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The Effect of the Hot-Air Lance on the Adhesion of Sealants used in Roadway Maintenance

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ABSTRACT

The hot-air lance (HAL) is widely used in crack sealing work based on the premise that it improves sealant adhesion. The effectiveness of the HAL in promoting adhesion is uncertain, however. Our goal was to measure the effect of the hot-air lance (HAL) on the adhesion strength of bituminous crack sealants. To this end, we monitored the use of the HAL in the field and reproduced its effect on asphalt concrete pavements by using an automated HAL in a series of laboratory experiments. In those experiments, we compared the adhesion strength of three sealants applied to unheated, heated and overheated asphalt concrete substrates prepared with quartz or limestone aggregates. The results show that the use of the hot-air lance in sealing pavement cracks is not advantageous if the crack sealant is exposed to cold winter temperatures. Furthermore, the hot-air lance does not enhance the adhesion of good sealants and may, on the contrary, cause premature sealant failure.

INTRODUCTION

Pavement cracks can be sealed by one of several methods [1]. In regions experiencing severe winters, the sealing step is often preceded by routing, cleaning, and heating of the crack. Sealant performance is thought to be enhanced by this procedure as routing reduces mechanical stresses at the sealant/asphalt concrete interface [2, 3] and the heat treatment of the rout faces is expected to provide stronger adhesion [4, 5]. The heat treatment of cracks can be especially useful if the rout is wet since the hot-air lance (HAL) both removes the excess moisture and dries the crack surface [6, 7]. Notwithstanding these beneficial effects, the usefulness of the HAL in sealing dry cracks is still uncertain [7] since it has recently been demonstrated that this technique may enhance debonding by damaging the surface of the rout [8]. Few studies have been undertaken to understand how the HAL subsequently affects the adhesion of crack sealants to routed joint faces and little is known about extreme application temperatures to which these routs are subjected. If the use of the HAL is to continue, it would be useful to know those instances in which it can most effectively be used and those, of course, in which it is unlikely to provide advantage over simply cleaning the rout with a blast of compressed air.

In this work, we have examined the effect of the HAL on sealant adhesion by monitoring the use of the HAL in the field and thereafter reproducing the observed effects in a series of laboratory experiments. The field study consisted of working along three

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crack sealing crews and measuring the rise in the temperature of the rout when it was heated with the HAL. Knowing the temperature to which these materials are subjected is important because if exposed to temperatures above 200 °C they may oxidize and thereby form a weak bonding surface; they become hence predisposed to premature debonding. Furthermore, it enabled us to obtain information necessary to reproducing these field conditions in a laboratory setting. Accordingly, an automated, variable speed, HAL device was built which reproduced the heat treatment conditions measured in the field. We then monitored the relative change in surface characteristics brought about by the high temperatures acting on various types of bitumen by means of infrared spectroscopy and goniometry. The effect of heat treatment on the SARAs (saturates, aromatics, resins and asphaltenes) composition of bitumen was also assessed by means of thin-layer chromatography. Finally, in order to ascertain the significance of the surface treatment on low temperature sealant adhesion, we measured the adhesion of three sealants on untreated and heat treated AC surfaces at –30 to –40 °C. Adhesion tests were performed by pulling sealant-AC briquette assemblies in a tensile tester, and also by pulling real size sealant-AC slabs assemblies in a specially designed test table.

EXPERIMENTAL

Field Study

All three crews used a "L/A" hot-air lance, model B (L/A Manufacturing Inc., Covington, KY) which provides a maximum temperature of 1350 °C. We noted the color and temperature change at the surface of routed cracks after passage of the HAL. A type-K thermocouple was used to measure the rout temperatures. The thermocouple was glued to the AC surface with five-minute epoxy and the temperature readings were recorded with a hand held multimeter.

Laboratory study

Automated hot-air lance (HAL)

An automated HAL was built with a "L/A" lance as described above. The lance could be moved at a linear speed of 3 to 200 cm/s (about 0.6 to 60 ft/s). The distance between the lance tip and the surface of an AC sample could be varied from 0.5 and 30 cm (0.2 to 8 in.). Twenty-four test conditions were evaluated, including speeds of 3, 8, 15, 30, 40 and 50 cm/s, and lance heights of 30, 50, 75 and 100 mm. The air and gas manifolds on the lance were set such that maximum lance temperature of 1350 °C was achieved.

The temperature rise at the AC surface during heat treatment was measured by means of six thermocouples embedded in AC concrete briquettes. Each briquette of 60 mm x 150 mm x 40 mm (width, length, thickness) accommodated six thermocouples each spaced 25 mm (1 inch) apart. Thermocouples were placed in pre-drilled holes and their tips imbedded 1 to 2 mm into the AC surface. Temperature readings were monitored at a rate of 33 Hz. Based on this initial study, "normal heating" and "overheating" treatments were devised, methods which were subsequently used to heat the surfaces of substrates used in the tensile tests.

Materials

Two bitumens, three bituminous crack sealants, and two aggregates were used in this study. Bituminous films were used to study surface oxidation by infrared spectroscopy, thin-layer chromatography, and goniometry. These films were prepared by placing fifteen grams of bitumen into an aluminum cup and melting the samples 20 minutes at 90 °C. Films of about 3 mm thick were prepared with either a Petro-Canada 85/100 penetration grade bitumen (Bitumen A) or an Ashwarren 300/400 penetration grade bitumen (Bitumen B).

The three sealants, labeled A, L and M, were selected based on their satisfactory four-year field performance [8] and the range of application viscosities they provided. Their relative viscosities is thought to be related to adhesion [8]. At the application temperature of 185 °C, sealants A, L, and M had respective viscosities of 70, 6, and 19 Pa•s.

Limestone (>90% $CaCO_3$) and quartz (>90% crystalline SiO_2) aggregates were used in the preparation of briquettes for the small-scale adhesion test; the aggregate size and size distribution is given in Table 1 below.

TABLE 1
Aggregate Gradation Used in Briquette Fabrication

Passing Sieve No.	Size (mm)	Aggregate mix (wt. %)
2	9.5	100
4	4.75	50
8	2.36	36
16	1.18	25
30	0.60	16
50	0.30	7
100	0.15	3
200	0.075	2

Infrared spectroscopy (ATR-FTIR)

The infrared spectroscopy of bitumen surfaces was performed with a Bomem MB 100 spectrometer equipped with an Attenuated Total Reflectance (ATR) accessory containing a zinc selenide crystal. The ATR assembly was set at an angle of 45°. Spectra were obtained between 4000 cm^{-1} and 700 cm^{-1} as the average of 50 scans at a resolution of 4 cm^{-1}. Spectra were baseline corrected and normalized at the 1376 cm^{-1} peak. Bitumen films were characterized before and after treatment with the HAL. The heat treatments consisted of passing the HAL at 15, 30, and 40 cm/s and the height of 50 mm above the film surface.

Goniometry

The contact angle of distilled deionized water onto bitumen films was measured with a Rame-Hart goniometer, model NRL 100-00. About 6 μl of water was delivered to the surface of bitumen with a microsyringe. The reported contact angle is the average of fifteen measurements taken within ten minutes after treatment of the bitumen film surface with the HAL.

Fractionation of bitumen

The composition of bitumen was obtained by thin-layer chromatography flame ionization detection (TLC-FID) in a commercial Iatroscan™ apparatus [9]. Bitumen was fractionated into four distinct chemical families: the saturates, the aromatics, the resins, and the asphaltenes (SARAs). The fractionation was performed by depositing 2 μl of a 5% solution of bitumen in trichloroethylene at the base of ten glass rod covered with silica, and successive elution in heptane, toluene and tetrahydrofuran for 45, 20 and 6 minutes, respectively. The silica rods were dried 5 minutes at 50 °C between each elution. The reported SARAs values are averages calculated from the fractionation of bitumen onto ten rods.

Microscopy

Sealant and briquette surfaces were characterized by optical microscopy. The sample was illuminated with UV light at 354 nm to better define the surface characteristics, and more effectively separate surface components, i.e. aggregate, bitumen, sealant. Photographs were obtained with a 35 mm camera placed at the top of the microscope. Enlargements ranged from 6X to 66X.

Adhesion Testing

Both a small-scale and a full-scale adhesion test was used to assess the level of adhesion of sealants to heat treated substrates. In the small scale test, sealant-AC briquette assemblies were subjected to a tensile test at −37 °C by means of an Instron universal testing machine (Instron). The test temperature is representative of the harsh seasonal conditions to which sealants may be exposed during their service in Canada or Northern USA. Full scale tests were conducted to validate results obtained from small scale testing.

Small-scale adhesion test: Sealant-briquette assemblies for the small-scale test were prepared as shown in Figure 1. The briquettes were prepared with Bitumen A and either limestone or quartz aggregate; the briquette cross-section had an aggregate surface area of 35%, close to that of an Ontario HL3 type AC mix with 42%. Prior to pouring the sealants between the briquettes, the briquettes were cut in two and their exposed faces either left untreated (control) or heat treated as required for the evaluation. The heat treatment consisted of using the automated HAL and subjecting the surfaces of the briquettes to one of the following conditions: a) for normal heat treatment – passing the lance at a speed of 40 cm/s at a distance of 50 mm from the surface; b) for "overheating" treatment - at a speed of 15 cm/s and again, a distance of 50 mm.

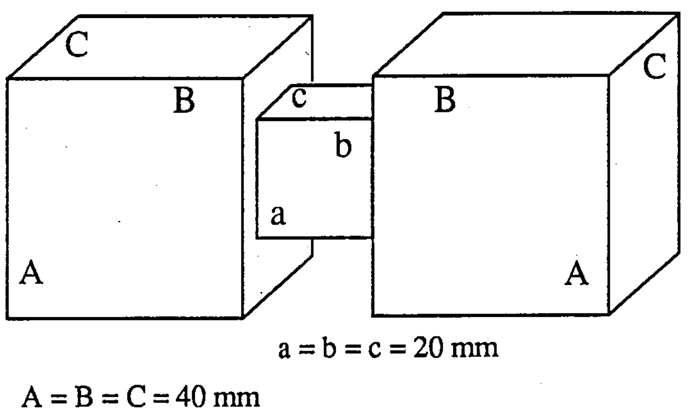


FIGURE 1
Schematic of sealant-briquette assembly. The briquette and sealant sizes are indicated by capital and lower case letters, respectively.

Sealants were heated in an oil bath to 185 °C and stirred slowly for 45 minutes before being poured between briquettes. The sealant within the assembly was a cubic bead having dimensions of 20 mm x 20 mm x 20 mm (Figure 1). After the sealant had slowly cooled to about 25 °C, the assemblies were conditioned 16 hours at −35 °C before being subjected to tensile testing with an Instron. The test was conducted at −37 ± 2 °C and at a crosshead speed of 10 mm/min. In these test conditions, the sealant products behaved as rigid elements and the area under the stress-strain curve could be equated to the energy to rupture the assembly, i.e. the adhesion strength. Each reported value is the average from nine to fifteen measurements.

Full-scale Tensile Tests: For full-scale tensile tests, we used asphalt concrete rather than briquettes as the substrate. The asphalt concrete was an Ontario HL3 mix containing limestone aggregate (maximum nominal aggregate size of 13 mm) which prior to being used in this study had aged three years at the laboratory's outdoor test facilities. Air temperatures during the aging period varied from −37 °C to +35 °C. The AC concrete was first routed with a Crafco router equipped with new carbide-tipped routing bits; the rout size was 20 mm x 20 mm. Sections of pavement, each of 300 mm by 600 mm (1 ft by 2 ft) and containing a routed portion in its center, were then removed from the outdoor site and brought to the laboratory where they were cleaned, heat treated, or cleaned and left untreated as required for the test conditions. Sealant was finally poured into the rout, forming a bead 20 mm deep by 20 mm wide and 300 mm in length, before the sealant-asphalt concrete assembly was placed onto the testing table (Figure 2).

The test table consists of two steel plates that can be moved independently of one another. The right plate (in Figure 2) moves vertically while the left plate moves horizontally. Typically, a specimen consisting of two slabs of AC is placed on and glued to these plates with the edge of the adjacent slabs forming the joint. Hence, each slab is on a plate which can move independently from one another. A joint sealant material poured between adjacent slabs can then be subjected to tensile, compressive and shear movements by means of coordinating the movements of either plate on the rig. This is achieved by means of computer controlled servo hydraulic actuators. Thus, thermal movements or movements due to traffic can readily be simulated by this apparatus. Locating the test rig in a cold room permits the simultaneous action of cyclic movement in two directions together with testing at sub-ambient temperatures as low as −40 °C.

In this study, sealant adhesion to an AC substrate which had either been heat treated with the HAL or left untreated was tested by simulating crack widening at a rate of 6 mm/h coupled to a small dynamic shear displacement of ±0.127 mm. Moreover, the temperature was lowered from −30.0 °C to −36.5 °C, at a rate of 1.5 °C/h, during the test. These conditions were based on a study which showed that similar test conditions could help differentiate between good and poor sealants used in cold conditions [10]. The test was conducted to failure along the entire length of sealant, or for 5h, whichever came first. During the test, the surface area where sealant had debonded from the rout was measured every 30 minutes. The reported debonded surface area is the average calculated from five test specimens.

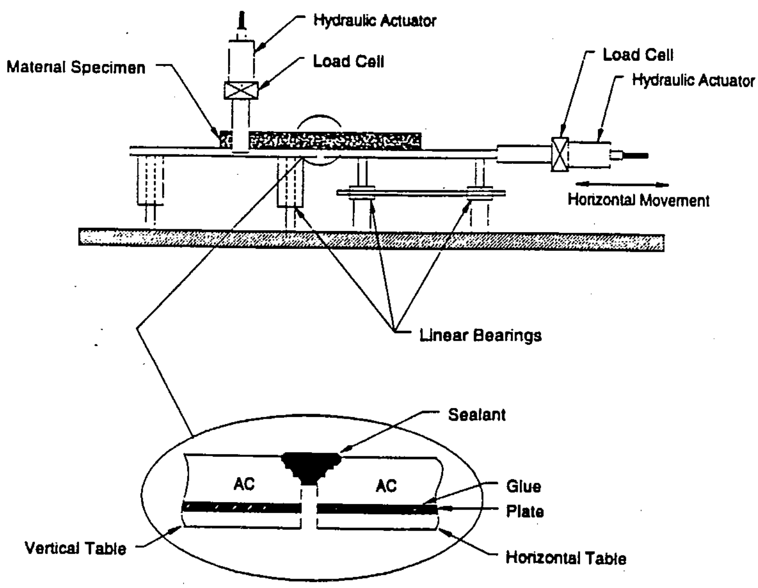


FIGURE 2
Schematic of the full scale tensile test set-up.

RESULTS AND DISCUSSION

Field study

<u>Hot-Air Lance</u>

The typical temperature of the routed crack when the rout surface is slightly darkened is shown in Figure 3. The temperature rises rapidly to about 220 °C and then returns to equilibrium temperature (30 °C) within one minute. We were unsuccessful at measuring the rout temperature when the rout was heavily darkened, i.e., overheated (Figure 4). In those instances, the adhesive holding the thermocouple in place degraded to the point that the thermocouple lifted off the surface. Surface temperatures obtained during overheating were, however, measured in the laboratory study.

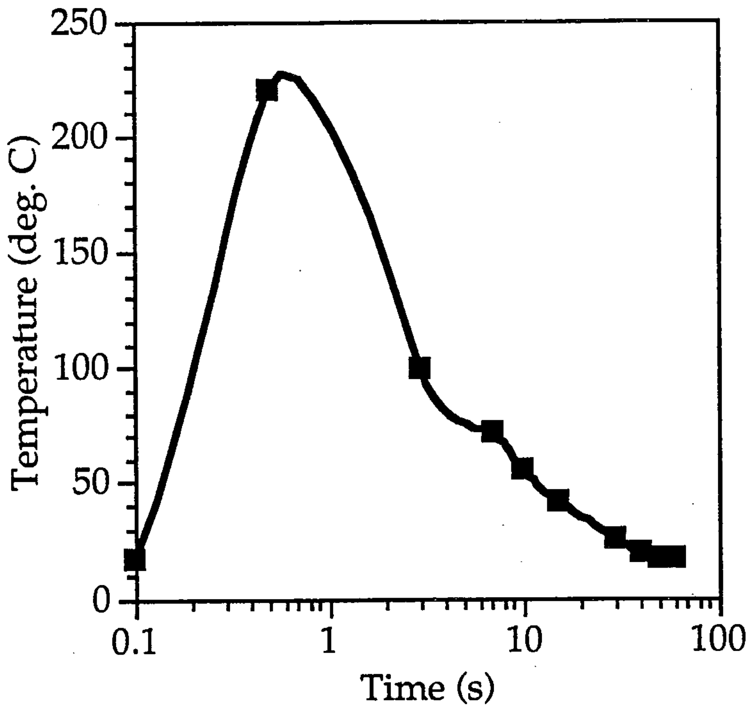


FIGURE 3

Typical temperature profile of the rout when it is heated with a HAL

The temperature profile of the rout reveals that the HAL cannot promote sealant adhesion; this is contrary to preconceptions about the usefulness of the HAL [4, 6]. It has been suggested that the HAL enhanced sealant adhesion by melting the bitumen at the rout surface thus allowing the interdiffusion of bitumen and sealant. The results in Figure 3 show that this cannot be. In order for the bitumen to become tacky, it must be maintained at 115-160 °C, the temperature at which the pavement is laid [11]. Figure 3 shows that in normal conditions, the rout temperature is above 100 °C for less than 10 seconds after the passage of the HAL. Since the time between the heating of the rout and the sealing of the crack varies from 1 to 5 minutes [12, 13], the sealant then, cannot be poured onto a tacky crack surface.

It is well known that the heating of bitumen to 130 °C causes oxidation and embrittlement [14]. Despite the short heating time, the heating of routs to 220 °C with a HAL may cause the oxidation and the embrittlement of the bitumen film at the surface of the rout, where sealant adhesion takes place. If such a transformation were to occur, then fracture (brittle failure) of the binder surface may be possible at low temperatures when the tensile forces acting on the sealant are high. Such fracture would promote premature sealant failure. As we will see, embrittlement of the surface is confirmed in the laboratory investigation.

FIGURE 4

Typical blackening of an overheated rout.

Laboratory study

Simulation of HAL treatments

The treatment of AC with the automated HAL provided six distinguishable surface conditions, with the maximum surface temperatures ranging from 100 °C to more than 500 °C (Table 2). Conditions 3 and 4 in Table 2 are representative of conditions observed after typical field treatments. These surface conditions, henceforth defined as overheated and (normally) heated respectively, were most easily obtained at a lance height of 50 mm and lance velocities of 15, 30 and 40 cm/s; these heights and velocities provided respective rout temperature maxima of 250, 200 and 150 °C. The use of these same parameters in subsequent tasks allowed us to reproduce field conditions in the laboratory, and therefrom help us determine if the HAL increases sealant adhesion onto AC or if, on the contrary, the HAL oxidizes the bitumen surface.

TABLE 2
Temperature and Condition of AC Surface Treated with the Automated HAL

Condition	Description
1	The HAL causes the surface temperature to exceed 500 °C. It causes extensive damage to the AC surface; depth of damage is usually greater than 3 mm and is characterized both by a loss of large aggregates and that of bitumen.
2	The HAL heats the AC surface to 350-500 °C. It causes a loss of bitumen and ejects from the surface most of the aggregates smaller than 2 mm. The larger aggregates are covered by a layer of bitumen.
3*	The HAL heats the AC surface to 250-350 °C and causes a loss of bitumen to a depth of about 1 mm. The small aggregates, and portions of larger aggregates, become covered with bitumen.
4*	The HAL heats the AC surface to 150-250 °C; There is little loss of aggregate but small aggregates and a portion of the larger aggregates become covered with bitumen.
5	Surface temperature is below 150 °C. The bitumen melts but does not flow over aggregates.
6	The surface temperature does not exceed 100 °C and the AC surface is not affected to any noticeable extent.

* Surface condition commonly encountered in the field.

Oxidation and change in surface composition

The angle of contact of water onto bitumen provides an indication of its surface polarity. As the polarity increases, the angle of contact decreases. The polarity of bitumen can be increased either by oxidation or by an increase in the concentration of its polar components: aromatics, resins, and asphaltenes [14]. Provided in Figure 5 is an example of the decrease in contact angle of water on three bitumens with different compositions.

The heating of bitumen with a HAL also causes a decrease in contact angle, the decrease being product dependent (Table 3). The decrease in contact angle can indicate that the bitumen has oxidized upon heat treatment or that its polar content has increased, or both.

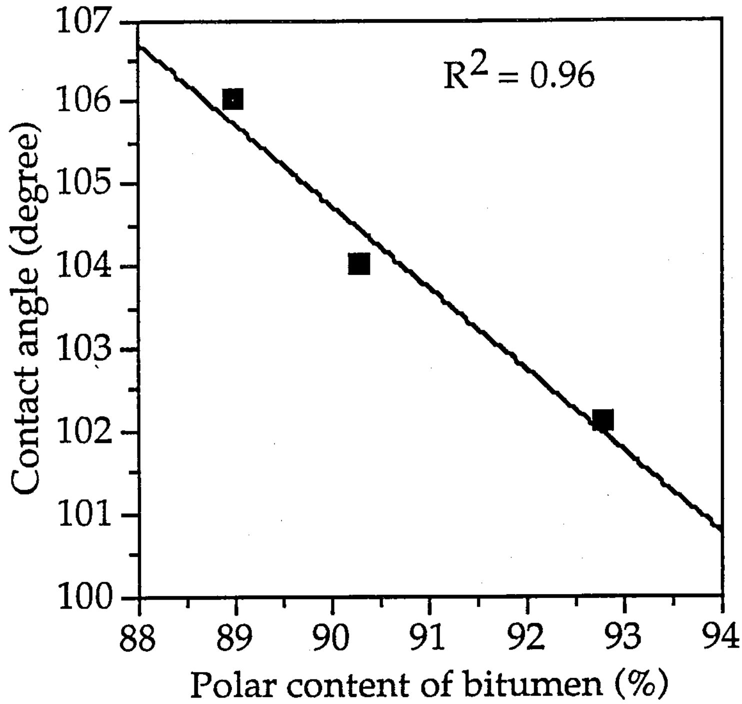


FIGURE 5
The contact angle of water onto three bitumens of different polarity. In this instance the polarity is equated to the sum of the aromatics, resins and asphaltene contents in bitumen.

Table 3
Contact Angle of Water onto Bitumen Before and After Heat Treatment

	Bitumen A	Bitumen B
Control	102.5	106.3
Heated	99.6	105.0
Overheated	101.8	104.9

Results from infrared spectroscopy and SARAs analysis show that the polarity of bitumen has increased with the heat treatment but that it has not oxidized. Indeed, in the infrared spectrum, bitumen oxidation is often made visible by the appearance or an increase of carbonyl and sulfoxide absorbances at 1700 and 1030 cm^{-1}, respectively. In this case, however, the absorbance at 1700 cm^{-1} is absent from the spectra of bitumen films after their heat treatment (Figure 6). Similarly, the sulfoxide absorbance at 1030 cm^{-1} shows no increase but rather a decrease after heat treatment. It is thought that this decrease in sulfoxide concentration is a result of the thermal decomposition of the sulfoxide group during pyrolysis [15].

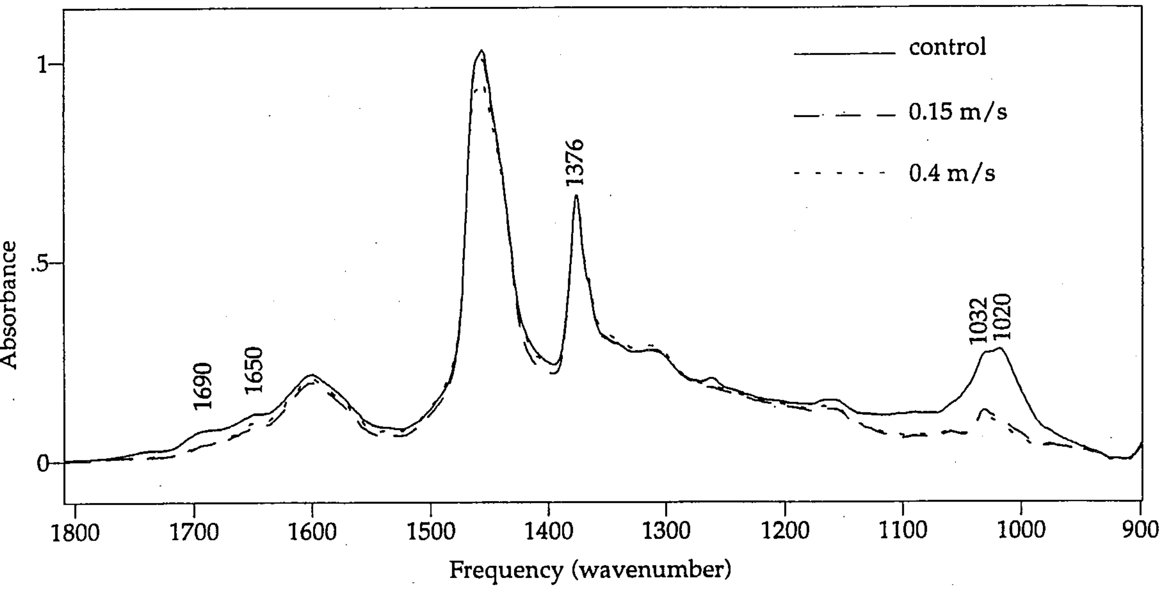
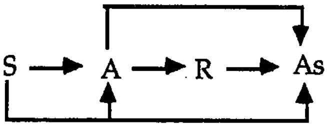


FIGURE 6
Infrared spectra of the surface of Bitumen A before and after treatment with the hot-air lance. The spectra for Bitumen B are not shown but they reveal the same trend.

The FTIR spectra of the bitumen also show a decrease in the absorbance peaks at 1690, 1650 and 1020 cm^{-1} after heating. These peaks correspond to substituted aromatics [16]. Their decrease in the spectra of both Bitumen A and B indicate that aromatics or resins are lost and transformed according to the usual aging process [17]:



More precisely, the SARAs analysis obtained by chromatography indicates that in Bitumen A, the resins are transformed into asphaltenes (Figure 7). An increase in asphaltene content in bitumen causes its embrittlement [14]. Similarly, Bitumen A is embrittled by the HAL. The same embrittlement is not seen in Bitumen B, however, as the SARAs composition is apparently little affected by heat (Figure 7).

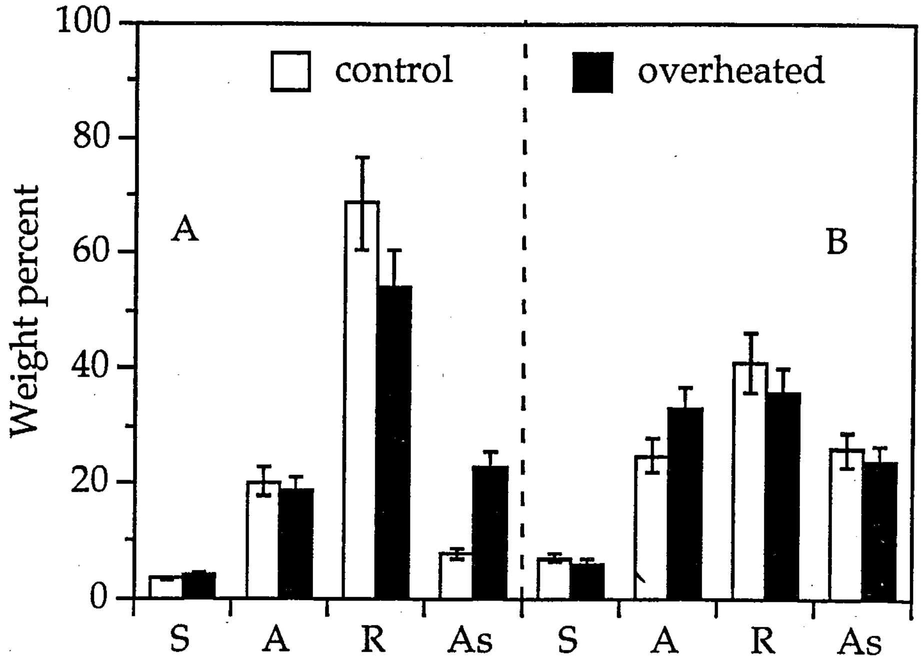


FIGURE 7
SARAs composition of Bitumen A and B before and after overheating.

The results in Figures 6 and 7 show that the HAL can embrittle various bitumens to different extents. Moreover, they show that this embrittlement is restricted to the surface. That embrittlement is a surface effect can be recognized by considering that infrared spectroscopy characterizes the bitumen surface to a depth of 0.5 to 5 mm [18] whereas for thin-layer chromatography, the bitumen surface must be sampled with a blade, the sampling depth being a fraction of a millimeter. Accordingly, the sampling depth for chromatography is one hundred times greater than that for spectroscopy (0.5 mm). The constant SARAs composition of bitumen B upon heating thus indicates that the effect of the HAL is limited to a fraction of a millimeter. Despite the shallowness of the embrittled layer, it may nonetheless affect sealant adhesion and performance because it is at the sealant-AC interface.

Adhesion Study

Small-scale tests: The adhesion strength of the sealants to substrates of heat treated and unheated AC briquettes, as measured with the Instron, is shown in Table 4. The HAL does not increase the adhesion of sealant over what is possible on unheated briquettes; the adhesion of sealants to heat treated briquettes is statistically the same as that onto unheated briquettes. On the other hand, if the briquette is overheated, then the adhesion strength of the sealant is most often reduced by 50% or more.

The measured adhesion strengths are related to the mechanism of sealant failure. When the AC surface is untreated, or normally heated, the adhesion strength is high and failure at the sealant-AC interface is both cohesive and adhesive. The cohesive failure comes from the pull-out of fines and aggregates from the AC surface (Figures 8 and 9), and the adhesive failure comes from the debonding of sealant over the large aggregates (Figure 9).

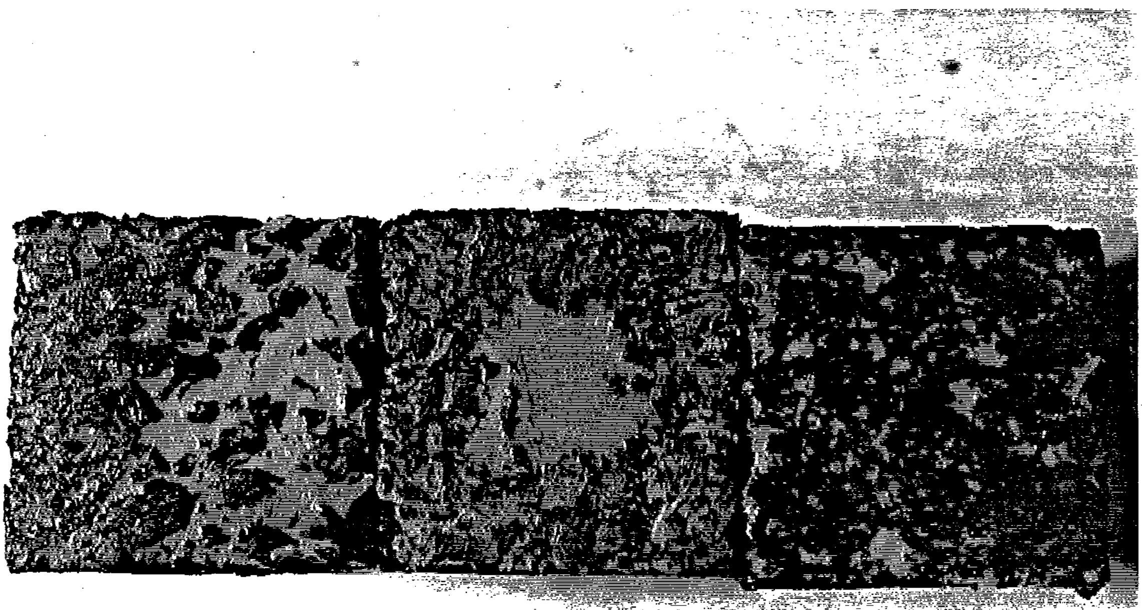


FIGURE 8
Surface of AC briquettes after tensile tests on sealant-briquette assemblies when the briquette is untreated (middle) and overheated (left). On the right, is the briquette surface without sealant. The briquettes were covered with dyed paste to increase the contrast between the holes in the briquette and the unaltered surface. On the untreated briquette, the sealant pulls out aggregates from the surface, leaving a hole in the middle of the briquette. On the overheated surface, there is no hole where the sealant was adhering. Instead, small holes are scattered across the surface where the hot-air lance caused damage.

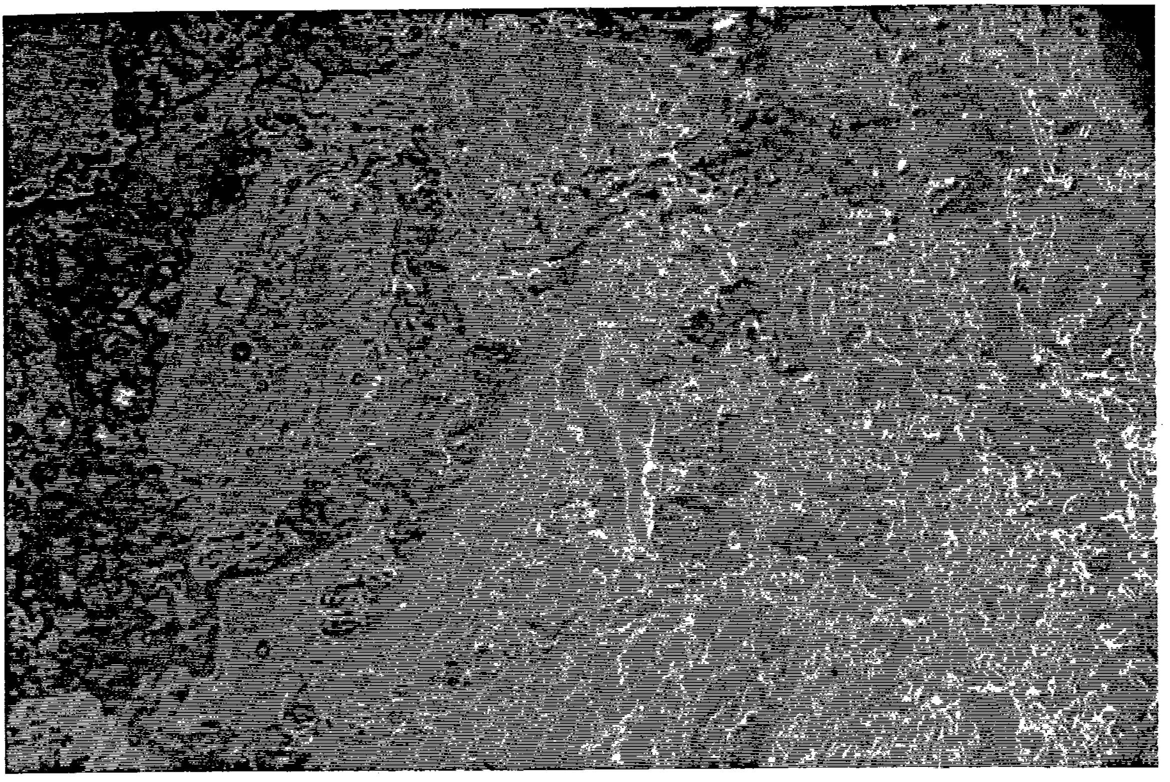


FIGURE 9
Sealant surface after a tensile test on a sealant-briquette assembly when the briquette was untreated. The sealant surface is a replica of the briquette surface. It contains fines, aggregates and bitumen pulled-out from the briquette (in black) and shows a clean surface in white and light grey when sealant has debonded.

In contrast, when the AC surface is overheated, the adhesion strength is low and failure at the sealant-AC interface is adhesive (Figure 10). In this case, the sealant shows an irregular surface, a replica of the holes in the briquette surface, introduced by the disappearance of fines and aggregates blown away by the HAL. The sealant surface contains little bitumen and few fines, if any, as if the sealant could not grip onto the surface. It may be that the relatively high sealant viscosity prevents it from flowing deep into holes to completely wet the AC surface.

From these observations, it is concluded that better adhesion is obtained when sealant bonds to a network of fines and aggregates strongly interconnected by bitumen. Low adhesion is obtained when the network is damaged (by overheating) such that fines and bitumen are blown off the surface.

FIGURE 10
Sealant surface after a tensile test on a sealant-briquette assembly when the briquette is overheated. The sealant surface is a replica of the briquette surface that contains few fines and no bitumen. The light reflected from curved surfaces (in white) provide a pattern of texture, reminiscent of the contour lines on a topographical map.

Table 4 also shows that the adhesion of sealants to briquettes made with either quartz or limestone aggregate is different. Sealant A adhered to briquettes made with quartz almost twice as strongly as it did to briquettes containing limestone. The stronger adhesion to quartz briquettes caused more aggregate pull-outs than the weaker adhesion to limestone, the situation is analogous to that shown in Figure 8 for the heat treated and untreated surfaces. The other sealants did not show preferential adhesion. In practice, this implies that a sealant may perform well and adhere strongly to asphalt concrete at one site because it is compatible with the aggregate therein, and that the same sealant may perform poorly at another site because it not as compatible with those aggregates in the asphalt concrete of the latter site.

Table 4
Mean Adhesion Strength of Sealant Adhered to a Bituminous Briquette

Quartz aggregates			Limestone aggregates		
Sealant A	Adhesion (mJ)	S *	Sealant A	Adhesion (mJ)	S
control	191	41	control	102	31
heated**	148	48	heated	76	35
overheated***	66	21	overheated	41	13
Sealant M	Adhesion (mJ)	S	Sealant M	Adhesion (mJ)	S
control	128	42	control	120	46
heated	185	85	heated	105	5
overheated	62	17	overheated	65	26
Sealant L	Adhesion (mJ)	S	Sealant L	Adhesion (mJ)	S
control	79	27	control	110	25
heated	78	22	heated	70	24
overheated	53	23	overheated	50	16

* standard deviation
** lance velocity of 40 cm/s
*** lance velocity of 15 cm/s

Full-scale Tests: The full-scale test results are shown in Figure 11. They first indicate that there is significant difference between the capacity of sealants to follow crack openings in low temperatures without debonding. For example, sealant L debonded rapidly upon a 30% crack widening. In contrast, sealant M showed little debonding after elongation of about 130 %.

The results also indicate that there was little benefit in using the HAL when the sealant has a relatively low modulus and can readily accommodate crack widening (sealant M). In this instance, the tensile stress at the sealant-AC interface is sufficiently low to insure that debonding will not occur, irrespective of the AC surface treatment. On the other hand, when the sealant had a higher modulus, it exerted a large stress on the AC surface upon cracks widening, and in these instances the use of the HAL accelerated a debonding which was already rapid (sealant L). In the intermediate situation when the sealant had a low temperature modulus that was intermediate between either extreme (sealant L), the use of the HAL improved sealant adhesion but only when crack widening exceeded 80% (sealant A). From the large-scale tests, it can be concluded the HAL may in some instances improve sealant adhesion to AC but that if the sealant is properly selected for use in cold climates then the HAL will not provide additional reliability towards the long-term performance of crack sealants.

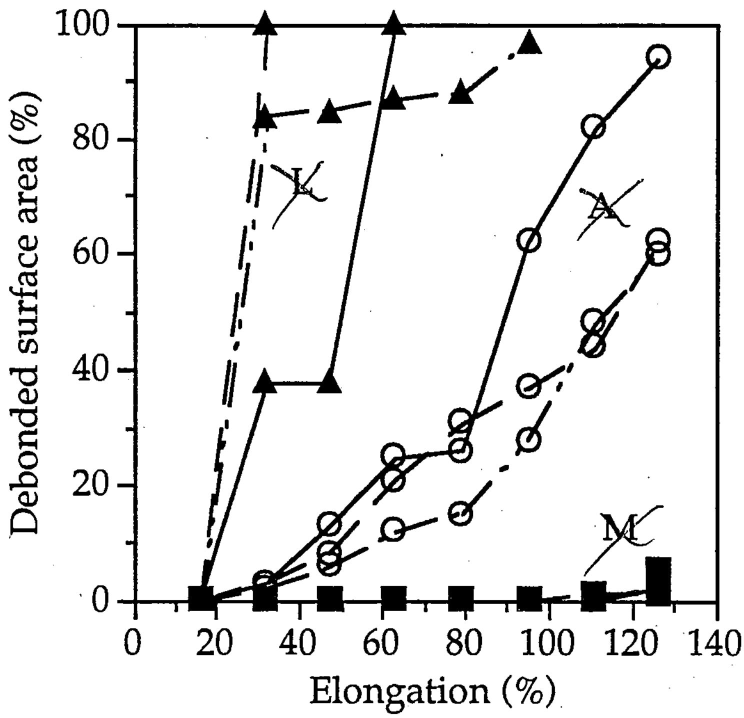


FIGURE 11
Debonding length of sealants upon elongation during the full scale tensile test when the rout was untreated (full), heated (dash), and overheated with the hot-air lance (dash dot).

CONCLUSIONS

The hot-air lance (HAL) is used in Canada and Northern US to heat pavement cracks, or routs, before they are filled with bituminous crack sealant. It has always been assumed that the HAL promoted sealant adhesion and thus increased sealant performance but previous field studies have not been useful in clearly demonstrating this effect. In this study, we conducted both field evaluations and laboratory studies to ascertain the effect of the HAL on bitumen and asphalt concrete (AC) surfaces. Field studies were invaluable in providing insight into the temperature maxima which exist at the surface of a rout treated with the HAL. Laboratory studies focused on reproducing the most salient aspects of the HAL field operations and thereafter, on subjecting both AC briquettes and larger-scale pavement specimens to heat treatment. This provided a basis from which we could compare the effect of different treatments on the chemical, physical and mechanical characteristics of the

AC substrates and related sealant adhesion. Ultimately, these studies helped determine quantitatively the effect of the HAL on low temperature sealant adhesion.

The key findings in this work were:

- During normal heat treatment, the rout temperature increases up to 220 °C and the blow of the HAL causes aggregates to become partly covered with bitumen.
- In normal practice, the HAL does not oxidize bitumen but it may embrittle its surface by increasing the asphaltene contents at the surface. This transformation does not appear to affect sealant adhesion much, however, because the general state of the rout surface is more important.
- When the rout surface is overheated, the temperature may rise up to 350 °C, and bitumen, fines and small aggregates are blown off the surface.
- Simple tensile tests of sealant-AC briquette assemblies have shown that in normal practice the HAL does not improve sealant adhesion to AC.
- The simple tensile test has also shown that the adhesion strength of sealant onto the surface is most often reduced by about 50% when the AC surface is overheated by the HAL.
- Full-scale adhesion test on sealant poured into routs of AC slabs showed that if the sealant is:
    - correctly selected for cold temperature conditions and remains elastic, the HAL becomes unnecessary because it does not increase sealant adhesion.
    - improperly selected and is prone to becoming rigid at low temperatures, then the HAL accelerates debonding.

It is therefore suggested that the HAL not be used in crack sealing work.

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