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ABSTRACT

Hot-poured bituminous sealants are typically selected based on standard, but empirical tests such as penetration, resilience, flow, and bond to cement concrete briquettes (ASTM D3405). There is, however, no indication of the pertinence of these standard tests to predict field performance. In an effort to bridge the gap between sealant fundamental properties and field performance, performance-based guidelines for selection of hot-poured crack sealants are currently being developed. A procedure to measure sealant viscosity is proposed as part of that effort. Using a sealant with an appropriate consistency at the recommended installation temperature would provide a better crack filling, and would ensure appropriate bond strength. Therefore, to ensure that sealant-crack wall adhesion is achieved and that the sealant penetrates hot-mix asphalt (HMA) during installation, a testing procedure for bituminous based crack sealant viscosity at installation temperature is suggested. This paper proposes the use of a rotational viscometer to measure the viscosity of hot-poured crack sealant materials. Based on the results of this study, the measured viscosity of hot-poured crack sealant using SC4-27 spindle at 60rpm at the recommended installation temperature is reasonably representative of sealant viscosity at shear rates resembling field application. To ensure measurement consistency and stability, a 20min melting time and a 30-s waiting time prior to data collection are recommended. The repeatability of the measurements was acceptable with an average coefficient of variation less than 5%. Variability between operators and variability between sealant samples were acceptable.

Keywords: viscosity, crack sealant, shear rate, non-Newtonian fluid.

INTRODUCTION

Crack sealing and filling is the most widely used maintenance activity for in-service pavements (*1*). This preventive maintenance activity is particularly favored among pavement agencies because it is inexpensive, quick, and well-proven to delay pavement deterioration caused by other mechanisms, such as weakening of sub-grade and aggregate layers caused by water infiltration and stripping of hot-mix asphalt (HMA) layers. If an appropriate sealant material is properly installed at the appropriate time of the pavement life, it retards pavement deterioration and increases its service life at a relatively low cost. To ensure a cost effective crack sealing/filling operation, several factors that affect the field performance of crack sealants have to be controlled.

Although, ASTM and AASHTO standards are used to classify sealing/filling materials, these specifications do not provide a good indication of field installation and performance. These tests are empirical and their measured values are not based on the material's rheological properties. Therefore, it is thought that the most promising method to evaluate the performance of sealing/filling materials is through field evaluations. However, even results from field tests are sometimes controversial since a sealant can perform well in one site and fail in another mainly because of differences in environmental conditions.

In addition, proper crack sealant application is important to ensure adequate performance of the material throughout its service life. Although poor preparation and cleaning of routed cracks is a major contributor to early failure, crack sealant installation directly affects its adhesive, bulk, and aging properties; especially during its short-term service life. For optimum performance, a sealant should penetrate into HMA, fill the crack wall voids, and follow the surface irregularities. Adequate initial bonding to crack walls is critical to long-term sealant performance. Concurrently, a sealant should not experience high flow at high temperature under pressure from tires after being in-service. Therefore, laboratory-measured parameters indicative of the expected success of the installation need to be specified and adopted.

Although it is acknowledged that crack-sealant viscosity has a significant impact on the success of installation (*2, 3*), the research efforts to quantify the effect of viscosity at application temperature on its performance have been limited. Due to its quick and reliable measurement, viscosity has long been used as a quality control parameter for asphalt binder and to determine mixing and compaction temperatures for HMA. Despite its ease of measurements, viscosity is also one of the most sensitive rheological properties and is influenced by parameters such as aging, molecular weight and distribution, and temperature. Therefore, it may be used effectively to characterize factors such as processability and material consistency. In addition to quality control, such measurements can be used to regulate and monitor installation, and to quantify the impacts of undesirable effects such as overheating.

Hence, the objective of this paper is to present a suggested laboratory procedure to effectively measure the viscosity of hot-poured bituminous crack sealants at conditions indicative of field installation.

BACKGROUND

Viscosity is a fundamental rheological property defined as the resistance of fluid to flow. In general, two rheological behaviors are encountered when dealing with viscosity measurements: Newtonian and non-Newtonian. A Newtonian fluid has a viscosity that is independent of shear rate. On the other hand, a non-Newtonian fluid is defined as a material in which the ratio between shear stress and shear strain rate is not constant. For non-Newtonian fluids, the measured viscosity is called the "apparent viscosity" and is only accurate when experimental parameters are set and adhered to. Non-Newtonian flow may be regarded as a fluid in which the molecules' size, alignment, shape, and cohesiveness change with the amount of force applied.

In general, two major types of non-Newtonian flow behaviors may be encountered, characterized by the way a fluid responds to change in shear rate. Pseudoplastic (shear thinner) fluid is characterized by a decrease in viscosity with the increase in shear rate. In contrast, dilatant (shear thickener) fluid is characterized by an increase in viscosity with the increase in shear rate. Another common Non-Newtonian rheological behavior that may be observed with hot-poured crack sealant material containing heavy filler is the Bingham plastic behavior. In this case, the fluid behaves as a solid (no flow) unless a stress greater than the yield stress is applied. Once the yield value is exceeded, plastic fluids may display a Newtonian, pseudoplastic, or dilatant flow behavior.

The viscosity of asphalt binder increases with the addition of rubber. Rubber-modified asphalt binder resistance to loading increases with the increase in rubber content (*4*). At low shear rates, it exhibits shear-thickening behavior, while at high shear rates, shear thinning behavior is usually observed. The degree of shear thinning or thickening behavior decreases as the amount of rubber content increases (*4*). However, the extent of shear thinning at any given shear rate is dependent on the shear history and the duration of shear stress application (*5*). In addition, viscosity usually decreases as shear rate increases.

The effect of temperature on viscosity is equally important. Viscosity usually decreases as temperature increases (*3, 5*). In more general terms, viscosity of Newtonian liquids decreases as the free volume in the liquid increases. Free volume is related to the difference between the current temperature and the glassy temperature (T_g) of the fluid; therefore the factors that govern T_g also affect viscosity. Hence, structural parameters such as chain rigidity and molecular weight affect measured viscosity (*4, 6*). It should be noted that the influence of molecular weight on T_g levels off at high molecular weight, while the influence of molecular weight on viscosity does not (*6*).

A rotational viscometer is usually used to measure binder viscosity. The coefficient of viscosity is determined based on the measured torque necessary to rotate a spindle at a constant speed. Based on a review of available viscometers, the Brookfield Thermosel viscometer and temperature control system (Figure 1), currently part of the SuperPave™ specification system, was selected for this study. The Brookfield Thermosel viscometer consists of a motor, spindle, control keys, digital readout, and temperature controller. The Thermosel system is specifically designed for viscosity measurement of small samples (8 to 13ml) in the temperature range of approximately 40 to 300°C. Many sizes and shapes of spindles are available. The process of selecting a spindle for an unknown fluid is based on trial and error. An appropriate selection will result in measurements between 10 and 100 on the instrument percentage torque scale. The SuperPave™ binder specification system recommended the use of the coaxial cylindrical SC4-27 spindle, which allows for a wide-range of shear rates (from 0.08 to 93.0s^{-1}) in the test. The appropriate spindle size was evaluated in this study and is defined later in this paper.

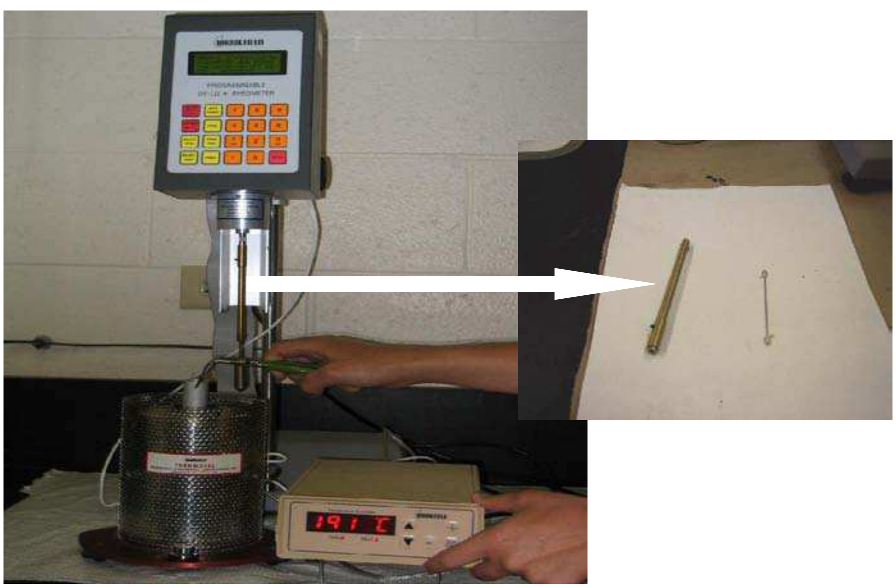

Figure 1. The BrookField Thermosel system, rigid and regular rods used in viscosity testing of crack sealants and asphalt binder, respectively.

Viscosity Measurements of Crack Sealants

Sealant viscosity during application is thought to have a significant impact on its performance. However, the effect of viscosity on sealant performance has yet to be quantified, as studies on sealants have been more qualitative and empirical in nature. For instance, Chehovits and Manning reported that a viscosity less than 7Pa.s at application temperature led to sealant self-leveling, easy pumping, and adequate penetration in cracks less than 9.5mm wide (*2*). Masson and Lacasse also reported that the filling of microvoids significantly depends on the sealant viscosity (*3*), emphasizing that a low viscosity sealant may wet and fill microvoids effectively, whereas sealants with high viscosities may not be as effective. More recently, Masson *et al.* showed that low sealant viscosity during installation was beneficial to performance (*5*). They indicated that sealants with viscosity less than 10Pa.s were self-leveling and could be easily installed, and those with viscosity greater than 30Pa.s were undesirable because it led to difficulties in pouring (*3, 5*).

Zanzotto measured the viscosity of various hot-poured crack sealants with known field performance at a temperature of 190°C. He reported that the poorest observed field performance was associated with the crack sealants having very low or very high viscosity (*8*). Therefore, an upper and lower limit should be defined to ensure sealant flows properly and produce good bond with the crack walls. Not very low to cause the sealant to flow out of the crack, and not very high to clog the crack opening before getting into it. In general, Zanzotto recommended that the maximum permissible viscosity should be set at 3Pa.s (*8*). Table 1 presents the suggested viscosity thresholds based on the results of a few studies. As can be noticed, discrepancies exist among the recommended thresholds.

TABLE 1. Suggested Viscosity Thresholds.

Authors		Viscosity Limits (Pa.s)	
		Lower	Upper
Chehovits and Manning (1984)	Application	----	7.0
Zanzotto^ (1996)	190.0	----	3.0
Masson et al. (2000, 2002)	Application	----	10.0

^ Acknowledged the importance of a lower limit to prevent flow of the sealant out of the crack.

EXPERIMENTAL PROGRAM

Various factors may affect the measured viscosity of hot-poured crack sealant. Before setting limits on the measured viscosity, it is essential to identify the material characteristics that influence the rheological behavior of hot-poured crack sealant. These characteristics would need to be set at reasonable limits to simulate field installation as closely as possible. In general, responses of crack sealant were found to be quite complex due to the relatively high polymer content. In the case of a non-Newtonian fluid, Schweyer showed that the rheological behavior could change from pseudoplastic to Newtonian and dilatant as the shear stress is increased (*8*). Since hot-poured crack sealants behave as non-Newtonian fluids, variations in the experimental parameters (equipment, spindle speed, temperature, sealant type, and container size) in the aforementioned research studies led to inconsistency in the recommended viscosity limits for hot-poured crack sealant. Alternatively, adherence to a test setup and testing parameters would ensure that results are consistent.

The experimental program was designed to evaluate the effects of the aforementioned parameters on the measured viscosity. Three sealants were selected: The expected softest and the stiffest sealants along with a medium-stiffness sealant. These sealants were labeled BB, QQ, and NN, respectively. Unless otherwise noted, the installation temperature recommended by the manufacturer was used as testing temperature (193°C for sealants BB and QQ, and 185°C for sealant NN). The sealants were tested inside a 19.05- mm-diameter container. Each sealant was tested in four replicates. Although several testing parameters were modified, the specified procedure by AASHTO TP48-96 was followed as a general guideline.

Field Conditions at Installation

Laboratory conditions should simulate sealant installation conditions as closely as possible. In the field, the sealing operation consists of installing sealant materials into routed and cleaned reservoirs or cracks in flexible pavements. A thermosel unit is typically used to change the sealant materials from the solid state to the liquid state and to ensure thermal consistency of the sealant during application. When sealant reaches the recommended application temperature, it is then applied to the crack through a pump-fed applicator wand and nozzle.

A critical issue in this research was to determine the shear rate imposed on the material during application. In the field, an application wand with an inner diameter ranging from 19.05 to 25.4mm is commonly used. A nozzle with an inner diameter of 12.7mm is then connected to the wand to allow for higher precision during sealant application. The sealant application-rate, which depends on the depth of the crack, ranges from 63cm^3/s for shallow cracks to 378.5cm^3/s for deep cracks. Assuming a steady flow and no slippage at the wall, it can be shown that the shear rate for a Newtonian fluid can be calculated as follows (*9*):

$$\dot{\gamma} = \frac{4Q}{\pi R^3} \tag{1}$$

where,

$\dot{\gamma}$ = shear rate (s^{-1});
Q = volumetric rate (cm^3/s); and
R = inner radius of the pipe (cm).

Using Equation (1), the shear rate imposed on the material during installation was calculated (Table 2) and the corresponding spindle speed, using spindle SC4-27, was determined as follows:

$$\dot{\gamma} = k\nu \tag{2}$$

where,

k = spindle constant;
$\dot{\gamma}$ = shear rate at the surface of spindle (s^{-1}); and
ν = velocity of the spindle (rpm).

The results presented in Table 2 are for two pipe diameters with and without an end-nozzle. As shown in the table, a spindle speed ranging from 115 to 5536rpm should be used to simulate the shearing of the sealant as it enters the crack during installation. However, a significant reduction in the shear rate may occur as the sealant exits the applicator wand due to the sharp temperature drop, as well as the high friction with the crack walls. It has been shown that a drop of more than 50^{o}C could occur as the sealant enters the crack. In addition, an important factor that may affect the selection of the spindle speed is the stability of the measurements at the selected speed along with their repeatability. Although the SuperPave™ currently adopted Brookfield Thermosel system is not a high-shear rheometer, the maximum allowable spindle speed is 250rpm, after extensive testing, it has been proven to be sufficient for sealant testing as presented below.

TABLE 2. Shear Rate and Corresponding Spindle Speed for Different Application Rates and Pipe Diameters

	Shear Rate (s^{-1})			**Spindle Speed (rpm)**		
D (mm) Q (cm^3/s)	12.7	19.05	25.4	12.7	19.05	25.4
63	314	93	39	923	273	115
378.5	1882	558	235	5536	1640	692

Spindle Size Selection

If the spindle radius is decreased while all other parameters are kept constant, the shear strain would increase; and therefore, the viscosity would decrease. All sealants were originally tested twice using two different spindles: SC4-29 (7.6-mm-diameter) and SC4-27 (11.76-mm-diameter). A comparison of the resulting measured viscosities is presented in Table 3. It appears from these measurements that the SC4-29-spindle results in smaller viscosities than the SC4-27-spindle. For the three sealants, the average coefficient of variation (COV) for the SC4-29-spindle was 4%, while the average COV for the SC4-27-spindle was 3%. In general, results for the SC4-27 spindle were more repeatable. Hence, the SC4-27-spindle was adopted in this study. As previously mentioned, the SuperPave™ binder specification system also selected the SC4-27 spindle.

TABLE 3. Sealant Viscosities Using Different Spindles

		Average (Pa.s)	**Average (Pa.s)**	**COV (%)**	**COV (%)**
		#29 Spindle	**#27 Spindle**	**#29 Spindle**	**#27 Spindle**
BB	193	1.075	1.752	5.30	3.60
NN	185	4.877	6.102	3.76	1.73
QQ	193	4.975	5.108	2.97	3.90

Sample Preparation

Homogenized sealant prepared in accordance with ASTM D5167 (Practice for Melting of Hot-Applied Joint and Crack Sealant and Filler for Evaluation) was adopted. Such a procedure usually results in a homogenized beam with a cross-sectional area no greater than 25x25mm. The sealant was obtained from the homogenized beam by cutting small vertical pieces. These vertical pieces were then cut into cubes with a cross-sectional area less than 5x5mm. The sealant cubes should be small enough to be inserted into the Thermosel sample chamber without adhering to the edge of the container. This process was repeated until a sample weight of 10.5±0.1g was obtained. No sealant is lost to the sides of the container during sample preparation when this procedure is followed. The tested sample weight would, therefore, remain constant.

Instead of the regular soft rod regularly used in the testing of asphalt binders, a rigid rod was used to connect the rotating shaft to the spindle (see Figure 1). The use of a rigid rod allowed for a firm grip between the spindle and the rotating shaft and prevented the rubber particles from interfering with the spindle rotation. The repeatability of the test was significantly improved when the rigid rod was used. For example, the coefficient of variation for the viscosity test of sealant QQ was reduced from 18.5 to 5.5% when the rigid rod was used. A sample chamber was then placed into the Thermosel at the desired testing temperature, which was the installation temperature recommended by the manufacturer.

Waiting Time before Viscosity Measurement

Due to the initial acceleration of the spindle, the Brookfield viscometer may provide inaccurate viscosity readings during the first few seconds of the test. The time required to reach constant viscosity readings depends on the equipment, the spindle type, size and speed, and the sealant viscosity. On the other hand, although a stable viscosity is desired, the elapsed time during installation is usually very short. To investigate balancing these two factors, and to ensure repeatable measurements while simulating field pumping, sealants BB, QQ, and NN were evaluated.

Figure 2 shows viscosity results after different waiting times; the results are the average of four replicates. A 95% confidence interval was also built around the average of each sealant viscosity. As shown in the figure, it appeared that the viscosity for all tested sealants stabilized after 5 to 10s of spindle rotation. If a long waiting time is specified to stabilize the viscosity, the measured viscosity would not be representative of field installation. In contrast, if a short waiting time is specified the viscosity may not be repeatable, especially for sealants containing heavy rubber. To balance these two effects, a 30 s waiting time was suggested.

The selected waiting time is significantly shorter than the 120s specified by the SuperPave™ binder specification system. The difference in the waiting time is due to two major factors. First, the mixing and pumping operation in HMA is a lengthy process and requires a much longer waiting time to simulate field conditions. For ease of operation and specification purposes, the waiting time in SuperPave™ was not selected to simulate field conditions, but was only controlled by the repeatability of the measurements.

Second, as presented in the following sections, the recommended spindle speed during testing of a hot-poured sealant is much faster than that for a binder (60 vs. 20 rpm). This results in a faster stabilization of the measurements.

Effect of Spindle Speed

To determine the rheological behavior of hot-poured sealant, viscosity measurements were conducted at different spindle speeds. The test was conducted using increments of 5rpm for spindle speeds ranging from 2 to 122 rpm; conducting frequency sweeps was time consuming, in excess of 4h per test. Based on the average of four replicates, the variation of viscosity with the spindle speed is shown in Figures 3(a and b) for sealants BB, NN, and QQ. Testing results suggest that the measured viscosity experience two distinct regions of rheological behavior (Regions I, II,).

In Figure 3a, the viscosity of the tested crack sealants initially decreased with the increase in shear rate to a certain value (shear thinning – Region I). The measured viscosity then stabilized (Newtonian flow – Region II). Sealants QQ, NN, and BB seemed to stabilize at viscosity of approximately 4.0, 4.5, and 1.2Pa.s, respectively. The viscosity of sealant BB appears to be independent of the shear rate.

To evaluate the rheological behavior of the tested sealants, it is also essential to consider the relationship between shear rate and shear stress throughout the course of the experiment. For a Newtonian fluid, this relationship should be linear. In contrast, for a non-Newtonian fluid, this relationship should deviate from linearity. Figure 3b presents the relationship of shear rate to shear stress for the three crack sealants. The relationship between shear rate and shear stress is linear with a coefficient of determination (R^2) greater than 0.99. However, one may notice, from the results shown in Figure 3b, that most of the measurements for sealants NN and QQ were slightly above the linearity line, indicating that the crack sealants exhibit shear thinning (non-Newtonian behavior) with the increase in shear rate.

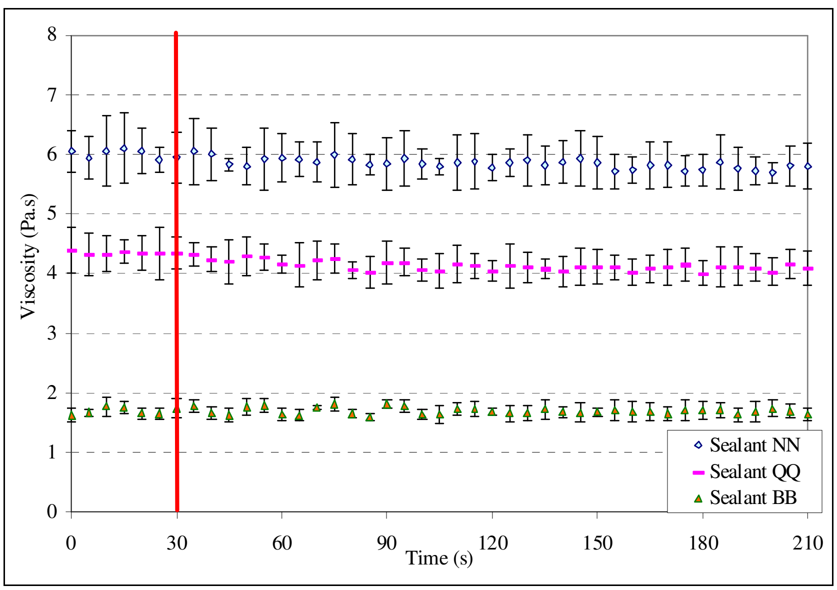

Figure 2. Elapsed time requirement prior to recording data.

Effect of Speed Reversal

Frequency sweep tests on different sealant samples were conducted in ascending and descending speed orders to evaluate changes that may occur to the molecular structure throughout the test. Figure 4 shows the result of this test for sealant NN. Regardless of the speed order, the crack sealant viscosity decreased with the increase in shear rate (shear thinning). In addition, there was no major difference between the two tests, which indicates that the molecular structure of the sample change is identical with the increase in shear rate regardless of speed order. The change in viscosity with the increase in speed may indicate that some of the shear deformation experienced in the viscosity test is not recoverable. Hence, it is critical to ensure that the specified test setup and procedure are followed and that the shear history of the samples is kept identical for all tested sealants. Based on the results of the spindle speed and the speed reversal effects on measured viscosity, sealant viscosity testing is recommended at 60rpm.

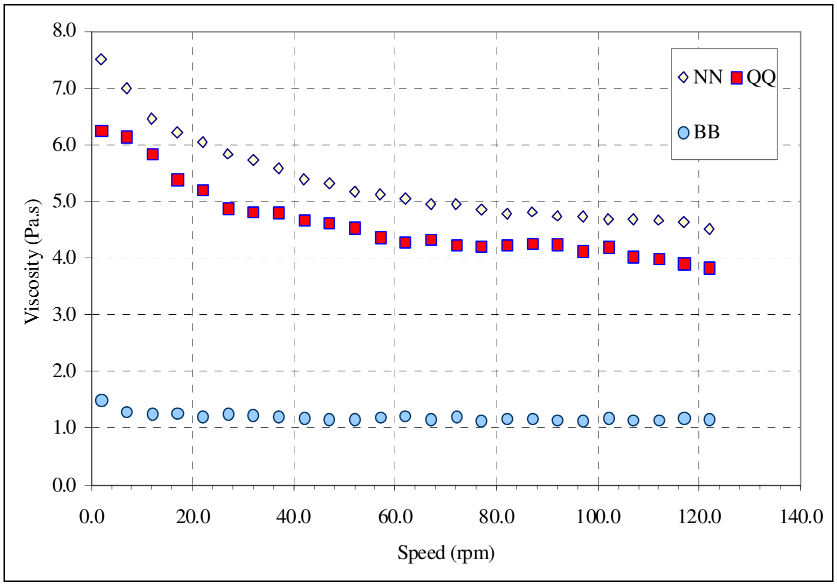

Figure 3-a. Results of frequency sweep tests at a spindle speed between 2 and 122rpm.

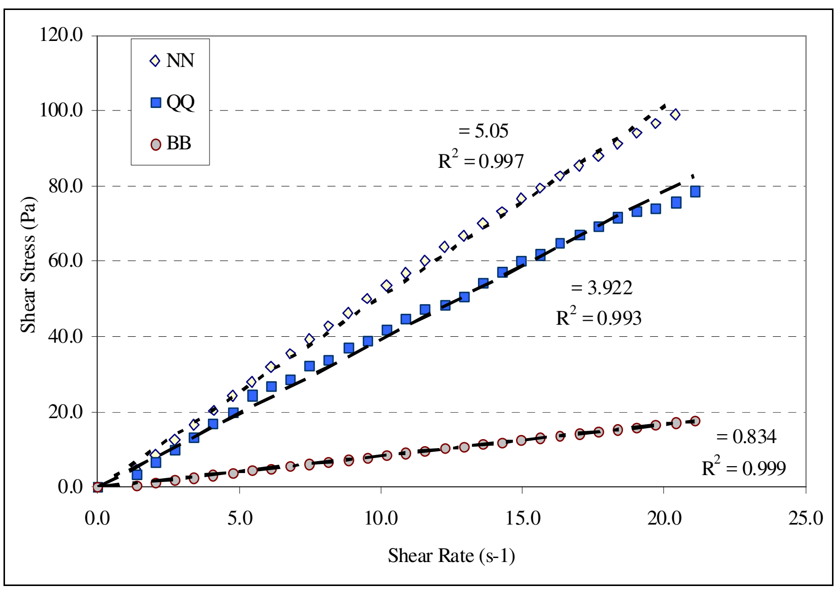

Figure 3-b. Shear stress-shear rate relationship for three crack sealants.

Effects of Temperature Fluctuation during Installation

The temperature susceptibility level significantly affects field performance (*3*). Modified asphalt binders tested at low temperatures and low shear stresses generally exhibit pseudoplastic or Bingham plastic behavior, while shear thickening (dilatant) is often observed when tests are done at intermediate to high temperatures using fairly high stress levels (*8*). Therefore, deviation from the installation temperature recommended by the manufacturer may significantly affect sealant performance. It has been reported that contractors may sometimes overheat sealant in the kettle because either the temperature is not accurately controlled or the flow of the sealant is interrupted for periods exceeding 15min (*10*). To quantify the impact of temperature fluctuation on the applicable viscosity during placement, six sealants were tested at the recommended installation temperature and at ±10°C.

Figure 5a presents the estimated percentage drop in viscosity resulting from 10°C increase above the installation temperature recommended by the manufacturer. As a reference for each sealant, the numbers above each column represent the viscosity measured at the recommended installation temperature. It is evident from these measurements that the effect of temperature on viscosity varies greatly among sealants. Low viscosity sealant may become excessively fluid, and may start flowing through the crack without adhering to its walls. Similarly, Figure 5b presents the percentage increase in sealant viscosity due to 10°C drop below the recommended installation temperature. The resulting undesirable behavior is an excessively high viscosity sealant during installation. For example, should the installation temperature drop by 10°C for NN, the sealant may not flow properly and adhere to the crack wall (knowing that the sealant temperature drops by as much as 50°C in the crack).

It is imperative to emphasize that the measured viscosity is affected by container size, spindle geometry, testing temperature, sample preparation, spindle speed, and shear history. Hence, the following procedure and equipment are suggested to determine a sealant's "apparent" viscosity.

TESTING PROCEDURE

The viscosity of sixteen sealants was measured. The rational used in selecting these products was the availability of field performance data, being the hardest or the softest sealant, or extreme rheological behavior. All sealants were tested at manufacturer recommended installation temperatures in four replicates. The results in Table 4 show that:

- Recommended installation temperature varies greatly amongst different products, ranging from about 150°C to 195°C.
- Results were repeatable and reliable. The average coefficient of variation for all tested sealants was 4.1%, with a minimum of 1.5% and a maximum of 8.9%.
- The lowest viscosity was 0.5Pa.s for sealant AD and the highest viscosity was 7.0Pa.s for sealant YY.

TEST VARIATION

Following the recommended testing procedure, the Brookfield DV-III Thermosel viscometer showed acceptable repeatability for all tested sealants, with an average coefficient of variation less than 5%. Statistical analysis was conducted to estimate variability between operators and sealant samples. The repeatability of the results of the viscosity test for the same sealant was acceptable with an average coefficient of variation at 4.1%. However, it has to be emphasized that the control of several factors is essential to ensure repeatability of the measurements:

- The variability of the viscosity test is dependent on the homogeneity of the sealants, especially with products containing a high percentage of rubber and filler. The procedure highlighted in ASTM D5167 (Practice for Melting of Hot-Applied Joint and Crack Sealant and Filler for Evaluation) was used in this study to ensure homogeneity of the tested sealants and is recommended.

- The measured viscosity is dependent on the shear history. Pretreatment must be consistent and uniform for the sealants tested.
- Viscosity is highly influenced by temperature; hence, an actual temperature control is needed. In fact, previous researchers have recommended a temperature control within 0.02°C for good reproducibility of results (*11*). To achieve good reproduction of the results, it is recommended to ensure that the Thermosel temperature is within ±0.1°C of the testing temperature.

As recommended by ASTM C670-87 Standards, the precision of individual viscosity measurements needs to be checked. The maximum acceptable range for individual measurements is obtained by multiplying the standard deviation of the measurements by a factor reflecting the number of replicates. For three and four replicates, this factor is 5.9 and 7.4, respectively.

To evaluate the data variability between the operators, two operators tested sealants BB, NN, and QQ individually. A standard Analysis of Variance (ANOVA) was conducted to check whether the results of the two sets of testing were statistically different, Table 5. The results show no statistical evidence that the measured viscosity was different at a level of significance of 5%.

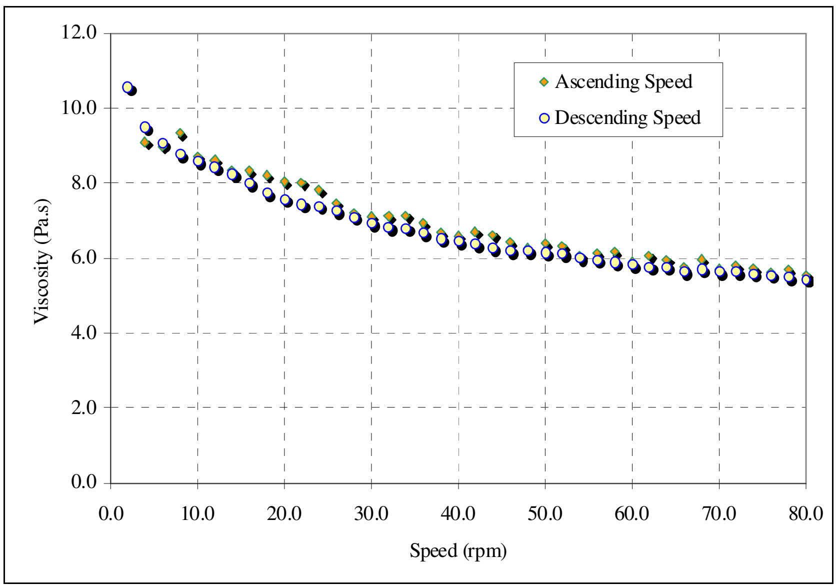

Figure 4. Viscosity variation with ascending and descending spindle speed for NN sealant.

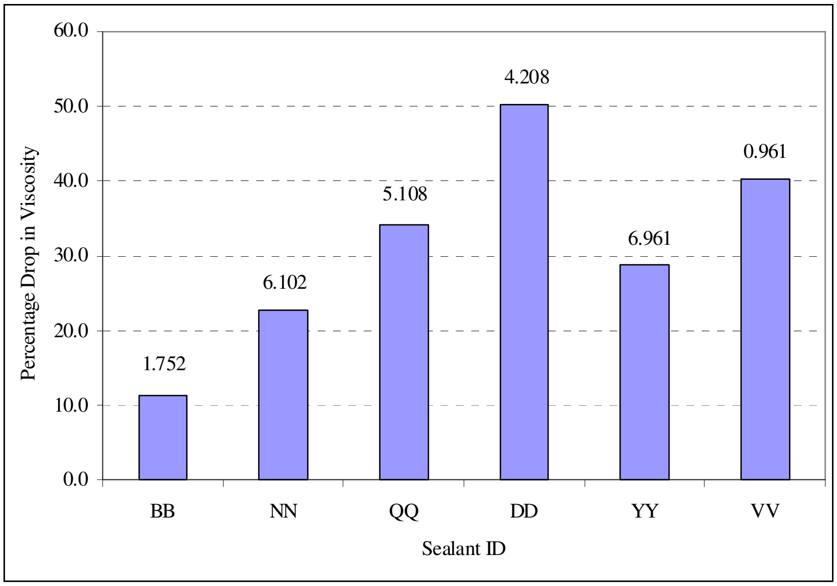

Figure 5-a. Percentage drop in viscosity due to 10°C increase in testing temperature.

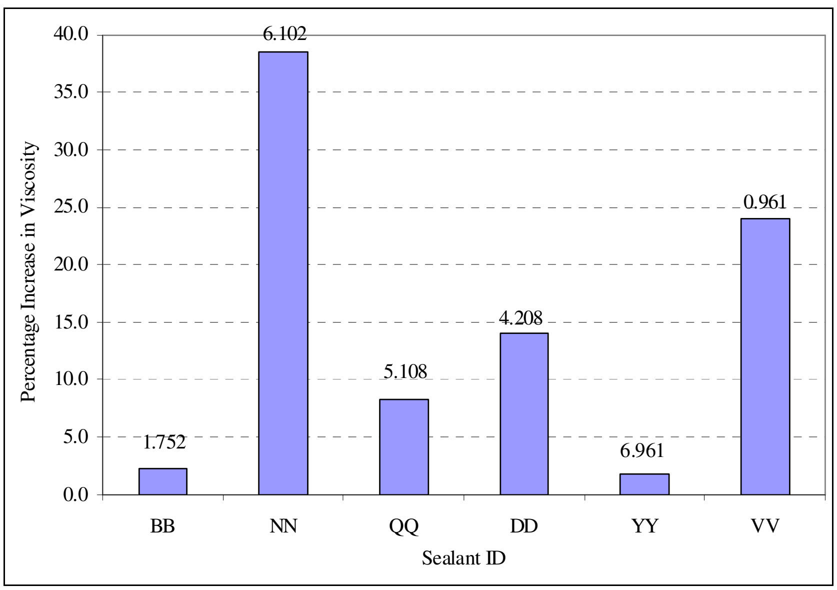

Figure 5-b. Percentage increase in viscosity due to 10°C drop in testing temperature.

TABLE 4. Viscosity Testing Results of 16 Selected Sealants

		Viscosity					
		Sample 1	Sample 2	Sample 3			
BB	193	1.825	1.725	1.708	1.753	0.063	3.60
DD	193	4.358	3.992	4.275	4.208	0.192	4.57
MM	170	1.642	1.700	1.633	1.658	0.036	2.19
NN	185	6.475	6.025	6.567	6.356	0.290	4.56
PP	193	3.042	3.000	2.950	2.997	0.046	1.53

VV	149	0.967	0.983	0.933	0.961	0.025	2.65
WW	188	2.558	2.667	2.500	2.575	0.085	3.28
AD	188	0.442	0.500	0.442	0.461	0.034	7.30
AE	189	1.567	1.717	1.633	1.639	0.075	4.59
UU	193	2.625	2.475	2.500	2.533	0.080	3.17
EE	193	1.783	1.742	1.858	1.794	0.059	3.29
QQ	193	4.883	4.875	4.417	4.725	0.267	5.65
YY	177	7.000	7.567	6.317	6.961	0.626	8.99
ZZ	193	4.058	4.350	4.058	4.156	0.168	4.05
AB	177	5.908	6.183	5.925	6.006	0.154	2.57

TABLE 5. Analysis of Variance between Operators

Sealant	*SS*	*dof*	*MS*	*F*	*P-value*	*F crit*
NN	95845.75	1	95845.75	2.01	0.228	7.708
QQ	220416.7	1	220416.7	3.97	0.117	7.708
BB	5601.852	1	5601.852	1.21	0.333	7.708

SUMMARY

This study concluded that the measured viscosity of hot-poured crack sealant at a spindle speed of 60rpm at the recommended installation temperature is reasonably representative of sealant viscosity at shear rates resembling field application. This viscosity is termed "global apparent viscosity" and is expected to be an acceptable indication of the sealant rheological behavior throughout the total shear rate spectrum, given that the suggested procedure and equipment are used. A melting time of 20min and a waiting time of 30s before collecting data are also recommended to ensure that the measured viscosity has stabilized. Since viscosity plays an essential role in field performance of hot-poured crack sealant, thresholds (upper and lower limits) for crack sealant viscosity have to be identified after the completion of an ongoing study on sealant adhesion.

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