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Performance of pavement crack sealants in cold urban conditions

J-F. Masson, P. Collins, and P-P. Légaré

Abstract: Twelve bituminous hot-pour crack sealants were evaluated over four years in temperatures ranging from -40°C to $+40^{\circ}\text{C}$. Each sealant was evaluated over 900 linear meters of transverse and longitudinal routs of $12 \times 12 \text{ mm}^2$, $19 \times 19 \text{ mm}^2$, and $40 \times 10 \text{ mm}^2$ (width $\times$ depth). Results show that sealant source, rout size, and rout orientation affected sealant performance, i.e., debonding and pull-out levels. Debonding levels were 0–50% and pull-out levels 0–30%. Sealant failure was proportional to rout width; it was lowest in 12 mm wide routs and highest in 40 mm wide routs. This result is attributed to the proportional exposure of sealants to slow moving traffic. The increase of sealant failure over time was also found to be nonlinear. Three stages were identified in the failure–time plot. In stage 1, failure is rapid; in stage 2, it plateaus; and in stage 3, it increases again. Failure in stage 1 is thought to be related mainly to a weak sealant – asphalt concrete interface, whereas that in stage 3 is thought to be related to sealant weathering and stiffening. It was also found that standard test results correlate poorly with field performance.

Key words: pavement, crack sealing, sealant, performance, cold weather, failure.

Résumé : Douze mastics bitumineux ont été évalués sur une période de quatre ans sous des températures allant de -40°C à $+40^{\circ}\text{C}$. Chacun a été évalué sur 900 mètres linéaires de fentes transversales ou longitudinales de $12 \times 12 \text{ mm}^2$, $19 \times 19 \text{ mm}^2$ et $40 \times 10 \text{ mm}^2$ (largeur $\times$ profondeur). Les résultats démontrent que la provenance du mastic, la taille de la fente et son orientation ont eu un effet sur la performance du produit, c.-à-d. sur les niveaux de décollement et d'arrachement. Les niveaux de décollement variaient entre 0 et 50% et les niveaux d'arrachement, entre 0 et 30%. La performance des mastics était inversement proportionnelle à la largeur des fentes; elle était meilleure dans les fentes de 12 mm de largeur que dans celles de 40 mm. Le plus grand taux de rupture des mastics de 40 mm correspond à leur exposition à la circulation. On a aussi constaté que l'aggravation de la rupture des mastics dans le temps était non linéaire. Trois stades ont été mis en évidence dans le graphique rupture–temps. Au premier stade, la rupture est rapide, au deuxième elle se stabilise et au troisième, elle reprend. On croit que la rupture observée au premier stade est attribuable en premier lieu à la faiblesse de l'interface mastic-béton bitumineux, alors que celle constatée au troisième stade serait due au vieillissement et au durcissement du mastic. On a aussi constaté que les résultats des essais normalisés concordaient mal avec la performance en service.

Mots clés : chaussée, fissure, mastic, bouche-fissures, calfeutrage, scellement, performance, rupture, basse température.

Introduction

The sealing of cracks in roadways is a common preventive maintenance technique (Chehovits and Manning 1984; Chong 1990; Eaton and Ashcraft 1992; Hubrecht 1986; Knight 1985; LCPC 1981; Tessier 1990). Many studies on bituminous crack sealants pertain to their performance on rapid ways located in regions experiencing “warm winters,” that is, with minima of about -5°C (Erickson 1992; Evers 1991; Ward 1993). Little is known about the performance of

sealants on roadways experiencing minima of -35°C or lower (Belangie and Anderson 1985; Chong and Phang 1988; Lupien et al. 1987); and even less is known about performance in cold urban conditions (Chai 1989). The latter conditions are common and most demanding. Light and heavy vehicles stop, accelerate, and turn over the sealant and it is subjected to shear forces almost inexistent on rapid ways. Cold urban conditions can significantly limit the number of sealant materials that perform well over many years and, thus, prevent the ingress of water and incompressible materials into the roadway base.

To select sealant for use in cold temperatures, 1-year field tests (Pearson and Lynch 1992) and modified or extended ASTM standard specification (Belangie and Anderson 1985; City of Montreal 1991; Quebec Ministry of Transportation 1996) have been used. In either case, the selection of sealant for use in a cold climate has remained a difficult task. In an effort to better understand the deterioration of sealant performance in cold urban conditions, we monitored the debonding and pull-out lengths of twelve bituminous crack sealants installed in Montreal, Canada, where streets have a bituminous overlay and a concrete base, and where yearly

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Written discussion of this article is welcomed and will be received by the Editor until December 31, 1999 (address inside front cover).

Table 1. Standard test results.

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

*ASTM D3405 requirements. Levels beyond acceptable limits are underlined.

†1 dmm = 0.1 mm.

‡Meets ASTM D1190 specification.

air temperatures vary from -40°C to $+40^{\circ}\text{C}$. We compared the short-term (1-year) and mid-term (4-year) failure levels and determined the effect of rout size on sealant performance. From the data for eleven sealants, installed in three rout sizes with two orientations (transverse and longitudinal), we sought trends in the increase of failure over time. In the end, we compared the 4-year field performance with standard test results.

Experimental investigation

Sealant materials

The twelve sealants selected for this study were those available to Montreal contractors. Sealants were from Canada, U.S.A., 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 1). Nonetheless, all sealants were retained for field trials to compare the standard test results with field performance.

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

Preparation and installation

Cracks were sealed after they were routed, cleaned, and heat treated. A single contractor installed all the sealants. Twenty-four kilometers of cracks with little branching were selected for sealing. Cracks smaller than 4 mm in width were routed to $12 \times 12 \text{ mm}^2$. Large cracks, 10–15 mm in width, were routed to 40 mm wide by 10 mm deep. Other cracks were routed to $19 \times 19 \text{ mm}^2$. In all cases, the ratio of rout width to crack width was about 3; and in the absence of a bond breaker, the percent adhesion area at the bottom of the routs varied little. 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 car-

Table 2. Early overall percent failure lengths of sealants.

Sealant	Before first winter		After first winter	
	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

bide tipped rotating star-shaped cutters (Masson 1997). 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. Before being filled with sealant, the routs were heated with a hot-air lance (Eaton and Ashcraft 1992; Smith and Romine 1993) from L/A Manufacturing, Co., Model B. The sealant was poured to a level just even with the pavement surface.

Surveys

The sealants were installed in autumn, when average air temperature was about 13°C . Debonding and pull-out lengths were periodically measured with a measuring wheel. Full-depth and partial-depth debonding were not differentiated. The percent failure lengths were recorded according to rout size and orientation. The reported average failure lengths are weighed averages, not arithmetic means, calculated from the failure lengths in individual rout sizes and orientations. An example of the calculations will be found in Table 3.

The first field survey was completed after 3 months of service, when the lowest temperature had reached -5°C . Other surveys were done in spring, after 7, 18, 32, and 44 months of service. During the four winters of this study, air temperatures reached -33°C to -40°C .

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 Parker-Kalon nails placed on either side of the rout. The measurements of horizontal crack displacements were used to calculate the percent sealant elongation in the various routs. These displacements are for asphalt concrete overlaying a Portland cement concrete base.

Results and discussion

In this study, the practice of an experienced contractor was monitored closely but without our intervention. It was observed that sealants were sometimes heated above the recommended installation temperature, and that in other instances, the rout was overheated because of an improper use of the hot-air lance. These observations catalyzed studies on the use of the hot-air lance (Masson and Lacasse 1999) and

Table 3. Percent debonding length of crack sealants after four winters.

Sealant	Transverse routs*			Longitudinal routs*			Combined orientations			Wt. avg. [†] (%)
	12	19	40	12	19	40	12	19	40	
A	14	16	17	4	6	9	7	10	14	11
B	22	22	31	13	21	15	16	21	24	22
C [‡]	32	29	35	18	6	9	26	24	27	26
D	20	25	33	12	16	23	15	20	30	22
E	12	16	31	3	13	24	9	14	28	20
F	19	16	19	8	9	22	14	13	19	15
G	30	42	47	30	29	32	30	36	40	36
H	16	9	20	0	6	5	13	8	15	9
J	15	13	17	7	5	6	14	11	16	13
K	29	36	27	8	9	26	17	24	27	21
L	10	8	7	3	5	6	7	5	7	6
M	19	19	21	12	11	16	15	14	17	16

*12: 12 × 12 mm²; 19: 19 × 19 mm²; 40: 40 × 10 mm² (width × depth).

[†]Weight average: wt. avg. = $\Sigma (pL_i)/L_t$, where p is the percent failure in rout i of length L_i and L_t is the total rout length, e.g., sealant A, $[(0.14 \times 87 \text{ m}) + (0.16 \times 188 \text{ m}) + (0.17 \times 216 \text{ m}) + (0.04 \times 165 \text{ m}) + (0.06 \times 222 \text{ m}) + (0.09 \times 139 \text{ m})] / 1017 \text{ m} = 0.11$.

[‡]Results after the first winter; monitoring discontinued thereafter.

Table 4. Percent pull-out length of crack sealants after four winters.

Sealant	Transverse routs*			Longitudinal routs*			Combined orientations			Wt. avg. (%)
	12	19	40	12	19	40	12	19	40	
A	19	15	20	4	12	15	9	13	18	14
B	0	2	1	0	0	0	0	1	1	1
C	31	19	14	6	1	3	21	16	11	16
D	3	12	6	4	3	5	3	7	6	6
E	5	1	4	1	0	1	3	1	3	2
F	11	9	3	6	4	20	9	4	5	5
G	17	7	30	8	9	15	13	8	24	14
H	10	5	10	0	1	1	8	3	7	4
J	18	10	15	3	7	6	15	9	14	12
K	9	24	5	3	5	12	5	16	16	11
L	7	4	2	0	16	0	4	14	1	10
M	3	5	11	1	4	2	2	5	5	5

*12: 12 × 12 mm²; 19: 19 × 19 mm²; 40: 40 × 10 mm² (width × depth).

sealant heating practices (Masson et al. 1998). Here the performance of sealants in the 11 km of routs (about 900 m per sealant) where sealant installation was acceptable is reported, rather than over the total 24 km of routed cracks.

Short- and mid-term performances

The initial survey was carried out three months after installation and did not reveal substantial sealant pull outs or appearance changes, but it showed that most sealants exhibited some debonding when exposed for several weeks with temperatures down to -5°C (Table 2). After exposure to temperatures of -35°C during the first winter, sealants then showed a marked increase in debonding and pull-out length from previous levels (Table 2). At that point, sealant C had showed exceedingly high failure levels and was deemed inappropriate for further study.

Sealant performance continued to deteriorate with time. Subsequent surveys showed that sealants weathered and changed significantly; their surface showed cracks, scratches, and pin-holes due to intrusion of stones and fine particles. Each spring, survey showed that debonding and pull-out

levels could increase significantly during winter. Tables 3 and 4 show the four-year percent failure lengths for transverse and longitudinal routs, and total percent failures of the sealants. The latter shows the wide spectrum of performance, or lack of it, that can be expected from different products. This is consistent with the observations of others (Lynch and Janssen 1997). Here, debonding levels ranged from 0 to almost 50% and pull-out levels ranged from 0 to 30%, depending on rout size and sealant source. The results also show that with few exceptions, and irrespective of rout size, sealant in transverse cracks are more susceptible to failure than that in longitudinal cracks, probably because transverse cracks open wider than longitudinal ones (Table 5). No attempts were made to correlate individual sealant performance with the opening of the various routs because too little data was available for a meaningful analysis of such performance.

The effect of rout size on performance can conveniently be looked at when failures in the transverse and longitudinal routs are combined (columns 8–10, Tables 3 and 4). With a 1% (10 m) difference deemed significant, each sealant and

Table 5. Opening of routs in a 1-year cycle (in mm).*

Rout width	Orientation [†]	Min.	Max.	Range	Mean 1 [‡]	Mean 2 [§]	Mean opening , %	Max. (min.) opening, %
12	T	-0.17	0.63	0.80	1.82	1.73	14	(6)
		-0.24	1.25	1.49				
		-0.54	0.81	1.35				
		-1.29	1.61	2.90				
		-0.68	1.89	2.57				
	L	-0.00	1.24	1.24	1.62			24
		-0.24	0.66	0.90				
		-0.95	0.99	1.94				
		-0.24	2.17	2.41				
19	T	-0.74	2.06	2.80	3.09	2.83	15	
		-1.04	2.47	3.51				
		-0.53	1.81	2.34				
		-0.71	1.97	2.68				
		-1.65	2.81	4.46				
	L	-0.40	2.33	2.73	2.06			23
		-0.33	1.70	2.03				
		-0.55	1.54	2.09				
40	T	-0.40	3.37	3.77	3.62	3.41	8	11
		-0.63	3.79	4.42				
		-0.37	2.50	2.87				
		-1.39	1.57	2.96				
		-0.41	2.98	3.39				
	L	-0.91	3.40	4.31	2.79			(6)
		-1.12	1.25	2.37				
		-0.61	2.60	3.21				

*From opening in April when the weekly average temperature was 7°C.

†T, transverse; L, longitudinal.

‡Mean according to orientation and rout width.

§Mean according to rout width.

||Mean percent opening (mean 2 / rout width).

rout size combination was compared and qualified as low, medium, or high. The results are shown in Table 6. Unexpectedly, they revealed that sealants in routs of 12 × 12 mm² debonded less than sealants in routs of 40 × 10 mm².

Based on numerical models (Kuri and Tons 1992; Tons 1962; Wang and Weisgerber 1993), sealants in 40 mm wide routs, with a width-to-height ratio, W/H , of 4 should have performed better than sealants in 12 or 19 mm wide routs, with $W/H = 1$. Factors peculiar to field conditions, not included in the models, are most likely responsible for the discrepancy between the observed and expected performances. Some factors can readily be excluded. Table 5 shows, for example, that differences in percent crack opening and associated tensile stresses cannot account for the discrepancy. Sealants in 40 mm wide routs had been exposed to only half the extension of other sealants. Sealant adhesion at the rout bottom also does little to explain the inconsistency, as it can only account for greater cohesive failure due to an increase in stress immediately above the crack (Wang and Weisgerber 1993). Moreover, the relative adhesion area amongst the routs had been held constant by adjusting the ratio rout width to crack width to about 3. Consequently, factors other than sealant adhesion to asphalt concrete and the tensile (compressive) stress induced by the crack opening (closing) influenced sealant performance.

Sealant aging and unaccounted shear stresses at the sealant surface can explain the discrepancy between the observed and expected performances. Wider sealants are subjected to more weathering and may age more quickly. Sealants can lose a substantial amount of plasticizing oil within a single year (Masson and Lacasse 1997) and the relative loss of oil may be greater in the largest sealant. In the urban setting, the shear stress at the sealant surface possibly play a dominant role, however. With the current practice, the sealant is most often leveled with the pavement surface. Consequently, it may be sheared by tires from vehicles that move slowly, stop, accelerate, and turn while in contact with the sealant surface. The large surface and the exposure of the 40 mm wide sealant to shear stresses would also explain its tendency towards greater pull-out levels (Table 6).

Performance trends

In service, sealants do not remain unchanged as they are exposed to water, sunlight, and freezing and thawing cycles. They weather like other bituminous materials (Minkarah et al. 1992; Petersen 1984). As a result, they may harden (Bahia and Anderson 1991) and loose elasticity in cold temperatures. For that reason, sealants are sometimes selected based on field tests, the one-year test being most common (Pearson and Lynch 1992). Figure 1, with a trend typical of

Table 6. Frequency of failure levels in different routs.*

Sealant	Debonding [†]			Pull-out [†]		
	12	19	40	12	19	40
A	L	M	H	L	M	H
B	L	M	H	L	H	H
C	M	L	H	H	M	L
D	L	M	H	L	H	M
E	L	M	H	H	L	H
F	M	L	H	H	L	M
G	L	M	H	M	L	H
H	M	L	H	H	L	M
J	M	L	H	H	L	M
K	L	M	H	L	H	H
L	H	L	H	M	H	L
M	M	L	H	L	H	H
Totals						
H	0	0	12	4	5	6
M	5	6	0	2	2	4
L	6	6	0	5	5	2

*12: 12 × 12 mm²; 19: 19 × 19 mm²; 40: 40 × 10 mm².

[†]L, M, and H represent low, medium, and high failure levels, respectively.

the observed time-dependent performance, shows that sealant failure did not increase linearly and that a one-year test would have failed to accurately predict a longer-term performance. The increase in sealant failure could typically be divided in three stages. The initial stage, a steeply rising slope, covered the first year of service. This stage was followed by a period of nearly two years where pull-out lengths remained fairly constant. In the final stage, from 32 months to 44 months in the example, the failure increased again, with that in the 12 mm wide rout exceeding that in the others.

The change in sealant performance is evidently more complex than anticipated. The grouping of 66 failure curves (eleven sealants, three rout geometries, two orientations) such as those in Fig. 1 allowed for highlighting recurrent trends. These are shown in Figs. 2 and 3. Pull-out trends were labeled P1 to P4 (Fig. 2) and debonding trends were labeled D1 to D4 (Fig. 3). In the best case, failure levels remained low and increased quasi-linearly (P1, P2, D3). In contrast, failure could reach a plateau after a one- or two-year period of rapid failure (P3, D4). In cases where final failure levels were high (D1, D2, P4), initial sealant failure was high and the plateau was short.

The exact reasons for the changes in failure rates remain unknown, but they are likely linked to specific components in the sealant – asphalt concrete system, namely, the interface and the sealant itself. Excessive sealant stiffness and a weak interface may be responsible for the initial and rapid increase in debonding. A weak interface may result from interfacial defects such as microcracks at the asphalt concrete surface and voids due to dust or incomplete sealant wetting. Sealant weathering and stiffening may be responsible for the later increase in debonding. On this ground, an extended first phase would be characteristic of stiff sealants, or alternatively of an aged and brittle pavement, whereas an ex-

Fig. 1. Typical failure profile for a sealant in the various routs.

tended second phase, a long plateau, would be characteristic of a better sealant.

Sealant selection for long-term performance

To estimate long-term performance and rank the twelve sealants, the 4-year pull-out and debonding levels were considered. For that purpose, a performance index was calculated. A simple addition of the respective debonding and pull-out levels would have implied that both types of failures were equally damaging to pavements, and would have underestimated the effect of pull-outs on pavement degradation. Consequently, pull-out lengths were given more weight than debonding lengths in the determination of a performance index. To that effect, the following equation was used:

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

where PI is the sealant performance index; D is the percent debonded length of the sealant; P is the percent pull-out length; and n is an integer that accounts for the effect of pull-outs over debonding on performance.

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 (Peterson 1982), and also allow the penetration of much more water than a simple sealant debonding over the same length, a value of $n = 4$ was thought reasonable. The approach is admittedly simplistic and the choice of n subjective, but it allowed us to fairly appreciate the performance of the sealants and it made for an easy comparison of the individual performances (values of $n < 4$ provided a similar ranking of materials but the difference of PI between the sealants was somewhat reduced).

Accordingly, sealants could be ranked in decreasing order of field performance and the performance compared to ASTM test results (Table 7). Little correlation between field and laboratory test results could be found, which is consistent with the work of others (Lynch and Janssen 1997). Seal-

Fig. 2. Pull-out trends for sealants in Montreal. The trends occurred with equal frequency.

Fig. 3. Debonding trends for sealants in Montreal. Occurrences were 40%, 8%, 33%, and 19% for trends D1, D2, D3, and D4, respectively.

ants H and E, which showed good field performance, failed to meet the requirements of the specification. In contrast, Sealant K, which met the standard requirements, showed poor field performance. In the end, average performers (e.g., Sealants M, L, D) were more likely to meet the ASTM D3405 specification than sealants at the performance limits, the good and the poor sealants. The usefulness of the specification in selecting good sealants, those required for demanding conditions, may thus be questioned. The results for penetration can be especially misleading. It has been shown by Lu and Isacsson (1997) that there is little correlation between the performance of polymer-modified bitumens, e.g., crack sealants, and their penetration values. The existing

Table 7. Sealant acceptance based on standard and field tests.

Sealant	Performance index	4-year performance	ASTM acceptance*
H	75	Good	No
B	74		Yes
E	72		No
F	65	Average	No
M	64		Yes
L	54		Yes
D	54	Poor	Yes
J	39		No
K	35		Yes
A	33	Very poor	No
C [†]	10		No
G	8		No

*From Table 1.

[†]After one year of service.

specification limits the penetration to 90 dmm but three of the four best performers in this study exceeded that limit.

Conclusions

Twelve bituminous crack sealants were installed in routs of $12 \times 12 \text{ mm}^2$, $19 \times 19 \text{ mm}^2$, and $40 \times 10 \text{ mm}^2$ (width $\times$ depth), and evaluated over 4 years in an urban setting with air temperatures ranging from -40°C to $+40^\circ\text{C}$. The pavement, in which crack opening ranged from 6% to 24%, was a bituminous overlay with a concrete base. The short-term (1-year) and mid-term (4-year) debonding and pull-out levels were compared; the effect of rout size on performance was determined; failure trends were identified, and overall performance was compared with standard test results.

Sealant performance was found to vary tremendously from one product to the next. The four-year debonding levels varied from 0 to 50% whereas pull-out levels varied from 0 to 30%, depending on sealant shape (rout size) and crack orientation. Relative failure levels often correlated with sealant width, overall performance increasing in the order $40 \text{ mm} < 19 \text{ mm} < 12 \text{ mm}$. The trend follows the increased exposure of sealants to weathering and slow moving traffic.

Sealant debonding and pull-out did not increase linearly, as three stages were identified in the time-failure curve. In stage 1, failure increased rapidly. In stage 2, little failure occurred and in stage 3, failure increases again but at a slower rate than in stage 1. Failures in stage 1 are thought to be related to a weak sealant – asphalt concrete interface whereas those of stage 3 are thought to be related to sealant weathering and stiffening.

It was also found that sealants with either good or poor field performance failed to meet the requirements of the ASTM D3405 specification. Sealants demonstrating average performance were more likely to meet the specification.

In corollary to this study, it can be said that crack sealing is still an evolving technique. This method of preventive maintenance has been shown to extend the service life of rapid ways, which translates into economic benefits. These

benefits are identical in the urban setting, but the service conditions are different. For maximum benefits, it is required that sealant installation be adapted to urban conditions and that installations suitable for rapid ways not be used indiscriminately in the city, the rout size being a case in point. The existing sealant specification also does little to provide maximum benefits. To select sealants adapted to the demanding cold urban conditions, a performance-based specification is required.

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