Evaluation of the Impact of Silo Storage on Thermal Cracking of the Hot Mix Asphalt with RAP

Hawraa Kadhim (presenter), PhD candidate, CPATT, University of Waterloo

Hassan Baaj, Associate Professor, CPATT, University of Waterloo

Centre for Pavement and Transportation Technology, Department of Civil and Environmental Engineering, Faculty of Engineering, University of Waterloo, Waterloo N2L 3G1,Canada

Paper prepared for presentation at the GREEN TECHNOLOGY IN GEOTECHNICAL AND MATERIALS ENGINEERING Session of the 2018 Conference of the Transportation Association of Canada Regina, Saskatchewan

Acknowledgements

The authors would like to thank the research team at Imperial Oil Limited for funding this project. Special thanks to Payman Pirzadeh and Daniel Grant for their substantial support throughout this research. The authors would like also to extend their thanks to The Miller Group for supplying the HL-3 and HL-8 mixes at the required time intervals and their lab personnel for compacting our dynamic modulus samples.

ABSTRACT

The use of Reclaimed Asphalt Pavement (RAP) in Hot Mix Asphalt (HMA) production is consistent with the concept of sustainability and when designed and constructed properly, it can potentially provide a more cost-effective alternative to conventional road practices. However, RAP is suspected to have negative effects on thermal cracking resistance of Hot Mix Asphalt mixes. The extent of blending between aged binder and virgin binder in asphalt mixtures could affect both the performance of the produced HMA and the economic competitiveness of the recycling process. During the production process of HMA with RAP, it is generally understood that a partial blending occurs between aged and virgin binders. Yet, a limited number of studies have considered the time-temperature effects of the silo storage on the performance of HMA RAP mixes. In this study, the effect of silo storage time on mitigation of thermal cracking of the HMA containing RAP is examined. HMA samples of HL-3 and HL-8 mixes, designed with 15% and 30% RAP respectively, were collected after production from the asphalt plant at different silo-storage intervals (1, 4, 8, and 12 hours), with their temperature being closely monitored and recorded. The thermal cracking resistance of the resulting mixes were characterised using Thermal Stress Restrained Specimen Test (TSRST). Results indicate that the samples collected after 8 and 12 hours of silo storage exhibited an improvement in the thermal cracking resistance accompanied with a reduction in their corresponding stiffness compared to those collected at 0 hours. These results indicate that silo storage would then improve the blending between aged and virgin binders and improve the low temperature behaviour of the asphalt mix.

Keywords: Asphalt plant, Silo storage, Blending, Thermal cracking

1 INTRODUCTION

1.1 Background

Reclaimed Asphalt Pavement (RAP) has been favoured over virgin materials in the light of the potential cost savings, shortage of quality aggregates, and compelling need to preserve the environment and natural resources. Mixes containing up to 20% RAP are commonly considered to have similar behaviour to virgin mixes [1]. In the interest of sustainable development, higher RAP percentages (> 25%) can be considered for incorporation into Hot Mix Asphalt (HMA) mixtures. However, more than 20% RAP content is perceived to have negative effects on the performance of the resulting HMA mixtures in comparison with conventional mixtures, especially with respect to thermal cracking resistance. It is stated that using RAP in HMA likely decreases the rutting, but increases the possibility of thermal cracking at low temperatures [2]–[6]. Thermal cracking is a serious concern in the cold regions in the world as it is associated with the growth of high tensile stresses under repetitive exposures to extremely low temperatures or multiple freezing-thawing cycles [7].

1.2 Literature Summary

Due to mostly economic and environmental considerations, RAP has been commonly used in asphalt paving mixtures for pavement construction and maintenance activities since the 1970s [8]. Yet, the type of the virgin asphalt binder, air void content, RAP content, and the type and the size of aggregate have a significant effect on the fracture temperature and fracture stress of the HMA pavement [9], [10]. The rheological behavior of the aged binder differs from the virgin binder due to the loss of some of its components during the construction and service life. Kandhal and Mallick resolved that the use of 5-20% of RAP in HMA does not affect the properties of the blend of new and RAP binder. However, more than 20% of RAP can significantly affect the properties of the blend and may change the stiffness of the binder. This is related to the aging condition and the associated brittleness of the asphalt binder contained in RAP which may be a source of poorer low temperature performance for the final asphalt mixture [11].

The RAP binder exists as thin layer that coats RAP aggregates and does not exist as a free mass in the asphalt mixture [12]. Then, it may be unreasonable to assume mechanical blending between the aged binder and virgin binder during the mixing process. The blending can be described by a phenomenon which can help the two binders blend at proper temperatures for a required time [13]. This mechanism is called diffusion, which allows molecules transfer in the matter when they have enough energy to move. According to Arhenius theory [14], at higher temperatures, the likelihood that two molecules will interact with each other is significantly increased . Moreover, the time effects the average distance that the molecules travels to interact with its neighbours [15]. The aged binder in RAP causes an increase in the stiffness in mixtures with high in RAP content. This could potentially reduce the performance of RAP mix [16]. Thus, increasing the blending efficiency between aged and virgin binder, and obtaining the maximum contribution of the aged binder in the mixture would help decreasing the stiffness and increasing the durability of the RAP pavement.

According to different studies, at least some partial blending occurs during mixing process of the HMA. However, it depends on different parameters, such as mixing time and temperature [17]–[19]. Yet, full blending of the two binders might happen over time. In a recent study on diffusion, it is shown that the diffusion between the in-contact layers of the aged and the virgin binders may explain the blending process [20]. A significant part of the blending takes place during the mix production, storage and placement of mixture, but diffusion continues and drives further blending during the service life of the pavement. While prolonged silo-storage may result in a homogeneous binder blending within few hours, it might make the binder more susceptible to significant aging during storage. In addition, Time-temperature effect of the silo-storage on HMA containing RAP can optimize the blending between virgin and RAP binders.

An experimental-based study was utilized to quantify the time and temperature responsiveness of the diffusion rate and final degree of blending that happens between aged and virgin binders. The authors confirmed that at conditioning temperatures below 100°C very limited blending between the virgin and RAP binder occurs. Thus, increasing the temperature could enhance the blending phenomenon [21].

The level of blending affects both the performance of the produced HMA and the economic competitiveness of the recycling process. If the designer assumes that the materials blend totally when it is actually behaving as a black rock, the binder will not be stiff enough and insufficient asphalt binder will be used. Many design methods assume that the aged binder effectively contribute to the blend [22]. Hence, the amount of virgin asphalt binder can be decreased in the mix design by the full amount of the RAP binder for the percentage specified [23]. In contrast, if it is assumed that RAP does not blend with the virgin asphalt binder when it is actually blending, then the binder will be stiffer than expected. The problem can be further complicated if one considers that the blending process may take some time to occur and is influenced by the rejuvenating agent [24], [25]. Despite some differences between the mix design procedure for a mix containing RAP and one that does not, both mixtures should have good characteristics and deliver a good pavement performance. The uncertainty in the degree of blending may be the main reason behind some of the durability issues of RAP mixtures.

In a recent study [26], the rheological properties of HL-3 plant-mix samples were characterised using the Complex Modulus Test by considering the effect of the silo storage time. The analysis of these results indicated a noticeable reduction in the stiffness of the mix for 8 hours and 12 hours at the test temperatures above 4˚C. This change is particularly observed at the higher temperature and lower frequencies of the complex modulus test. Therefore, it can be affirmed that the silo storage time had a strong impact on the rheological behaviour, which indicated a better blending of aged and virgin binders with higher storage time for a given silo conditions. More blending could theoretically have a positive effect on the overall performance of the HMA RAP mixes. However, in a different study [27], the analysis of the Dynamic Modulus Test results indicate that there was a general increase in the stiffness of HMA containing RAP with the increase of the silo storage time to 7.5 hours due to oxidation. This indicated that the silo conditions play a key role in changing the HMA characteristics and would lead to some aging which would have a negative impact on the behaviour.

From the above literature summary, it appears that the blending efficiency of the RAP and the virgin binder is still unexplored clearly. Some researchers believe that the blending efficiency is depending on the percentage of RAP on the asphalt mixture, mixing temperature, and time of mixing. Others believe the blending procedure is temperature independent. However, it is clear that the appropriate amount of the RAP aged binder that effectively contributes to HMA (containing RAP) needs further investigation. An improved understanding of binder blending would be beneficial in the improvement of the thermo-mechanical behaviour of asphalt mixes, which may lead to long lasting and better-performing asphalt pavements.

In this study, Thermal Stress Restrained Specimen Test (TSRST) has been conducted to examine the low-temperature cracking susceptibility of silo stored HMA mix with RAP at 0, 8, and 12 hours respectively. The main objective of this study is then to evaluate the effect of silo storage time on the mitigation of thermal cracking of the HMA containing RAP by utilizing TSRST.

2 MATERIALS AND METHODS

2.1 Materials: HL-3 and HL-8

Achieving an improved blending quality of plant-produced mixtures was considered by utilizing silo-storage facilities. The asphalt mixes were manufactured using the batch plant from the Miller Group asphalt plant in Markham, Ontario (Fig. 1). Batch plants do not require the use of silos, but plants often have them to increase their production capacity. Storage silos are usually insulated to prevent heat losses and to prevent mixture oxidation.

FIGURE 1 Miller Group batch plant

Conventional batch plant is the most common type of asphalt plants in the world as it usually produces asphalt mixes with high RAP content [28]. In addition, it provides the highest level of flexibility in production and quality of the product. In this plant, the specifications can be regularly modified to satisfy the client requirements, while keeping a high level of quality. The full mixing time in this plant usually takes 40-50 seconds.

For this study, two Marshall mixes, a surface course HL-3 containing 15% RAP and a base course HL-8 containing 30% RAP, were produced and collected from the batch plant. The HL-3 mix has a total of 5% asphalt binder (approximately 4.4% virgin binder and 0.6% RAP binder). The mixing temperature was 148˚C and the compaction temperature was 135˚C. On the other hand, the HL-8 mix has a total of 4.7% asphalt binder (approximately 3.5% virgin binder and 1.2% RAP binder). The mixing and compaction temperatures for HL-8 mix were 145 ˚C and 131 ˚C, respectively. Table 1 represents some properties of these mixes.

TABLE 1 HL-3 and HL-8 properties

Mix Properties	**Mix Type**	
	HL-3	**HL-8**
Total % of Asphalt Cement (%AC)	5	4.7
Virgin AC grade	58-28	52-34
% RAP content	15	30
% AC RAP content	0.6	1.2
Nominal Maximum Aggregate Size (NMAS) (mm)	13.2	19
Theoretical Maximum Specific Gravity of HMA (G_{mm})	2.49	2.503
Specific Gravity of Asphalt (G_b)	2.673	2.671
Voids in Mineral Aggregate (% VMA)	15.3	14.6

To investigate the time-temperature effect on blending efficiency, the samples were collected as a function of storage time in the silo. The first sampling was done immediately after production (t = 0 hour), and then at several time intervals of silo-storage at 1, 4, 8, and 12 hours. In order to avoid reheating the mixtures and inducing any bias in the temperature profile of the tested samples, some mixes were immediately compacted using Superpave Gyratory Compactor at the Quality Control Laboratory of the asphalt plant. Complex modulus of these samples was then measured to determine the effect of storage time on their stiffness [16]. The compacted and loose mixtures were then transported to the University of Waterloo and kept in a storage room at 7 ˚C until the day of testing to eliminate any further diffusion. Temperatures of the collected samples were closely monitored and recorded throughout this study.

2.2 Sample Preparation

After a curing period of 14 days, the loose mixtures were compacted using ShearBox Slab Compacter to a targeted air void content of 7 ± 1%, coming down to around 5% ±0.5%. The resultant slabs were then saw cut to fabricate three rectangular TSRST specimens (50mm x 50mm x 250mm) for 0, 8, and 12 hours silo samples for both HL-3 and HL-8. It is worth mentioning that 1 and 4 hours silo samples for both mixes were not tested using TSRST assuming there would be no change in the thermal resistance as there was no noticeable reduction in their overall stiffness as compared with the 0 hours samples [26].

2.3 Thermal Stress Restrained Specimen Test (TSRST)

TSRST method has been utilized to evaluate the low temperature cracking in asphalt pavement by many researchers. To estimate the low temperature cracking performance of HMA mixtures considering silo storage time, TSRST was conducted at CPATT using MTS device (Fig. 2), according to AASTHO TP-10-93 specification, Standard Test Method for Thermal Stress Restrained Specimen Tensile Strength [29]. Each specimen was glued to two aluminium end platens with thermoset DC-80 epoxy. The epoxy bond is allowed to cure for at least 6 hours prior to conditioning the test specimen at 5°C in the CPATT MTS-651 environmental test chamber for 3 hours until the specimen reaches thermal equilibrium. Actual testing is performed at a constant cooling rate of 10°C/hr.

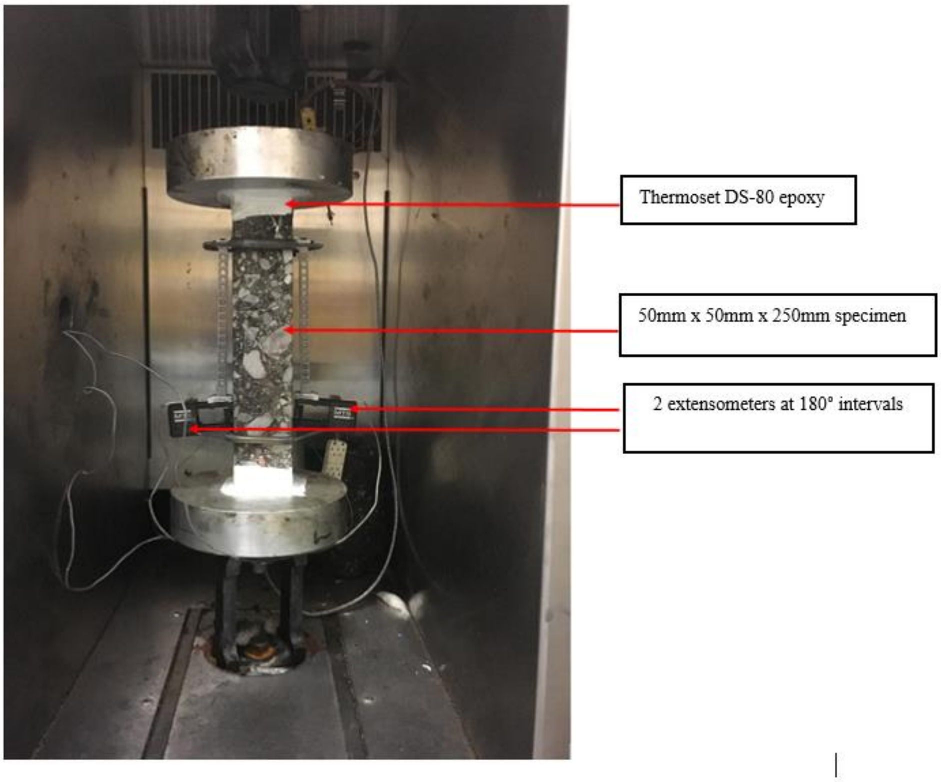

FIGURE 2 MTS loading farm with TSRST setup

Figure 3 illustrates a typical stress-temperature curve from TSRST. As the temperature inside the chamber decreases at a constant rate of 10 °C/h, tensile stresses develop within the sample, which leads to failure by restrained thermal contraction.

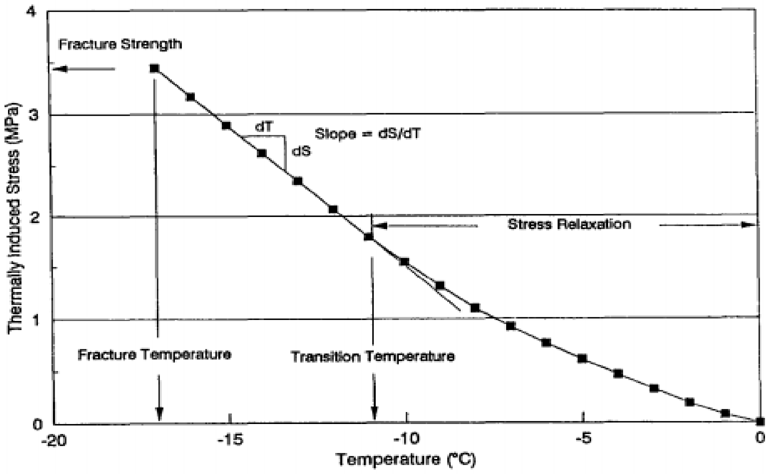

FIGURE 3 Typical result from TSRST

The slope of the curve (dS/dT) (Fig. 2) gradually growths until it reaches its upper limit of the glass transition temperature. After the transition temperature, (dS/dT) becomes constant and the stress temperature curve becomes linear until the specimen breaks. The tensile stress and the temperature at which the break point occur are called the fracture strength and the fracture temperature, respectively. The contraction of the specimen is controlled during the cooling process using two Linear Variable Differential Transformers (LVDTs).

3 RESULTS AND DISCUSSION

Resistance to low temperature cracking is a major concern for asphalt mixes containing RAP. In point of fact, the RAP asphalt binder is generally harder than virgin asphalt binder. Asphalt mixes with additional recycled materials could then have a brittle behaviour at low temperatures and premature thermal cracking could be exhibited. Table 2 reports the test results in terms of the average maximum stress at which the specimen fails (fracture stress) with an average corresponding fracture temperature.

A general observation of the results reported in Table 2 is that the values of the standard deviations for fracture temperature ranged from 0.52 °C to 1.3 °C for all tested mixes. The results indicate both mixes showed good repeatability in terms of fracture temperature. However, it seems that a higher scattering is observed with the fracture stress were the standard deviations range from 0.19 MPa to 0.66 MPa. These values are significantly high if we know that the mean fracture stress values vary from 1.7 MPa to 2.8 MPa which means that the standard error could be up to ±33% of the measured values.

The examination of the results in Table 2 shows that for the 0 hours mixes, or the mixes that were collected directly from the plant without silo storage, it is observed that the fracture temperature of the HL-3 mix with PG 58-28 binder exceeded the critical low grade of the virgin binder by 3.08 °C; whereas the HL-8 mix with PG 52-34 failed to meet the anticipated -34 °C limit for mix fracture temperature.

TABLE 2 Fracture temperature and fracture stress for HL-3 and HL-8

		Fracture Temperature (°C)		**Fracture Stress (MPa)**	
Mix Type	**Silo time (hours)**	**Mean**	**Standard deviation**	**Mean**	**Standard deviation**
HL-3	**0**	-31.08	1.3	2	0.66
	8	-31.41	0.52	2.1	0.22
	12	-34.93	0.091	1.7	0.5
HL-8	**0**	-31.65	0.61	2.8	0.15
	8	-32.82	0.92	2.78	0.7
	12	-34.99	0.86	2.1	0.19

Yet, the fracture temperatures of the 8 hours samples of HL-3 and HL-8 mixes have reached -31.41 and -32.82 respectively. Additionally, the fracture temperatures of the 12 hours samples for both mixes have exceeded the critical low grade of the virgin binders by 6.93 °C and 0.99 °C respectively. Thus, the increased silo time has improved the performance of the binder which primary controls thermal crack resistance of the HMA at low temperatures. Figure 4 illustrate the reduction in the fracture temperature with respect to the silo storage time. The examination of this graph shows that although the difference between the results at 0 hours and 8 hours do not appear to be significantly different, the results obtained at 8 hours are significantly different and confirm the trend of the improvement of the critical cracking temperature for both mixes.

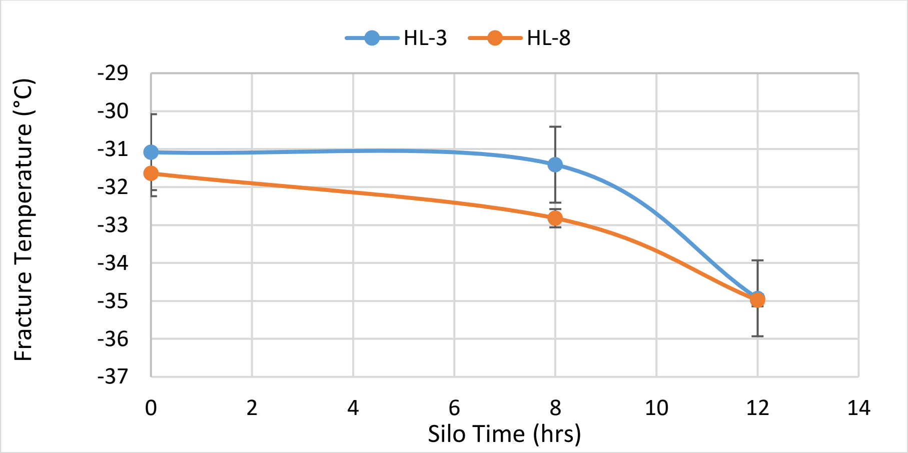

FIGURE 4 Average fracture temperature for HL-3 and HL-8

Moreover, a decrease in the fracture stress was found with the improvement of the thermal resistance of both HL-3 and HL-8. It is also noted that a lower fracture stress is exhibited for the mix with 15% RAP (HL-3) compared to the mix with 30% RAP (HL-8). Figure 5 shows that the 12 hours samples for both HL-3 and HL-8 have lower fracture stress comparing with the 0 hours samples by 0.3 and 0.7 MPa respectively. Figure 5 represents the reduction of the fracture stress with the increase of silo storage time. However, due to the fact that the standard deviation values for fracture stress were high, it seems that the decrease of the stress is not significantly different of most of the cases.

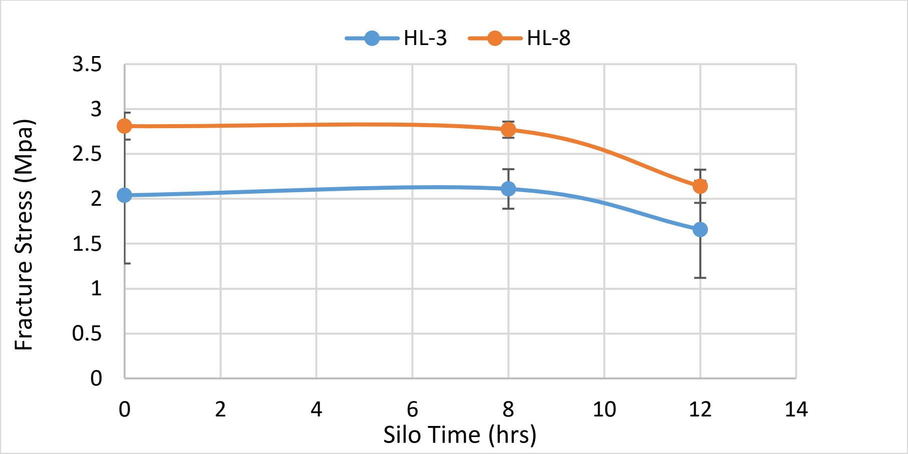

FIGURE 5 Average fracture stress for HL-3 and HL-8

Generally, the results of the TSRST suggest that the fracture temperature of the HL-8 mixtures was to some extent lower than that of the HL-3 mixtures for all silo time samples. This is probably due to the fact that the HL-8 used a softer virgin binder (PG52-34) compared to the HL-3 mixture which used a PG58-28 virgin binder. On the other hand, HL-8 samples had higher fracture stresses than HL-3 samples. This is more possibly because HL-8 had less asphalt content, more RAP content, and larger Nominal Maximum Aggregate Size (NMAS) which results in a stiffer overall mixture. Higher stiffness mixes could exhibit higher build-up of cracking [30]. However, it is noted that more silo time has a positive influence on the fracture temperature and fracture stress of both HL-3 and HL-8. This is due to the improved degree of blending between aged and virgin binder and greater homogeneity in the mixture with higher storage time. Hypothetically, more blending would result in increasing the thickness of the film of the “efficient” binder on the aggregates and enhancing the adhesion of the mix. This is more likely because the RAP binder had an increased contribution to the efficient asphalt binder used within the mixture, which is a major criterion of the thermal cracks initiation in HMA. This would improve the quality of the HMA and enhance thermal cracking resistance.

Overall, the results of the TSRST indicated that the 12-hrs specimens had a better resistance to the thermal cracking than the ones without silo storage for both HL-3 and HL-8 due to more homogeneous binder blending for the 12-hrs mixes. Figure 6 and 7 graphically show the fracture curve behaviour of both HL-3 and HL-8 respectively for the three replicates of 0, 8, and 12 hours silo storage time.

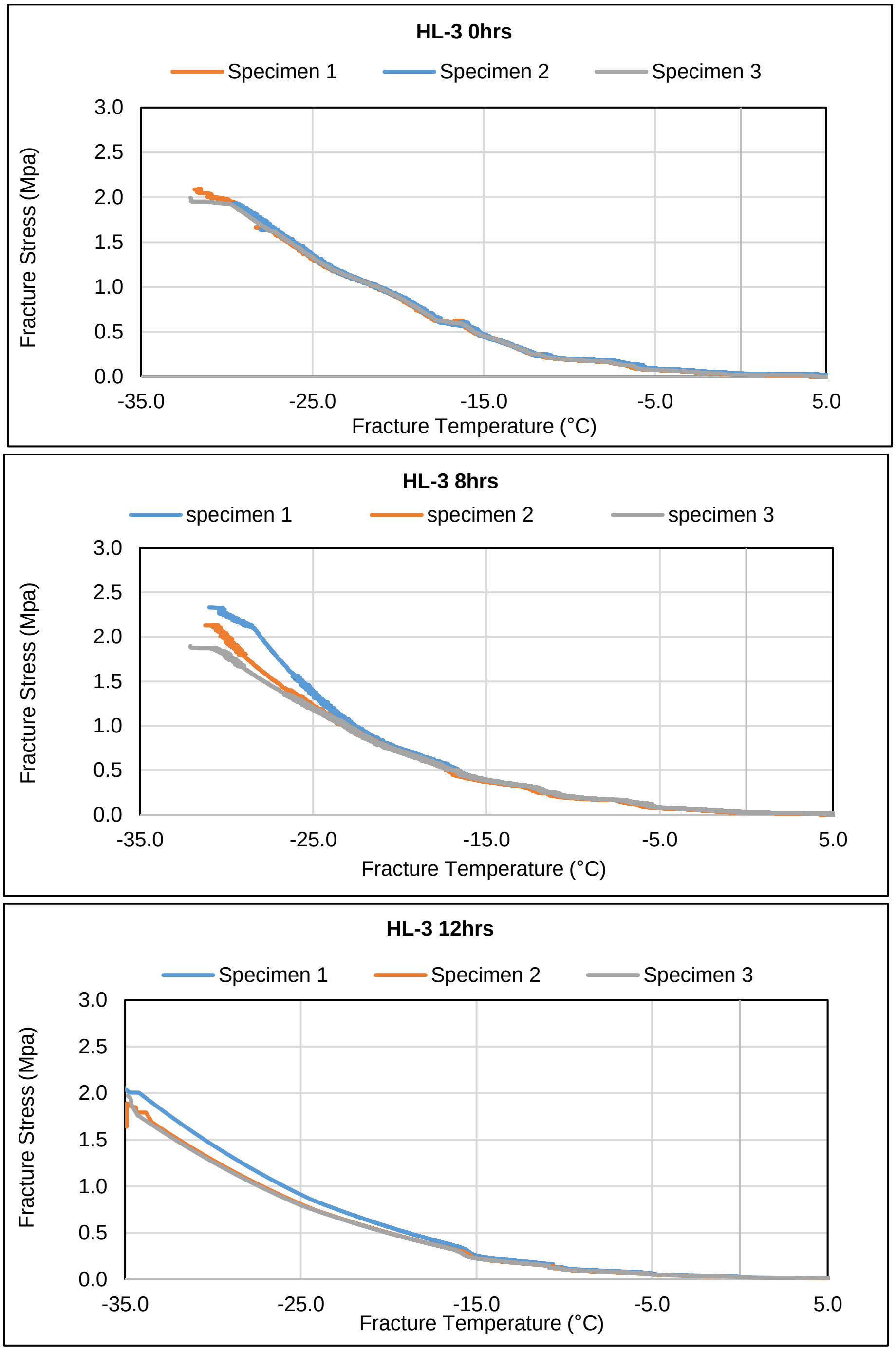

FIGURE 6 Fracture curve behavior of the tested samples of HL-3 mixes

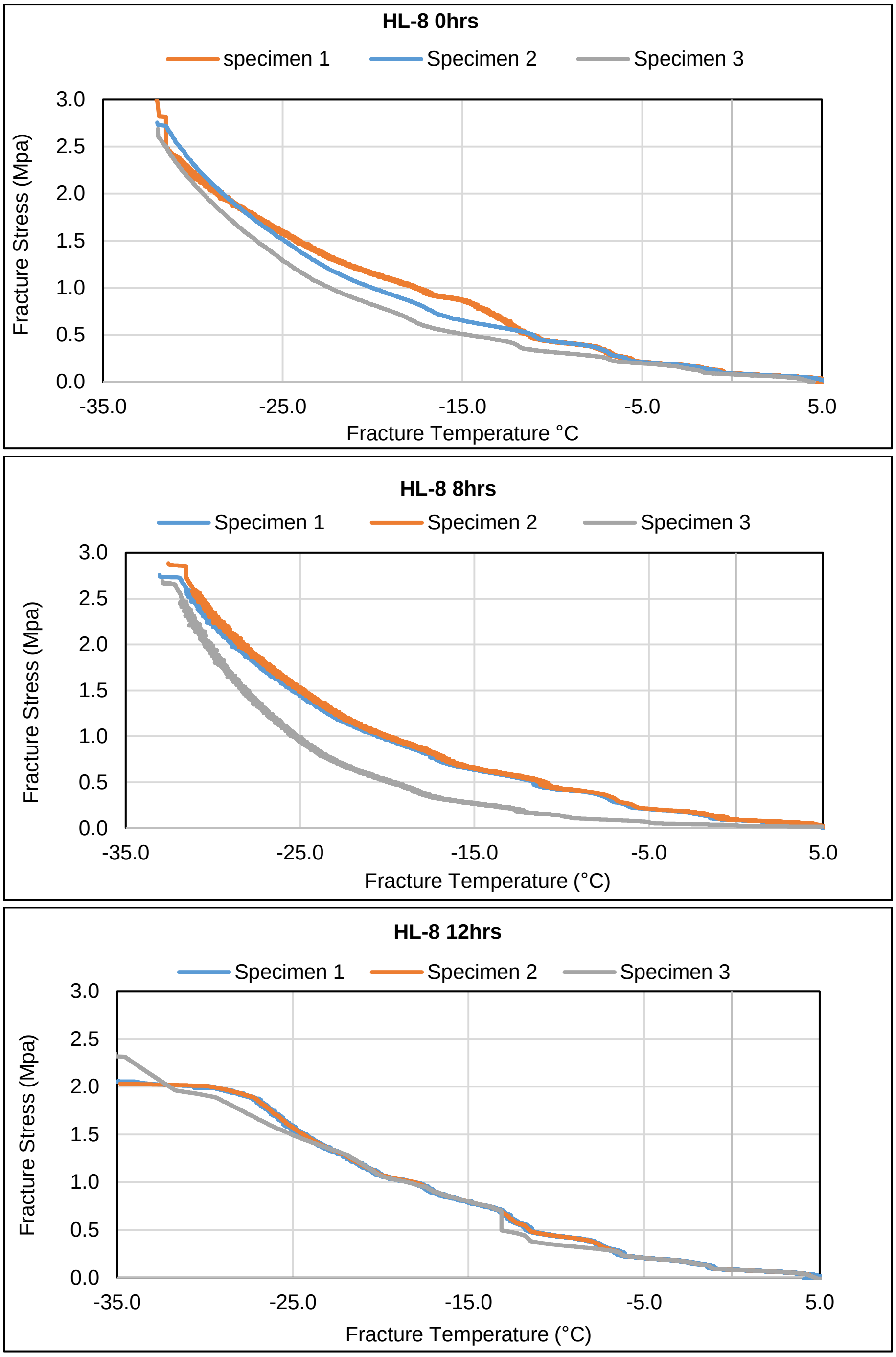

FIGURE 7 Fracture curve behavior of the tested samples of HL-8 mixes

It is worth mentioning that the variability of the test results within the same mix was due to an issue with the valve control of the cooling system. However, the final results were not impacted significantly by this issue.

It can be concluded that for this particular case, higher storage time could potentially improve the blending of RAP and virgin binders which impacts the rheology of the mix and then the thermal performance of HMA-RAP mixtures. Despite the fact that the thermal cracking resistance has slightly improved by -3.85 and -3.52 °C for HL-3 and HL-8 respectively with 12 hrs storage time, these results are encouraging and suggest more samples with different RAP content and different silo conditions to be investigated and analysed to draw more solid conclusions.

Despite the fact that test results show a substantial trend in the reduction of both fracture temperature and fracture stress with the increase of silo time, it is necessary to utilize appropriate statistical analysis to determine the significance of the test results.

4 CONCLUSIONS

The conclusions of the study on the mitigation of thermal cracking of the hot mix asphalt containing reclaimed asphalt pavement by considering the effect of silo storage time are as follows:

- The fracture temperature of both HL-3 and HL-8 was generally affected by their virgin binder grades. All HL-8 samples slightly exhibited lower fracture temperature than HL-3 samples.
- For both HL-3 and HL-8, an improvement of the thermal resistance was found for the 8 and 12 hours samples as compared with the 0 hours samples. The fracture temperatures of the 12 hours samples for both HL-3 and HL-8 have exceeded the critical low grade of the virgin binders by 6.93 °C and 0.99 °C respectively.
- A decrease in the fracture stress was found with the improvement of the thermal resistance of both HL-3 and HL-8. In general, a lower fracture stress is found for the mix with 15% RAP mix (HL-3) compared to the 30% RAP mix (HL-8). The results however do not seem to be significantly different due to high standard deviation values.
- From the TSRST results, it can be summarized that increasing storage time for a given silo conditions has improved the performance of the binder which primary controls thermal crack resistance of the RAP HMA at low temperatures.

REFERENCES

[1] McDaniel, R. S., Soleymani, H., Anderson, R. M., Turner, P., & Peterson, R. (2000). Recommended use of reclaimed asphalt pavement in the Superpave mix design method. *NCHRP Web document*, *30*.

[2] Stroup-Gardiner, M., & Wagner, C. (1999). Use of reclaimed asphalt pavement in Superpave hot-mix asphalt applications. *Transportation research record: journal of the transportation research board*, (1681), 1-9.

[3] Baaj, H., Ech, M., Tapsoba, N., Sauzeat, C., & Di Benedetto, H. (2013). Thermomechanical characterization of asphalt mixtures modified with high contents of asphalt shingle modifier (ASM®) and reclaimed asphalt pavement (RAP). *Materials and structures*, *46*(10), 1747-1763.

[4] Ambaiowei, D. (2014). Innovative Evaluation of Crumb Rubber Asphalt and Recycled Asphalt Pavement.

[5] Varamini, S., Ambaiowei, D., Sanchez, X., & Tighe, S. L. (2014). Evaluation of Asphalt Binder Characteristics of Typical Ontario Superpave CRM and RAP-HMA Mixtures. In *Transportation 2014: Past, Present, Future-2014 Conference and Exhibition of the Transportation Association of*

Canada//Transport 2014: Du passé vers l'avenir-2014 Congrès et Exposition de'Association des transports du Canada.

[6] Yang, J., Ddamba, S., UL-Islam, R., Safiuddin, M., & Tighe, S. L. (2013). Investigation on use of recycled asphalt shingles in Ontario hot mix asphalt: a Canadian case study. *Canadian Journal of Civil Engineering*, *41*(2), 136-143.

[7] Aschenbrener, T. (1995). Investigation of low temperature thermal cracking in hot mix asphalt. No. CDOT-DTD-R-95–7

[8] Copeland, A. (2011). *Reclaimed asphalt pavement in asphalt mixtures: State of the practice* (No. FHWA-HRT-11-021).

[9] Jung, D., & Vinson, T. S. (1993). Thermal stress restrained specimen test to evaluate low-temperature cracking of asphalt-aggregate mixtures. *Transportation research record*, 12-12.

[10] Li, X., Marasteanu, M., Williams, R., & Clyne, T. (2008). Effect of reclaimed asphalt pavement (proportion and type) and binder grade on asphalt mixtures. *Transportation Research Record: Journal of the Transportation Research Board*, (2051), 90-97.

[11] Kandhal, P. S., & Mallick, R. B. (1998). *Pavement Recycling Guidelines for State and Local Governments: Participant's Reference Book* (No. FHWA-SA-98-042).

[12] Rad, F., Sefidmazgi, N., & Bahia, H. (2014). Application of diffusion mechanism: Degree of blending between fresh and recycled asphalt pavement binder in dynamic shear rheometer. *Transportation Research Record: Journal of the Transportation Research Board*, (2444), 71-77.

[13] Kriz, P., Grant, D. L., Veloza, B. A., Gale, M. J., Blahey, A. G., Brownie, J. H., ... & Maccarrone, S. (2014). Blending and diffusion of reclaimed asphalt pavement and virgin asphalt binders. *Road Materials and Pavement Design*, *15*(sup1), 78-112.

[14] Lindemann, F. A., Arrhenius, S., Langmuir, I., Dhar, N. R., Perrin, J., & Lewis, W. M. (1922). Discussion on “the radiation theory of chemical action”. *Transactions of the Faraday Society*, *17*, 598-606.

[15] Aquilanti, V., Mundim, K. C., Elango, M., Kleijn, S., & Kasai, T. (2010). Temperature dependence of chemical and biophysical rate processes: Phenomenological approach to deviations from Arrhenius law. *Chemical Physics Letters*, *498*(1-3), 209-213.

[16] Mogawer, W. S., Austerman, A. J., Pauli, T., Salmans, S., & Planche, J. P. (2016). *Determination of the Binder Grade and Performance of High Percentage RAP-HMA Mixes* (No. SPRII-15-57946).

[17] Gaitan, L. (2012). Evaluation of the degree of blending of reclaimed asphalt pavement (RAP) binder for warm mix asphalt. (Master thesis). Rowan University

[18] Huang, B., Li, G., Vukosavljevic, D., Shu, X., & Egan, B. (2005). Laboratory investigation of mixing hot-mix asphalt with reclaimed asphalt pavement. *Transportation Research Record: Journal of the Transportation Research Board*, (1929), 37-45.

[19] Shirodkar, P., Mehta, Y., Nolan, A., Sonpal, K., Norton, A., Tomlinson, C., ... & Sauber, R. (2011). A study to determine the degree of partial blending of reclaimed asphalt pavement (RAP) binder for high RAP hot mix asphalt. *Construction and Building Materials*, *25*(1), 150-155.

[20] Kriz, P., Grant, D. L., Veloza, B. A., Gale, M. J., Blahey, A. G., Brownie, J. H., ... & Maccarrone, S. (2014). Blending and diffusion of reclaimed asphalt pavement and virgin asphalt binders. *Road Materials and Pavement Design*, *15*(sup1), 78-112.

[21] Rad, F. Y. (2013). Estimating blending level of fresh and RAP binders in recycled hot mix asphalt. *Master of Science, University of Wisconsin Madison*.

[22] Aurangzeb, Q. (2014). *Impact of reclaimed asphalt pavements on pavement sustainability*. University of Illinois at Urbana-Champaign.

[23] Al-Qadi, I. L., Elseifi, M., & Carpenter, S. H. (2007). *Reclaimed asphalt pavement—a literature review*. Federal Highway Administration, IL, USA. Report No.: FHWA-ICT-07-001. Contract No.: ICT R27-11

[24] Carpenter, S. H., & Wolosick, J. R. (1980). Modifier influence in the characterization of hot-mix recycled material. *Transportation Research Record*, (777).

[25] Moghaddam, T. B., & Baaj, H. (2016). The use of rejuvenating agents in production of recycled hot mix asphalt: A systematic review. *Construction and Building Materials*, *114*, 805-816.

[26] Kadhim, H., Mikhailenko, P., Baaj, H., and Tighe, S.L. (2017) T*he Effect of the Silo-Storage on the Rheological Behavior of a Surface Course Asphalt Mix Containing Reclaimed Asphalt Pavement (RAP).* In proceeding of Canadian Society of Civil Engineering (CSCE): Vancouver, BC.

[27] Jacques, C., Daniel, J. S., Bennert, T., Reinke, G., Norouzi, A., Ericson, C., ... & Kim, Y. R. (2016). Effect of Silo Storage Time on the Characteristics of Virgin and Reclaimed Asphalt Pavement Mixtures. *Transportation Research Record: Journal of the Transportation Research Board*, (2573), 76-85.

[28] Kennedy, T. W., & Huber, G. A. (1984). *The Effect of Mixing Temperature and Stockpile Moisture on Asphalt Mixtures* (No. FHWA/TX-85/49+ 358-1). The Center.

[29] TP10, A. D. (1993). Standard test method for thermal stress restrained specimen tensile strength. *American Association of State Highway and Transportation Officials*.

[30] Mogawer, W., Bennert, T., Daniel, J. S., Bonaquist, R., Austerman, A., & Booshehrian, A. (2012). Performance characteristics of plant produced high RAP mixtures. *Road Materials and Pavement Design*, *13*(sup1), 183-208.