Investigating Thermal Cracking Potential of Ontario RAP-HMA Mixtures

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Abstract
Thermal cracking on flexible pavements poses serious concerns in cold-regions of the world, especially in Canada. Influenced by temperature changes, thermal cracks are known to initiate other forms of pavement deterioration. The prevention of thermal cracks would guarantee better performance of roads built with asphalt concrete mixtures. Recognizing asphalt recycling as a key sustainable practice in the pavement industry, this paper examines the low-temperature cracking resistance of four dense-graded laboratory-prepared Ontario Superpave asphalt concrete mixtures. The asphalt mixtures were produced with 0%, 20% and 40% Reclaimed Asphalt Pavements (RAP) contents and three different binder grades. The low-temperature cracking resistance has been determined using the Thermal Stress Restrained Specimen Test (TSRST) method. The effects of different binder grades and RAP contents on the fracture stress and fracture temperature of the asphalt mixtures have been mainly investigated. Moreover, the influences of air voids content, binder aging, aggregate interaction, and laboratory compaction method have been observed. Test results revealed that binder grade and RAP content did not significantly affect the fracture resistance of asphalt mixture. These results are encouraging and demonstrate the value of TSRST as an important test for material characterization.

Keywords: Asphalt concrete mixtures, Reclaimed Asphalt Pavement (RAP), Low-temperature cracking, Thermal Stress Restrained Specimen Test (TSRST).

1. INTRODUCTION

1.1 Background

Reclaimed Asphalt Pavement (RAP) has been successfully used for decades because of its economic and environmental benefits. For the sake of sustainable development, higher RAP percentages (i.e. > 25% by mass) can be considered for incorporation into Hot Mix Asphalt (HMA) mixtures. However, contractors in Ontario are particularly reluctant to use more than 20% RAP since it is perceived to have negative effects on the performance of the resultant HMA mixtures in comparison with conventional mixtures, especially with respect to thermal cracking resistance.
Thermal cracking is attributed to the development of high tensile stresses under repetitive exposures to extremely low temperatures or moderate daily temperature cycles otherwise referred to as thermal fatigue cracking. Gardiner and Wagner reported that including RAP in HMA mixtures decreases the rutting potential, but increases the likelihood for thermal cracking at low temperatures [1]. Thermal cracking is a primary failure mode in asphalt concrete pavements and it initiates the other forms of deterioration. This issue poses serious concern to many pavement and materials engineers not just in Canada, but in other cold regions of the world. Without compromising other performance characteristics, such as resistance to rutting, researchers and engineers are continuing to work towards identifying the requirements to minimize low-temperature cracking in asphalt concrete pavements [2].

The past studies piloted by Jung and Vinson indicated that the type of asphalt binder, air void content, and the type of aggregate all have an effect on the fracture temperature and fracture stress of asphalt mixture [3, 4]. In particular, the low-temperature failure strain of an asphalt binder is considered the most important factor that influences the occurrence of thermal cracks in asphalt concrete pavements. The aged asphalt binder in RAP is believed to boost the susceptibility of HMA mixtures to thermal cracking [5]. The findings from past studies have indicated significant correlations between the low-temperature failure strain of asphalt binders and the low-temperature failure strain of HMA mixtures [6]. In addition, some other variables such as cooling rate and volumetric changes in the HMA layers are also considered to have significant effects on the low-temperature cracking resistance of asphalt mixtures.

In this study, the Thermal Stress Restrained Specimen Test (TSRST) has been employed to investigate the low-temperature cracking susceptibility of HMA mixtures incorporating RAP. The TSRST system applied an initial tensile load to laboratory-compacted asphalt concrete beam specimens whilst simultaneously cooling them at a constant rate as well as restraining them from contracting by reestablishing the initial length of the specimens. This was done to determine the fracture stress and fracture temperature of the asphalt concrete mixtures. The TSRST results mainly revealed the effects of different binder grades and RAP contents.

1.2 Scope and Objectives

This paper explores the low-temperature thermal cracking potential of typical Ontario HMA mixtures containing varying RAP percentages in an effort to remove and/or reduce the uncertainties associated with the inclusion of high RAP content in asphalt concrete mixtures. The effects of the different binder grades and RAP contents have been mainly investigated in this study. In addition, the influences of several factors such as air voids content, aggregate interaction, binder aging, and laboratory compaction method are briefly discussed. The applicability of the TSRST procedure to characterize the susceptibility of asphalt mixtures to thermal cracking is also emphasized in this paper.

2. MATERIALS AND MIXTURE DESIGN

Four dense-graded HMA concrete mixtures were prepared in this study. The Superpave (SP) mixture design procedure was implemented in the preparation of the 12.5 mm Nominal Maximum Aggregate Size (NMAS) HMA (SP12.5) mixtures including 0%, 20% and 40% RAP contents, and three different asphalt binder grades typically used across northern and southern Ontario. These binders cover wide stiffness range. The compositions and volumetric properties of the HMA mixtures prepared in this study are presented in Table 1.

2.1 Preparation of Specimens

The loose HMA mixtures were subjected to short-term conditioning in a forced-draft oven for four hours at 135°C, prior to compaction, to simulate plant mixing and placement effects according to *AASHTO R 30-02, “Mixture Conditioning of Hot Mix Asphalt (HMA)*” [7]. A vibration force of 115 kPa was applied using an Asphalt Vibratory Compactor (AVC) to fabricate 390 mm × 125 mm × 78 mm asphalt beams, and saw-cut into 250 mm × 50 mm × 50 mm TSRST specimens. The target air voids content of the TSRST specimens was 7±1%, which is representative of typical construction values for compaction [8, 9]. Figure 1 shows the compacted asphalt beam and saw-cut TSRST beam specimen.

Table 1: Composition and Volumetric Properties of Lab-prepared HMA Mixtures

Mixture ID	M1	M2	M3	M4
RAP content (%)	0	0	20	40
Performance-graded asphalt binder	52-34	58-28	58-34	58-28
Virgin AC (%)	5.2	5.2	4.3	3.3
AC from RAP (%)	0	0	0.9	1.8
Total AC (%)	5.2	5.2	5.2	5.1
Dust proportion	0.7	0.7	1.2	1.1
% VMA	15	14.8	14.7	14.3
% VFA	73.4	73.1	73.1	72.1
G_{mm} (lab-prepared samples)	2.537	2.532	2.515	2.526
Mixing temperature	140	145	151	145
Compaction temperature	129	134	139	134

Note: G_{mm} = Maximum theoretical specific gravity; AC = Asphalt Content; PG = Performance Grade; VMA = Voids in Mineral Aggregates; VFA = Voids Filled with Asphalt

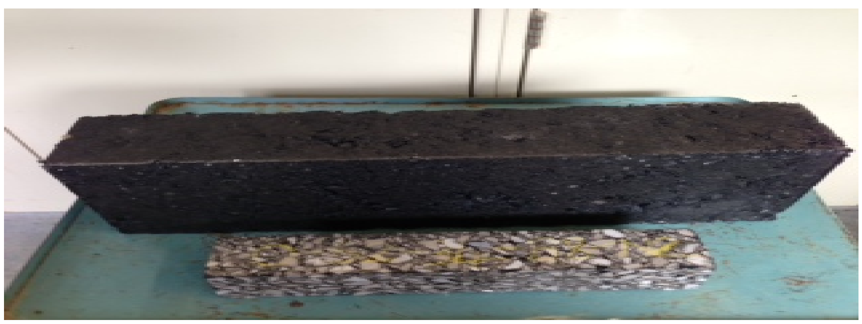

Figure 1: Compacted Asphalt Beam and Saw-cut TSRST Beam Specimen

Epoxy adhesive was applied on the cylindrical platens to hold top and bottom ends of the specimens. The epoxied bonds between platen and specimen end were allowed to cure at room temperature for at least 12–16 hours prior to conditioning the asphalt beam specimen for TSRST.

3. TSRST AND TEST RESULTS

Three replicate TSRST beam specimens were tested for the respective HMA mixture. In total, twelve specimens were tested in accordance with *AASHTO TP 10-93, "Standard Test Method for Thermal Stress Restrained Specimen Tensile Strength"* [9]. Figure 2 shows the typical TSRST setup. The test specimens were conditioned at 5°C in an environmental test chamber for six hours, while actual testing was performed at a monotonic cooling rate of 10°C/hr. The extensometer attached to the specimen sensed movement during cooling and contraction, and sent a signal to the computer system, which in turn caused the hydraulic actuator to stretch the specimen to its original length. In TSRST, the thermal force/stress in the specimen increases until fracture as temperature decreases gradually in the test chamber [10]. Typical force-temperature curves for different asphalt concrete mixtures tested in this study are provided in Figure 3.

Figure 2: Typical TSRST Test Setup

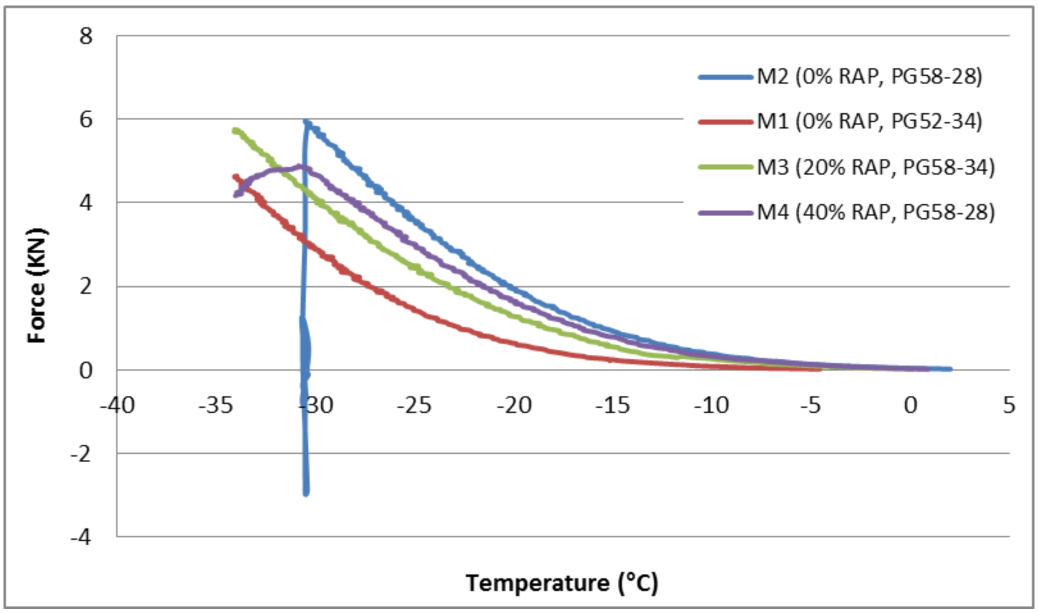

Figure 3: Typical Force-Temperature Fracture Curves of Tested HMA Mixtures

The test results are reported in terms of the maximum stress at which the specimen failed (i.e., the fracture stress) with a corresponding fracture temperature. Table 2 highlights the fracture stress and fracture temperature results at failure for three replicate specimens tested for each asphalt concrete mixture. The air voids for the specimens tested are also included in Table 2.

4. ANALYSIS OF TSRST RESULTS AND DISCUSSION

The application of the TSRST results to predict field performance is a subject of research. The TSRST results indicate that the colder (i.e. more negative) the fracture temperature, the greater is the potential of the asphalt mixtures to resist low-temperature thermal cracks. According to Table 2, the fracture temperatures of all HMA mixtures tested meet the corresponding low temperature performance grade of the respective asphalt binder used. The low temperature performance grades were either met or exceeded by up to -2.9ºC.

Table 2: TSRST Results of Different Asphalt Concrete Mixtures

Mixture ID	Beam ID	Air Voids (%)	RAP Content (%)	Binder PG	Fracture Temp. (°C)	Fracture Stress (MPa)
M1	B1	8.7	0	52-34	-34.1	1.56
	B2	8.7			-34.1	2.18
	B3	7.9			-34.1	1.86
M2	B1	6.7	0	58-28	-29.8	2.05
	B2	6.0			-30.6	2.38
	B3	6.7			-30.3	2.09
M3	B1	6.4	20	58-34	-34.0	2.86
	B2	7.9			-34.1	2.30
	B3	7.1			-34.1	2.33
M4	B1	8.3	40	58-28	-28.6	2.21
	B2	6.7			-30.8	2.66
	B3	6.7			-30.9	1.95

The fracture temperatures for mixture M1 (control mixture: 0% RAP, PG 52-34) and mixture M3 (20% RAP, PG 58-34) are comparable, as evident from Table 2. The fracture temperatures of mixture M2 (control mixture: 0% RAP, PG 58-28) and mixture M4 (40% RAP, PG 58-28) are also comparable. Both M2 and M4 mixtures fractured at around -30ºC, but the later exhibited sudden failure.

The binder grade and RAP content affected the fracture stress of the asphalt concrete mixtures. However, in terms of the fracture stress, the control HMA mixtures (M1: 0% RAP, PG 52-34 and M2: 0% RAP, PG 58-28) could be considered to be the least resistant to thermal cracks in comparison with the HMA mixtures incorporating RAP (M3: 20% RAP, PG 58-34 and M4: 40% RAP, PG 58-28). The mean fracture stress values for all tested mixtures are illustrated in Figure 4. The highest fracture stress was obtained for mixture M3 (20% RAP, PG 58-34), followed by mixture M4 (40% RAP, PG 58-28). However, the fracture stress values for the HMA mixtures incorporating RAP are not significantly high to suggest that they will be prone to thermal cracking at low temperatures.

The TSRST results of each asphalt mixture showed specimen-to-specimen variations, as can be seen from Table 2. The standard deviation and coefficient of variation for the test results of all asphalt mixtures are summarized in Table 3. As expected, the coefficients of variation for fracture stress were significantly higher compared to those for fracture temperature. This is why fracture temperature is used to rank low-temperature cracking resistance of asphalt concrete mixtures [11].

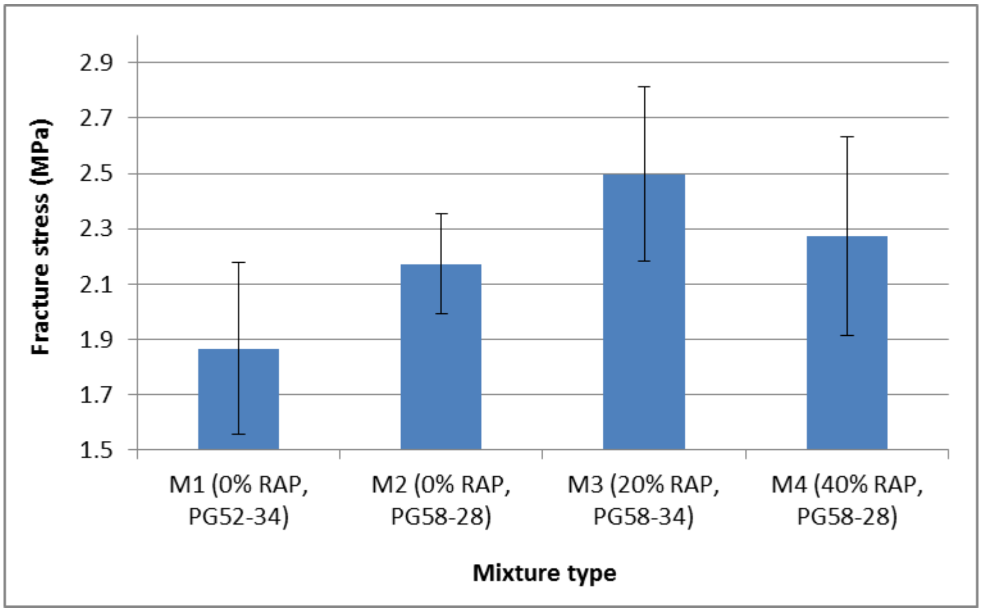

Figure 4: Fracture Stress of Different Asphalt Concrete Mixtures

Table 3: Summary of Variations in TSRST Results

Mixture ID	Std. dev. for fracture temp. (^{0}C)	COV for fracture temp. (%)	Std. dev. for fracture stress (MPa)	COV for fracture stress (%)
M1	0	0	0.3	16
M2	0.4	-1.3	0.2	9
M3	0.1	-0.3	0.3	12
M4	1.3	-4.3	0.4	17.6

Variations in fracture stress values for each asphalt mixture could be attributed to changes in the air voids of the specimens or possible stone-to-stone contact within the mixture composition leading to weak spots in the test specimen. Regardless of the variation in fracture stress values, all HMA mixtures tested showed good repeatability for fracture temperature. This is a good indicator that laboratory-prepared samples have the potential to effectively simulate field effects. Moreover, meeting the lower PG temperature while maintaining the air voids in the desired range, it can be inferred that the laboratory compaction method used in this study is capable of simulating field densities. The fracture temperature of the asphalt mixtures in this study was mostly affected by the binder grade and RAP content. The other significant factors can be aging of the binder, mixing of asphalt concrete, and method of compaction. The authors note these factors because the HMA mixtures incorporating RAP were stiffer than the control mixtures as observed during mixing. The RAP mixtures required a longer mixing time than the control mixtures. However, there were no observable differences in compaction time between RAP and control mixtures. The 20% and 40% RAP mixtures were compacted for 12 seconds while the control mixtures were compacted for 15 seconds to achieve the target air voids content of 7±1% in TSRST specimens.

TSRST results also varied for the asphalt concrete mixtures tested due to different binder grades and RAP contents. However, an ANOVA analysis showed that these variations were not statistically significant. Considering the fracture stress results from the three replicate specimens of each asphalt concrete mixture, the ANOVA analysis was performed. This analysis revealed that with a probability of 95% the difference among the data is not statistically significant, with F_{actual} (2.30) < $F_{critical}$ (4.07) and a p-value of 0.15. To verify this deduction, t-tests were performed for different coupled asphalt mixtures; the results are shown in Table 4. In all cases, $t_{statistic}$ is less than $t_{critical}$; then with a confidence of 95%, it can be concluded that differences among the results are not statistically significant, that is, from the TSRST results of the four asphalt mixtures tested, it can be deduced that the increase in the RAP content does not affect the fracture resistance of a SP12.5 mixture, and up to 40% RAP can be incorporated without affecting the low-temperature performance of asphalt concrete mixture.

Table 4: t-test results for fracture stress differences

Asphalt concrete mixtures couple		$t_{statistic}$	$t_{critical\ two\text{-}tail}$
M1 (0% RAP, PG52-34)	M2 (0% RAP, PG58-28)	1.48	2.78
M1 (0% RAP, PG52-34)	M3 (20% RAP, PG58-34)	-2.47	2.78
M2 (0%RAP, PG58-28)	M4 (40% RAP, PG58-28)	-0.43	2.78
M3 (20% RAP, PG58-34)	M4 (40% RAP, PG58-28)	0.81	2.78

5. CONCLUSIONS

This study evaluated the laboratory performance of typical Ontario asphalt mixtures with RAP content up to 40%. Based on the overall findings of this study, it is strongly recommended that the TSRST test be used in determining the low-temperature cracking resistance of asphalt concrete mixtures with and without RAP.

The main objective of the study presented in this paper was to investigate the low-temperature thermal cracking potential of HMA mixtures incorporating 20% and 40% RAP in comparison with control HMA mixtures, all of which included three different binder grades. It is generally assumed that the addition RAP in HMA produces a stiffer mixture which increases the susceptibility to thermal cracking; however, from all results and observations presented herein, it is reasonable to conclude that the HMA mixtures incorporating RAP exhibit the potential to withstand thermal cracks arising from low temperatures if the asphalt mixtures are properly designed, mixed and compacted.

The critical cracking temperatures of the 20% and 40% RAP mixtures examined are comparable to those of the control mixtures as observed from ANOVA analysis t-tests. This finding supports the need to encourage the inclusion of RAP content as high as 40% in HMA, especially for low-volume road. The use of RAP in pavements is desirable since it offers economic benefits without compromising the performance of asphalt concrete. From a sustainability perspective, incorporation of RAP reuses the recycled aggregates and old binder, thus reducing the need for new materials and energy required to produce asphalt mixtures.

6. RECOMMENDATIONS

This paper is based on the preliminary results of an ongoing study at the Centre for Pavement and Transportation Technology (CPATT), University of Waterloo, aimed at evaluating the laboratory performance of typical Ontario asphalt mixtures with high RAP content. It is highly desirable that the plant-produced RAP HMA mixtures be studied since their physical and mechanical properties are considered to differ from the lab-prepared mixtures. Additionally, long-term aging should be considered in future studies involving RAP in HMA mixtures. This is necessary to simulate and provide verification of adequate field performance of the asphalt concrete mixtures for over a period of five to seven years, regardless of environmental conditions and mixture properties.

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