Asphalt mixture performance and testing

Impact of Asphalt Plant Silo Storage to Enhance Blending between RAP & Virgin Binders in Hot Mix Asphalt

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Abstract

Recycled Asphalt Pavement (RAP) is used in manufacturing of new asphalt mix due to economic and sustainability incentives. A 2016 industry survey indicated an average increase in RAP content of new asphalt mixes from 15 to 20% in North America. The RAP content in newly manufactured mix depends on the mix design and asphalt mix plant capability. Increased RAP content necessitates better understanding of blending between aged and virgin binder. This understanding helps to develop and implement best practices in asphalt plant to ensure maximum blending between binders is achieved. Proper blending between binders impacts cohesion of binder and adhesion to aggregates. The quality of blending ultimately is reflected in hot mix asphalt (HMA) performance in the field. Plant produced HMA samples containing RAP between 15 and 40%, were sampled from storage silo at different storage times ranging between 0-24 hours. Data indicate that silo storage can help diffusion between binders to progress faster towards completion. It was demonstrated that improved binder blending in plant-produced lab-compacted HMA samples results in reduced rutting depths, improved binder-aggregate adhesion, and resistance to fatigue and low temperature cracking. Trends in evolution of asphalt mix dynamic modulus mastercurves also indicate that there is an optimum time during which diffusion is the dominant process helping to maximize blending and thus improving HMA properties. Beyond this optimum time, binder oxidative aging becomes a dominant process and mix properties start to deteriorate.

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1. Introduction

Reclaimed asphalt pavement (RAP) is extensively used to manufacture new asphalt mixes [1-3]. Recycling available aggregates and binders in RAP further enables the industry to be both environmentally and economically sustainable [4-7]. In North America, a recent survey by National Asphalt Pavement Association (NAPA) indicates that the national average of RAP content in new asphalt production has increased from 15% in 2009 to 20% in 2016 [8]. While higher RAP contents help better utilizing the increasingly limited aggregate and binder resources, it also introduces challenges in design and performance of new asphalt pavements. The binder in RAP has undergone a period of service life; therefore, it has been exposed to different weather conditions and has experienced aging [4,9-12]. This aging makes the binder in RAP stiffer than its original virgin state [4,9,10]. Therefore, increased content of RAP in new asphalt raises concerns about premature failure of pavement due to excess stiffness of RAP. In addition, RAP is milled from a pavement that had its own design and gradation based on intended performance. In order to effectively re-incorporate and blend RAP into manufacturing of new virgin asphalt, one has to (1) manage the increased stiffness of the aged binder in RAP, (2) achieve the correct final mix gradation when RAP aggregates get incorporated, and (3) reach proper cohesion between virgin and RAP binders as well as adhesion to aggregates [4,11,12]. Achieving the appropriate level of binder cohesion and adhesion to aggregate content is influenced by the progress of blending between RAP's aged binder and the new virgin binder in asphalt. Upon insufficient blending, RAP can act as a black rock resulting in a heterogeneous blend in a new asphalt; this heterogeneity makes the new asphalt susceptible to stress build-ups at interfaces of RAP and virgin asphalt [9-12]. Earlier works have shown that blending between RAP and virgin binder can be modelled in two stages (see Fig. 1) [9,10,13]. First, mechanical mixing in an asphalt plant creates contact surface area between the aged and virgin binders. This step is impacted by plant design, production temperature and production rates [13-18]. Upon creation of contact surface, the second step is the diffusion between binders. During diffusion, components of binders migrate in the direction of concentration gradients to achieve a final homogeneous mixture. Studies conducted on blending between RAP and virgin binders have concluded that diffusion is the major contributing factor in quality of blending [9,10,13]. Since earlier studies demonstrated that binder diffusion follows Arrhenius Law, it is inferred that temperature has a significant impact diffusion progress, i.e. higher temperatures increase the diffusion rate [9,10,12]. It is this diffusion step that helps the discrete interfaces between the aged binder of RAP and the new virgin binder to disappear.

Due to complex nature of bitumen binders, a variety of methods have been developed to investigate progress of diffusion in bitumen. Utilizing radioactive tracers [19], staged solvent extraction of binders [20-24], dynamic shear rheometers [9,10,25,26], Fourier Transform Infrared spectroscopy [27,28] and Fluorescent microscopy [29,30] are among the established approaches. However, investigation of diffusion in a RAP-containing asphalt is even further challenging due to sensitivity of diffusion to temperature, the heterogeneous nature of the asphalt and variation in an asphalt plant during production. Even at a laboratory-scale sample preparation and analysis, limited number of studies can be found that have considered temperature history of asphalt samples to probe impact of diffusion rather than mechanical mixing [9,10]. Imperial Oil and ExxonMobil pioneered in understanding the nature of diffusion between RAP and virgin binders to help improvement in pavement performance and service life [9-12]. A recent work by Imperial Oil and ExxonMobil in collaboration with University of Waterloo, Canada, intended to understand the diffusion process and its impact on asphalt performance in the field [11]. A plant trial was designed to manufacture RAP-containing asphalts with different RAP contents [11] for laying surface and base courses. Since temperature governs the progress of diffusion, it was hypothesized that storing the newly manufactured asphalt in silos at a temperature range of 140-150°C helps further progress of diffusion. Asphalt samples were collected from two plants at pre-defined duration of silo storage, nominally 0, 1, 4, 8, 12 and 24 hours. These asphalt mixes were designed based on specifications in the province of Ontario, Canada. Extra care was exercised to control the thermal history of collected samples to ensure evolution in asphalt properties are limited to diffusion progress. Analysis of silo-stored samples indicated that resistance to rutting and fatigue cracking increased up to 12 hours of silo storage; however, not much improvement was observed between 12 and 24 hours of storage (see Fig 2b) [11]. Examining the dynamic moduli of the collected asphalt samples pointed out to a decrease in $|E^*|$ at lower frequencies up to 12 hours of storage; but an increase in $|E^*|$ was noted when samples were stored up to 24 hours in the silo (see Fig. 2a). Looking at volumetric properties of asphalt also indicated that void filled with asphalt binder (VFA) and void between mineral aggregate (VMA) also evolved during silo storage. VMA and VFA exhibited a decreasing and an increasing trend, respectively, up to 12 hours of silo storage but plateaued between 12 and 24 hours [11]. This observation suggested that more of the RAP binder content was activated over the course of silo storage. Binders of the collected asphalt samples were extracted and were examined for their rheological and chemical properties. While no significant Superpave grade change was noted between 0-12 hours of silo storage, a deterioration was noted between 12 and 24 hours of storage in examined samples [11]. This deterioration in performance was mainly attributed to excess heat resulting in absorption and evaporation as aging processes, while in one case excessive oxidation was noted by FTIR analysis with possible chemistry of binder being a contributin factor [11]. Combining performance assessments of the extracted bitumen and asphalt samples pointed out to existence of an optimum silo storage duration of about 12 hours during which diffusion was the dominant process, after which asphalt hardening was noted. The 12 hour duration was proposed earlier in the works conducted on binders [10]. Therefore, the field study verified the results and predictions of the earlier laboratory works on diffusion progress [9,10].

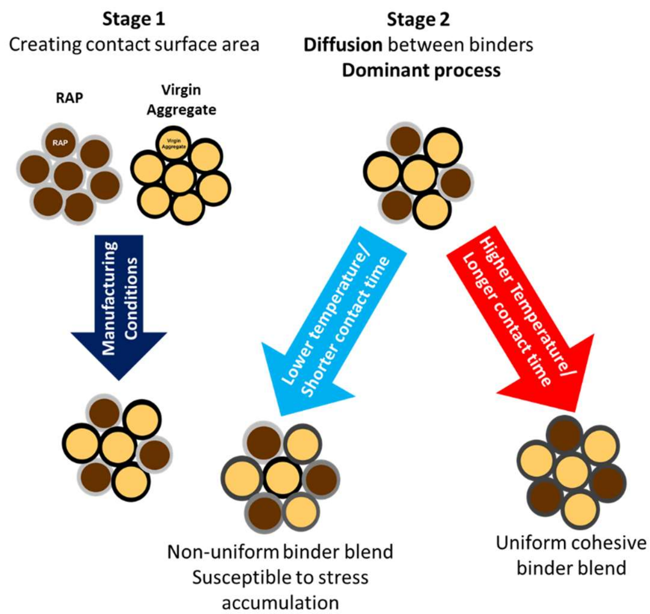

Figure 1: Blending between RAP and virgin binders in a RAP-containing asphalt can be modelled in two stages: mechanical mixing (stage 1) and diffusion (stage 2).

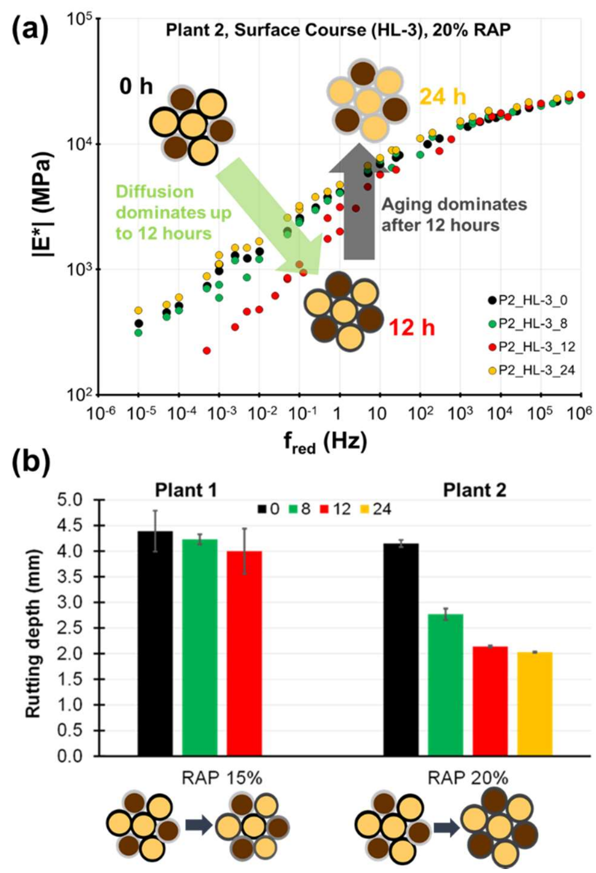

Figure 2: Impact of diffusion progress on performance of surface course asphalt samples during silo storage. (a) Measured dynamic moduli for a surface course sample with 20% RAP content from Plant 2. (b) Measured rutting depths of two asphalt samples with 15% and 20% RAP content from two plants; see Table 2 for the corresponding operating conditions. . Data corresponding to 0, 8, 12 and 24 hours of silo storage are presented by black, green, red and orange, respectively. Different shades of black in the schematics of asphalt mix demonstrate quality of bitumen blending at different stages of silo storage. Figure adapted from Refs. [11,12].

In this work, fatigue performance of collected asphalt samples at various levels of loading and the low temperature cracking resistance are evaluated and discussed. This additional information complements the observations discussed in the Introduction section [11] and provides the bigger picture on the importance of diffusion on pavement performance. The improved homogeneity of asphalt is manifested in superior performance of the examined samples under different temperature and exposure conditions, which speaks to improved binder cohesion and adhesion to aggregates due to progress of diffusion between binders.

2. Materials and Methods

2.1. Materials.

Asphalt samples were produced and collected at two plants, noted as Plant 1 and Plant 2, located in Ontario, Canada. Two sets of asphalt mixes, designed based on Ontario specifications, were collected at each site: surface course mix (HL-3) and base course mix (HL-8). All produced mixes were intended for paving jobs. Plant 1 produced surface and base mixes with 15% and 30% RAP content, respectively, while Plant 2 manufactured the same mixes with 20% and 40% RAP, respectively. Both plants used PG 58-28 and PG 52-34 virgin binders for the surface and base asphalt mixes, respectively, per AASHTO recommendations (AASHTO M323, 2017). RAP sources differed between the plants. Table 1 summarizes the asphalt mix design of surface and base courses manufactured at each plant. Mix samples were collected at 0, 1, 4, 8, 12 hours at both plants, and 24 hours samples were collected at Plant 2. Silos at both plants were equipped with a heated oil circulated jacket to heat the bottom of the silo. Sampling was performed from pads of mix collected immediately after production in the plant for 0 hour storage and from silos for stored samples.

Production and sampling conditions of each plant versus the type of the mix sampled are summarized in Table 2. To produce specimen for dynamic modulus analysis from Plant 1, mix samples were immediately compacted at plant's quality assurance laboratory dynamic modulus analysis which was performed later. All loose mix collected samples were then refrigerated at site before transporting to University of Waterloo. Careful attention was paid for this step to minimize further diffusion between the time of the sampling and laboratory testing. In case of Plant 2, collected samples were immediately transferred to University of Waterloo for compaction. All loose mix collected samples were stored in a refrigerator at University of Waterloo. In addition to silo-stored samples, RAP samples were collected from both plants. No information on history of RAP samples was available.

2.2. Methods

2.2.1. Flexural beam fatigue test: The fatigue lives of the collected asphalt samples were examined with the four-point bending fatigue test. The test setup was entirely computer-controlled and consists of a load frame, a closed-loop control, and data acquisition system. The test was carried out in accordance with the AASHTO T321 procedure. Triplicate 380L×63W×50H mm beam specimens were fabricated for this test for both surface (HL-3) and base (HL-8) course samples. The test beams were subjected to repeated flexural loading at a frequency of 10 Hz. The deflection level (strain level) was selected to allow the specimen undergo a minimum of 10,000 load cycles before its stiffness is reduced to, at least, 50% of the initial stiffness. The initial stiffness was estimated by applying 50 load cycles at a constant strain level of 250–500 μm/m. The tests were performed at a temperature of 20˚C.

2.2.2. Low temperature cracking susceptibility: Thermal Stress Restrained Specimen Test (TSRST) method was utilized according to AASTHO TP-10-93 specification to evaluate the low temperature cracking in the collected asphalt samples. Three rectangular test specimens (50mm x 50mm x 250mm) were prepared for 0, 8, 12, and 24 hours silo samples for both surface (HL-3) and base (HL-8) samples. Each specimen was glued to two aluminium end platens with thermoset DC-80 epoxy. The epoxy bond was allowed to cure for at least 6 hours prior to conditioning the test specimen at 5°C in an MTS-651 environmental test chamber for 3 hours. Performance assessment was conducted at a constant cooling rate of 10°C/hr.

Table 1: Mix design job formula of the surface (HL-3) and base (HL-8) mixes collected from Plants 1 and 2

Plant	Mix Type	Virgin Binder PG	AC Content (%)	RAP Content (%)	RAP AC Content (%)	Sieve Size (mm)												
						26.5	19	16	13	9.5	6.7	4.75	2.36	1.18	0.6	0.3	0.15	0.075
#1	HL-3	58-28	5.0	15	4.0	100	100	100	98.7	82.9	66.8	57	49.4	43.1	34.6	18.6	6.6	3.3
#1	HL-8	52-34	4.7	30	4.0	100	96.7	88.4	81.7	67.3	55.4	49.7	44	38.6	31	16.9	6.3	3.1
#2	HL-3	58-28	5	20	4.2			100	99.6	83.9		58.7	50.7	38.4	23.3	11	6.4	4.2
#2	HL-8	52-34	4.7	40	4.2	100	97.5	92.4	87.5	71.6		49.2	41.4	31.8	20.7	11	6.6	4.2

Table 2: Production and operating conditions of Plants 1 and 2 during collection of samples

Plant	Plant 1		Plant 2	
Asphalt Course	**Surface (HL-3)**	**Base (HL-8)**	**Surface (HL-3)**	**Base (HL-8)**
Production Temperature (°C)	160	150-170	165	170-180
Silo Temperature (°C)	140	140	147	147
Silo Status	Off-loading	Off-loading	Stagnant	Stagnant
Production Rate (tons/h)	178	180	180	150
Virgin Binder	PG 58-28	PG 52-34	PG 58-28	PG 52-34
AC Content (%)	5.0	4.7	5	4.7
RAP content (%)	15	30	20	40

3. Results and Discussion

As it was mentioned in the Introduction section and reported elsewhere [11], the hypothesis behind the plant trial was to verify impact of silo storage on further promoting progress of diffusion by keeping the manufactured asphalt at higher temperatures. Earlier reports demonstrated that resistance to rutting and moisture susceptibility improved with silo storage duration up to 12 hours [11,12]. Figure 3 summarizes the fatigue data for the four examined set of samples. A few trends are observed in the Figure 3. ANOVA analysis of the collected data suggests that at lower strain rates, specifically 250 µm/m, the impact of silo storage and thus diffusion progress is not very obvious in the four sample sets. At 250 µm/m, standard deviations of measured number of cycles to failure exhibit a large overlap at different storage times. However, as the strain rate increases, influence of silo storage and diffusion progress becomes more resolved. A statistically significant difference is observed between 0 and 12 hours of silo storage at 500 µm/m strain rate (insets of Fig. 3); the only exception was the case of base course (HL-8) from Plant 2, where unusual binder chemistry was identified as a possible source of expedited aging [11]. Considering this statistical significance at higher strain rates, more confidence is established to infer that the 12 hour storage resulted in a better fatigue performance of asphalt material compared to 0 hours. In other words, further progress of diffusion appears to improve both binder cohesion (and adhesion to the aggregates [12]) so that resistance to fatigue had improved. However, not much change was noted between 12 and 24 hours of storage as the data for Plant 2 suggests.

Figure 4 and 5 present the summary of low temperature performance assessment of the collected asphalt samples as a function of silo storage measured by TSRST. Figure 4 demonstrates that fracture temperature decreased (improved) with increase in the silo storage period, where diffusion progressed towards completion. There are trends in the evolution of fracture temperatures between the asphalt samples from the two Plants. First, Fig. 4 illustrates that the fracture temperatures of samples from Plant 1 for 0 and 8 hours of storage are lower than their counterparts in Plant 2. This could be due to higher RAP content of asphalts from Plant 2, resulting in more heterogeneous texture that requires more energy and time to homogenize. Second, the rate of evolution in fracture temperature is more drastic in asphalt samples from Plant 2. This difference in rate of evolution could be related to differences in manufacturing parameters of the two Plants and operating conditions of their silos (see Table 2) [11]. Asphalt Plant 2 had a higher manufacturing temperature and slower production rate which helped providing higher initial driving force for the diffusion between RAP and virgin binders to take place. In addition, Plant 2 silos were stagnant, unlike the continuous off-loading status in Plant 1. This stagnancy help the silo to better maintain the temperature and further facilitate the progress of diffusion towards completion. The enhanced progress of diffusion could be inferred from the apparent lower fracture temperature of both base and surfaces courses from Plant 2 at 12 hours of silo storage. The third trend (in the case of Plant 2) is that after 12 hours of storage the fracture temperature has deteriorated; this negative impact could be due to aging of binder at higher temperatures of silo. This pattern is consistent with the observations noted on the dynamic moduli of these samples (see Fig 2a) as well as the performance grading of the extracted binders [11].

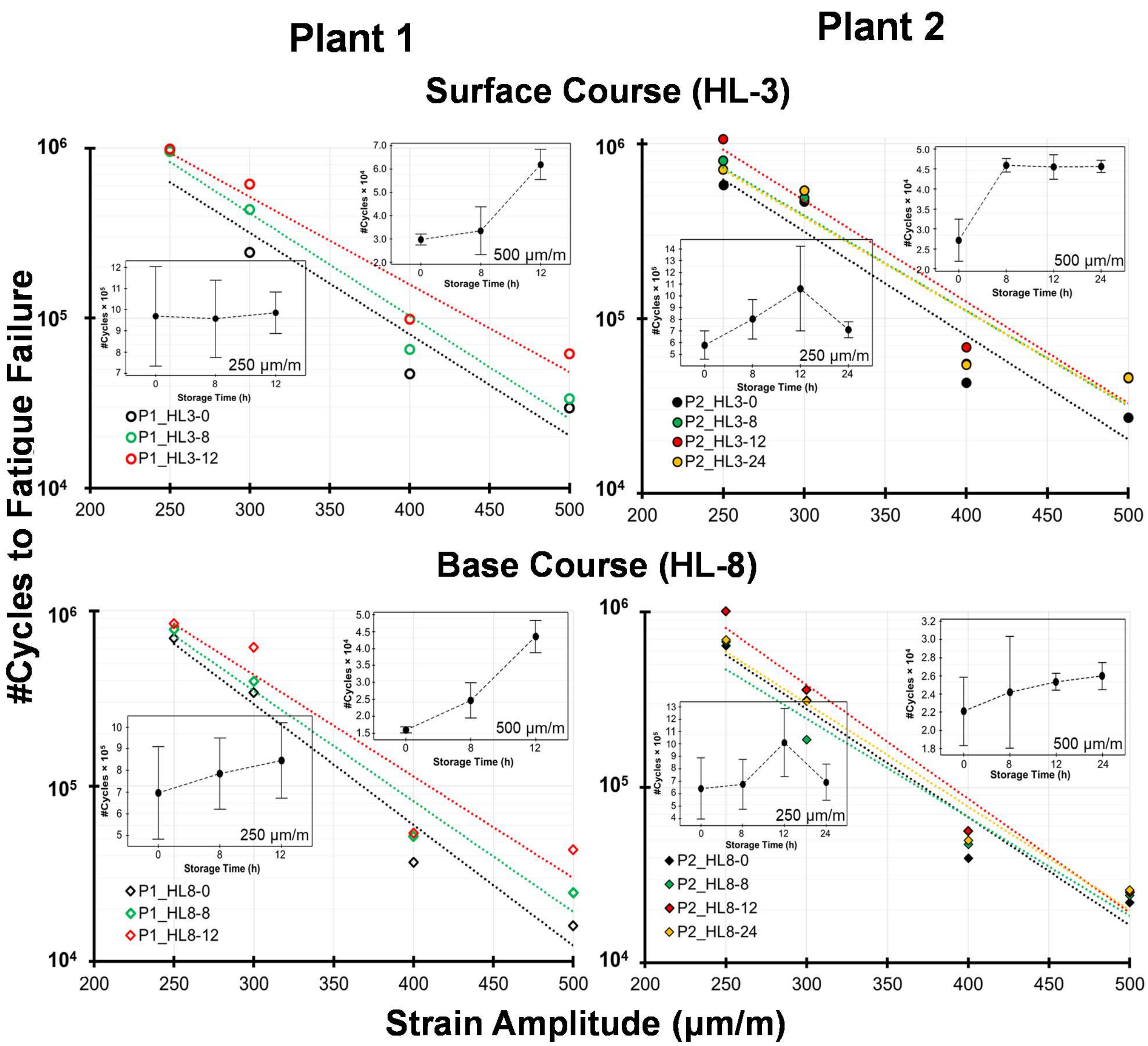

Figure 3: Fatigue resistance of collected asphalt samples as a function of strain amplitude. Summary of ANOVA analysis at 250 and 500 µm/m are presented in the inset panels, representing #cycles to fatigue failure as a function of silo storage (0, 8 and 12 hours for Plant 1; 0, 8, 12 and 24 hours for Plant 2). The dashed line in each inset connects average values. Plant 1 (P1) and 2 (P2) data are presented with open and closed symbols, respectively. Data associated with surface and base mix samples are presented with circles and diamonds, respectively. Data corresponding to 0, 8, 12 and 24 hours of silo storage are presented in black, green, red and orange colours, respectively.

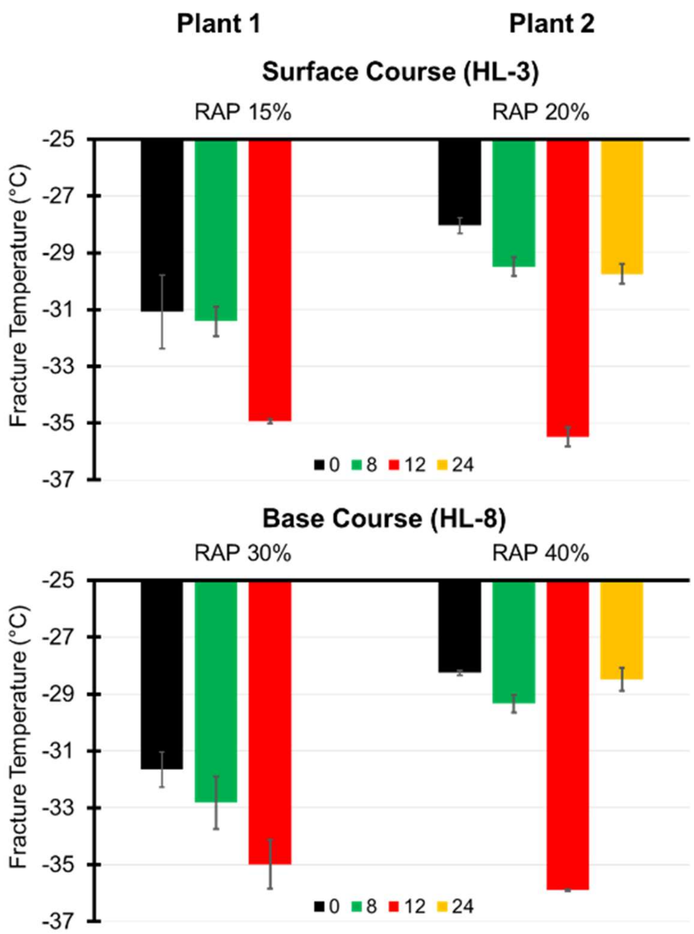

Figure 4: Fracture temperature of asphalt samples collected at different silo storage time from Plants 1 and 2. Top and bottom panels present the surface and base courses, respectively. Data on 0, 8, 12 and 24 hours of storage are presented with black, green, red and orange, respectively.

Figure 5 presents the fracture stress of the collected asphalt samples. Due to high variability in measured stresses, no firm conclusions could be drawn on the impact of silo storage on measured stress levels. However, it is noted that the average of fracture stresses in samples from Plant 2 are higher than those in Plant 1. This could be due to better progress of diffusion in Plant 2 samples. Improved diffusion could have further dissolved the interfaces between RAP and virgin binders, thus minimizing stress build-up areas in the mix. As mentioned earlier, a better binder cohesion is probably achieved in the binder texture of Plant 2 asphalt samples.

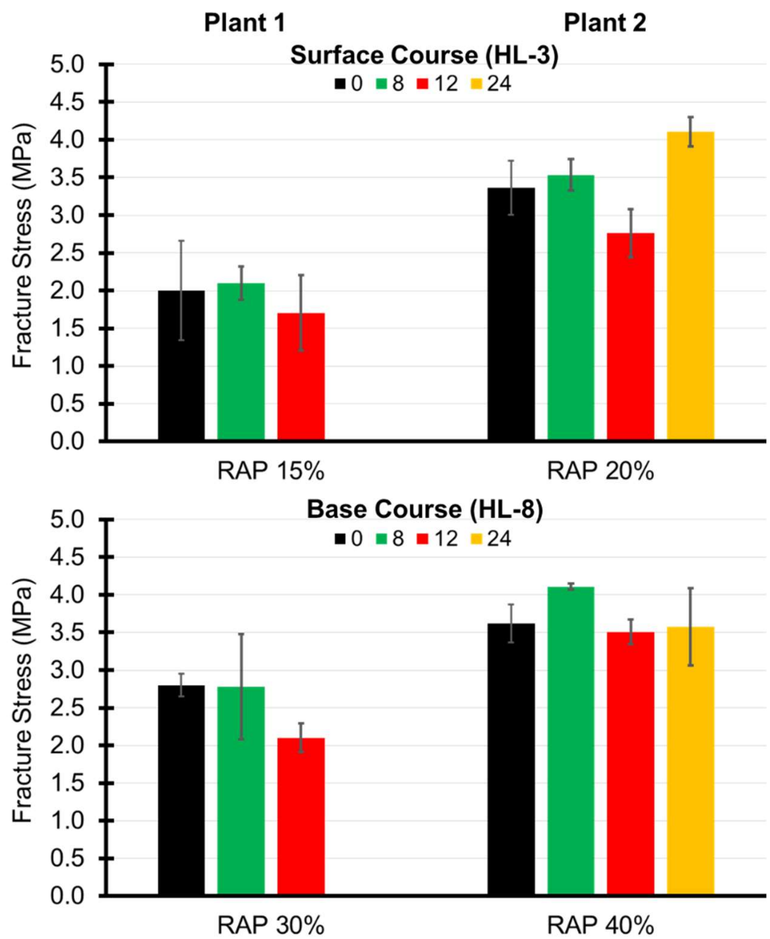

Figure 5: Fracture stress of asphalt samples collected at different silo storage times from Plants 1 and 2. Data on 0, 8, 12 and 24 hours of storage are presented with black, green, red and orange, respectively.

4. Conclusion

A plant trial was executed to investigate the impact of silo storage on the diffusion between RAP and virgin binders in a RAP-containing asphalt. Results from a variety of asphalt performance tests confirmed the progression of binder diffusion in the collected samples. As silo storage time increased, improvements were observed in resistance to rutting and moisture susceptibility [12], fatigue cracking and low temperature cracking, to a point where significant oxidative aging was observed (24 hours of storage) [12]. However, data collected from various performance tests also confirm that there is an optimum storage time during which diffusion is the dominant process. This optimum storage duration was found to be 12 hours for the samples and manufacturing conditions examined in this study. These field results correspond well with earlier work on the diffusion of laboratory-scale asphalt samples [10]. This work further highlighted that, as binder diffusion progresses towards completion, the resulting asphalt performed better under higher strain conditions. It was also observed that a lack of blending due to incomplete diffusion between RAP and virgin binder can have a significant negative impact on the low temperature cracking of the newly manufactured asphalt. It is also emphasized that the manufacturing and storage conditions can also have major influence on the progress of diffusion. Higher temperatures typically promote diffusion; although the duration of higher temperature application and binder chemistry should be considered to avoid expedited aging due to artificial softening agents [11].

Data from recent works suggest that the properties of RAP-containing asphalt evolve over time, as diffusion between binders progresses [9-12]. Therefore, engineers should consider the impact of diffusion progress on the fraction of RAP being re-activated as part of effective binder in the newly manufactured asphalt. Otherwise, the produced asphalt may not meet the intended designed performance parameters. The results of these studies also demonstrate that multiple performance parameters of asphalt, including resistance to rutting, fatigue and low temperature cracking, can be simultaneously optimized by progressing diffusion towards completion and without changing the binder to softer grades.

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