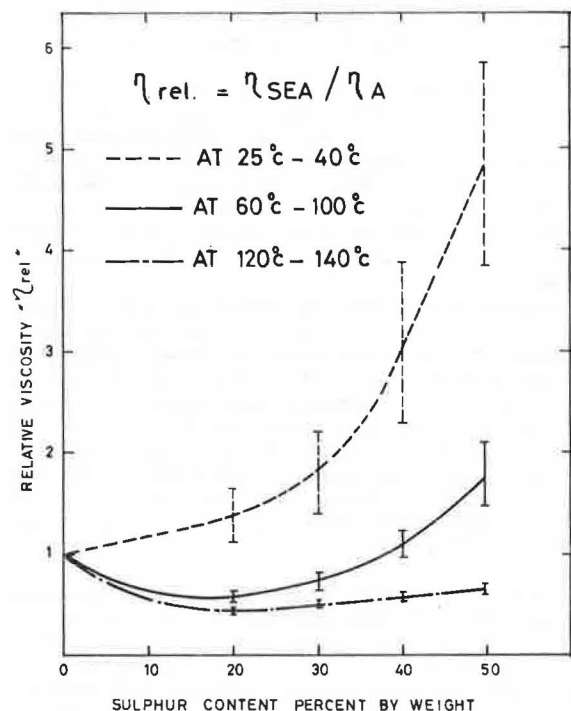
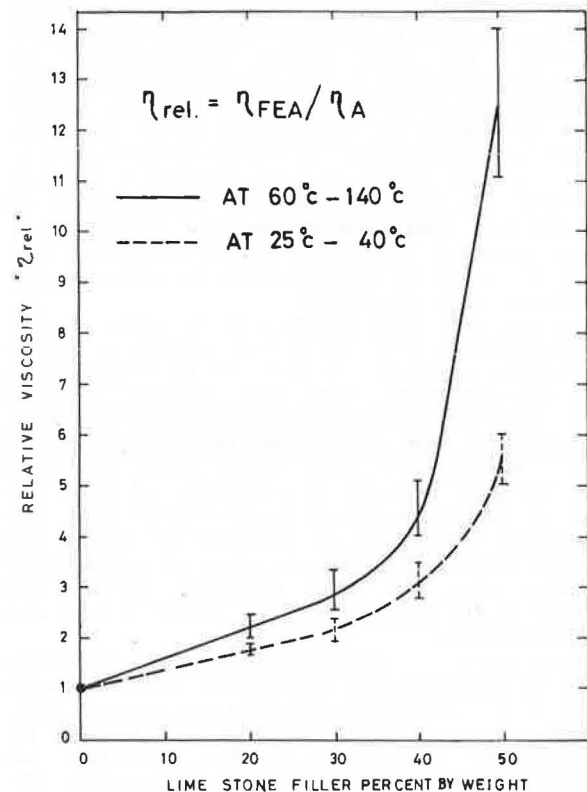


Figure 5. Relative viscosity of FEA versus limestone filler content.



Temperature Susceptibility

For SEA, the change in viscosity of the binder with changing temperature is described here by means of a viscosity-temperature susceptibility (VTS) index and compared with that for FEA and AC. For calculating VTS within a given temperature range, the following expression is used:

$$VTS = (\log \log \text{viscosity at } T_2 - \log \log \text{viscosity at } T_1) / (\log T_1 - \log T_2).$$

In most VTS calculations, viscosities measured at 135°C and 60°C were used. However, because SEA gives viscosity-temperature curves that consist of two straight lines, which differ from those of AC and FEA, viscosities at 100°C and 40°C were considered. Figure 7 shows that for SEA composed of 50 percent by weight of sulfur, the curve of log-log viscosity versus temperature consists of two branches that have nearly equal slopes. It can be seen that at temperatures lower than 100°C, where the sulfur is crystallized, the slope of the viscosity temperature line goes above that for AC and they are nearly parallel. However, at high temperatures, where the sulfur is molten, the curve for SEA is considerably lower. Between these two straight branches there is a transition range in which the test data are scattered because of differences in thermal history; the range is represented by the dashed line in Figure 7.

For SEA composed of 20 percent by weight of sulfur, the viscosity test data could be represented by a straight line, within the repeatability of the tests, as shown in Figure 7. However, the line has a steeper slope than that of AC, which indicates that the temperature susceptibility of SEA (of 20 percent by weight of sulfur) is much higher than that of SEA of 50 percent by weight of sulfur. Figure 8 provides a comparison of temperature susceptibilities of FEA composed of 20 and 50 percent by weight of limestone filler. From the VTS index calculated, it is found that SEA binders are more temperature-susceptible than asphalt cement. VTS values decrease from an average of 3.96 to 3.59 and the increase of sulfur content is from 20 to 50 percent by weight. However, lower VTS values calcu-

Figure 6. Relative viscosities of SEA and FEA as a function of volume concentration.

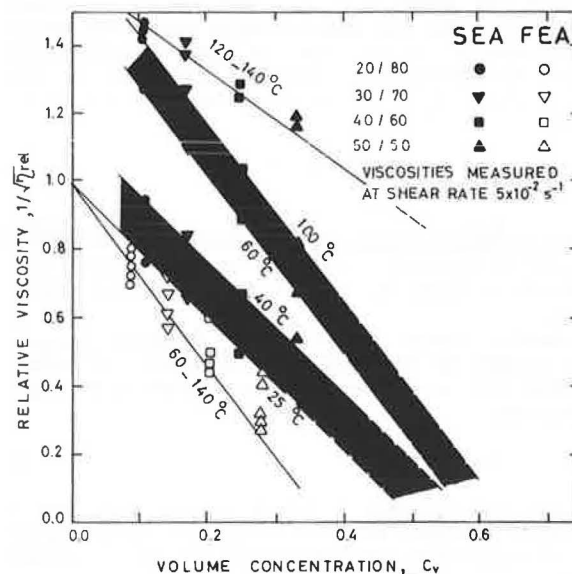


Figure 7. Viscosity-temperature relationship for SEA.

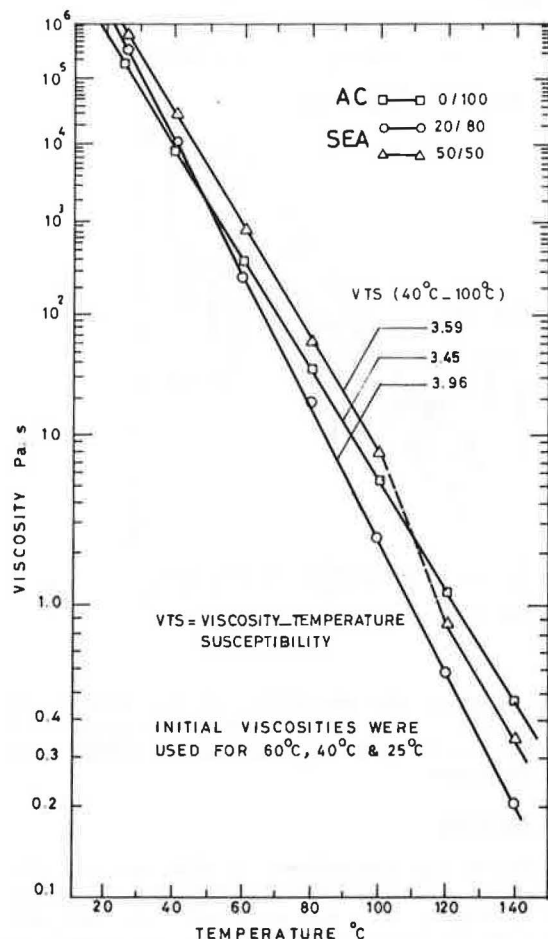
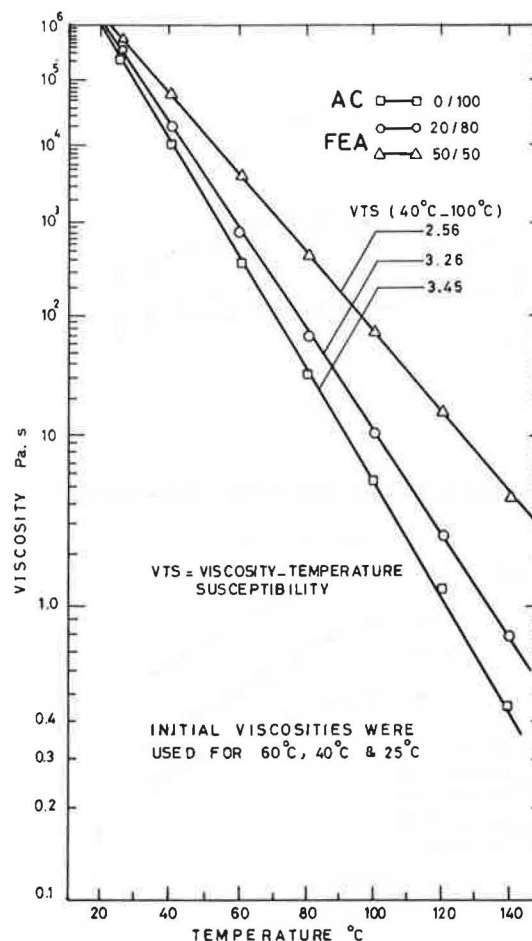


Figure 8. Viscosity-temperature relationship for FEA.



lated for limestone FEA (3.26 and 2.56 for 20 and 50 percent by weight, respectively) indicate a less-pronounced viscosity change of FEA with changing temperature compared with that of SEA binders.

At temperatures higher than 120°C, viscosities measured for SEA were found to be much less than those for AC and FEA of the same volume concentration. As may be seen in Figures 7 and 8, at 120°C, the viscosity of AC is about twice that of SEA (20/80) and about 1.5 that of SEA (50/50). However, viscosities measured for FEA at the same temperature were found to be five times higher than that of SEA for a 20/80 ratio by weight and they increase to about 15 times that of SEA for a 50/50 ratio by weight. It should be noted that these relatively low viscosities of SEA at a temperature range between, say, 120°C and 140°C lead to questions related to the mixing, laying, and compaction-temperature requirements of sulfur paving mixtures, which should be included in the specifications of SEA, and to find out the benefits that can be derived or expected from such requirements in specifications.

Shear Susceptibility

Figures 9-11 depict viscosity versus shear rate for SEA compared with that of AC and FEA, each at three temperatures that vary from the ambient room temperature of 25°C to 60°C. Figures 9-11 were prepared by plotting the logarithm of apparent viscosity in pascal seconds against the logarithm of shear rate in reciprocal seconds. It should be noted that at 60°C, within the indicated range of

shear rate, all asphalt binders tested except FEA made up of 50 percent by weight of limestone filler behave approximately as a simple Newtonian liquid; their viscosities are not affected much by the varying shear rate. Shear susceptibility calculated at 60°C (tangent at an angle of the plot of log viscosity versus log shear rate at a shear rate of 5×10^{-1}) was found to range from about 0.25 for SEA and AC to about 0.5 for FEA (Figure 9).

However, the non-Newtonian behavior becomes progressively more apparent as test temperature decreases. As illustrated by the gradually increasing slopes of the curves in Figures 10 and 11, the viscosities of SEA, AC, and FEA become more dependent on shear rate. Shear susceptibility calculated at 25°C was found to vary between 1.12 and 1.18 for SEA and AC. For FEA it ranged between 0.7 and 0.85. The curves for low shear rate are horizontal and parallel to the shear-rate axis. This part of the curve, which is not dependent on shear rate, is called the initial viscosity.

It was difficult to evaluate the effect of volume concentration on shear susceptibility due to factors other than shear rate, which influences viscosity measurements, specifically at 25°C. Factors such as the effects of loading sequence and sample conditioning were not considered in this work. However, it has been found during the shear test that the reversal of the loading sequence resulted in a difference in the apparent viscosity values. Measurements with gradually increasing shear stress generally resulted in higher apparent viscosity values.

Figure 9. Relationship between apparent viscosity and shear rate at 60°C.

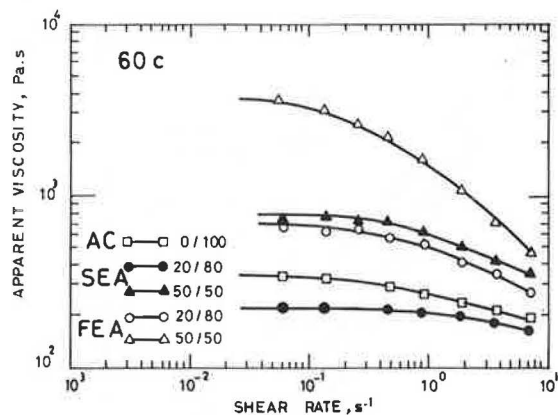


Figure 10. Relationship between apparent viscosity and shear rate at 40°C.

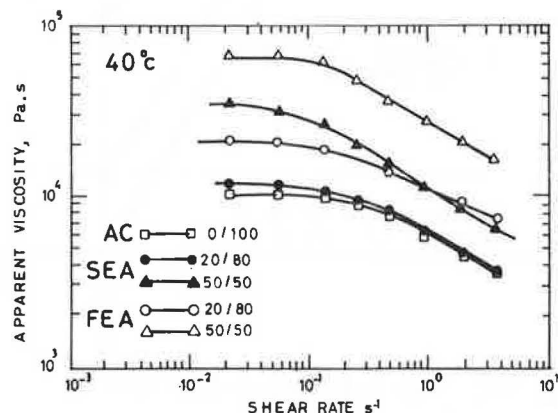
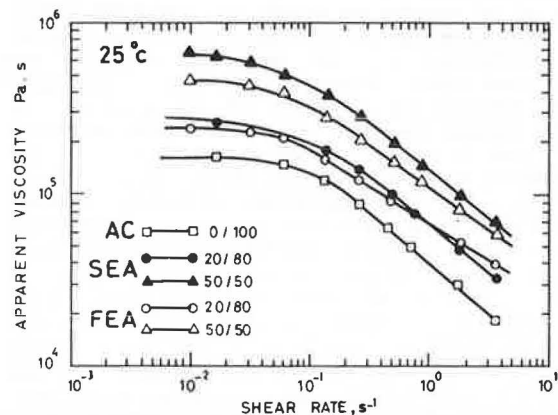
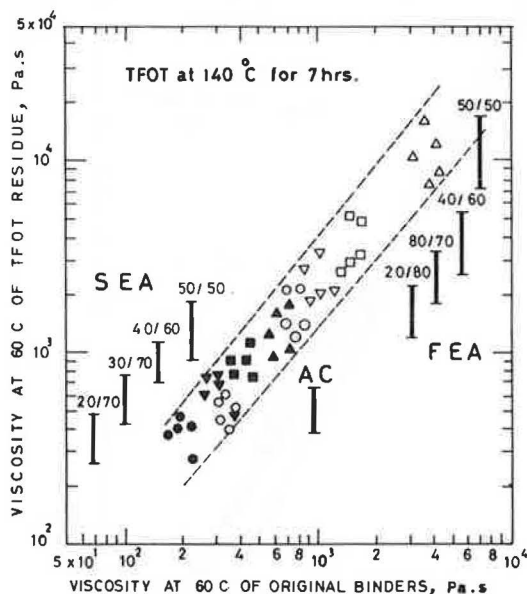


Figure 11. Relationship between apparent viscosity and shear rate at 25°C.



Also, the conditioning of samples of SEA, FEA, and AC held in the viscometer at 25°C for 24 and 72 h before the shear test was run at the same temperature resulted in higher apparent viscosity values in the range of low shear rates (less than 0.1 s^{-1}). The measured increase in viscosity values after three days' aging for both SEA and AC at a shear rate of 5×10^{-2} was found to be about 150 percent of the fresh tested sample. This could be due to the internal structure developed in these asphalt binders but it is not an indication of the crystallization process of sulfur in SEA, which was

Figure 12. Relationship between viscosity at 60°C of original and of heated SEA, FEA, and AC.



found to increase the stability of the sulfur-asphalt mixture. The crystallization process of sulfur seems to be effective if SEA is mixed with mineral aggregates.

Effect of Heating

A comparison of the viscosities of SEA, AC, and FEA at 60°C before and after TFOT heating (7 h at 140°C) is shown in Figure 12. The vertical bars indicate the ranges of viscosity after heating. It should be noted that the straight lines are used to envelop the data points plotted on the logarithmic coordinates. This suggests a certain regularity in the increase of viscosity at 60°C for SEA, AC, and FEA due to the TFOT heating condition prescribed. It is evident that, based on the original viscosity of the tested asphalt binders, aging-index values were found to vary between a minimum of 1.5 and a maximum of 4.5. The heat sensitivity of SEA does not vary substantially from that of AC and FEA under the TFOT heating conditions considered. It is assumed that if the test temperature is raised to 163°C (according to ASTM D2872) and the exposure time is changed, expected different aging-index values could result due to the effect of sulfurization, which may occur at temperatures above 150°C. Since SEA binders are not exposed during the mixing and paving operations to temperatures of more than 150°C, it was decided to look at the effects of heat and air at 140°C.

CONCLUSIONS

This study presents an evaluation of the physical properties of SEAs made with currently produced asphalt cement (60-70 penetration grade) used in Kuwait for asphalt pavement mixes. The main study objective was an evaluation of the physical properties of SEA with the emphasis on such properties as locally high pavement service temperatures compared with conventional limestone FEAs with same volume concentrations.

Test data presented in this study led to the following observations and conclusions:

1. Viscosity grading of SEA at 60°C provides a

fundamental measure of consistency for use at relatively high pavement service temperatures. It is less subject to test-imposed variables such as shear-susceptibility variations and less subject to binder-improved variables such as variations in inherent complex flow. On the other hand, penetration measurements as a control of the consistency of SEA would not be adequate to evaluate the temperature susceptibility of these binders.

2. At the average maximum service pavement temperature in Kuwait ($\approx 60^{\circ}\text{C}$), the volume concentration of sulfur needed to maintain a relative viscosity of $\eta_{\text{SEA}}/\eta_{\text{AC}} = 1$ was found to be equal to 0.21, which is equivalent to 35 percent by weight. However, at 25°C , relative viscosity values of both SEA and FEA were found to be similar. These results are only valid for the materials used locally. Asphalt cements from different sources or of other grades may have a different effect on the rheological properties of SEA.

3. The dissolved sulfur in SEA (16-18 percent) results in lowering the viscosity of asphalt cement at a range of temperature between 140°C and 40°C and in an increase of the temperature-viscosity susceptibility. However, the suspended sulfur particles in SEA showed a similar effective volume concentration compared with that of limestone filler particles with reference to the increase in viscosity at temperatures below the melting point of sulfur. It is recommended that the filler effect of suspended sulfur particles in SEA be compared with that of other types of filler materials used in asphalt mixes.

4. Viscosities of SEA at temperatures above the melting point of sulfur were found to exist at all sulfur ratios lower than that of asphalt cement and much lower than that of FEA. This characteristic of SEA has a significant effect on improving the workability of the paving mix.

5. The crystallization process of sulfur in terms of dynamic growth of the sulfur crystals seems to be effective if SEA is mixed with mineral aggregates and represents the major part of the stiffness improvement of finished pavement with age. Increase in viscosity of SEA due to increase of effective volume concentration of dispersed sulfur particles represents only a minor part of the stiffening effect.

6. In paving mixtures, at temperatures of pavement use, SEA is admixed with a variety of mineral

aggregates and forms binders varying greatly in properties from the original in bulk. The response of SEA to heating in the preparation of the hot paving mixture differs from that in the laboratory. Therefore, measurement of paving-mixture properties, rather than properties of SEA binder, appears to be a more rational approach. Generally, the responses for SEA, AC, and FEA to TFOT heating at 140°C are almost the same. The viscosity at 25°C is affected by heating more than that at higher temperatures.

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Predicting Surface Friction from Laboratory Tests

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The objective was to develop and refine methods for preevaluating aggregates and paving mixtures so that predictions can be made of properties of proposed and in-service pavement types. A usable correlation was established between the field testing by using the data from the British portable tester and the locked-wheel pavement friction trailer at speeds of 40 and 55 mph. To extend this correlation, core samples were extracted from the locked-wheel tester skid path and were subjected to wear on the small-wheel circular track with periodic surface friction testing by using the British portable tester. The final step was to remix and remold the cored pavement samples or make samples with new materials to obtain an "as-new" surface and to subject these samples again to wear on the small-wheel circular track with

periodic testing by using the British portable tester to find the British pendulum number (BPN). Other segments of the project included efforts to correlate (a) the stereophotography number (SPN) with the locked-wheel pavement friction tester skid number, (b) the SPN with BPN, and (c) the linear traverse number with BPN on the wear and polish machine. Research with various chat (chert) and limestone mixtures shows that the blend offers good skid resistance.

The objective was to develop and refine methods for preevaluating aggregates and paving mixtures so that predictions could be made of the skid-resistance