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Low Temperature Characterization of Hot-Poured Crack Sealant Using Modified SHRP Direct Tensile Tester

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ABSTRACT

The current specifications for selecting crack sealants correlate poorly with actual field performance. In order to address this issue and assist in predicting the low temperature properties of hot-poured bituminous crack sealants, a modified Direct Tensile Tester (DTT) method has been developed. Sample geometry is modified in order to accommodate testing sealants. A sensitivity analysis considering various loading rates, sample lengths, and cross-section areas was conducted to define both optimized specimen geometry and testing protocol. Two types of sealants, having a wide range of rheological behaviors (one polymer-modified and one having crumb rubber), were tested at low temperature. Results showed that the rich polymer-modified sealant has a high resistance to failure compared to the sealant with crumb rubber modified. Each sealant was tested at the lowest corresponding expected service temperature. A performance parameter, strain energy density, was proposed in order to differentiate crack sealant material in the laboratory.

Keywords: Direct Tensile Tester, Crack Sealant, Toughness

INTRODUCTION

ASTM standard D5535 defines a sealant as a material that has both the adhesive and cohesive properties to form a seal which works as a barrier to prevent liquid and solid penetration into the pavement system. Crack sealing has been widely accepted as a routine preventative maintenance practice. Hence, after proper installation, the sealant must be capable of withstanding crack movement, degradation, and weathering. Crack sealants usually fail in one of two mechanisms at low temperature: cohesiveness or adhesion. The former occurs in the sealant, while the latter occurs at the sealant-pavement wall interface. At low temperatures, the sealant becomes more brittle due to physical hardening. At low temperatures, the hardened sealant is subject to short-duration loading, such as crack movements associated with stick-slip motions and truck trafficking, along with long-period environmental loading.

Over the past two decades, a new generation of highly modified crack sealants has been introduced to the market (1). These sealants exhibit quite complex behavior compared to those of traditional sealant materials (2). However, the current specifications widely adopted by state DOTs or sealant manufacturers, ASTM D6690, measure the consistency of the sealant rather than its fundamental properties. Hence, the current specification correlates poorly with field performance. Some sealants that provided superior field performance were ranked equally with those sealants that performed poorly. This inconsistency between field performance and the current specification system has been widely reported in the literature (3). Therefore, there is a definite need to develop a performance-based specification to select sealants.

After acknowledging the deficiencies of the current specification system, more than 26 State and Province departments of transportation, manufacturers, cities, and research agencies in North America have partnered to develop performance-based guidelines for selecting bituminous-based hot-poured crack sealants. The aim of this study was to make use of the current methods and equipment developed during the five-year Strategic Highway Research Program (SHRP) as part of the Performance Grade (PG) system for asphalt binders. As part of the study, the SHRP direct tensile tester (DTT) was modified and then utilized to characterize the performance of hot-poured bituminous-based crack sealants at low service temperatures. This modification was done to accommodate the testing of crack sealants, which typically experience significant deformation during the winter season.

The objective of this study was to evaluate the mechanical properties of hot-poured bituminous-based crack sealants using the modified DTT at low temperatures. Two types of sealants are evaluated: polymer-modified sealant and sealant containing crumb rubber. Modifications to the current DTT include tensile loading rate and size of the specimen. In this paper, an indicator of sealant performance at low temperatures is presented. The criteria used to select this indicator include the ability to describe the mechanical behavior of the sealant at low temperatures, and ease of measurement and calculation. The paper also presents a methodology to correlate the rate of crack movement to the laboratory sample loading rate.

BACKGROUND ON CRACK MOVEMENT

Typically, there are two types of crack movement in the pavement: vertical and horizontal. The vertical movement primarily results from traffic loading on working cracks and the horizontal movement is primarily due to thermal expansion and contraction of the pavement. If the stress inside the sealant builds up during loading, it may ultimately fail. In a viscous material, rapid crack movement can result in a faster sealant failure than slow crack movement. Therefore, crack movement rates should be considered in any sealant testing protocol.

Many research studies have conducted measurements to evaluate horizontal crack movement (3-6). However, few attempts have been made to measure vertical crack movement because of the difficulties posed. Masson and Lacasse measured the opening that occurred over the period of one year in various routed cracks in the City of Montreal (4). The treated cracks were in hot-mix asphalt (HMA) overlaying concrete pavements and were exposed to air temperatures ranging from -40°C to 40°C . As shown in Table 1, transverse cracks could extend up to 16% per year. In general, crack movement is governed by crack direction with respect to traffic loading as shown in Table 1. Transverse cracks are more prolonged to open than the longitudinal ones.

As a part of the Strategic Highway Research Program (SHRP), Smith and Romine conducted a study to evaluate the performance of different materials used to seal transverse and longitudinal cracks (3). The experimental program utilized 15 various sealants (hot- and cold-applied), which were placed in five different sites: Abilene, Texas; Elma, Washington; Wichita, Kansas; Des Moines, Iowa; and Prescott, Ontario. In this study, horizontal crack movements were measured. The study suggested that crack movement was affected by crack configuration (longitudinal versus transverse) and pavement design. Average crack movement, percentage crack extension, and the rate of crack movement at different locations are presented in Table 2.

Linde reported an extensive study on measuring crack movements in various airport and highway pavements in Sweden (5). A summary of data from five airports is presented in Table 3. The study results include the following: (1) short-term measurements (up to 24hrs) yield an average crack movement of approximately $4 \times 10^{-2} \text{ mm}/^{\circ}\text{C}$ or $10^{-3} \text{ mm}/\text{min}$; (2) long-term measurements yield an average crack movement ranging from 0.4 to $1.25 \text{ mm}/^{\circ}\text{C}$ or 5×10^{-5} to $8 \times 10^{-4} \text{ mm}/\text{min}$; (3) the largest crack movement from a reference point was 25mm over approximately 100 days; (4) the reference point does not return to its zero position; the reference point moved as much as 5mm during four years; and (5) crack movements ranged from 0.12 to 0.17mm per meter of crack/joint spacing.

In a study comprising three different sites, pins and PK nails were installed to measure the crack opening (6). As predicted, it was found that most cracks opened up as temperature decreased and closed as temperature increased. However, some crack movements did not follow this expected pattern and barely moved when the temperature changed. The maximum reported crack extension was 2.5mm, which is equivalent to 100% extension. In general, crack extensions varied from 6% up to 100% and the rate of crack movement varied from 0.0004 to 0.04%/min.

Current ASTM specifications used by most state agencies have shown a poor correlation with field performances because the specifications are based on empirical tests (6). Hence, it is imperative to develop a mechanical test to predict the field performance of crack sealant due to its movement. Uniaxial tensile extension, at a constant rate and temperature, is believed to be the most appropriate test to achieve this goal.

DIRECT TENSION TESTER

The Direct Tensile Tester (DTT), which was originally introduced in 1992 as part of the original SuperPave binder specification system, is used to measure the tensile failure properties of asphalt binder at low in-service temperatures according to AASHTO T-314 and ASTM D6723. After several modifications, a new SuperPave DTT was introduced in 1995. This new system, which is compact compared to the original system, utilizes a fluid-based temperature control system, and is reported to produce accurate results (7).

The equipment applies a constant strain rate on a dog-bone specimen supported from one end. The deformation at the specimen end is measured using a linear variable differential transducer (LVDT). In addition to deformation, the load and temperature during the test, are also measured and acquired by the equipment's data acquisition system. To control the testing temperature, a fluid bath reservoir, made of stainless steel and insulated with high-density foam backing, is used. A re-circulating chiller allows the bath temperature to go as low as -40°C , with a stability of $\pm 0.1^{\circ}\text{C}$. During the test, the dog-bone-shaped specimens are pulled till rupture occurs or until the maximum traveling distance is achieved. The original SuperPave specimen has a total length of 40mm with an effective length of 33.8mm and a cross-section of 6x6mm.

For the purpose of characterizing sealant materials, which usually undergo up to 100% elongation in the field, the dimensions of the original specimen have been modified to achieve the maximum strain level during service. The modified geometry was also found to be more effective in preparing the specimen. Two modifications were made to the specimen geometry: shortening its length and decreasing its thickness. The effect of these two modifications is discussed in this paper.

GEOMETRY OPTIMIZATION

Although sealant in the field may experience up to 100% strain, typical DTT specimens may not travel more than 32% because of current equipment limitations. To simulate field crack movement, only a smaller-size specimen may be needed in DTT testing. To examine the feasibility of using a relatively small-size specimen, a finite element (FE) analysis was conducted to determine an optimal specimen size. The optimal specimen size must meet two criteria: uniform stress distribution within the specimen web as well as ease of specimen preparation. In the FE analysis, 10 specimen sizes were evaluated. Each specimen was fixed at one end and a displacement rate was applied at the other end at 1mm/min. Results of the FE quasi-static analysis were obtained for each specimen's geometry. Figure 1a shows the calculated tensile stress distribution in a specimen having the following dimensions: 20mm flange width, 18mm web length, and 40mm total length.

The finite element analysis showed that a specimen, having a 14mm flange width, 12mm-long web, and an overall length of 24mm, met the aforementioned criteria and was the optimum size (Figure 1b).

EXPERIMENTAL PROGRAM

The procedure used in this study follows AASHTO TP3-97. Two types of sealants were selected to be used in the study: crumb rubber-modified and sand polymer-modified sealants. The crumb rubber-modified sealant, identified as YY and ZZ, is a highly viscous sealant which is formulated by asphalt binder mixed with vulcanized, granulated crumb rubber. The rubber particle is usually greater than 100 μ m. The lowest service temperature for the rich rubber-modified sealant is between 0 to -10°C. The polymer-modified sealant, identified as AD, BB, NN, PP and WW, is typically formulated with high percentages of polymer such as styrene-butadiene-styrene block copolymer (SBS), ethylene-butadiene block copolymer (EBS), plasticizer, and fillers. The polymer-modified sealant offers high flexibility at low service temperature. Per the manufacturers' recommendation, crumb rubber sealants were tested at -10°C; while polymer-modified sealants were tested at -34°C. In addition, sealants were tested at various low temperatures because of the variation in their composition and suggested application location.

In order to prepare DTT specimens, the sealant is heated to the manufacturers' recommended installation temperature for 30min, and then firmly stirred before pouring into dog-bone shaped aluminum molds. The sealant must be kept fluid and homogeneous during sample preparation. The specimens are then allowed to cool to room temperature for one hour. Specimens are then de-molded and placed in the fluid bath to condition for one hour at testing temperature. Due to sealant pouring difficulties and the presence of crumb rubber particles, the variation in testing results was found to be significant. Therefore, a specimen preparation procedure for the asphalt binder suggested by Ho and Zanzotto (8) was adopted. In this method, the specimens are maintained in a liquid state for only a short period after they come into contact with the mold. This is accomplished by placing the DTT molds over a heated ceramic tile. This method shows great improvement in specimen preparation and resulted in better measurement repeatability.

In order to investigate the effect of geometry on sealant stress-strain relationship, three specimen dimensions were examined (Table 4): Type A, which is the original specimen adopted by the SuperPave binder specifications; Type B, which measures 40mm long (effective length is 33.8mm), 6mm wide, and 3mm thick; and Type C, which measures 24mm long (effective length is 20.2mm), 6mm wide, and 3mm thick. Rubber particles have a high tendency to block the sealant from flowing uniformly into the mold corners. Therefore, thin specimens (3mm) yield better pouring control. This results in a homogeneous specimen having a strong bond with the end tabs, and it requires relatively lower tension force to pull the sealant to failure. In addition, a shorter specimen allows higher testing elongation, with up to 100% strain.

Crack sealant is a rate-dependent material. A common way to determine the proper loading rate for testing is by applying different loading rates and plotting the stress-strain response curve. The elongation rates used in the study were the following:

0.6, 1.5, 3.0, 4.5, and 6.0mm/min for type A and B specimens. However, for specimen type C, an elongation rate of 1.8mm/min was used. It has to be noted that the deformation rates used in this study are considerably high compared to the field-measured rates, however, no edge failure was observed.

DISCUSSION

Effect of Cross-Section on Stress-Strain Response

The effect of cross-section areas on the stress-strain relationship was investigated by comparing the results obtained from testing Type A (6x6mm²) and Type B (3x6mm²) specimens using polymer-modified sealants. As illustrated in Figure 2, polymer-modified sealants WW and PP showed insignificant effects due to changes in specimen cross-section areas.

Effect of Specimen Length on Stress-Strain Response

The effect of specimen length on stress-strain response for types B and C specimens was investigated (Figures 3a and 3b). Utilizing the same elongation rate in both types resulted in a greater stress response in the C specimen compared to B specimen. Since it is of interest to compare the stress response at the same strain level, two elongation rates, 3mm/min and 1.8mm/min, were applied to specimens B and C, respectively. Considering the corresponding specimen length, the variation in elongation rates resulted in an identical strain rate of 8.8%/min for each type.

Figure 3 illustrates that specimen C elongates about two to three times greater than specimen B. In addition, polymer-modified sealants have shown 10 to 20 times more elongation and up to two times greater tensile strength compared to crumb-rubber modified sealants. Regardless of specimen geometry, polymer-modified sealants have shown equivalent peak stress at its maximum elongation state. Hence, the length effect is negligible in the sealant tensile strength when rich polymer-modified products were used.

Loading Rate Effect on Stress-Strain Response

Figures 4 and 5 depict the stress-strain relationships for the type B specimen at different elongation rates. It is clear that the stress level increases with an increasing strain rate. As viscoelastic materials, sealants tend to relax the imposed stress over time; but at different levels. For example, sealant PP exhibits a cold drawing behavior as the stress becomes constant with increasing strain. This could be due to the sealant rearranging the polymer chains and molecules, as well as the initiation of necking at the mid-span. On the other hand, no cold drawing was observed for sealant WW at various strain rates.

The polymer-modified sealant in general has shown ductile responses with no sign for failure up to 30% elongation. On the other hand, failures of the crumb rubber-modified sealant (YY and ZZ) occur at a strain level lower than 3%. Visual inspection has yielded that YY and ZZ specimens failed at the binder-rubber particle interface.

To identify an optimal elongation rate for testing sealants, a rate compatible with in-field crack movement at a low service temperature was considered. Generally, the

crack opening rate in the field is extremely slow and the rate used in the current test is relatively higher. This may increase the chance of de-bonding failure at the specimen-end tab interface. Based on laboratory testing, it was found that testing at an elongation rate between 1.5 to 3mm/min is appropriate.

PRELIMINARY PERFORMANCE PARAMETER

Sealant materials can be exposed to a variety of strains in the field depending upon the geographic location. In the northern areas, crack sealant strain can reach as high as 100% elongation due to thermal effects. In the southern areas, crack movement may reach up to only 10%, as the temperature variation is comparatively small. Under these conditions, sealant should maintain two essential characteristics: extendibility and toughness. The former is qualitative and allows the sealant to flow and expand as the crack opens and the latter is related to the cohesive failure of the sealant. Therefore, both characteristics should be taken into consideration as the performance-based test is being developed.

The strain energy density (strain energy per unit volume) of a material refers to its capacity to absorb applied energy prior to its failure. The value is equal to the area under the stress-strain curve which comprises both strength and ductility. For ductile sealant, such as polymer-modified ones, toughness may be evaluated at a strain level of 30% while for brittle sealant, such as crumb rubber-modified ones, toughness is determined at the rupture strain.

There is a clear difference between sealants if stress values are compared. The stresses for the polymer-modified sealants vary from 270 to 1600kPa, while for the rubber modified-sealant, the ultimate stresses at fracture for sealants YY and ZZ are 300 and 760kPa, respectively (Figure 6). With respect to toughness, Figure 7 depicts the comparison between sealants at various elongation rates. As the strain rate increases, the toughness of polymer-modified sealants increases. The results also depict that sealant PP is less able to absorb the applied energy resulting from crack movement, compared to sealant WW. For the crumb rubber-modified sealants, measurements indicated that at a slow elongation rate the sealant behaves as a ductile material, resulting in greater toughness compared to results of testing at a rapid elongation rate.

CORRELATION BETWEEN LABORATORY LOADING RATE AND CRACK MOVEMENT IN THE FIELD

The loading rate suggested in this study does not represent the loading rate experienced in the field. Therefore, a testing scheme that takes into account temperature and loading rate effects must be considered. A master curve utilizing uniaxial test results at various elongation rates and temperatures can be constructed. For viscoelastic polymer materials, Smith (9) demonstrated the applicability of using superposed tensile stress data to construct a reduced stress-strain curve. The curve accurately represents the viscoelastic behavior of the sealant material. Smith stated that the stress-strain curves can be related to a generalized Maxwell model and when a constant strain rate is applied to a material, the relationship between stress-strain curves is given as follows:

$$\sigma / R = \int_{-\infty}^{\infty} M(\tau) \tau (1 - e^{-\varepsilon / R}) d \ln \tau, \quad (1)$$

where, σ = applied stress, ε = strain, τ = relaxation time, R = strain rate, and $M(\tau)$ = relaxation distribution function. The equation shows that data obtained at various strain rates is expected to result in a single curve on $\log \sigma/R$ vs $\log \varepsilon/R$. If different temperature data is obtained, shift factors can be used to form a single master curve (10). Once this is obtained, any loading configuration can be applied to evaluate the response of the sealant over a wide range of time. Therefore, the real performance of the sealant in cracks over various loading times can be simulated utilizing simple tensile test results.

Figure 8 illustrates three loading rates (0.6, 3.0, and 6.0mm/min) applied on sealants WW and YY. It shows that a single curve is obtained if experimental data are normalized with respect to the testing strain rate. For a wider range of the sealants' stress-strain response, further testing at various temperatures is needed and is currently being conducted.

CONCLUSIONS

A method to evaluate hot-poured crack sealant's cohesive properties using modified DTT was proposed. Finite element analysis was conducted to determine the optimum specimen size by analyzing several specimen geometries to maintain uniform stress distribution in the web portion. A modified specimen, with reduced thickness and length, was introduced and used in this study. These modifications resulted in better specimen preparation, and improved test result accuracy and repeatability. Laboratory testing on three specimen sizes found that shorter geometry showed more expandability while thinner geometry showed insignificant effect.

Two sealant types, polymer-modified and crumb rubber were evaluated in this study. The former showed better ductility and strength than the latter when testing at the manufacturers' recommended in-service temperature. The study found that testing at a loading rate ranging from 1.5 to 3mm/min is appropriate. The study concluded that sealant toughness, determined from DDT testing, is a promising performance indicator of crack sealant behavior. The indicator was evaluated at various specimen extension levels based on sealant ductility. Polymer-modified and crumb rubber sealants were evaluated at 30% and failure strain level, respectively. The polymer-modified sealant was shown to be significantly tougher than crumb rubber-modified sealants.

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TABLE 1 Crack Extension Percentage at Montreal (after 6)

Crack Length, mm	Crack Movement			
	Transverse Crack, mm	Extension, %	Longitudinal Crack, mm	Extension, %
12	1.82	15.2	1.62	13.5
19	3.09	16.3	2.06	10.8
40	3.62	9.1	2.79	7.0

TABLE 2 SHRP-H106 Test Sites Investigating Crack Movements (after 7)

Test Site	Pavement Type	Crack Movement (Mean $\pm$ StdDev), mm	Mean Rate of Crack Movement, mm/°C	Extension, %	Mean Rate of Crack Movement, mm/min
Abilene	Conventional AC with fabric interlayer	0.91 ± 0.51	0.057	5.7 ± 3.2	2.77×10^{-4}
Wichita, East	Full Depth AC	2.03 ± 0.9	0.145	12.7 ± 5.6	5.27×10^{-3}
Wichita, West		1.63 ± 1.06	0.136	10.2 ± 6.6	4.94×10^{-3}
Elma	Full Depth AC	1.04 ± 0.42	0.13	6.5 ± 2.6	N/A
Des Moines	Composite AC/JRC	1.52 ± 0.94	0.058	9.5 ± 5.9	7.94×10^{-4}
Prescott	Composite AC/JPC	1.17 ± 0.35	0.03	7.3 ± 2.2	N/A

TABLE 3 Summaries, Rate of Crack Movement and Extension Percentage at Five Swedish Airports (after 8)

Type of Movement	Rate of Crack Movement			Max. Extension, %
	mm/°C	mm/min	%/min	
Daily	0.04	0.001	0.0079%	100
Yearly	0.4~1.25	$5 \times 10^{-5} \sim 8 \times 10^{-4}$	0.0004~0.0063%	

TABLE 4 Evaluated DTT Specimen Dimensions

Specimen Type	Width (mm)	Thickness (mm)	Nominal Length (mm)	Effective Length (mm)
A	6	6	40	33.8
B	6	3	40	33.8
C	6	3	24	20.2

FIGURE 1 Stress distribution in (a) typical DTT specimen, and (b) proposed specimen.

FIGURE 2 Effect of cross-section area on stress-strain relationship of polymer-modified sealant at 4.5mm/min.

a)

b)

FIGURE 3 Effect of specimen length on stress-strain relationship under the same strain rate for a) polymer-modified sealant; and b) crumb-rubber sealant.

a) WW

b) PP

FIGURE 4 Stress-strain relationships at various elongation rates for polymer-modified sealants: (a) WW, and (b) PP at -34°C .

(a) ZZ

(b) YY

FIGURE 5 Stress-strain relationships at various elongation rates for crumb rubber sealants: (a) ZZ, and (b) YY at -10°C.

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(a)

(b)

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(a)

(b)

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