Effective Sealing of Pavement Cracks in Cold Urban Environments
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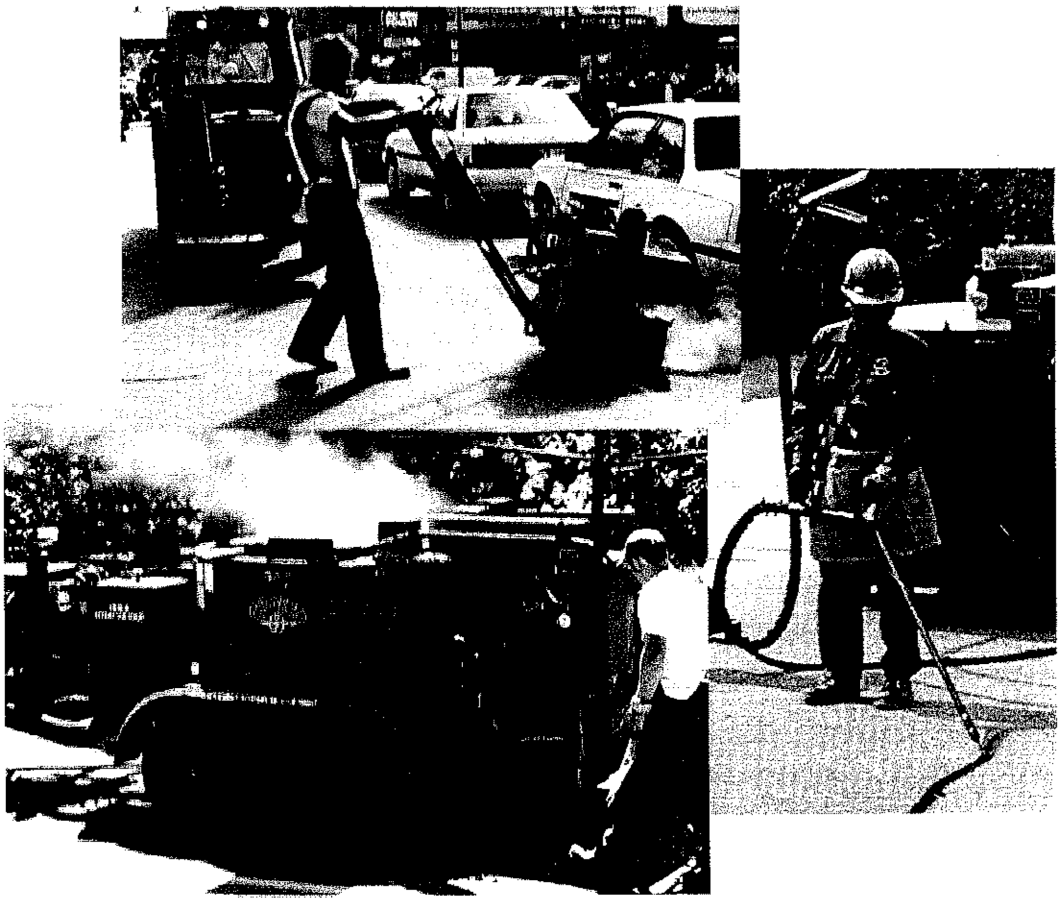

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Effective Sealing of Pavement Cracks in Cold Urban Environments

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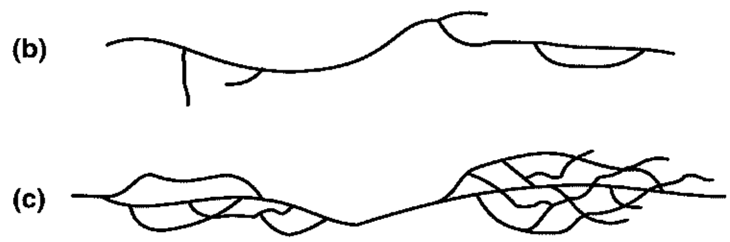
PREFACE

Crack Sealing, Is It Really the Answer?

In the last few years, the sealing of pavement cracks has gained tremendous popularity. And deservedly so, because it slows down pavement degradation. It is estimated that a crack sealant can last for more than five years and extend the service life of pavement by two years. A longer service life translates into reduced expenditures of public moneys.

Notwithstanding the popularity of crack sealing, municipal engineers should step back and ask themselves whether crack sealing is a fully matured technique and whether it is always appropriate. In both cases, the answer is *no*. But regardless - crack sealing is still applied to streets and roadways already in poor condition. And when crack sealing is appropriate, then the sealant often fails after only a couple of years of service. That goes to show that crack sealing is still an evolving technique.

This book applies to crack sealing used in a timely matter as a preventive-maintenance tool. In other words, it deals with crack sealing as it applies to streets in good condition, where cracks show little or no branching as it should be (see a and b in the figure below), and where crack movement is due only to seasonal changes in temperatures. In this work, we look critically at crack sealing. Our critique is based on studies of crack sealing and sealants undertaken by NRC between 1990 and 1997. Many of these studies were in collaboration with the Ville de Montréal, Transport Canada, the Ministry of Transportation of Québec, and half a dozen contractors working in Ontario and Québec cities. We hope that this publication will catalyze more progress in crack sealing and that it will benefit municipal engineers and contractors alike.



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Introduction

The aim of this publication is to help municipal engineers answer these two questions:

- How can the pavement crack sealant that offers 5 years of performance without much debonding in a cold urban setting be chosen? and
- Which application method will achieve the expected sealant performance?

Pavements in all major North-American cities, are maintained in various ways to extend their service life. Measures such as crack sealing are almost always the most cost-effective approach (see Figure 1). For each metre of pavement treated, it costs only $1 to seal cracks but $15 to patch and $45 to reconstruct. As a result, crack sealing should be at the top of a municipal engineer's maintenance list.

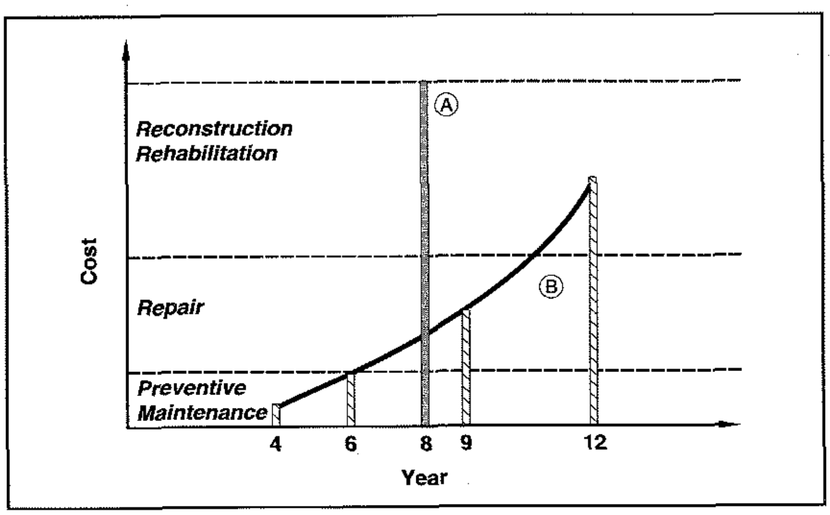

Figure 1. Preventive maintenance, such as crack sealing, allows for delaying pavement degradation. The periodic sealing of cracks after 4 and 6 years and patching at 9 years, for example, can delay the more costly rehabilitation work until the 12th year (B). The frequency of major rehabilitation or reconstruction, and the cost thus remains below that incurred without maintenance work (A).

(*Source*: Robert Tessier, Guide de construction et d'entretien des chaussées. Association québécoise du transport et des routes, Montréal, 1990. With permission)

Crack sealing can be very simple: a crack is cleaned with compressed air and filled with hot sealant. This very economical and simplified procedure offers several advantages: it is fast, uses little sealant, and requires small work crews. The county of Napierville, Quebec, uses this method with success. Every spring, while the cracks are still fresh, maintenance crews seal all the cracks in Napierville county roads. They do not need an exceptional sealant that will last several years. This procedure is ideal for a small jurisdiction where pavements are well drained, cracks not very active, and where crack sealing is an annual ritual. But it would not be practicable in a large jurisdiction like Montreal. In such cities, crack sealing must be performed differently, and it then entails several additional tasks:

1. widening the crack by routing;
2. removing the routed material with a power sweeper and vacuum;
3. heating and drying the rout with a hot-air lance;
4. pouring the hot sealant into the rout from a container or hose;
5. dusting the sealant with fine sand or Portland cement to prevent adhesion to tires; and finally
6. continuing the diversion of traffic until the sealant has hardened (about 30 minutes).

As part of a preventive measure, a crack sealant should be able to provide a service life of 5 years with no debonding or, at the very least, until cracks can be resealed — that is to say, until all the sealable cracks of a city roadway network have been treated. Regrettably, sealants often last less than 5 years. The potential for improved performance may lie both with the sealants themselves and with the methods of installation. The ASTM D3405 specification, which currently guides engineers in the selection of sealants, often fails to predict the performance of sealants in cold urban environments. In fact, to select a sealant for use in cold temperatures, some transportation agencies rely on 1-year field tests, rather than the ASTM D3405 specification. Others rely on a modified or extended ASTM standard specification. Regardless, the selection of sealant for use in a cold climate has remained a difficult task. It has been equally difficult to find an appropriate installation procedure. The qualification "appropriate" refers to an installation procedure for which the peculiarities of cold urban environments have been thoroughly considered. Despite a number of reports about sealant evaluation, studies pertaining to the performance of sealants in cold environments are few. Reports about the performance of crack sealants in cold urban environments have been even fewer.

Peculiarities of Cold Urban Environments

Sealants used in cities that experience arctic and subarctic climates, i.e., most Canadian cities and those of the northern United States, must be able to endure unusual stresses. The low temperatures during a typical Canadian winter can make a sealant inelastic, so that it can no longer adapt to the temperature-induced changes in the dimensions of a crack. The sealant then no longer rests tightly against the walls of the crack. Consequently, water, salt and grit enter it. At this point, the function of the sealant has been irreversibly compromised. The particular concern for crack sealants in cities implies that there is greater stress on them because of the traffic's turning, stopping and accelerating. Also, urban traffic is slower than that on throughfares, and therefore the sealed cracks must endure more frequent and longer pounding from the tires of cars and trucks.

Estimating the Quality of Sealants

We usually select sealants based on field or laboratory tests. Here we compared the two methods.

Field Test

In the course of field tests held in Montreal, we measured the full-depth debonding and pull-out lengths of 12 crack-sealing materials monitored over 4 years when temperature minima remained at –33°C to –40°C for up to 5 days and maxima reached +35°C to +44°C. (Table 1 lists the sealants investigated in this study. Each sealant is hereafter referred to by a letter from A to L.) In the installation, we poured the sealants in routs with one of three geometries: 12 by 12 mm, 19 by 19 mm, and 40 by 10 mm. (Here and wherever rout geometries are given, the first number pertains to the width of the rout, the second to its depth or height.) Details of the installation and the field evaluation are given in Appendix A.

Table 1. Crack Sealants Studied in Montreal (sealants reportedly meet or exceed the ASTM D3405 specification)

Sealant	Producer	Origin
Beram 195	McAsphalt	Canada
Bakelite 590-13A	Bakor	Canada
Husky 1074	Husky Oil	Canada
Husky 1627	Husky Oil	Canada
Superflex 100	Bitumar	Canada
Hi-spec	W.R. Meadows	United States
Sof-seal*	W.R. Meadows	United States
Roadsaver 522	Crafco	United States
Roadsaver 221	Crafco	United States
Sealz 6165	Hydrotech	United States
Flexochape J	Beugnet	France
Pertex	Esha	Netherlands

* This sealant reportedly meets or exceeds the ASTM D1190 specification

After 3 months of service, sealants did not reveal substantial pull-outs or changes in appearance, but all sealants partly debonded (see Table 2). After exposure to a first winter with temperatures as low as –35°C, all sealants showed an increase in debonding and pull-out levels.

Sealant performance continued deteriorating. Each subsequent spring survey showed that debonding and pull-out levels had increased significantly during winter. (The debonding and pull-out lengths measured after the first and fourth winters of service are shown in Tables 2 through 4.) The percent failure length has been calculated separately for the various routs in the transverse and longitudinal orientation before the overall percent failure length was calculated.

Table 2. Overall Percent Failure Lengths of Sealants Before and After the First Winter of Service

Sealant [1]	After 3 Months of Service		After 7 Months of Service	
	Debonding	Pull-out	Debonding	Pull-out
A	1	<1	12	9
B	5	<1	5	<1
C	15	<1	26	16
D	7	<1	10	1
E	1	<1	11	1
F	2	<1	19	4
G	3	<1	24	3
H	7	<1	13	2
J	1	<1	8	6
K	2	1	2	2
L	1	<1	8	3
M	<1	<1	7	2

[1] The alphabetical order of the sealant labels does not correspond to that of Table 1.

Table 3. Percent Debonding Length of Crack Sealants as Measured in Montreal After Four Winters

Sealant [1]	Transverse Routs [2]			Longitudinal Routs [2]			Combined Orientations			T Routs [3]	L Routs [3]	Wt. Av. [4]
	12	19	40	12	19	40	12	19	40			
A	14	16	17	4	6	9	7	10	14	16	6	11
B	22	22	31	13	21	15	16	21	24	27	17	22
C*	32	29	35	18	6	9	26	24	27	32	13	26
D	20	25	33	12	16	23	15	20	30	28	16	22
E	12	16	31	3	13	24	9	14	28	24	15	20
F	19	16	19	8	9	22	14	13	19	17	10	15
G	30	42	47	30	29	32	30	36	40	41	31	36
H	16	9	20	0	6	5	13	8	15	12	6	9
J	15	13	17	7	5	6	14	11	16	15	7	13
K	29	36	27	8	9	26	17	24	27	31	9	21
L	10	8	7	3	5	6	7	5	7	9	4	6
M	19	19	21	12	11	16	15	14	17	20	13	16

*Results after the first winter, monitoring discontinued thereafter.

[1] The alphabetical order does not correspond to that of Table 1.

[2] 12 by 12 mm, 19 by 19 mm, 40 by 10 mm (width, depth).

[3] T=transverse; L=longitudinal.

[4] Wt. Av.= Weight average calculated from the failure lengths of sealants in all routs and orientations.

Table 4. Percent Pull-out Length of Crack Sealants as Measured in Montreal After Four Winters

Sealant[1]	Transverse Routs[2]			Longitudinal Routs[2]			Combined Orientations			T Routs[3]	L Routs[3]	Wt. Av.[4]
	12	19	40	12	19	40	12	19	40			
A	19	15	20	4	12	15	9	13	18	18	10	14
B	0	2	1	0	0	0	0	1	1	1	0	1
C *	31	19	14	6	1	3	21	16	11	21	4	16
D	3	12	6	4	3	5	3	7	6	8	4	6
E	5	1	4	1	0	1	3	1	3	3	1	2
F	11	9	3	6	4	20	9	4	5	5	6	5
G	17	7	30	8	9	15	13	8	24	18	10	14
H	10	5	10	0	1	1	8	3	7	6	1	4
J	18	10	15	3	7	6	15	9	14	14	6	12
K	9	24	5	3	5	12	5	16	16	13	9	11
L	7	4	2	0	16	0	4	14	1	5	12	10
M	3	5	11	1	4	2	2	5	5	8	3	5

*Results after the first winter, monitoring discontinued thereafter.

[1] The alphabetical order does not correspond to that of Table 1.

[2] 12 by 12 mm, 19 by 19 mm, 40 by 10 mm (width, depth).

[3] T=transverse; L=longitudinal.

[4] Wt. Av.= Weight average calculated from the failure lengths of sealants in all routs and orientations.

Because sealants weather and may harden with time, they may lose elasticity in cold temperatures. It is therefore difficult to predict long-term performance based on failure lengths measured after only a single year when the sealants are still relatively unweathered. The long-term performance of crack sealants may be better assessed based on failure levels — pull-out and debonding — measured after 4 years of service.

For that purpose, a "performance index" can be calculated using the following equation:

$$PI = 100 - (D+nP)$$

where,

PI = sealant performance index;
D = percent debonded length of the sealant;
P = percent pull-out length; and
n = integer that accounts for the effect of pull-outs over debonding on performance.[1]

A value of n=4 is reasonable, given that the absence of sealant over 1 m of crack may allow

- the ingress of sand and stones that can damage the pavement during its expansion, and also
- the penetration of much more water than a simple sealant debonding over the same length.

The approach is admittedly simplistic and the choice of n subjective. Nevertheless, it permits a fair appreciation of the performance of sealants and an easy comparison of individual performances. (Values of n<4 provide a similar ranking of materials but the difference in *PI* between the sealants is somewhat reduced.) Accordingly, the performance index of the various sealants is as shown in Table 5.

[1] A simple addition of the respective pull-out and debonding levels would imply that both failures are equally damaging to pavements (which is not true) and, in turn, underestimate the effect of pull-outs on pavement degradation. Pull-out lengths must be given more weight than debonding lengths in the determination of a "performance index."

Table 5. Sealants in Decreasing Order of Performance

Sealant	Debonding	Pull-out	Performance Index	4-year Performance
H	9	4	75	
B	22	1	74	good
E	20	2	72	
F	15	5	65	
M	16	5	64	average
L	6	10	54	
D	22	6	54	
J	13	12	39	
K	21	11	35	poor
A	11	14	33	
C	26	16	10	very poor
G	36	14	8	

Elements Affecting Sealant Performance

The results of the surveys have shown that sealant performance and durability can be affected by the crack orientation and the aspect ratio (width/height, or W/H) of the sealant.

Crack Orientation. Without exception, it was noted that sealants in transverse cracks show more failure than those in longitudinal cracks (see Tables 3 and 4 earlier). This holds true irrespective of rout size, because transverse cracks open wider than longitudinal ones (Table 6, columns 3 and 7).

Sealant Aspect Ratio. In principle, the performance of a sealant is governed by the sealant aspect ratio and the magnitude of the movements to which it is exposed. In essence, the larger the W/H ratio of the sealant (or rout) and the lower the elongation of the sealant, the better should be its performance. In practice, several rout geometries have been used. The next section explores this topic in detail. It merits the detail because it presents an area where the cold urban environments prove current practices quite wrong.

Rout Geometry

The crack-sealing procedure used today in cities with cold climates is the result of the evolution of the technique over the last 30 years or so. It used to be a matter of simply blowing debris out of a crack with pressurized air and then filling the crack with sealant. The resulting sealant geometry is then as shown in Figure 2a. In a variation of this method, the sealant can be struck with a blade running along the crack to spread the sealant over both sides of the crack (see Figure 2b). In either case, the sealant geometry is such that the W/H ratio is below 1, i.e., W/H<1. Installed sealants conforming to such ratio can successfully seal static cracks, but not dynamic cracks in pavements in cold regions. In these conditions, sealants with W/H<1 fail within a short time, because of the high amplitude of the cyclic crack movement.

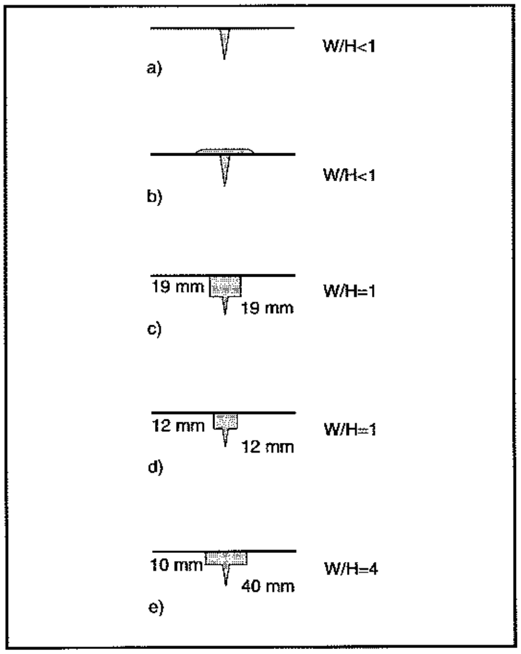

Figure 2. Crack geometries with (c-e) and without (a, b) routing. A sealant with W/H<1 and placed in an active crack is strained more than one with W/H≥1.

Table 6. Opening of Routs in a 1-year Cycle as Measured in Montreal in 1991-1992

1 Site*	2 Rout Width (mm)	3 Orientation[1]	4 Min. Opening[2] (mm)	5 Max. Opening[2] (mm)	6 Difference[3] (mm)	7 Average Opening[4] (mm)	8 Average Opening[5] (mm)	9 Percent Opening[6]
1	12	+	-0.17	0.63	0.80			
7	12	+	-0.24	1.25	1.49	1.82		
14	12	+	-0.54	0.81	1.35			
29	12	+	-1.29	1.61	2.90			
35	12	+	-0.68	1.89	2.57		1.73	14
2	12	//	-0.00	1.24	1.24			
9	12	//	-0.24	0.66	0.90			
28	12	//	-0.95	0.99	1.94	1.62		
32	12	//	-0.24	2.17	2.41			
10	19	+	-0.74	2.06	2.80			
18	19	+	-1.04	2.47	3.51	3.09		
19	19	+	-0.53	1.81	2.34			
22	19	+	-0.71	1.97	2.68		2.83	15
31	19	+	-1.65	2.81	4.46			
34	19	+	-0.40	2.33	2.73			
3	19	//	-0.33	1.70	2.03	2.06		
5	19	//	-0.55	1.54	2.09			
4	40	+	-0.40	3.37	3.77			
8	40	+	-0.63	3.79	4.42	3.62		
13	40	+	-0.37	2.50	2.87			
17	40	+	-1.39	1.57	2.96			
20	40	+	-0.41	2.98	3.39		3.41	8
24	40	+	-0.91	3.40	4.31			
12	40	//	-1.12	1.25	2.37	2.79		
15	40	//	-1.12	2.60	3.21			

* Routs were in sections where the asphalt concrete had a cement concrete base.

1 + means transverse rout ; // means longitudinal rout.

2 Reference point taken at an average weekly temperature of 7°C (April).

3 Difference between the maximum and minimum rout opening.

4 Average opening according to rout orientation.

5 Average opening according to rout size.

6 Maximum rout opening (column 8/column 2).

The performance of sealants can, according to mathematical models, be improved by routing cracks so that the W/H ratio is increased. That is so because as the W/H ratio increases, the tensile stresses brought about by the sealant onto the interface decrease. Hence, a router is used to normalize the crack geometry. Depending on the alignment of the carbide-tipped cutters (see Figure 3), the rout profile often becomes W/H = 1 or W/H = 4 as routs of 12 by 12 mm, 19 by 19 mm and 40 by 10 mm are most common in cities which experience winters with very low temperatures. According to the models, sealants of 40 by 10 mm should show better performance than sealants of 12 by 12 mm or 19 by 19 mm.

Unexpectedly, all twelve sealants tested in Montreal showed a worse performance in routs of 40 by 10 mm than in routs of 19 by 19 mm or 12 by 12 mm (see Table 7).

It is likely that the wider a sealant, the more exposed it is to tires and the more exposed it is to shear stresses. The sealant in the 40-mm wide rout probably shows more debonding than sealant in 19- or 12-mm wide routs, because it is more exposed to urban traffic. Accounting for the shear stresses at the surface of a sealant and its exposure to traffic would also explain the reasons why pull-out levels tend to rise as sealant width increases (see Table 7).

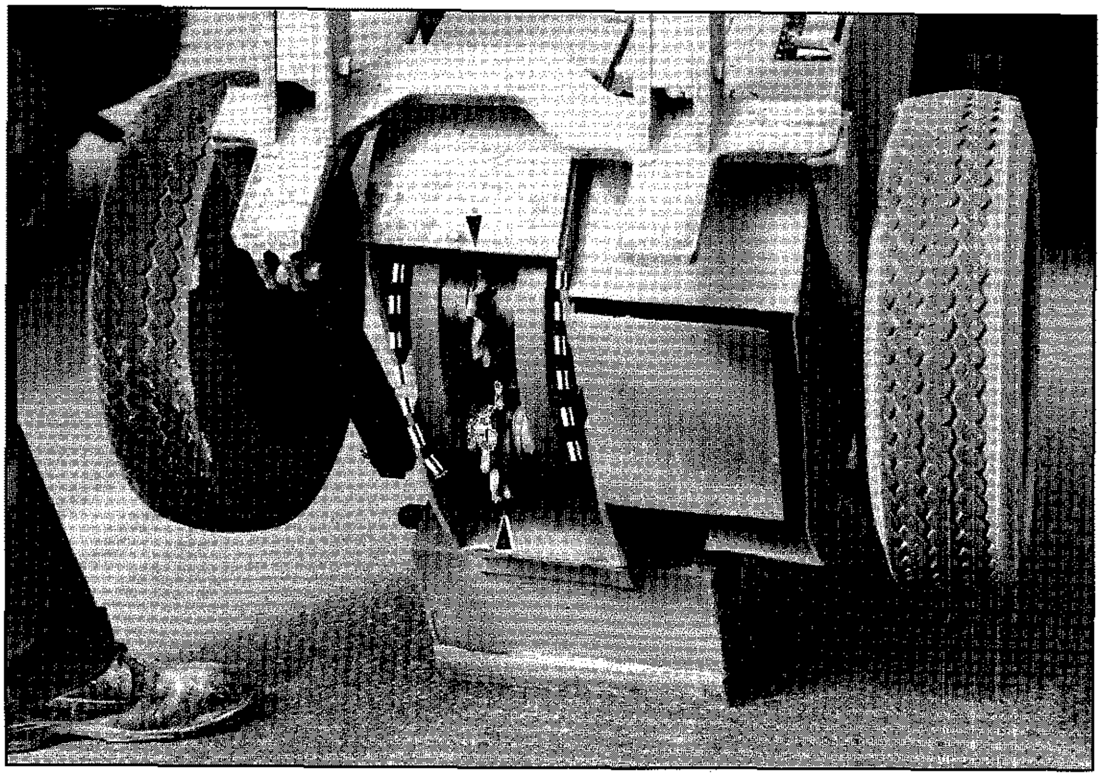

Figure 3. View of the carbide-tipped cutters under the router

Table 7. Frequency of Failure Levels in Different Routs

Rout Size (mm x mm)	Debonding			Pull-out		
	low	medium	high	low	medium	high
12 x 12	6	5	0	5	2	4
19 x 19	6	6	0	5	2	5
40 x 10	0	0	12	2	4	6

Standard Test

Rapid evaluation of crack sealants and quality control are normally performed by subjecting sealants to penetration, flow, resilience and bond tests as described in ASTM D5329 (formerly D3407). Test results must be within the limits set by ASTM D3405. Of the twelve sealants field-tested, seven failed to meet the requirements of the ASTM specifications (see Table 8). A comparison of the standard test results and the field results show, however, that there is little correlation between the two sets of results (see Table 9).

Table 8. Results of the Tests Performed According to ASTM D3407

Sealant	Penetration (<90 dmm)*, †	Flow (<3 mm)*	Resilience (>60%)*	Bond (3 cycles)*
A	86	0.5	**57**	**no**
B	68	0.5	64	yes
C	78	0	**59**	yes
D	67	0.5	62	yes
E	**104**	1	73	yes
F	**122**	2	**42**	yes
G	50	0.5	**51**	**no**
H	**93**	0.5	**48**	yes
J	66	**6**	**48**	yes
L	67	0	64	yes
L	76	0.5	63	yes
M	53	0.5	61	yes

* ASTM D3405 specifications. Results in boldface type indicate levels exceeding the specifications.

† 1dmm = 0.1 mm

The standard specifications successfully predicted the rather poor performance of sealants A, C and G. The failure of sealant C was not as convincingly predicted, however, because it failed the resilience test by very little. The sealants that met the requirements of the ASTM D3405 specification were mostly those displaying average field performance after 4 years. Three of the best performers in the field, sealants H, E and F failed to meet the specification. Hence, the usefulness of the specification in selecting good sealants may be questioned.

Table 9. Sealants in Decreasing Order of Performance

Sealant	Debonding	Pull-out	ASTM Acceptance	Performance Index	4-year Performance
H	9	4	no	75	
B	22	1	yes	74	good
E	20	2	no	72	
F	15	5	no	65	
M	16	5	yes	64	
L	6	10	yes	54	
D	22	6	no	54	average
J	13	12	yes	39	
K	21	11	yes	35	
A	11	14	no	33	
C	26	16	no	10	poor
G	36	14	no	8	

The ASTM test methods fall short as a guide in the selection of a sealant appropriate for cold urban environments, because they do not recognize the associated conditions. For example, in none of the tests have temperatures of –35°C to –40°C, which are typically reached in Montreal each winter, or heat-aging, or weathering been considered.
As a case in point, Table 10 shows that resilience at 25°C does not correlate with elongation at low temperatures, where proper elasticity is critical. This may explain the failure of good cold-temperature performers (sealants F and H) in the resilience test. Similarly, a 25°C penetration test, which measures the consistency of a bituminous material, indicates the viscosity of the material at 25°C and at no other temperature. The usefulness of the penetration test for the characterization of a crack sealant used in Canada is thus severely limited.

Table 10. Comparison of the elongations[1] of sealants at –37°C with their resilience[2] at 25°C

Sealant	ΔL at –37°C (%)	Resilience at 25°C (%)
E	700	73
F	300	42
C	120	59
D	100	62
A	25	57
M	6	61
G	6	51

[1] According to specification ASTM D638
[2] According to specification ASTM D3405

Installation Procedures — Are They Suitable?

As alluded to earlier, a sealant may fail for reasons other than having a composition unsuitable for use in cold urban environments. These reasons may lie with the equipment and procedures used in their installation. We shall now take a close look at them. We will want to see what happens to the sealant as it is heated to make it fluid enough for pouring.

We will further want to examine what happens to the crack during routing and during treatment with the HAL.

But first let us examine what trouble bubbles where the sealants are melted before their installation.

Temperature Control in the Melter

The installation of bituminous crack-sealant materials requires that they be heated to a temperature that makes them fluid. Heating is done in a melter. Once melted, they can be poured into the rout with a wand or a heated wheelbarrow. Despite recommendations prescribing the use of melters equipped with automatic temperature controllers, melters without one are still used by some contractors operating in urban centres. We therefore compared the performance of two melters:

- Melter A, which had no automatic temperature controller; and
- Melter B, which had a built-in automatic temperature controller.

Working alongside crews using either melter A or B, we collected temperature data to compare the conditions in which the sealants were kept during a regular working day. First, and as might be expected, we observed that melter A, the one without an automatic temperature controller, tended to bring the sealants to a temperature that exceeded the supplier's recommended installation temperature (see Table 11, column A).

The control of temperature with Melter B was better than that with Melter A, but not as much as anticipated from a unit equipped with an automatic temperature controller. Therefore, the temperature still had to be closely monitored by the crew. The temperature was fairly stable at 193 ± 4°C, for example, for up to 3 to 4 hours. When the outgoing flow of sealant was stopped for more than 15 minutes, however, the temperature could easily rise by more than 10°C above the initial application temperature.

Table 11. Crack Sealants and their Application Temperatures and Viscosities

Sealant	A	B		C	D
	Application Temperature (°C)			Viscosity (Pa•s)[1]	
	Suggested	Measured		185°C	210°C
A	190-205	205	(A)[2]	70	35
B	170-200	215	(A)	30	16
C	190-200	-	(B)	20	15
D	175-185	-	(A)	15	10
E	185-195	195	(A)	9	5
F	190-200	-	(A)	9	5
G	170-180	175	(B)	8	6
H	190-200	197	(B)	5	3
J	185-195	-	(A)	16	5
K	170-190	210	(A)	7	4
L	190-200	215	(B)	6	3
M	185-200	200	(B)	19	14

[1] 1 Pascal-seconds = 1000 centipoises.
[2] The letters in parentheses correspond to the melter, i.e., Melter A or Melter B.

Fluidity and the Cost of Expedition

There is an inverse relationship between the viscosity of sealants and the temperature of application. The higher the temperature of the sealant, the more fluid it becomes and the more quickly it can be poured into cracks or routs. Hence, contractors often perceive an advantage in increasing the flow of sealant by heating it to the maximum level of the supplier's recommended temperature range or even above, i.e., in the range from 200°C to 210°C.

Two factors contribute to these high application temperatures:

1. insufficient temperature control in sealant melters, with or without automatic temperature control, and
2. the natural tendency of crews to overheat sealant to ease pouring.

The latter is especially true for sealants that are not self-levelling at the recommended application temperature. Of the sealants tested, 50% fall within this category. This implies that when a sealant is selected at random among those available, there is an even probability that it will be overheated during its application.

The Behaviour of Sealants

In the laboratory, through viscometry, thermogravimetry and tensile testing, we measured the effect of the application temperature and the heating time on crack sealant materials. (Appendix B describes the experimental procedures.)

Effects of Heat on Viscosity

Before we deal with the effects of heat on the viscosity of sealants, let us understand that sealants are a combination of bitumen and elastomers. It is the composition and the relative proportions of its bituminous and elastomeric (polymer and recycled rubber included) components that determine the viscosity of a sealant. The contribution of bitumen to the melt viscosity of sealants is low (compare the viscosity values in Figures 4 and 5). Instead, what dictates the viscosity of a sealant is:

- the size of the elastomer-bitumen dispersion,
- the concentration and molecular weight of the elastomer, and
- the compatibility between the elastomer and the bitumen.

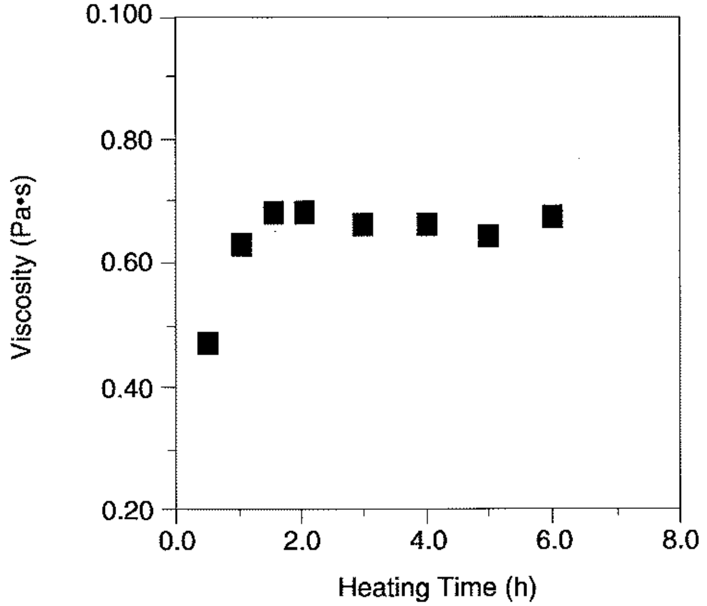

Figure 4. The shear viscosity of a 300/400 penetration grade bitumen at 185°C

Although all sealants show an inverse relationship with temperature, they all have a different viscosity at the same application temperature (see Table 11, columns C and D). At 185°C, the viscosity of the 12 sealants studied varied from 5 to 70 Pa•s. Sealants with viscosities lower than about 10 Pa•s are self-levelling, while sealants with viscosities above 30 Pa•s are difficult to pour. At 210°C, the viscosity is reduced to a range of 3 to 35 Pa•s. The percentage decrease in sealant viscosity between 185°C and 210°C is product-dependent, ranging from 25% to 70%.

The viscosity of a sealant is a function of the application temperature and of the duration of heating. Figure 5 shows the variation in the viscosity of the sealants held at 185°C and 210°C for up to 6 hours. At 185°C, a typical application temperature, the decrease in viscosity varied from very rapid (Sealants A and D), to moderate (Sealants B and L) and very slow (Sealants E, F and G). Other sealants showed a constant viscosity (Sealants K and H) or a slight increase (Sealants C and M).

For many sealants the decrease in viscosity at 210°C appears to be an extrapolation of the decrease in viscosity at 185°C. This is especially true of sealants A, D, F and L. By contrast, sealants B, C, J and M show a significantly lower viscosity at 210°C than at 185°C. As we will see later, this behaviour is reflected in the tensile properties of the sealants.

In subjecting sealants to heat, their viscosity is affected; the trend in the variation indicates the type of chemical changes occurring in the sealant. Given that the viscosity of a sealant is directly proportional to the molecular weight of its elastomer, then any decrease in its viscosity during heating indicates a lowering of its molecular weight, i.e., a thermal degradation. This type of degradation is not unique to crack sealants; it also occurs in other elastomer-bitumen mixtures.

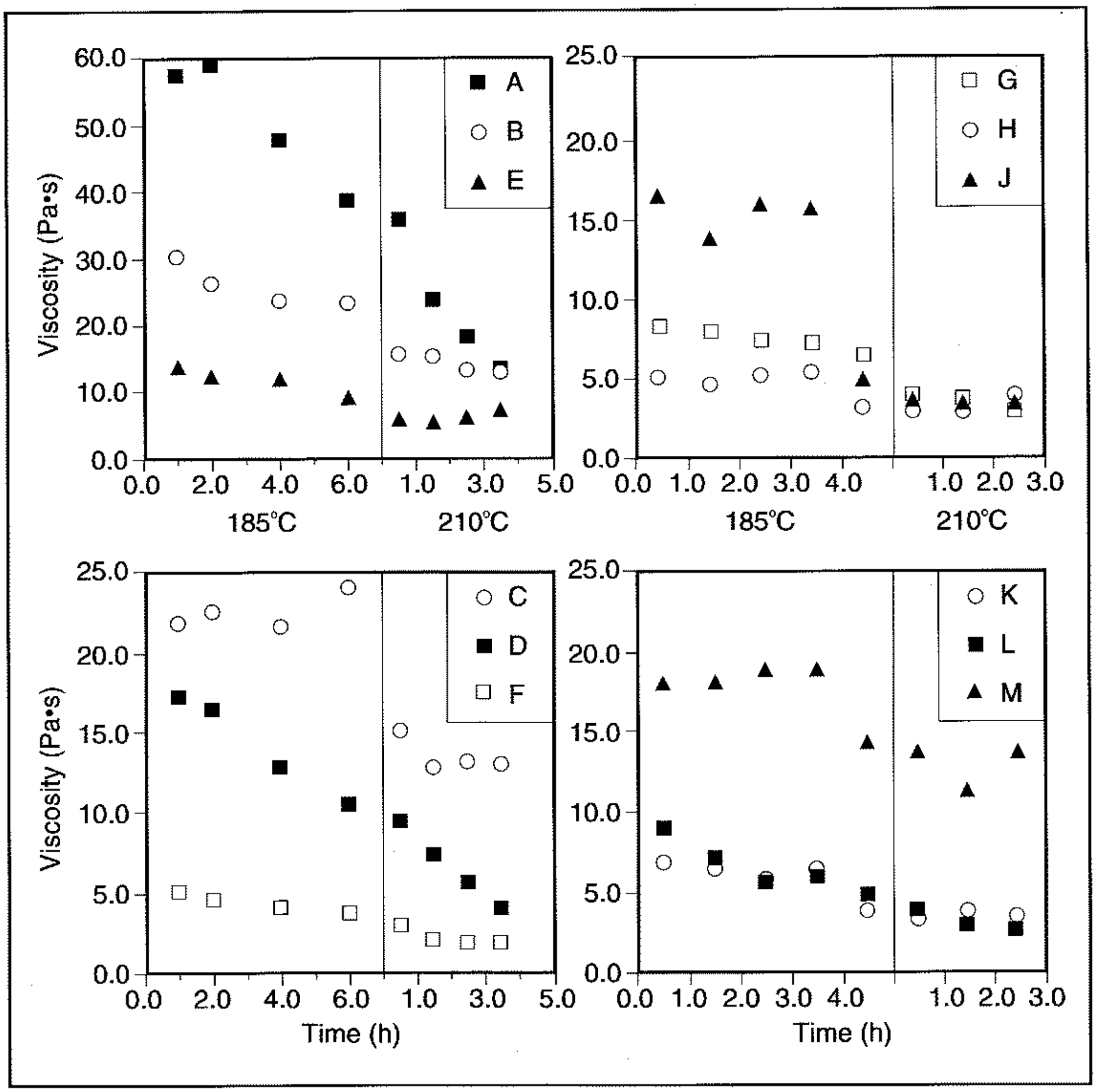

Figure 5. Shear viscosity of sealants as a function of time and temperature. In each graph, the values at the left of the tie-line were measured at 185°C; those at the right, at 210°C.

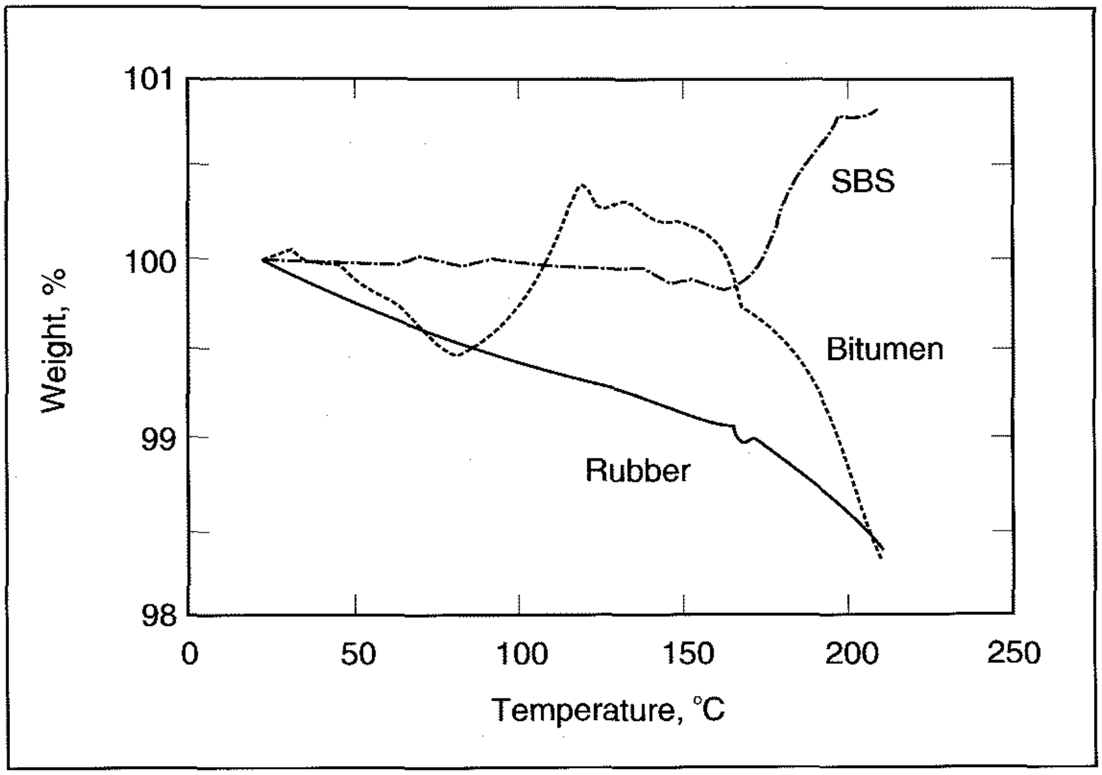

Figure 6. Typical weight change of representative sealant raw materials during heating in air at 5°C/min as measured by thermogravimetry. The weight of the SBS copolymer remains constant until about 170°C and then increases because of its gain in oxygen, i.e., oxidation. In contrast, the recycled powder loses weight as process oils gradually volatilize. Bitumen shows a combined weight loss due to the volatilization of light oils and a weight *gain due to oxidation.*

Effects of Heat on Sealant Components

Bitumen and elastomers — the main components of sealants — are made of compounds containing mostly carbon, hydrogen, oxygen and nitrogen. Consequently, bitumen and elastomers may oxidize, degrade, or lose volatile components when heated (see Figure 6). Representative raw materials may lose more than 15% in weight when kept at 210°C for 1 hour (see Figure 7).

Sealants also lose weight when heated (see Figure 8). Because their individual compositions are different, sealants lose weight at a different rate, but the trend in weight loss is identical for all sealants. The weight loss increases with time and temperature. Most of the weight loss occurs within the first hour of heating. At 185°C, it can lose 17% of its weight during that time. After 3 hours of heating, the weight loss still progresses, but the difference in weight loss between the various sealants diminishes. The fumes from heating sealants during their installation attest to volatilization.

The weight loss of sealants during heating is due mostly to the evaporation of light oils that make sealants soft and rubbery, and as we will see later, this loss of oil affects the performance of the sealant. The loss of weight during heating may also be due to the degradation of the elastomer in the sealant and the evaporation of the degradation products. The elastomer degradation in a hot sealant is easily seen by a reduction in its viscosity (see Figure 5).

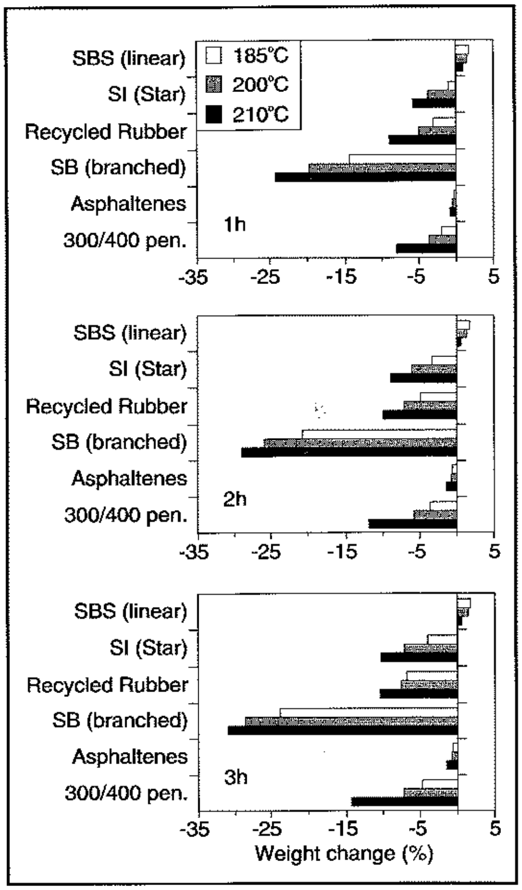

Figure 7. After rapid heating to temperatures representative of those found during sealant installation, raw materials were kept isothermally at those temperatures. All materials, but SBS, showed an increasing weight loss with time and temperature as measured by thermogravimetry.

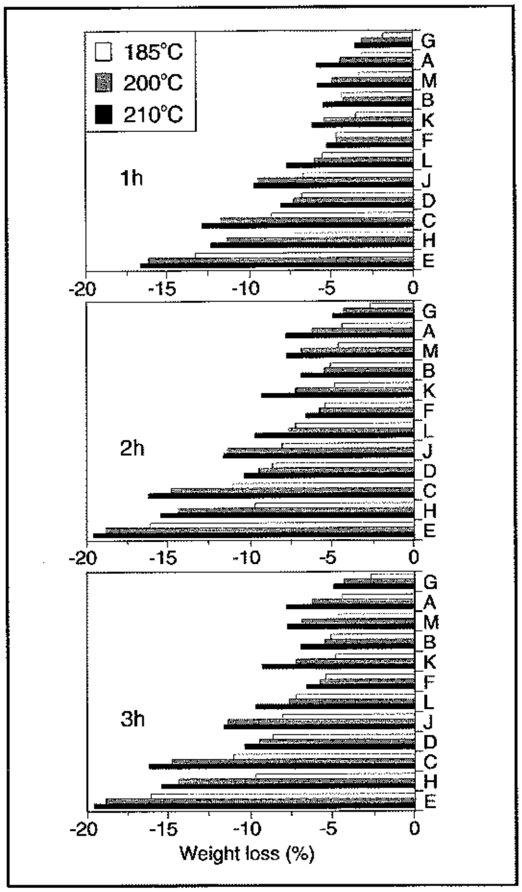

Figure 8. Weight loss of sealant with time and temperature; for example, after 2 hours at 185°C, sealant H had lost almost 10% of its weight.

Sealants that show a decrease in viscosity with time contain an elastomer that is prone to thermal oxidation, whereas sealants that retain a constant viscosity contain an elastomer that may be more resistant to oxidation and degradation. We emphasize *may* here, because a constant viscosity can result from two competitive processes:

1. a loss of light oils, which increases viscosity; and
2. a loss of elastomer, which reduces viscosity.

In this case, the tensile properties can tell us whether there has been no change.

Effects of Heat on Tensile Properties

Sealants are viscoelastic materials. Hence, after initial tension-loading, they deform and elongate, with the percentage elongation being reduced as temperatures get lower. At any given temperature, the mechanical properties of a sealant, or that of other viscoelastic materials, is governed by its composition. The oil and polymer contents play key roles; high elastomer contents and high molecular weights provide high moduli, whereas compatible oils reduce brittleness. In sealants and other polymer-modified bitumens, the compatible oils come from the maltenes of the bitumen or from process oils added to the formulation. From the composition of a sealant, it is thus possible to anticipate its mechanical properties. The exact composition of the sealants tested here is unknown, but their relative composition can be obtained from the viscosimetry and thermogravimetry measurements (Figures 5 and 8, respectively). The relative compositions for sealants A, F and C are shown in Table 12.

Low Oil/High Elastomer Content. It is no surprise that sealant A has a high modulus and low elongation. Its content of oil is low and that of elastomer is high. The opposite is true of sealant F. When sealants are heated, their composition is affected, and hence their mechanical properties. From the trend in the latter and from the viscosity and weight loss, the change in the composition during heating can be readily deduced. With a sealant of low oil and high initial elastomer contents — e.g., sealant A — the thermal degradation of the polymer dominates over that from the loss of oils. As a result, the modulus decreases as the elastomer degrades, with the by-products of the degradation (oils) producing an increase in a low initial elongation (see Figures 9 and 10).

Table 12. Estimated Composition of Sealants

Sealant	Oil Content	Elastomer Content
A	low	high
C	intermediate	intermediate
F	high	low

High Oil/Low Elastomer Content. In a sealant of high initial oil content — e.g., sealant F — the loss of oil dominates over the degradation of the elastomer. As the oil content decreases, the material becomes more brittle, so that the modulus increases and the elongation decreases. In the intermediate case — e.g., sealant C — both the loss of oils and the degradation of the elastomer contribute to affect the mechanical properties. In the first hour of heating, the thermal degradation of the polymer dominates, with the by-products contributing to enhance the oil content, so that the elasticity increases. After 1 hour, the loss of oil dominates, so that the elasticity begins to decrease. It is noteworthy that this dual degradation mechanism correlates with the non-linear decrease in viscosity of the sealant between 185°C and 210°C (see Figure 5). When a single degradation mechanism dominates, the decrease in viscosity is linear, with the viscosity at 210°C being the extrapolation of that at 185°C.

Overheated Sealants Invite Poor Performance

According to the ASTM D3405 specification, application characteristics of the sealant shall remain relatively unchanged after being kept for 1 to 6 hours at the recommended pouring temperature. But the variation in tensile properties indicates that after 1 to 6 hours of heating at recommended pouring temperatures, the sealant properties did, in fact, change.

The occurrence of all this sealant degradation during heating would make *consistent* sealant performance exceptional. Poor performance can be expected from overheated sealants as well as from sealants poured after only a few hours at the recommended application temperature.

Best Time for Sealing Cracks

There are three facets to crack movement:

- crack closing and opening in response to thermal changes,
- lipping (vertical upward movement) at the crack primarily due to frost action and intrusion of incompressible material, and
- cupping (vertical downward movement) primarily as a result of loss of structural integrity of the pavement due to water infiltration and other water-related damage.

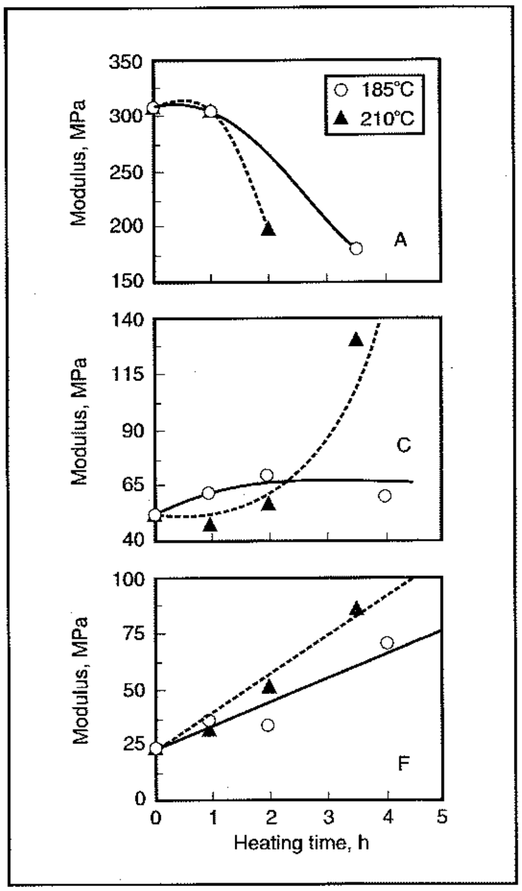

Figure 9. Change in the low-temperature (–37°C) tensile modulus of sealants after their heating at 185°C and 210°C

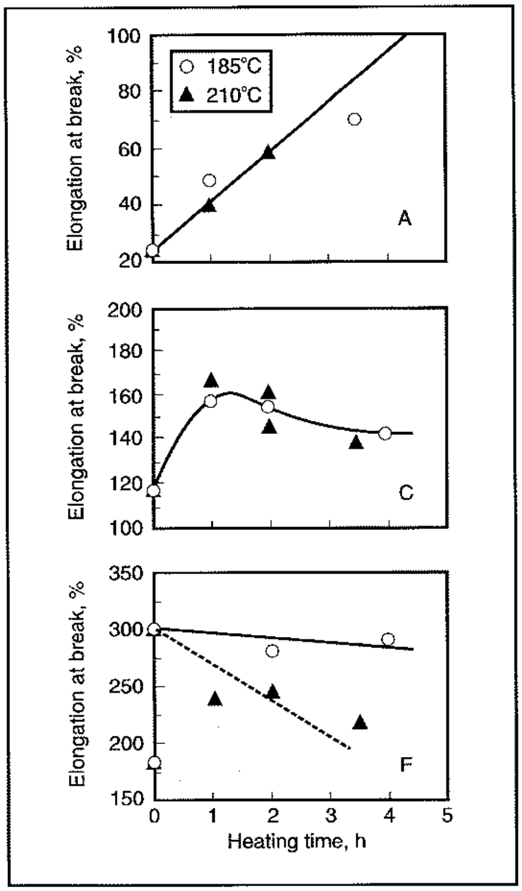

Figure 10. Change in the low-temperature (–37°C) elasticity of sealants after their heating at 185°C and 210°C

If there has been little or no water penetration (the objective of a crack-sealing operation), then crack closing and opening predominates. In the Northern Hemisphere, crack opening occurs in a 6- to 8- month period with a peak opening in February (see Figure 11). Crack motion is not consistent with daily air temperatures, however, but with temperature changes in the entire pavement structure. This change is relatively slow and in close correlation with a 4-day running average temperature. In general, crack movements are in the order of 5 to 25 mm in an annual cycle, and if a crack is kept clear of debris, the crack will close to a residual opening of about 1 mm greater than the opening at the start of a season.

Crack sealing should be conducted at a time of year when the temperatures are moderately cool, i.e., in the spring or fall. It is not uncommon, however, to observe crack-sealing operations during the summer months. Working conditions are pleasant and cracks have dried out. There is no doubt that sealant performance is very dependent upon proper and consistent workmanship during both crack preparation and sealing operation, and that good workmanship is most likely to be achieved during good conditions. Unfortunately, if cracks are sealed in the warmest period, the resulting seal will be in constant extension, thus increasing the chances of seal failure (see Figure 12). If cracks are sealed

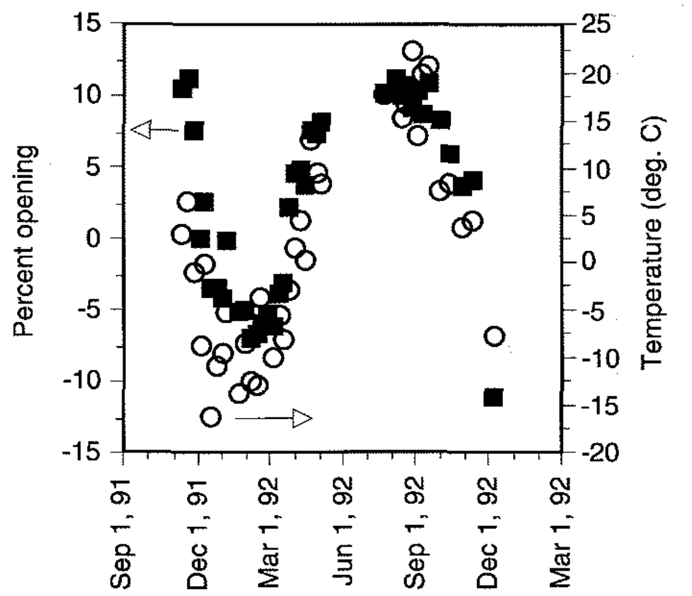

Figure 11. Comparison of the average rout width and temperature as measured in Montreal over one year. Pavements have a concrete base with an asphalt overlay. As a result, the response of the pavement to temperature variation is slow, and crack width varies accordingly. Crack width correlates weakly with average daily temperature but correlates strongly with the average temperature over four days.

while only half-open then the resulting seal will undergo neither excessive extension nor contraction. From Figure 11, it is evident that cracks are half-open only in December or April. Sealing cracks in December, after an autumn when infiltration and water damage can take place, bears little advantage. Crack sealing during spring, however, does have merit.

Most roads are snow-free in March and April. New cracks will have appeared during winter and their crack walls will have remained undamaged unlike older cracks. This is then the most appropriate time to seal cracks, especially new ones. The pavement structure may still be frozen, however, and cracks may be damp. After routing, we must then ascertain that a sufficiently dry rout has been obtained before the sealant is poured down. (As we will see later, the use of the hot-air lance is not recommended for drying damp cracks, and because dampness does not appear to be an obstacle to good adhesion, a damp crack may be cleaned with high-pressure air after it has been routed). After a spring intervention, high summer temperature may then enhance the sealant/pavement bond, so that winter performance will be improved, unlike sealants installed in December, which cannot benefit from any curing period before being subjected to the large tensile stresses that accompany winter.

The Equipment Used in Crack Preparation

The pieces of equipment commonly used in preparing a crack before it receives the sealant are the router and the hot-air lance (HAL). The role of the router was already discussed in connection with crack geometry. Routers mechanically enlarge the crack by hammering its cutters into the pavement, thus breaking the

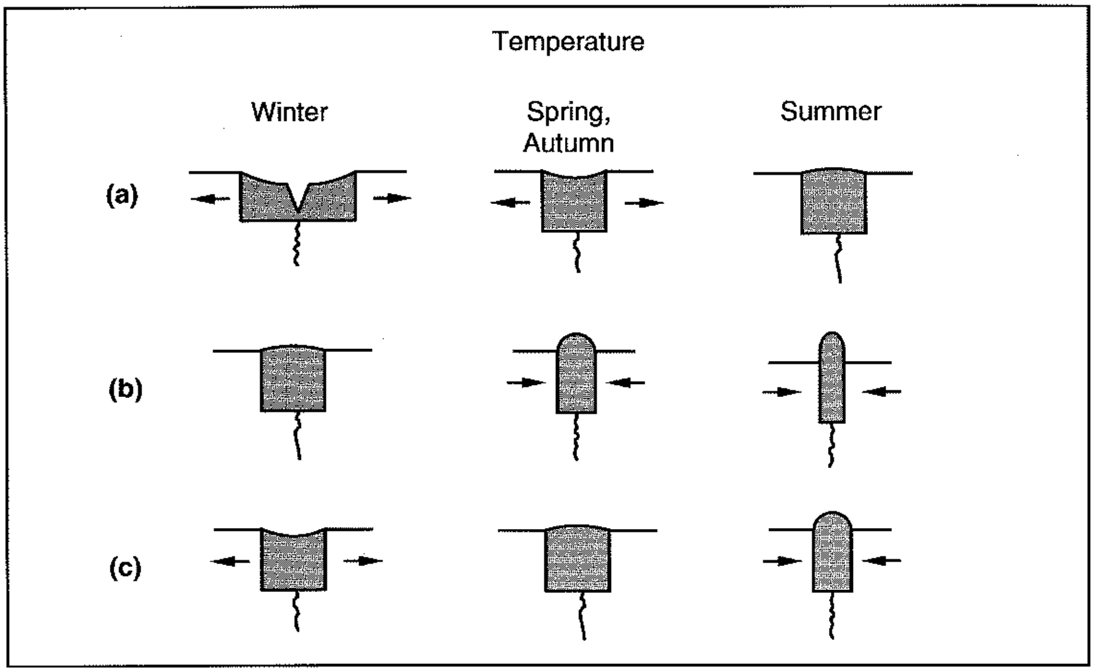

Figure 12. Potential effects of seasonal cycles on crack repairs carried out in summer (a), winter (b), and spring and autumn (c)

surface of the crack to provide a regular opening. Then a worker uses a HAL supposedly to help form a good bond between the pavement and the sealant that is about to be poured into the rout.

Sealant failures have been found to come about through more than one mechanism. Many failures arise not from the debonding of the sealant itself but from the presence of a weak layer at the surface of the rout. The weak layer may result either from the loss of cohesion of the AC following micro-cracking induced by the impact router or from the use of the HAL.

Effects of the Router on the AC

The effect of the router on the AC was investigated by studying numerous cross-sections of AC slabs under a microscope. All were free of micro-cracks prior to routing. After routing, however, micro-cracks appeared at the bitumen/aggregate interface and within aggregates themselves (see Figures 13 and 14). Micro-cracks propagate upon freezing and thawing and reduce the strength of the AC. They constitute defects at the sealant/AC interface where they can enhance debonding. A magnified view of the sealant-AC interface shows how this can occur (see Figure 15). As the sealant pulls on the aggregate during winter months (either because of thermal or traffic-related stresses), the cracked aggregate fractures further so that crystallites are left attached to the sealant. The bond between the sealant and the AC is thus broken. Alternatively, an entire aggregate may be pulled out of its bed by a sealant (see Figure 16). Seal failure is, in these instances, not caused by a debonding of the sealant, but by a loss of cohesion in the AC close to the surface of the rout. The frequency and the exact conditions leading to this type of failure remain to be investigated.

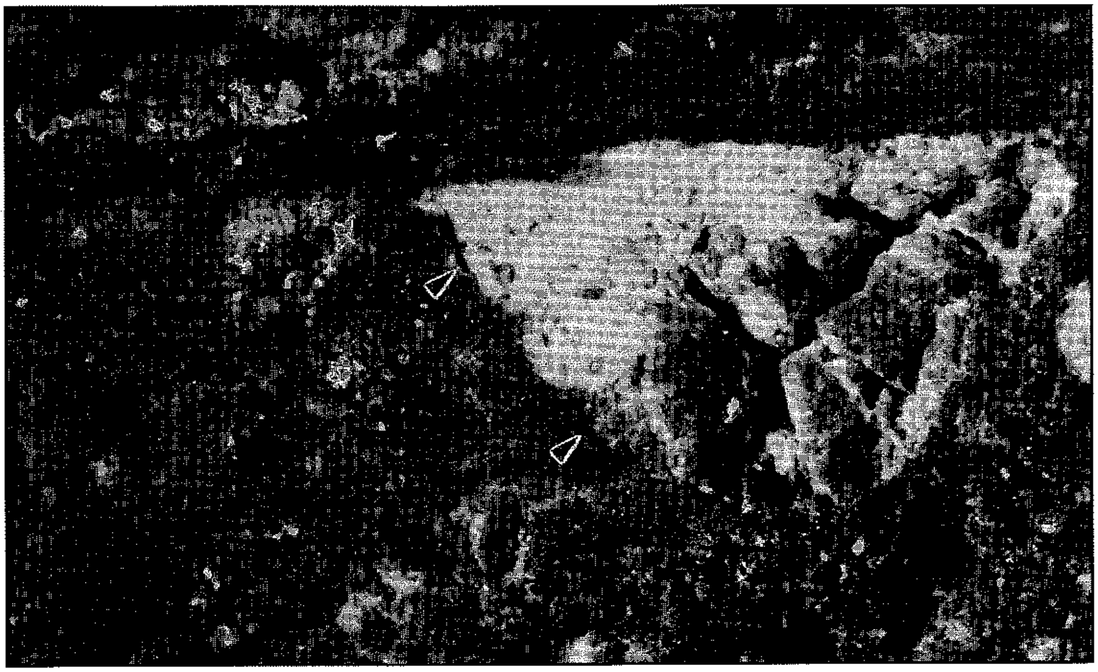

Figure 13. Magnified (6X) top view of an aggregate at the bottom of a rout. The use of the impact router has caused aggregate to shatter and debond from the bituminous binder (arrows).

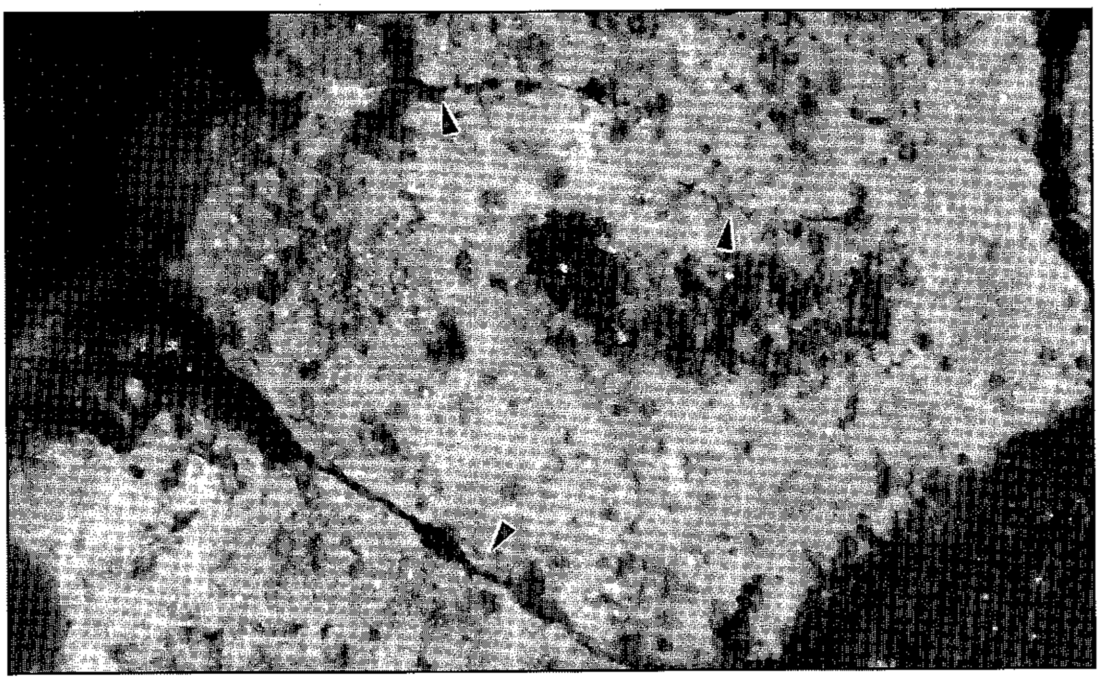

Figure 14. Magnified view (20X) of an aggregate in a rout. The arrows point to micro-cracks produced by the impact of the router's cutters onto the aggregate.

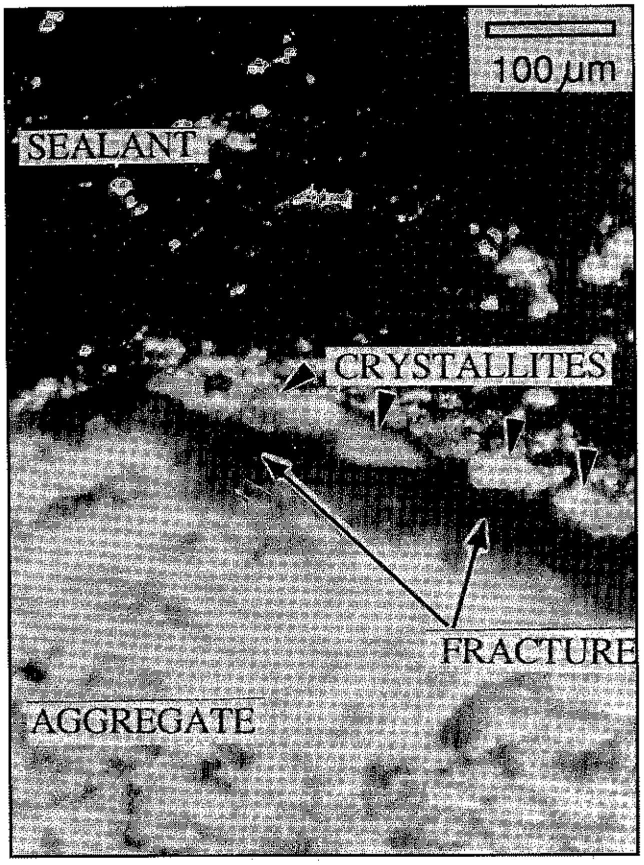

Figure 15. The effect of micro-cracks (long arrows) in aggregates at the sealant-AC interface. Upon the pulling of the sealant, the micro-crack widens and leaves crystallites (short arrows) attached to the sealant. As a result, the sealant is no longer adhering firmly to the AC.

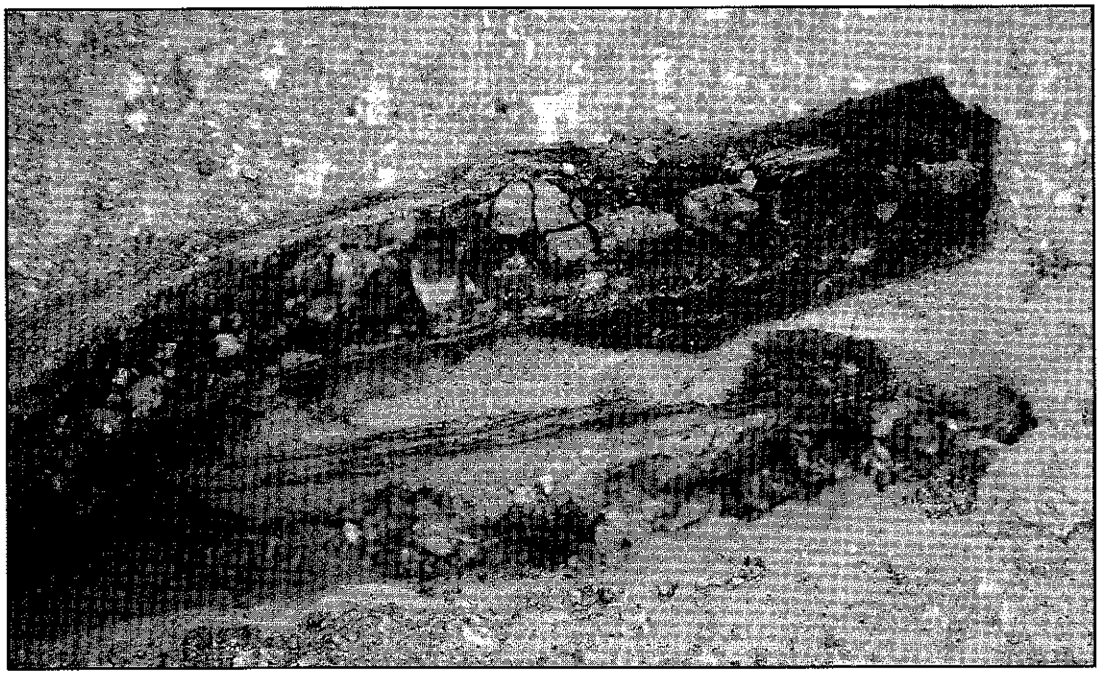

Figure 16. After micro-cracks have appeared at the aggregate-bituminous binder interface, aggregates can be pulled out of their bed by a strongly adhering sealant.

Effects of the HAL on the AC

Prior to being filled with sealant, the rout is treated with a HAL. The HAL is widely used in Canada and the northern United States to heat the routs before they are filled with bituminous crack sealant. Initially engineers used to think that they could derive certain advantages from using the HAL, such as extending the number of days in the year during which crack-sealing work could be performed and achieving crack sealing in damp conditions. These early studies, however, did not assess the effect of the HAL on sealant performance.

It has always been assumed that the HAL promoted sealant adhesion and thus increased sealant performance. But we had reservations about this and therefore set out to monitor 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.

We thus compared the adhesion strength of three sealants applied to unheated, heated and overheated AC substrates prepared with quartz or limestone aggregates. The results show that, whether the surface be damp or dry, the use of the HAL is not advantageous. The HAL does not enhance the adhesion of good sealants and may, on the contrary, cause premature sealant failure in cold winter temperatures. Let us examine this situation more closely.

Temperature Profile

In the field, the typical temperature profile of the routed crack when the rout surface is slightly darkened is shown in Figure 17. The temperature rose rapidly to about 220°C and then returned to equilibrium temperature of 30°C within 60 seconds. We could not measure the temperature rise in routs that were overheated (see Figure 18) and postponed its measurement until the laboratory evaluation of the HAL.

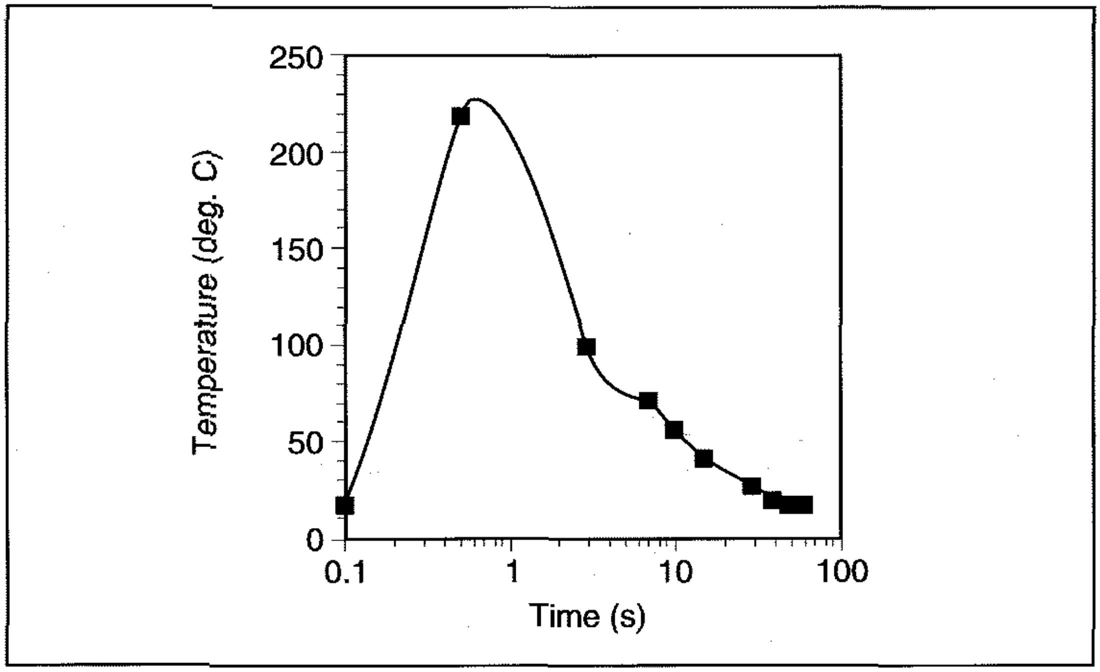

Figure 17. Typical temperature profile of the rout when it is heated with a HAL

It has been suggested that the HAL enhance sealant adhesion by melting the bitumen at the surface of the rout, thus allowing the interdiffusion of bitumen and sealant. But the temperature profile of the rout reveals that the HAL actually cannot promote sealant adhesion. For bitumen to become tacky, it must be maintained at 140°C to 160°C, the temperature at which pavement is laid. In normal conditions, the rout temperature is above 100°C for less than 10 seconds after the passage of the HAL (see Figure 17). Since the interval between heating the rout and sealing the crack varies from 1 to 5 minutes, the crack surface can no longer be tacky when the sealant is poured.

Adhesion to Dry AC

To assess the effect of the HAL on the AC and sealant adhesion, we built an automated HAL and reproduced field conditions as shown in Figures 17 and 18. After heating the AC with the HAL, we poured sealants onto the AC and thereafter measured their adhesion at low temperature by small- and large-scale adhesion tests. (Details of these tests can be found in Appendix B.)

In small-scale laboratory tests, the HAL did not increase the adhesion strength of sealants to substrates over what was possible on unheated briquettes (see Table 13); the adhesion of sealants to heat-treated briquettes is statistically the same as that onto unheated briquettes. On the other hand, if a briquette was overheated, then the adhesion strength of the sealant was often reduced by 50% or more.

The measured adhesion strengths are related to the mechanism of sealant failure. When the AC surface was left untreated, or normally heated, the adhesion strength was high and failure at the sealant-AC interface was both cohesive and adhesive. The cohesive failure was caused by the pull-out of fines and aggregates from the AC surface (see Figures 19 and 20). The adhesive failure resulted from the debonding of sealant over the large aggregates (see Figure 20).

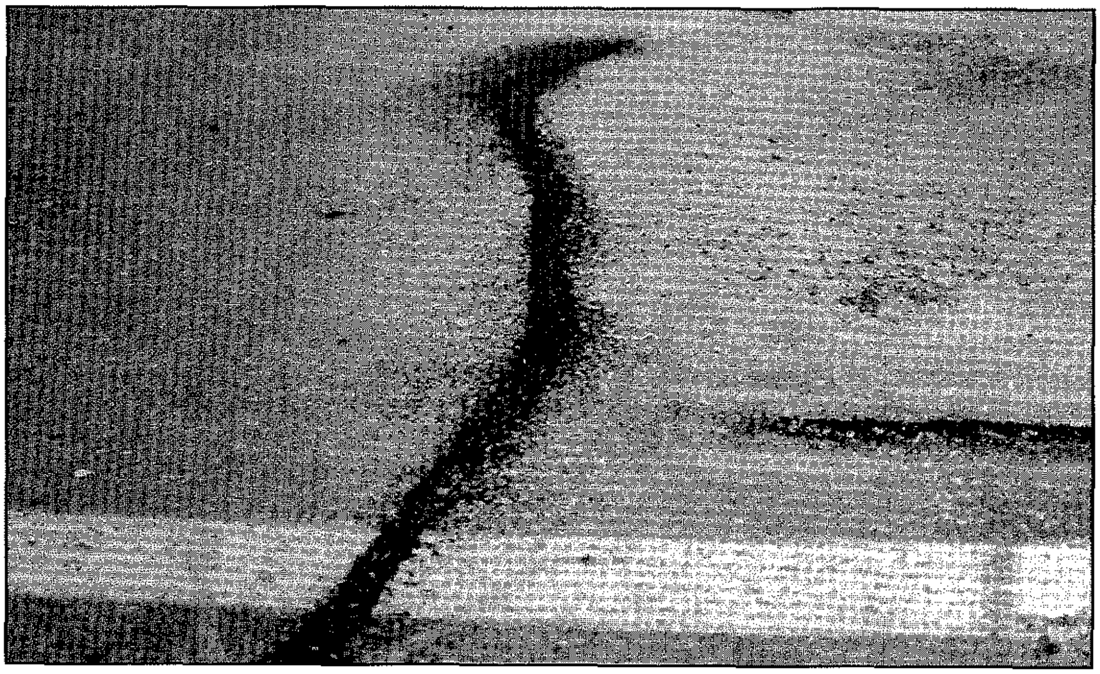

Figure 18. Typical blackening of an overheated rout

Table 13. Mean Adhesion Strength of Sealant, as Measured with an Instron, Adhered to a Bituminous Briquette

Quartz Aggregates			Limestone Aggregates		
Sealant A	**Adhesion (mJ/cm^2)**	**S**	**Sealant A**	**Adhesion (mJ/cm^2)**	**S**
control	53	11	control	28	9
heated	41	13	heated	21	10
overheated	18	6	overheated	11	4
Sealant M	**Adhesion (mJ/cm^2)**	**S**	**Sealant M**	**Adhesion (mJ/cm^2)**	**S**
control	35	12	control	33	13
heated	51	24	heated	29	1
overheated	17	5	overheated	18	7
Sealant L	**Adhesion (mJ/cm^2)**	**S**	**Sealant L**	**Adhesion (mJ/cm^2)**	**S**
control	22	7	control	30	7
heated	22	6	heated	19	7
overheated	15	6	overheated	14	4

S = Standard deviation

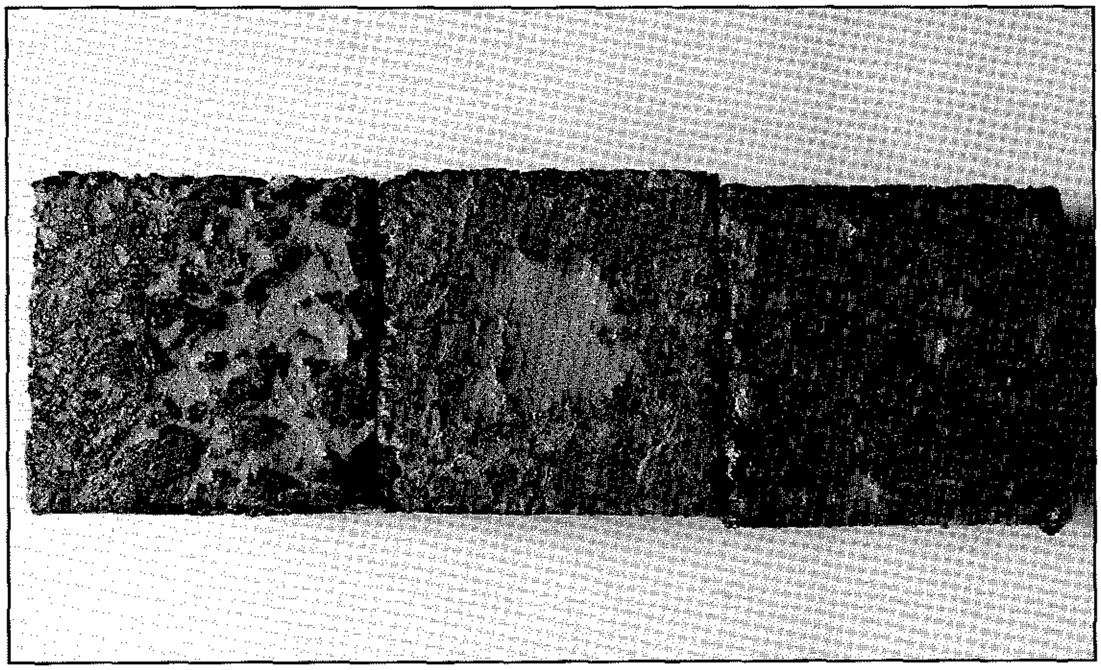

Figure 19. Surface of AC briquettes after tensile tests on sealant-briquette assemblies when the briquette is untreated (middle) and overheated (left). On the right, is the briquette surface without sealant. The briquettes were covered with dyed paste to increase the contrast between the holes in the 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.

By contrast, when the AC surface had been overheated, the adhesion strength was low, and failure at the sealant-AC interface was adhesive (see Figure 21). In this case, the sealant showed 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 contained little bitumen and few, if any, fines as if the sealant could not grip onto the surface. It may be that the relatively high sealant viscosity prevented it from flowing deep into the holes to completely wet the AC surface.

Full-scale test results indicate that the capacity of sealants to follow crack opening at low temperatures without debonding differed significantly (see Figure 22). For example, sealant L debonded rapidly upon a 30% crack-widening. By 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 high elongation (sealant M) that can readily accommodate crack-widening. In this instance, the tensile stress at the sealant-AC interface was sufficiently low to ensure that debonding would not occur, irrespective of the AC surface treatment. When the sealant had an average elongation (sealant A), then the HAL improved adhesion somewhat, but only after elongation had exceeded 80%. On the other hand, when the sealant had a low elongation (sealant L), it exerted a large stress on the AC surface upon crack-widening; and in these instances, the use of the HAL accelerated an already rapid debonding.

Figure 20. 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-gray where sealant has debonded.

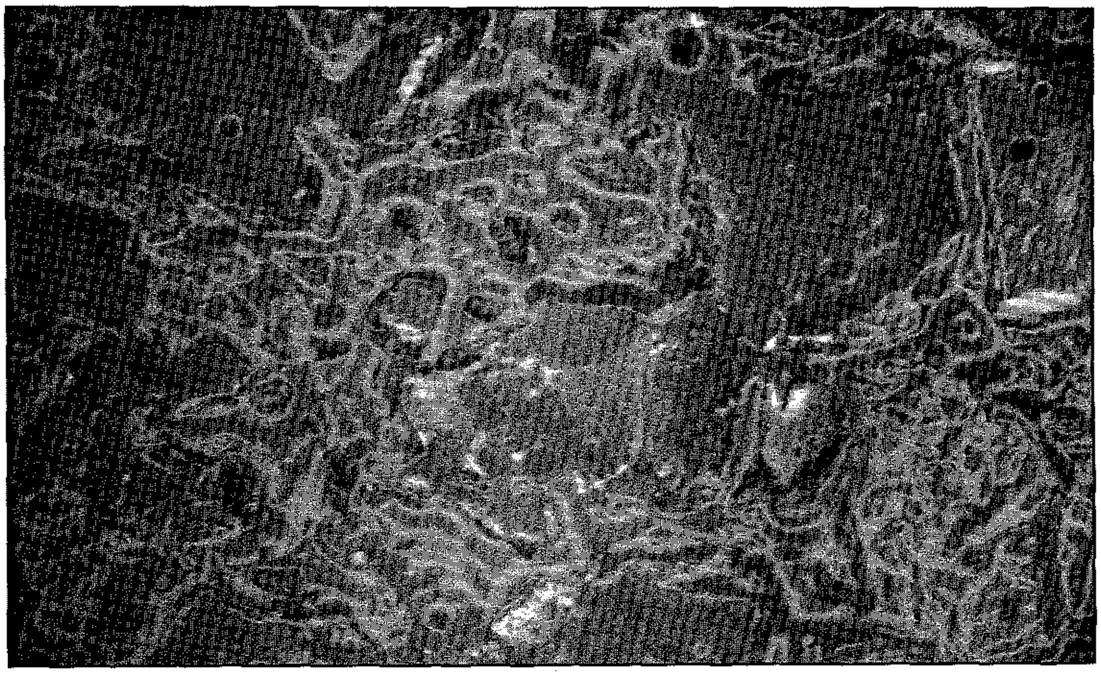

Figure 21. Sealant surface after a tensile test on a sealant-briquette assembly when the *briquette is overheated*. The sealant surface is a replica of the briquette surface that contains few fines and no bitumen.

Table 14. Adhesion Strength of *Sealant M on AC Briquettes Prepared* with Limestone

Sample Surface	Adhesion*, mJ/cm^2	Failure Mode
dry (control)	25 (6)	cohesive - in AC
dry (control #2)**	22 (3)	cohesive - in AC
damp	36 (11)	cohesive - in sealant
damp and heated	10 (3)	adhesive

* number in parenthesis is the standard deviation
**soaked in water for 1h and dried in vacuum for 20 minutes.

From the adhesion tests, it can be concluded that the HAL may in rare instances improve sealant adhesion to the AC. But if the sealant is properly selected for use in cold climates, then the HAL does not provide additional reliability toward the long-term performance of crack sealants.

Adhesion to Damp AC. In a second series of experiments, we measured the adhesion of sealant M onto just damp and damp HAL-dried AC. The results of the tensile tests, performed at –37°C, are shown in Table 14. We observed that the sealant bond is not much affected by dampness, but that it is more affected by the HAL. The sealant bond strength on dry or damp AC was statistically the same, but that onto the damp HAL-dried surface was lower. Hence, once again, the use of the HAL proved to be disadvantageous.

We also observed that failure at the sealant/AC interface was exclusively adhesive when the HAL was used, but that it was cohesive in the other cases (see Table 14). This situation is analogous to the one observed before with the dry AC. Moreover, we noted that when sealant was poured on damp AC, cohesive failure was in the sealant itself rather than in AC. The reasons for this behaviour remains to be determined but it shows, nonetheless, that a damp AC surface does not prevent good sealant adhesion on the AC.

The results obtained here must be used with caution. They should not be taken to indicate that damp or wet cracks can be sealed without any treatment. In our experiments, the AC concrete surface was damp but clean. In the streets, cracks are damp and dirty. Dampness may not affect bonding much but dirt certainly can. Because the HAL should not be used to dry routs, and since some dampness may be tolerated, it is suggested that routs be cleaned with *dry*- and *oil*-free high-pressure air. This cleaning method certainly has the potential for removing dampness and particles from a surface, without the risk of heating and damaging the AC.

Effect of Aggregate Type on Bonding
The adhesion of sealants to briquettes made with either quartz or limestone aggregate was in one case different (see Table 13). 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. In practice, this implies that a sealant may perform well and adhere strongly to AC 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.

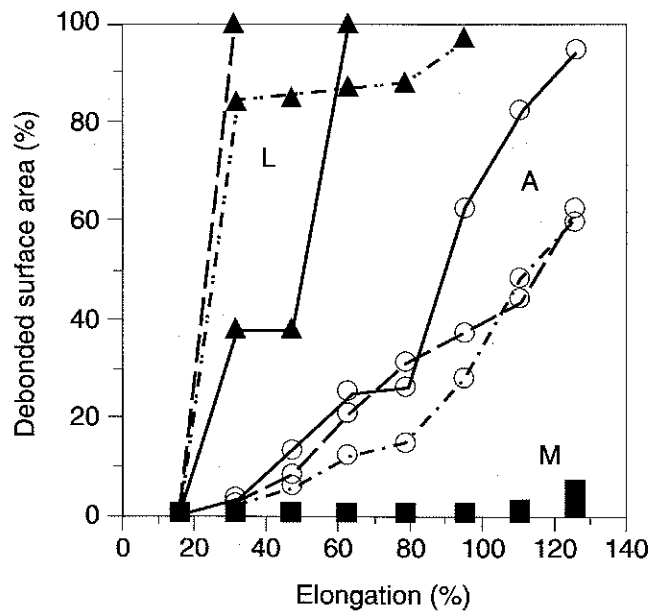

Figure 22. Debonding length of sealants upon elongation during the full-scale tensile test when the rout was untreated (full), heated (dash), and overheated with the hot-air lance (dash dot)

Recommended Application Practices

Pavement cracks are sealed to reduce infiltrations that lead to pavement degradation. But *crack sealing is not a perfect means of* preventive maintenance as we have seen. Sealant failure can be common, and in cold urban environments, it can be extensive within a few years of service.

Crack sealing is a maintenance procedure *which, first and foremost, must be used* judiciously. Not all cracks should be filled with sealant. Sealant products perform best in young cracks, because new cracks are less active and the AC is in better condition. That explains why the sealant applied to 12- by 12-mm routs in this study performed well, these routs having been *cut into the smallest cracks.*

Once it has been established that crack sealing is appropriate, the question arises, Which procedure should be followed? A summary of the findings of this study and the related knowledge can help in answering this question:

Rout Geometry. Performance of sealants in routs measuring 40 by 10 mm and 19 by 19 mm is less than satisfactory, while that of sealants in 12- by 12-mm routs is superior. In practice, it is difficult to cover a crack with a 12-mm rout. *Where the crack sealant width* exceeds its depth, performance is better; but beyond a certain width, it is too vulnerable to damage by tires. A practical solution seems self-evident here: the rout should be over 12 mm but under 40 mm in width and have a W/H > 1. Accordingly, we recommend that routs be 20 mm wide *and 10 mm deep or,* where a crack is relatively large (old), 30 mm wide and 15 mm deep.

Routers and routing. Routing provides an advantageous sealant profile which enhances sealant performance. On the other hand, routing causes micro-cracking *of the AC at the* surface of the rout and that can lead to seal failure. Micro-cracking is inherent to the impact router, however, and it will be difficult to eliminate it, unless a new routing technology comes along. In the meantime, micro-cracking can be minimized by treating cracks as soon as possible after their appearance. The longer it takes to seal them, the older and more oxidized they become, and the more prone to micro-cracking they will be.

Router Dust. Router dust is currently recovered by mechanical sweepers, and any dust remaining in the rout is often conveniently blown out with a HAL. This technique causes damage, because the HAL does not generate enough pressure to clear all residue from the rout in one pass, and the numerous passes required eventually cause damage to the AC. An appropriate technique would be to simply clean the rout with high-pressure, oil- and moisture-free, compressed air. Rout cleanliness can be easily verified by laying high-tack tape (e.g., duct tape) in the rout. A clean rout will leave no residues on the tape.

Hot-Air Lance. We could not demonstrate that in normal use the HAL improves crack-sealant adhesion or performance. In fact, it can damage the AC. If a sealant has been correctly selected for low-temperature conditions and remains elastic, the HAL becomes unnecessary. If the sealant has been improperly selected and is prone to becoming rigid at low temperatures, then the HAL accelerates debonding. Only two situations exist which warrant the use of a HAL, and even then, at temperatures not exceeding 400°C:

- on AC contaminated by clay, which resists removal by blowing, unless some heat is applied; and
- in cold weather (5 to 10°C). At such temperatures, sealant must be poured immediately (in less than 30 s) after heating.

Thus the HAL should not be used routinely. When used, the heating operation must be done side-by-side with the sealing operation, behind the sealant melter, whereas the rout-cleaning operation, done with high pressure air, takes place at the front of the crack-sealing train.

Heating of Sealant. Current practice in crack-sealant application involves heating the sealant for 3 to 6 hours, if not longer, at 180 to 210°C. Under those conditions, it degrades. To prevent degradation, sealants should be heated for less than 1 hour at 170°C. But at that temperature, most sealants are too viscous to be poured easily. They should be reformulated accordingly. In the meantime, degradation can be minimized by applying the sealant at the lower end of the temperature range recommended by the manufacturer. The sealant should also be kept in the melter for shorter periods, and smaller melters should be preferred. Current trends favour higher productivity and melters with a capacity of 800 L or more, where sealant may remain half a day or longer. In a smaller melter, e.g., 400 L capacity, the sealant would be heated for a shorter time. Alternatively, a large melter can be filled at half capacity.

Sealant Selection. The existing ASTM D3405 specification is useless for selecting the best sealants, those appropriate for the rigorous conditions encountered in cities experiencing very cold winters. In the context of today's reduced budgets, this situation is unacceptable, because it forces municipal authorities to re-apply crack sealant much sooner than anticipated. Moreover, given the often relaxed quality control during the production of sealants, it is difficult to establish a permanent list of the top performing products. There is a solution in sight, however: the performance-based specification. Such specifications describe and reproduce field behaviour and aging conditions. They are much more reliable than prescriptive specifications, such as the present specification for crack sealants. Unfortunately, a performance-based specification for crack sealants and AC/crack-sealant systems is not yet available. Until it is, the ASTM D3405 specification may be used to, at least, prevent the use of the very worst crack sealants.

Appendix A

Sealant Installation and Monitoring of Performance

Sealant Materials

The twelve sealants selected for study were those available to Montreal contractors in summer 1991. Sealants were from Canada, the USA, France and the Netherlands. All sealants but one were purported to meet or exceed the ASTM D3405 specification but only five did in fact meet the specification (Table 8). The sealants were evaluated according to the ASTM D3407 test procedures: *Joint Sealants, Hot-Poured for Asphalt and Concrete Pavements.*

For application, the sealants were heated in one of two melters, a Marathon melter not equipped with an automatic temperature controller, and a Crafco melter with a controller. Both reservoirs had a capacity of 1325 L. After each day of operation, remaining sealant was pumped out of the melter, and refilled the next morning with a new sealant.

Preparation and Installation

Cracks were sealed after their routing, cleaning, and heating. Sealant installations were completed by a single contractor, Legault et Touchette Ltée. Twenty-four kilometers of cracks with little branching were selected for sealing. Small cracks, < 4 mm in width, were routed to 12 x 12 mm^2. Large cracks, 10-15 mm in width, were routed to 40 mm wide by 10 mm deep. Other cracks were routed to 19 x 19 mm^2. Three routers were used concurrently, each with the cutters set to the predefined rout geometry. The routers were of the impact type and equipped with carbide tipped rotating star-shaped cutters. The cutters were changed after every 3-4 km of routing.

Routs were cleaned with a mechanical sweeper, and vacuum cleaned until no dust could be detected with the hand or eye. The routs were heated with a hot-air lance from "L/A" Manufacturing, Co., model B.

Surveys

The sealants were installed in September 1991. Full-depth debonding and pulled-out lengths were periodically measured with a measuring wheel. The percent failure lengths were recorded according to rout size and orientation. The reported failure length averages are weighed averages, not arithmetic means, calculated from the failure lengths in individual rout sizes and orientations.
The first field survey was completed in December 1991, when temperature lows had reached –5°C. Other surveys were done in the spring of 1992, 1993, 1994, and 1995 after sealants had been subjected to temperatures of –33°C to –40°C during each winter.

The cyclic closing and opening of the cracks was also measured during one year. Thirty six routs, twelve of each rout size were monitored once a week by measuring the distance between nails placed on either side of the rout.

Appendix B
Laboratory Testing

Sealants were compared according to their viscometric, thermogravimetric determinations as well as their tensile properties.

Viscometry

The viscosity of sealants kept isothermally at 185°C and 210°C was measured using a Bohlin Visco-88-BV viscometer. The latter was equipped with a cylindrical spindle of 14 mm in diameter and 20 mm in length. Measurements were taken periodically at a shear rate of 3.43 Hz in a container large enough to prevent border effects. The sealants were heated for up to 6 hours at the selected temperatures, so that the study could be related to the ASTM D3405 specification, which states that within 6 hours "relatively little change in application characteristics" must occur. Between readings, the sealant was slowly stirred in a closed vessel while the temperature was kept constant with a temperature-controlled oil bath. Each reported viscosity reading is the average of a 10-second measurement.

Thermogravimetry

For comparative purposes, three elastomers, a recycled-rubber powder, and one bitumen were also used in the thermogravimetric analyses as representative sealant raw materials. The bitumen was a 300/400 penetration grade with a respective composition of 11%, 53%, 26%, 10% in saturates, aromatics, resins and asphaltenes. The recycled-rubber powder, Ultrafine GF-80, used in bitumen modification was produced by Rouse Rubber Industries. It contained 13% of process oil. The oil-free elastomers, obtained from Shell, were advertised as bitumen modifiers. They were styrene-butadiene-styrene (SBS) copolymer (Kraton D1101), branched styrene-isoprene (SI) copolymer (Kraton D1320X), and branched styrene-butadiene (SB) copolymer (Kraton 4240P).

The weight loss of materials upon heating was measured with a Dupont 2200 thermal analyzer. Fifteen to twenty milligrams of the sealants and their representative raw materials were rapidly heated in air to 185°C, 200°C or 210°C and held isothermally for 3 hours. Sealant raw materials were also heated in air at a rate of 5°C/min from 25°C to 210°C. The weight changes were monitored in a stream of air of 100 mL/min.

Tensile Testing

Three sealants were heated as described for the viscosity measurements. At regular intervals, the sealants were poured into sheets of about 3-mm thickness and cured for 24 hours. The specimens were cut into a M-III dumbbell shape as described in the ASTM D638 test method, *Tensile Properties of Plastics*. The specimens were conditioned at –40°C for 24 hours and tested in tension at a rate of 50 mm/min in an Instron tensile tester equipped with an environmental chamber kept at a temperature of –37 ±2°C during the test.

Adhesion Testing

Both small- and full-scale adhesion tests were 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 the northern United States. 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 with a 85/100 penetration grade bitumen and either limestone or quartz aggregate (see Figure B1). The briquette cross-section had an aggregate surface area of 35%, close to that of an Ontario HL3-type AC mix with 42%. Before 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 slight darkening of the AC surface ("normal heating" which caused the rout surface to attain 150 to 250°C) obtained by passing the lance at a speed of 40 cm/s at a distance of 50 mm from the surface;

- a darkening of the AC surface ("overheating" which caused the rout surface to attain 250 to 350°C) obtained by passing the lance at a speed of 15 cm/s at a distance of 50 mm from the surface.

For the adhesion tests on damp AC, sealant was poured on one of two AC surfaces:
a) AC briquettes immersed 1 hour in water and then blotted dry with paper for cleaning optical lenses, i.e., paper that leaves no residue on the surface;
b) AC briquettes treated as in a) and then normally heated, as defined above.

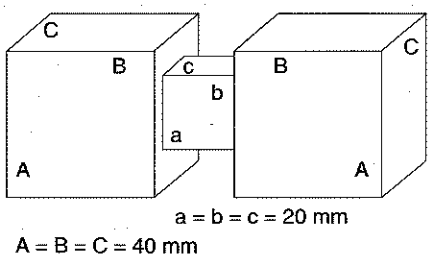

Figure B1. Schematic of sealant-briquette assembly. The briquette and sealant sizes are indicated by capital and lower case letters, respectively.

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 by 20 mm by 20 mm (Figure B1). After the sealant had slowly cooled to about 25°C, the assemblies were conditioned for 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 can be equated to the energy to rupture the assembly, i.e., the adhesion strength. Each reported value is the average derived from nine to fifteen measurements.

Full-Scale Tensile Tests
For full-scale tensile tests, asphalt concrete rather than briquettes was used as the substrate. The asphalt concrete was an Ontario HL3 mix containing limestone aggregate (maximum nominal aggregate size of 13 mm) which, before being used in this study, had aged 3 years at the laboratory's outdoor test facilities. Air temperatures during the aging period varied from –37°C to +35°C. The AC was first routed with a Crafco router equipped with new carbide-tipped routing bits; the rout size was 20 by 20 mm. Sections of pavement, each being 300 by 600 mm (1 ft by 2 ft) in area and containing a routed portion in its centre, 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 long, before the sealant-AC assembly was placed onto the testing table (see Figure B2).

The test table consists of two steel plates that can be moved independently of one another. The right plate (in Figure B2) moves vertically, whereas 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. 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 that had either been heat-treated with the HAL or left untreated, was tested by simulating crack-widening at a rate of 6 mm/hour coupled to a small dynamic shear displacement of ±0.127 mm. Moreover, the temperature was lowered from –30.0 to –36.5°C, at a rate of 1.5°C/hour, during the test. These conditions were based on a study that showed that similar test conditions could help differentiate between good and poor sealants used in cold conditions. The test was conducted either to failure along the entire length of sealant or for 5 hours, whichever occurred 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.

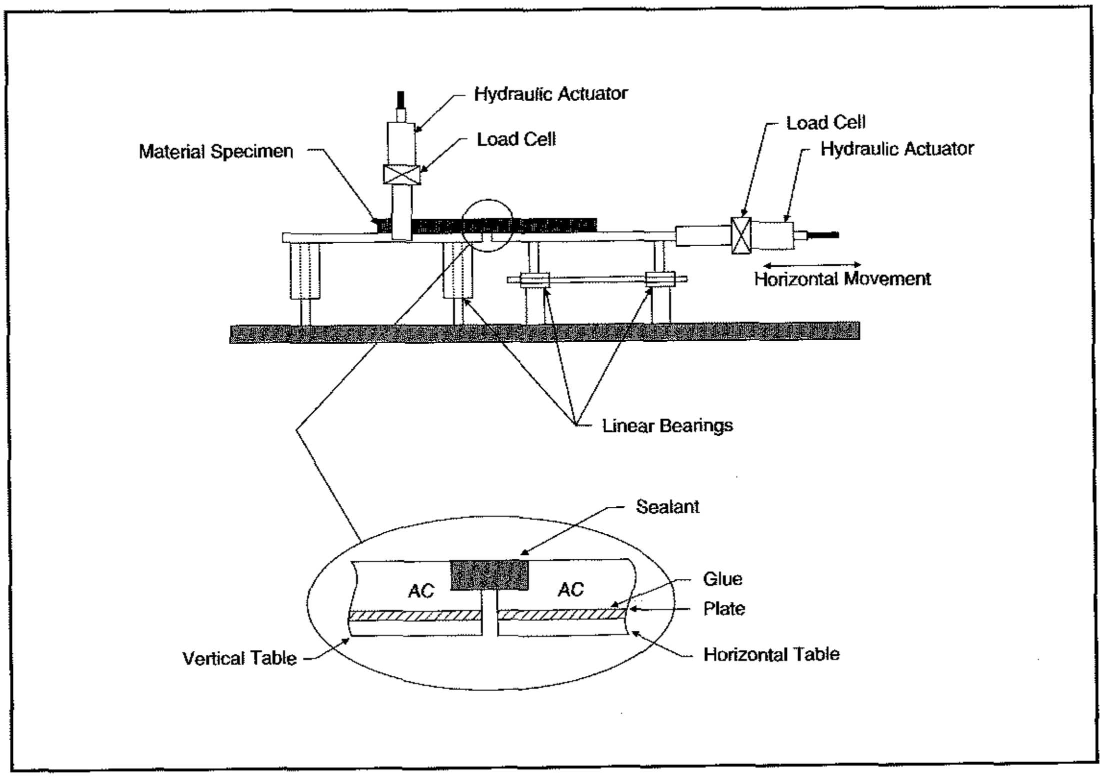

Figure B2. Schematic of the full-scale tensile test setup