Five-Year Experience of Low-Temperature Performance of Recycled Hot Mix

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The thermal cracking results of five recycled hot-mix (RHM) sites constructed between 1981 and 1983 during the early Ministry's recycling program are presented. The results are from laboratory and field evaluation, involving comparison between the two types of results and the use of McLeod's limiting stiffness criteria and fracture temperature method. The study confirms the common belief that RHM is less resistant to thermal cracking than non-recycled mixes. Fracture temperature method was found to be better than McLeod's limiting stiffness approach for evaluation of low temperature cracking. Recommendations to improve RHM low temperature performance are also made.

The Ontario Ministry of Transportation embarked on a hot-mix recycling program in 1979. It was based on the findings of a task force set up to study the use of recycled hot mixes as an alternative for rehabilitating highway pavements. The task force also recommended an implementation package that called for an immediate commitment of substantial tonnages in the construction programs to encourage capital investment in equipment by paving contractors for the recycling of hot mixes.

By 1980, some half a million tonnes of recycled hot mix (RHM) were constructed, representing about 20 percent of the annual paving program (*1*). Early performance of these mixes suggested that there were thermal cracking problems. This created a need for a long-term evaluation program involving laboratory testing and field crack monitoring. This paper presents the results of 5-year low temperature performance of RHM placed during the first few years of the hot-mix recycling program.

SCOPE OF EVALUATION

The primary objective is to investigate the relative resistance of recycled hot mixes to thermal cracking, as compared to conventional hot mix. However, having reviewed available evaluation techniques, it was found necessary also to examine and decide on the most appropriate methodology for evaluating the low temperature susceptibility of hot mix in the future. In more specific terms, the objectives can be stated as follows:

1. To review and compare existing methods for low temperature evaluation of hot mix,
2. To design an experimental program to evaluate the criteria for the methods selected,
3. To analyze the test results and field measurements and compare the low temperature performance of various RHMs with a conventional hot mix,
4. To determine if laboratory-mixed samples can be used for low temperature evaluation instead of plant-mixed samples,
5. To identify the best method for future low temperature evaluations of hot mix based on laboratory and field results, and
6. To suggest improvements in mix design procedures.

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EVALUATION METHOD

A number of procedures have been developed for evaluating low temperature susceptibility of bituminous materials. They can be categorized as follows: use of asphalt binder rheology, use of limiting stiffness, prediction of fracture temperature, and estimation of cracking frequency.

Asphalt binder rheology has been considered a controlling factor in cold temperature cracking. However, its use is not applicable to this case because it deals with only the binder and not the overall performance of asphaltic mixes. The approach of limiting stiffness has evolved as a result of field observations and much of the laboratory work (*2*,*3*). The method involves the determination of mix stiffness and compares such values with an established design guide (*4*). If the estimated value exceeds the design value, cracking is likely to occur.

The prediction of fracture temperature (FT) is based on the thermally induced stresses or strains in the bituminous layer. When the induced stress or strain, because of temperature drop, exceeds the failure stress or strain, cracking is expected to occur. The corresponding temperature is called the FT. The higher the FT of a material, the lower is its resistance to thermal cracking. In designing a mix, if the estimated FT is higher than the anticipated low winter temperature, cracking is expected to occur and the design should be rejected or modified.

The approach of estimating cracking frequency developed by Haas (*5*) is based on the stiffness of asphalt cement and not the asphaltic mix. This method is not considered in this investigation.

In summary, the method of evaluation is confined to two criteria: limiting stiffness and fracture temperature.

LABORATORY EXPERIMENT

A laboratory test program was designed to investigate the potential of different asphaltic mixes to resist thermal crack-

TABLE 1 Mix Design Properties of RHMs and HL4 Mix

CONTRACT NUMBER (Mix Type)	RECYCLING RATIO	ASPHALT CEMENT, %			Stability N	Flow 25mm	VMA %	Ret., % 4.75mm	Air Voids %
		ADDED	TOTAL	PEN					
81-224 (HL4)	60/40	2.7	5.2	300/400	10,000 (16,887)	9.2 (11.4)	14.6 (14.6)	40	2.8 (1.4)
82-19 (HL4)	30/70	4.5	5.3	150/200	10,000 (12,080)	13.5 (14.2)	12.5 (14.3)	45	1.6 (1.0)
81-74 (HL4)	50/50	2.3*	5.0	300/400	16,760 (14,469)	12.5 (12.1)	N/A (14.8)	45	2.8 (2.8)
82-04 (HL4)	70/30	1.7	5.3	150/200	16,280 (17,658)	13.8 (13.5)	15.6 (15.3)	36	3.0 (1.9)
83-43 (HL1)	25/75	3.8	5.3	85/100	23,000 (24,042)	18.1 (17.4)	11.8 (9.5)	45	2.7 (2.6)
(HL4)	-	-	5.3	85/100	13600	10.4	13.8	45	4.0

*0.5% antistripping agent added
Plant check results are given in parentheses

ing, using limiting stiffness and FT criteria. The program consists of a series of tests performed on a conventional hot mix (HL 4, similar to an Asphalt Institute IV B dense graded mix) and different RHM specimens to establish performance indicators for the mixes. The tests used in the program were direct tension tests at various temperatures and thermal contraction tests. A detailed description of theories, applications and interpretation of results of the direct tension test can be found elsewhere (*6*).

Material Selection

Materials were selected from five recycling contracts covering different regions, virgin asphalt cements (ACs), and recycling ratios (Table 1).

For the RHM, specimens were produced from plant mixes and individual mix components in the laboratory. However, for Contracts 81-74 and 82-04, the AC used for making laboratory mixes was different from that for the plant mixes because of nonavailability of the binders as used in the field. Penetration grade asphalt cements, ranging from 85/100 to 300/400, were used for the RHM (Table 1). Also, for Contract 83-43, only plant mix was available for making test specimens.

A crushed limestone aggregate and an 85/100 penetration grade AC were used for making conventional mix (HL 4) specimens.

Mix Designs

The RHM mix designs, which cover different recycling ratios, were designed to meet the usual Ministry specification requirements for gradations and properties. For Contract 83-43, the mix was designed using an HL 1 RAP material from a surface course of a freeway; the others were HL 4 mixes for secondary highways. The HL 1 RAP material consisted of a good quality steel slag coarse aggregate and natural sand fine aggregate. The mix design properties are presented in Table 1.

Because of the use of various recycling ratios and RAP with low recovered penetrations, virgin ACs of different penetrations were used to bring the overall penetration of the RHM to desirable levels (*1*), which are normally obtainable for virgin mixes.

Sample Preparation

Test samples were prepared according to procedures given in ASTM D3202 using the California kneading compactor. Compacted beam specimens of length 381 mm, depth 88 mm, and width 82 mm were saw cut into three shorter sections 100 mm in length and 76 × 76 mm in cross section. For the direct tension test, each specimen was glued to steel endplates with epoxy and allowed to cure overnight before temperature conditioning and testing. For thermal contraction measurements, the specimens were used as cut without additional treatment.

Direct Tension Test

Direct tension tests were performed using a MTS servohydraulic machine at 21°C, −5°C, and −35°C to determine the tensile strengths, strains, and stiffnesses of different mixes. Duplicate tests were performed for each of the test temperatures and sample preparation conditions (i.e., laboratory and plant mixing). The specimen was pulled at a constant rate of extension (3×10^{-2} mm/min for tests at −5°C and −35°C; 5 mm/min at 21°C) until failure occurred. The stress, strain and stiffness at failure were determined (Table 2). For testing at temperatures −5°C and −35°C, the specimens were precooled overnight, prior to testing, in an environmental chamber maintained at the low test temperatures.

Thermal Contraction

Determination of thermal contraction is an integral part of the thermal behavior analysis of asphalt mixes. Thermal con-

TABLE 2 Stiffness Modulus Values (MPa) of Plant and Laboratory Mixes

Mix	@ Test Temperature			% Difference, Plant/Lab		@ Fracture Temperature		Estimated Mcleod's
	21°C	-5°C	-35°C	21°C	-35°C	Estimated from graph (Figs.1a&b)	McLeod's Maximum	
HL4L	36	460.0	20618	-	-	5000	2760	1.8
81-74P	268.0	797.0	24635	-21	-30	3800	1800	2.1
81-74L	338.5	1275.5	35280			2800	790	3.5
81-224P	157.5	637.2	34341	-35	38	6100	2760	2.2
81-224L	243.0	938.0	24920			2900	1100	2.6
82-04P	754.0	2761.5	53940	-54	142	5400	790	6.8
82-04L	1631.5	3258.5	22231			5400	790	6.8
82-19P	148.4	480.6	38645	-37	20	9000	3200	2.8
82-19L	237.0	923.0	32315			7800	3050	2.6
83-43P	1151.0	3032.0	24185	-	-	3600	-	-

TABLE 3 Thermally Induced Strains ($\times 10^{-3}$ mm/mm) for Plant and Laboratory Mixes

Temperature °C	Contract					HL4
	81-74	81-224	82-04	82-19	83-43	
Plant Mixes						
-38	0.986	0.7	0.91	0.71	1.0	1.22
-29	0.796	0.7	0.815	0.71	0.8	1.12
-7	0.696	0.335	0.509	0.339	0.635	0.51
4	0.497	0.335	0.3	0.271	0.440	0.20
Laboratory Mixes						--
-38	1.479	1.49	0.689	0.996	--	--
-8	--	--	0.49	0.49	--	--
-5	0.39	0.49	--	--	--	--

traction was used to estimate the induced strain due to thermal shrinkage under restraint condition. Set points were selected for each sample, and the lengths were measured using a digital caliper before and after cooling the specimens for 24 hr at each temperature. Readings were taken during both the cooling and heating cycle for comparison. Thermally induced strains at various temperatures were calculated for all mixes by dividing the actual contraction of each specimen by its original length (Table 3).

RESULTS

Analysis of the low temperature cracking properties of the mixes was made in terms of both limiting mix stiffness and pavement FT criteria. Also, the results obtained from plant mixes were compared with those from laboratory mixes. All

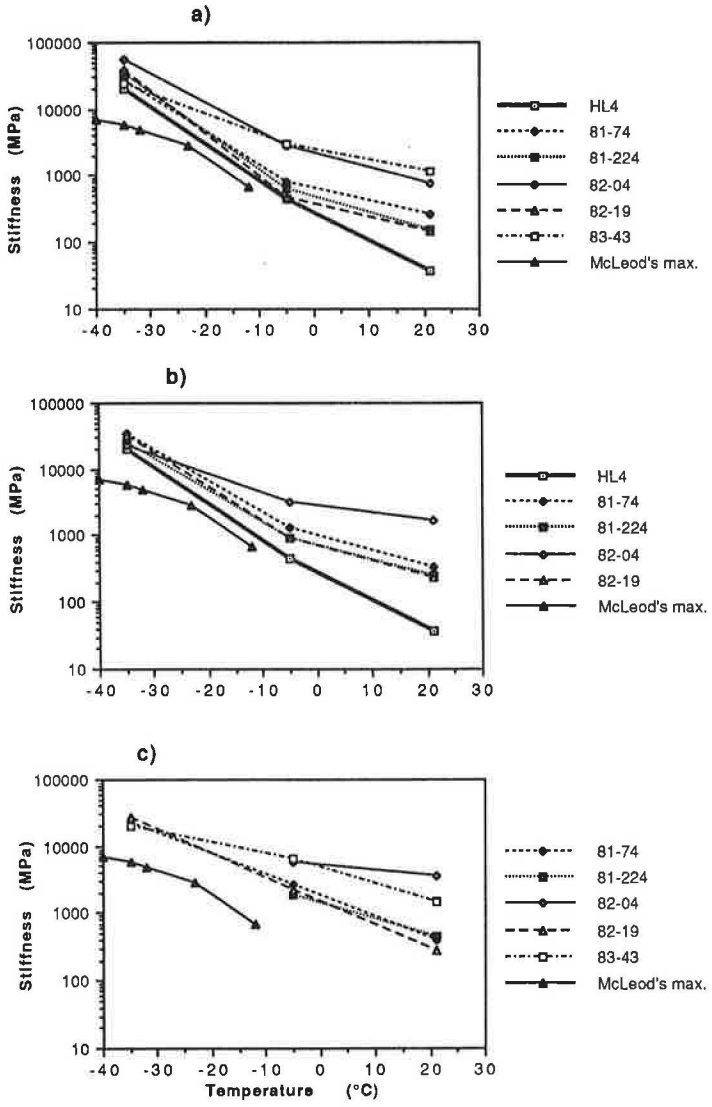

FIGURE 1 Fracture stiffness and temperature gradients: (*a*) plant mixes, (*b*) laboratory mixes, and (*c*) field samples at 5 years.

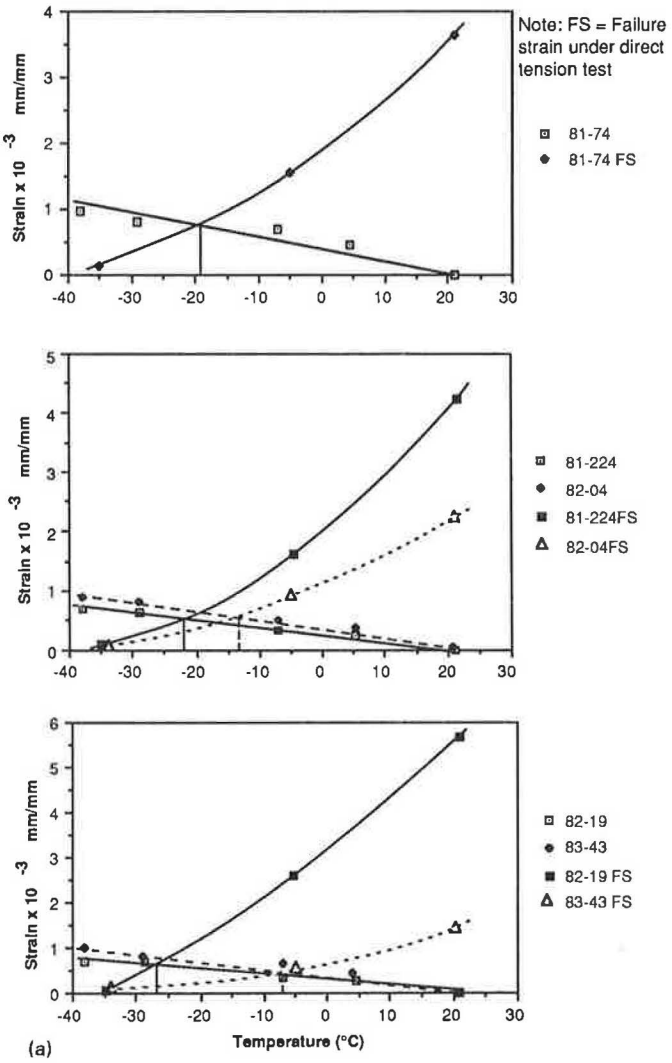

FIGURE 2 Estimation of fracture temperature for (*a*) plant mixes, (*b*) laboratory mixes, and (*c*) field mixes at 5 years.
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of these results were then, in turn, compared with the HL 4 mix and with field data and expected trends, using the recovered penetration and viscosity values of the asphalt cements.

Limiting Mix Stiffness Criterion

In general, the mix stiffness increases with decrease in temperature (Figure 1). McLeod's tentative design guide (*4*) has been used for the limiting stiffness analysis. The stiffnesses of RHM at the time of construction and after 5 years of service, and of the conventional mix at various temperatures, are compared with McLeod's maximum criterion. It appears that none of the mixes has resistance to cracking at low temperature (Figure 1). However, it is noted that McLeod's values for limiting stiffness, according to the Asphalt Institute Research Report (*5*), may be too conservative because of its dependence on the PVN values, which tend to give lower stiffnesses than the actual measured values. Additional safety factors could have been built into such procedures to produce these limiting values. This assumption is confirmed by comparing the McLeod's maximum stiffness values at which cracking is expected to occur with the measured values at the FTs. Results show that a range of factors of about 2 at $-23°C$ and 7 at $-13°C$ existed when dividing the stiffness values at FTs by McLeod's values (Table 2). The stiffness values at FT were obtained from the graphs in Figure 1 at the FTs shown in Figure 2 for the different mixes.

Relationship of Plant and Laboratory Mix Stiffnesses

One of the objectives has been to determine if laboratory-mixed samples can be used instead of plant-mixed samples for evaluation of the performance of RHM or other mixes at low temperature. This point is addressed by comparing the stiffnesses of mixes produced in the plant and in the laboratory. Laboratory-mixed specimens exhibit higher stiffness values (ranging from 21 to 54 percent) at warmer temperatures

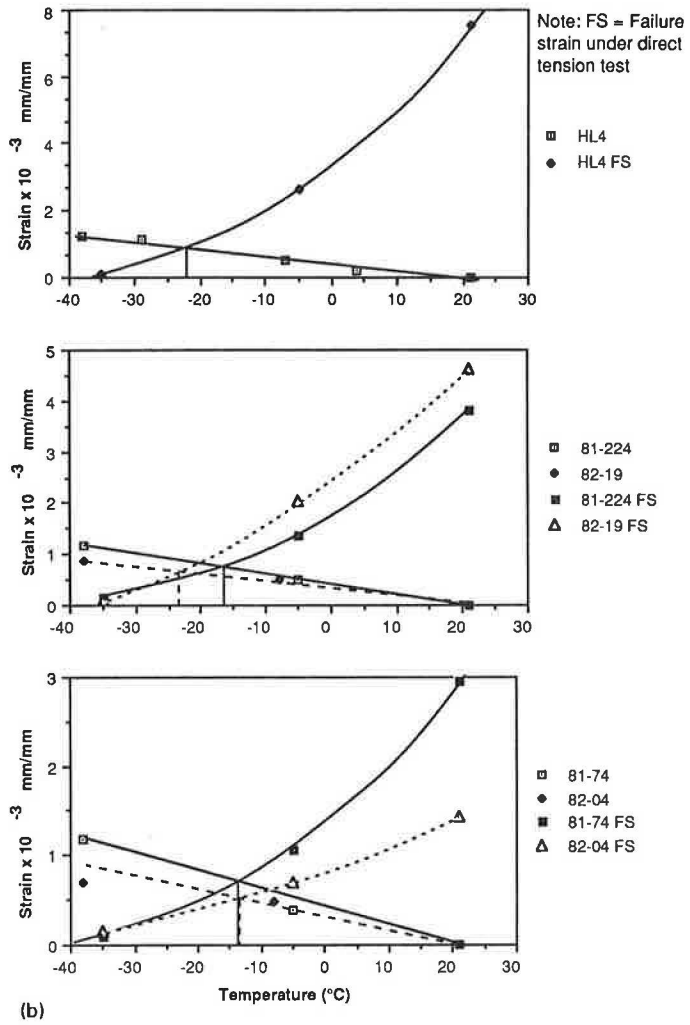

FIGURE 2 ***(continued)***
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(i.e., 21°C) than the plant-mixed specimens, and lower stiffness values (ranging from 38 to 142 percent, except for Contract 81-74), at very low temperatures (i.e., −35°C). From these results, it is clear that the stiffness value at any given temperature is not sufficient to adequately evaluate the behavior of asphaltic mixes at low temperatures (Table 2). However, the logarithmic relationship shows excellent correlation ($r^2 = 0.976$) between the plant and laboratory mix stiffnesses.

Based on the good correlation between the stiffness values obtained from the laboratory and plant mixes, future low temperature stiffness evaluation of RHM can reliably use samples that are prepared in the laboratory.

Comparison of Virgin Mix and RHM

The RHMs from all contracts show higher stiffness values than the HL 4 mix. This confirms the general perception that virgin mixes will perform better than RHM with respect to thermal cracking.

Fracture Temperature Criterion

Fracture temperature could be estimated by plotting the failure strains determined from direct tension tests and the induced thermal strains of different hot mixes against decreasing temperature, as shown in Figure 2. The temperature at which the induced thermal strain exceeds the failure strain corresponds to the FT of the mix.

Relationship of Plant and Laboratory Mix Fracture Temperature

Laboratory-mixed samples generally have higher FTs than plant mixes. This indicates that laboratory samples have a lower resistance to thermal cracking than plant samples. It appears, from the limited number of results, that there is a good relationship between the FT for the plant and laboratory mixes. Therefore, the use of laboratory mix to evaluate field performance is possible when the relationship is substantiated by more data.

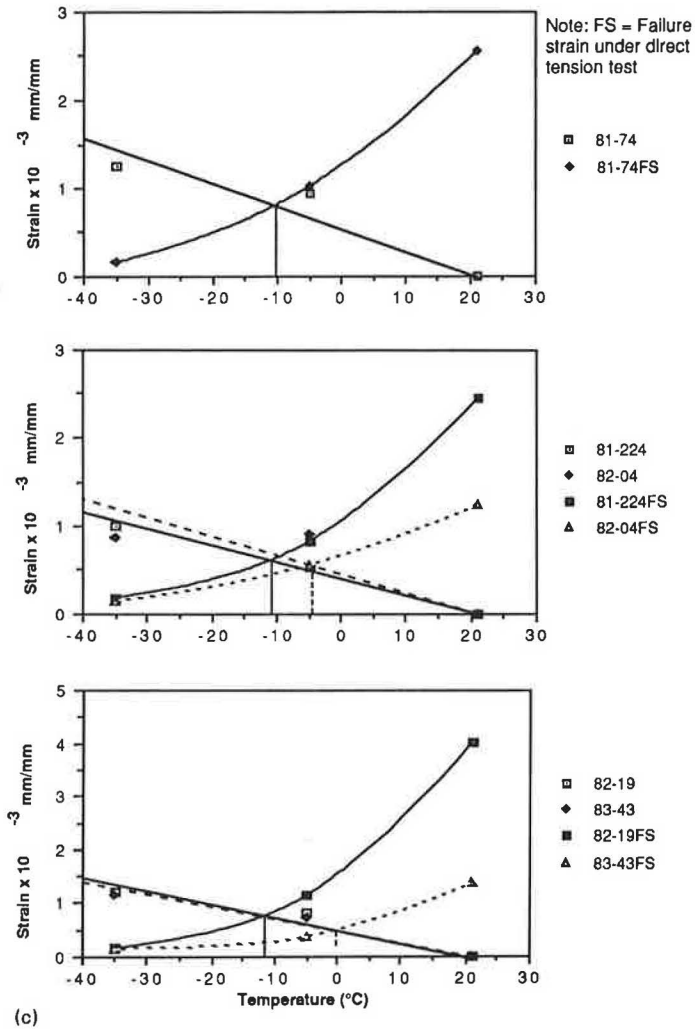

FIGURE 2 (*continued*)

Since the intent of this evaluation is to determine the low temperature thermal cracking properties of asphalt mixes, an examination of the stiffness measurement at −35°C is considered more appropriately related to the FT results than those at 21°C. At −35°C, the stiffness values of laboratory mixes are generally lower than those of plant mixes (Table 2), hence the former have a better resistance to thermal cracking. Also, because stiffness value at any given temperature is not sufficient to evaluate low temperature performance, and because FT is a more direct measure of the fracture property of a mixture, FT approach should be more reliable for predicting low temperature performance.

Comparison of Virgin Mix and RHM

Except for Contract 82-19, all mixes had FT above the −23°C FT of the virgin HL 4 mix (Figure 2b). This again confirms the previous findings, based on the stiffness modulus, and the general belief that RHM is more susceptible to thermal cracking than virgin mixes.

Effect of Aging on Stiffness and Fracture Temperature

As expected, after 5 years of aging, the resistance to low temperature cracking of pavements has been reduced on the basis of both FT (Figures 2a and 2c) and stiffness at FT criteria. In addition to an average increase of 10°C in the FT there is a corresponding increase in stiffness averaging 1700 MPa over the 5-year period.

Effect of Binder Properties on Stiffness and Fracture Temperature

Since fracture characteristics of asphalt mixes are generally believed to be more affected by the properties of the binder used, the relationship of the asphalt cement penetration and viscosity and mix stiffness and FT are examined.

Analysis of results revealed that mix stiffnesses at FT bear little relationship to the recovered penetration but have a slight trend with the viscosity values of RHM. This confirms

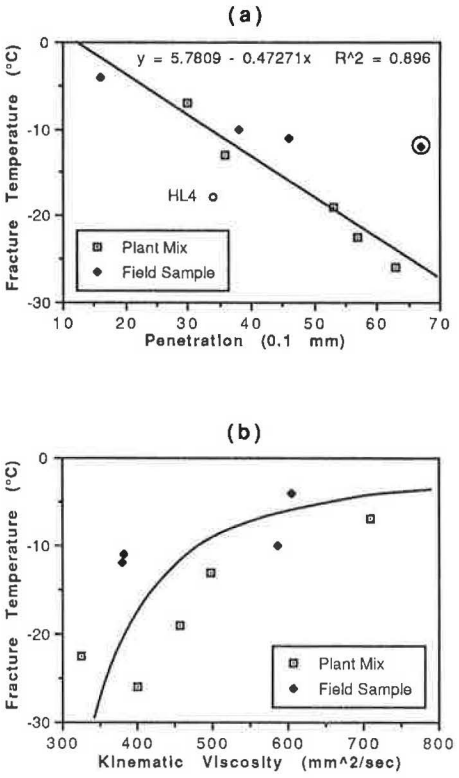

FIGURE 3 Plant mix and field sample fracture temperature versus (*a*) recovered penetration and (*b*) kinematic viscosity.

the common belief that the stiffness of a mix is more related to the viscosity than the penetration of the binder used.

However, a better relationship is obtained when mix FT is correlated with the results of recovered asphalt cement penetration and viscosity of the RHM (Figure 3). On the basis of these data, mixes with recovered penetration values of about 75, or viscosity of about 350 mm²/s at the time of construction, can be expected to be able to resist cracking to as low a temperature as −30°C. This is a significant finding in that it confirms the empirical rule or common belief that recovered penetration values of about 60 are sufficient for southern Ontario, and values greater than 70 are necessary for northern Ontario, for resisting low temperature pavement cracking. Also, this finding further emphasizes the importance of designing all asphalt mixes to meet penetration requirements. At the present state of the technology, this can be achieved either by using historic data on the percent retained penetration values after the TFOT (or RTFT) for conventional mixes or the method developed by Tam (*1*) for RHM.

Field Observation

Field condition surveys were carried out periodically including crack mapping of different types of crack as presented in Table 4. The crack surveys data, in terms of meters of cracks per lane-kilometer, are compared with the laboratory test results. The cracks measured can be considered exclusively due to the thermal effect rather than to loading because of the structural

TABLE 4 Crack Map Data After 3 and 5 Years of Service

Years After Construction	Contract	Cracks, m/km lane					
		Type A	Type B	Type C	Type D	Type T	Total
3	81-74	53	249	97	18	0	417
	81-224	30	168	127	0	0	325
	82-04	198	2068	492	151	1000	3909
	82-19	65	54	0	0	0	119
	83-43	190	108	5	0	2849	3152
5	81-74	267	418	117	0	0	802
	81-224	30	181	180	0	0	391
	82-04	108	2163	507	161	1000	4009
	82-19	113	121	0	0	0	234
	83-43	111	334	0	0	3014	3459

Note: A = Hairline crack
B < 5mm
C = 5-10mm
D = 10-20mm
T = Treated

soundness of the monitored sites. All of these sites were constructed with good base supports (400 to 500 mm granular) and thick asphalt layers (90 to 150 mm). As well, the traffic volumes were low (700 to 1,500 AADT) except for Contract 83-43, the site of which carried 35,780 AADT (1987) but was a full depth asphalt pavement (200 mm).

After 5 years of service, Contracts 82-19, 81-224, and 81-74 have total pavement crack lengths between 230 and 800 m as against about 3,800 m for Contracts 82-04 and 83-43. This indicates that the RHM from the former three contracts are less susceptible to cracking than from Contracts 82-04 and 83-43. This is in apparent agreement with the findings so far obtained, particularly in respect to the higher FT and lower recovered penetration values obtained for the latter two contracts (Figure 4a). In general, there is an average decrease in penetration of 18 units and an increase in viscosity of 230 mm²/s over the 5-year period (Figure 4b).

When the relationships of meters of cracks per lane-kilometer of pavements measured at the fifth year and their respective FT and stiffness are examined, a good correlation of $r^2 = 0.897$ for FT and a poor correlation of $r^2 = 0.065$ for stiffness are obtained. These relationships confirm the better use of FT than stiffness criteria for evaluating low temperature cracking. Also, excellent relationships between the logarithmic crack lengths and recovered RHM penetration ($r^2 = 0.94$) and the logarithmic viscosity values are obtained. These relationships are significant in demonstrating that (a) the use of FT to predict future crack lengths of aged pavements is possible pending further substantiation by more data and (b) the common approach of using penetration values at 25°C and viscosities at 135°C for selecting the AC grades in mix designs for low temperature performance appears to be valid, provided other requirements are met.

As expected, there was a bigger increase in crack lengths for the first year than for subsequent years (Figure 5). Also, when a mix has a penetration value below 20, a substantial crack length of 20,000 m/km of road can be expected within the first year (i.e., at the state of complete disintegration of the pavement).

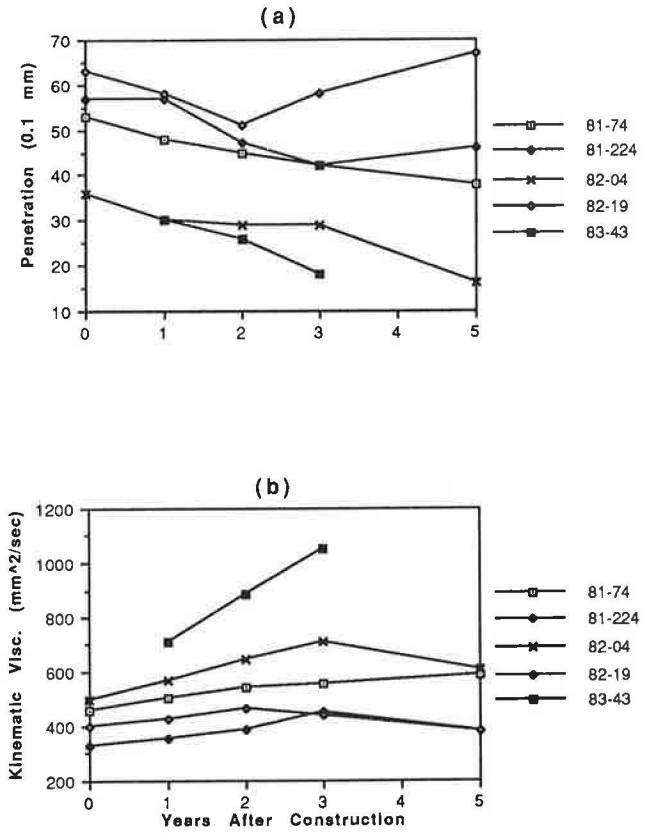

FIGURE 4 Effect of pavement aging on (*a*) binder penetration and (*b*) viscosity.

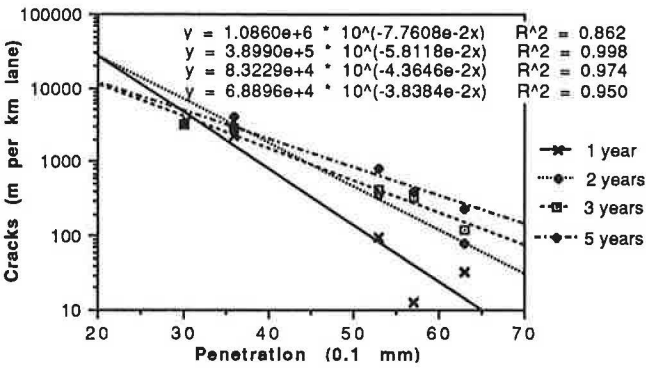

FIGURE 5 Total length of pavement cracks versus recovered RHM penetration at construction.

Performance Rating of Mixtures

For the purpose of evaluating the relative resistance of the mixes to thermal cracking, a rating system of 1 to 5 (very good to poor resistance) is used. The mixes are rated by their stiffness values, fracture temperatures, and field data (Table 5). Contract 82-19 and conventional HL 4 mixes show consistently better ratings than the others, except when they were rated under the stiffness criteria at −35°C. The other mixes from Contracts 82-04 and 83-43 were rated poor for causes

TABLE 5 Cracking Resistance Rating of Different Mixes Based on Fracture Temperature, Stiffness at −35°C, and the Field Data

Cracking Resistance Ranking	Mix (by Contract Number)				
	Fracture Temperature		Stiffness at -35°C		Field Data
	Plant	Lab	Plant	Lab	
1 (Very High)	82-19	HL4 82-19	81-74	HL4 82-04	82-19
2 (High)	81-224	81-224	81-224	81-224	81-224
3 (Medium)	81-74	81-74 82-04	82-19	82-19	81-74
4 (Poor)	82-04 83-43	-	82-04	81-74	82-04 83-43

previously discussed. The rating is consistent with the field results. The RHMs (Contracts 82-19, 81-224, and 81-74) that performed well are those mixes with recycling ratios at or below 60/40, 50 percent or more and of 300/400 penetration grade virgin asphalt cement, and recovered penetration values at the time of construction similar to conventional mixes, such as the HL 4 mix used in this study.

PREDICTION METHODS FOR LOW TEMPERATURE PERFORMANCE

Limiting Stiffness Criteria

Figure 6 shows that McLeod's limit is well below the fracture stiffness values obtained for this study. This provides further evidence to support the statement made previously that McLeod's values are conservative and inadequate for predicting low temperature behaviors of hot mixes. It appears that a family of limits could exist for different types of mixes (e.g., rich, medium, and harsh/dry mixes) (Figure 6). McLeod's data could well be for the early richer and finer asphaltic mixes of higher binder content type (e.g., 6 percent). The results of the medium mix type, represented by the three good mixes used in this study, are plotted as a solid line in Figure 6. A good correlation with $r^2 = 0.997$ is obtained. The dotted line is for the dry and aged mix type, similar to the mixes used in Contracts 82-04 and 83-43. If this argument holds true, the limiting stiffness method will have to be further examined and modified accordingly before it can be used with confidence.

Fracture Temperature

The findings so far obtained reveal that the FT approach is more suitable and reliable for evaluating low temperature performance of hot mixes, for the following reasons:

- It has been substantiated by the good correlation with field data.
- It correlates well with recovered penetration values and follows the expected trends of behaviors (i.e., higher penetration corresponds to lower fracture temperature, and increase in FT with aging of pavements).

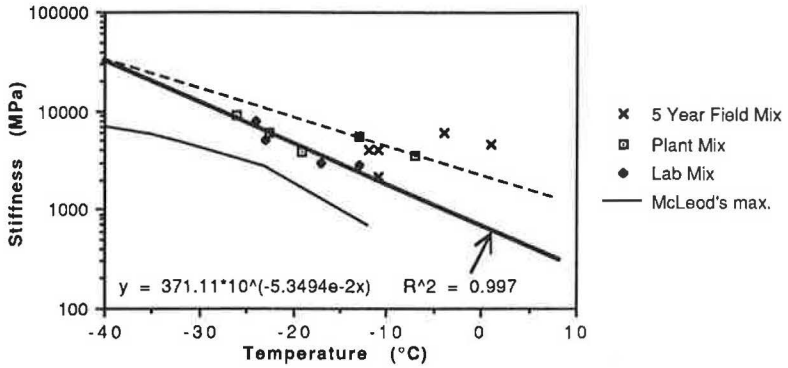

FIGURE 6 Stiffness modulus at various fracture temperatures.

- It is a direct measurement and can be compared with expected local/winter temperature of a given pavement to ensure that a mix to be constructed has adequate low FT properties.

In general, despite the common practice of using factors such as penetration (including penetration index and pen-visc number), resilient modulus, and viscosity gradients to predict low temperature performance of asphaltic mixes, it appears that the fracture temperature is the most appropriate method in the final analysis. Other methods become less significant because of the indirect nature of the tests, although these tests could be of value in screening potential bad actors.

CONCLUSIONS

The following findings are considered significant because they have contributed to clearing up some of the long-standing doubts on the correctness of past practices and identifying the use of FT as a preferred and direct method for testing of low temperature performance of asphalt mixes.

Materials Performance

The findings confirmed the general belief that RHMs are more susceptible to thermal cracking than conventional hot mixes.

Based on the fracture temperature results, recycled hot mixes from Contracts 81-74, 82-19, and 82-224 have better resistance to cracking than those from Contracts 82-04 and 83-43.

Field data and laboratory results reveal that hot mixes recycled at low recycling ratios (e.g., 30/70 as in Contract 82-19) or using high penetration virgin asphalt cement (e.g., 300/400 as in Contracts 81-74 and 81-224) have better performance than those with high recycling ratios (e.g., 70/30 as in Contract 82-04) or using low penetration virgin asphalt cement (e.g., 85/100 as in Contract 83-43).

Based on the RHM studied, an average increase in FT of 10°C and a corresponding increase in stiffness of 1700 MPa can be expected for a pavement after 5 years of service. Also, a reduction in penetration of about 16 units and an increase in viscosity value of about 230 mm^2/s have been observed.

The findings reveal that an asphalt cement with a recovered penetration of 75 and a viscosity of 350 mm^2/s can resist cracking to −30°C, confirm that the use of higher penetration grade asphalt cement (e.g., 150/200) in a standard mix in northern Ontario is appropriate because it has an expected FT of below −35°C, and support the common belief that higher penetration mixes tend to have lower fracture temperatures or better resistance to low temperature cracking.

Evaluation Methods

Fracture temperature method is considered more suitable than limiting stiffness criteria for evaluating the potential of mixes to resist low temperature cracking.

Fracture temperature ratings of mixes used in this study correlate well with ratings based on field data.

Fracture temperatures also correlate well with recovered penetration values, which are supported by the common experience that higher penetration mixes tend to have better resistance to low temperature cracking and vice versa.

Laboratory Sample for Predicting Low Temperature Performance

It appears from the limited data of this study that laboratory-manufactured samples could be used for predicting low temperature performance.

RECOMMENDATIONS

The following recommendations are made to minimize low temperature cracking and improve the accuracy of predicting fracture temperature:

- Limit recycling ratios to a maximum of 50/50;
- Select an appropriate virgin asphalt cement to produce desirable final/recovered mix penetrations using the method developed by Tam (*1*);
- Use fracture temperature method for mix evaluation to ensure compliance with expected winter temperature; and
- Obtain more data to support the use of laboratory samples for prediction/evaluation of low temperature performance in the field for both RHM and conventional mixes.

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