EFFECT OF SILO STORAGE TIME ON THE CHARACTERISTICS OF VIRGIN AND RAP ASPHALT MIXTURES

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ABSTRACT

Many hot mix asphalt plants store material in heated silos before they are ready to be transported to construction sites. The time that material is stored in the silo is not controlled and is widely variable, depending on several factors. As the material is exposed to elevated temperatures, short-term aging of the binder may occur. Another important consideration is the interaction between reclaimed asphalt pavement (RAP) and virgin binders, as blending or diffusion could occur between the binders. In this study, a virgin and 25% RAP mixture were sampled at incremental silo storage times up to 10 hours. Characterization testing included performance grading, rheological indices, Glover-Rowe parameter evaluation, and Rolling Thin-Film Oven (RTFO) aging on the binders; and complex modulus, simplified viscoelastic continuum damage model (S-VECD) for fatigue, and thermal stress restrained specimen testing of the mixtures. Simulations using the layered viscoelastic critical distresses pavement analysis to predict fatigue behavior from the S-VECD model, is utilized to show the potential effects silo storage time has on pavement life. Results from all tests indicated that mixtures age with an increase in silo storage time. RAP materials experienced a greater effect, which may be a function of the air void content or indication of blending/diffusion in the silo. RTFO aging showed that current laboratory conditioning methods do not necessarily simulate asphalt plant production. It was apparent that production parameters, such as silo storage time, have a significant impact on mixture performance.

Keywords: Silo storage, asphalt mixtures, reclaimed asphalt pavement, short-term aging, cracking

INTRODUCTION

At many hot mix asphalt (HMA) plants, the loose asphalt mixture is stored in silos before trucks are ready to transport it to the construction site. The asphalt materials are stored at or near mixing temperature and some silos are heated to help maintain workability of the mixture. As the material is exposed to elevated temperatures, additional aging of the asphalt binder may occur. Aging causes the asphalt binder to become stiffer and more brittle, which will affect its service performance. The length of storage time in the silos could therefore have a significant effect. Storage time is typically not controlled or recorded and can vary widely based on construction region, silo type, mix size, and truck schedules. It is important to gain a better understanding of the impact of mixture production parameters on the performance of the mixture in the field.

The use of reclaimed asphalt pavement (RAP) in mixtures is common practice due to its economic and environmental benefits. While most agencies are comfortable using 15-20% of RAP in mixtures, there is a desire to use higher percentages. Sabouri et al. (*1*) showed that higher percentages of RAP were tolerable with increased asphalt layer thicknesses. It was demonstrated that fatigue resistance deteriorated in all cases where rutting resistance improved, but a balance could be obtained that produced an economical and well-performing mixture. Daniel et al. (*2*) showed that the stiffening of RAP mixtures occurs at a much slower rate than virgin mixtures, likely because of the presence of already-aged binder. The fatigue performance showed widely varying results under stress and strain-controlled evaluations. This highlights the importance of integrating mixture and pavement design, as mixtures can perform differently depending on their location within a pavement structure.

It is important to understand the effect of silo storage on both virgin mixtures and those including RAP. At elevated temperatures, the interaction of the RAP and virgin binders needs to be considered. Several recent studies have attempted to characterize the interaction that occurs between virgin and RAP binders, which is a complex chemical process. Huang et al. (*3*) suggests that mechanical blending affects only a small portion of the aged RAP binder and instead forms a stiffer composite layer system. The two major processes that occur in the virgin-RAP binder interaction are mixing, or contact between the binders, and blending/diffusion after contact (*4*). The key mechanism is the diffusion process. Kriz et al. (*4*) conducted dynamic shear rheometer (DSR) simulations to understand the diffusion process and degree of blending in thick and thin binder layers. It was concluded that the diffusion process is completed (100% blending) within minutes of mixing for thinner binder layers, and only about 90% degree of blending completed after typical production stages for thicker binder layers. The degree of blending was analyzed using typical mixing, storage, transportation, and placement times. In this study, it is interesting to note that the assumed storage time was 60 minutes and that the majority of blending in thick binder layers occurred during the storage stage. As the storage time continues past one hour, it is hypothesized that the diffusion or blending could continue between the binders and that this phenomenon may have an appreciable impact on mixture performance. The storage time could have an effect on the short-term aging of the overall mixture and/or an effect on the blending between RAP and virgin binders.

Zhao et al. (*5*) also conducted research into blending between RAP and virgin binder, questioning the full mobilization assumption. The binder mobilization rate was found to be close to 100% for 10-20% RAP mixtures and approximately 75% for 25% RAP, which suggests that the 25% RAP binder could potentially mobilize further during longer silo storage times. In the study by Zhao et al., it was concluded that HMA containing higher amounts of RAP may affect the cracking resistance due not only to increased stiffness from the RAP materials, but also from an under-asphalted mixture or heterogeneous blending from the lower mobilization rate. An under-asphalted mixture could result in a pavement structure more prone to cracking (*6*).

Other studies utilized Bonaquist's approach of comparing the overlap of measured dynamic modulus master curves with those predicted from recovered binder testing to assess binder blending (*7, 8*). The main conclusions were that plant production practices, which are commonly ignored in their relation to mixture performance, will have an impact on mixture performance, and different contractors achieved various degrees of blending, including poor blending. Rad et al. (*9*) also suggests that the temperature of conditioning be controlled in the production stage to achieve full blending of the binders. It is also important to note that different virgin and RAP binders will cause different interactions among each other and varying stiffening effects can occur (*10*).

Another production parameter in the same family as silo storage time is haul distance or haul time. This parameter is also not typically documented or strictly limited, and additional short-term aging or embrittlement could occur during this time that the mix is kept at elevated temperatures. Howard et al. (*11*) investigated haul time effects on HMA and also explored using warm-mix technologies to facilitate long haul distances. They found no significant changes in binder properties for haul distances up to 8 hours. It appeared that continuous binder grades became warmer with longer haul times, but these increases were considered comparable with normal HMA production and placement.

Production parameters, such as silo storage time and haul time, among others, are important to consider. Mix designers do not have control over these parameters, and the potential effects on mixture performance are not taken into account. The objective of this paper is to gain a better understanding of the effect of silo storage time, a key production parameter, as it relates to asphalt binder and mixture performance. Silo storage time is evaluated for virgin and RAP mixtures to measure the short-term aging effect and determine if blending/diffusion occurs in the silo with the RAP mixture.

MATERIALS AND METHODS

Mixture Information

A virgin mixture and 25% RAP mixture with 12.5 mm nominal maximum aggregate size were evaluated in this study at incremental silo storage times. The virgin mixture used a PG 64-22 binder and included material sampled after silo storage times of 0, 2.5, 5, and 7.5 hours after production began. The 25% (by total mass) RAP mixture used a PG 64-22 binder and was sampled at 0, 2.5, 5, 7.5, and 10 hours. The RAP mixture was used for an active paving job and the material was sampled at the different times during production; therefore, the reported storage times are approximate. Specimens were produced by immediately compacting loose mix sampled from the plant without reheating the material. The target asphalt content of the mixtures was 5.4%. Mixture discharge temperatures were approximately 175°C, which is not unusual during shoulder seasons in the Northeast.

Binder Testing and Analysis

The asphalt binders were extracted and recovered from loose mix sampled from the asphalt plant in accordance with AASHTO T164 using tri-chlorethylene as the solvent. After the recovery process, the asphalt binder was tested for the respective high temperature PG grade, in accordance with AASHTO M320. The recovered asphalt binder was treated as an RTFO-aged

(Rolling Thin Film Oven) asphalt binder. Virgin binder was also conditioned in the RTFO at five conditioning times (45, 85, 135, 170, and 300 minutes) to evaluate how well RTFO aging simulated the plant production and storage time associated with the virgin mixture in this study.

Master stiffness curves for the recovered binders were generated using the dynamic shear rheometer results at varying temperatures (95, 80, 70, 60, 45, 35, 25, 15, 5, -5 and -15°C) and loading frequencies within a strain range of 0.005 to 0.02. Data quality checks and analysis were conducted using the software package RHEA^{TM}.

Anderson et al. (*12*) identified the difference between the bending beam rheometer (BBR) stiffness (S) and m-slope critical low temperature as a means of indexing the non-load associated cracking potential of asphalt binders. Asphalt binders that exhibit a greater difference between the S and m-slope low temperature have been recognized as being prone to non-load associated cracking. The parameter, defined as ΔT_{cr}, is shown in Equation 1:

$$\Delta T_{cr} = T_{cr(Stiffness)} - T_{cr(m-slope)} \tag{1}$$

where,

ΔT_{cr} = Difference in critical low temperature PG grade
$T_{cr\ (Stiffness)}$ = Critical low temperature grade predicted using the BBR Stiffness (S)
$T_{cr\ (m\text{-}slope)}$ = Critical low temperature grade predicted using the BBR m-slope

In Equation 1, as the ΔT_{cr} decreases, the asphalt binder is considered to be more prone to non-load associated cracking. Initially, Anderson et al. (*12*) set a limit of $\Delta T_{cr} \leq -2.5°C$ for when there is an identifiable risk of cracking and preventative action should be considered. Rowe (*13*) recommended that at a $\Delta T_{cr} \leq -5°C$ immediate remediation should be considered.

Glover et al. (*14*) proposed the rheological parameter, G'/(η'/ G'), as an indicator of ductility based on a derivation of a mechanical analog to represent the ductility test consisting of springs and dashpots. Rowe (*13*) re-defined the Glover parameter in terms of |G*| and δ based on analysis of a Black Space diagram and suggested use of the parameter $|G^*|\cdot(\cos\delta)^2/\sin\delta$, termed the Glover-Rowe (G-R) parameter, in place of the original Glover parameter.

Rowe proposed measuring the G-R parameter based on construction of a master curve from frequency sweep testing at 5°C, 15°C, and 25°C in the DSR and interpolating to find the value of G-R at 15°C and 0.005 rad/sec to assess binder brittleness (*15*). A higher G-R value indicates increased brittleness. It has been proposed that a G-R parameter value of 180 kPa corresponds to damage onset whereas a G-R value exceeding 450 kPa corresponds to significant cracking based on a study relating binder ductility to field block cracking and surface raveling by Anderson et al. (*12*). The test results generated during the master stiffness curve analysis was utilized to determine the G-R parameter.

The Christensen-Anderson-Marasteanu Model (CAM) master curve parameters (ω_o, R, and T_d) have specific physical significance. As crossover frequency, ω_o, increases, the hardness of the binder decreases, which indicates lower degrees of aging. The rheological index, R-value, is defined as the difference between the log of the glassy modulus and the log of the dynamic modulus at the crossover frequency. As R-value increases, the master curve becomes flatter indicating a more gradual transition from elastic behavior to steady-state flow. Normally, R-value is higher for oxidized/aged asphalt (*16*). Mogawer et al. (*17*) demonstrated that by plotting the crossover frequency vs. R-value, the relative change in aging, or rejuvenating, can be tracked.

Therefore, the use of the crossover frequency – R-value space can allow for an evaluation of aging occurring due to silo storage time.

Mixture Testing and Analysis

Dynamic Modulus

The Asphalt Mixture Performance Tester (AMPT) was used to perform dynamic modulus testing in unconfined uniaxial compression. Three replicate specimens were tested for each condition. These specimens were tested at target temperatures of 4.4°C, 21.1°C, and 37.8°C and standard frequencies of 25, 10, 5, 1, 0.5, and 0.1 Hz. The dimensions of the tested specimens were 100 mm in diameter by 150 mm tall with a 70 mm gauge length. Load levels were determined so that the resulting strain amplitudes were between 35 and 75 microstrain. Data was obtained from the final six cycles of each loading series.

The average dynamic modulus isotherms were shifted to a generalized logistic function (Equation 2) to construct the master curve at a reference temperature of 21.1°C. The time-temperature shift factors were allowed to free-shift, meaning no underlying shape of the shift factor versus temperature curve was assumed.

$$\log|E^*| = \delta + \frac{\alpha}{[1+\lambda(\exp^{\beta+\gamma(\log\omega_\gamma)})]^{1/\lambda}} \tag{2}$$

where,

$|E^*|$ = Dynamic Modulus
ω_r = reduced frequency
$\alpha, \beta, \gamma, \delta, \lambda$ = fitting parameters

S-VECD Fatigue Cracking

Fatigue testing was performed in uniaxial tension on the AMPT. Specimens were cut to dimensions of 100 mm in diameter by 130 mm tall and glued to end platens that were fixed in the AMPT. Air void content, determined by AASHTO T166, was 7.0±0.5%. Testing was performed at 20.0°C and 10 Hz. The virgin mixtures were tested with four replicate specimens (three for 7.5 hours) at varying microstrain levels ranging from 300 to 450 microstrain to cover a range of numbers of cycles to failure. Fatigue testing was not performed on the 25% RAP mixtures due to a lack of available specimens.

Analysis on the fatigue results was performed using the simplified viscoelastic continuum damage (S-VECD) model developed by Underwood et al. (*18*). S-VECD is a mode-of-loading independent, mechanistic model that allows the prediction of fatigue cracking performance under various stress/strain amplitudes at different temperatures from only a few tests. The S-VECD model is composed of two material properties, the damage characteristic curve and the energy-based failure criterion. The damage characteristic curve defines how fatigue damage evolves in a mixture and is developed by plotting two calculated parameters at each loading cycle, the secant pseudo-stiffness (C) and the damage parameter (S). The exponential form shown in Equation 3 was used to fit the damage characteristic curves.

$$C = e^{aS^b} \tag{3}$$

where,

a, b = Damage model coefficients

The S-VECD fatigue failure criterion, called the G^R method, involves the released pseudo strain energy. This concept focuses on the dissipated energy that is related to energy release from damage evolution only and is fully compatible and predictable using the S-VECD model. The G^R characterizes the overall rate of damage accumulation during fatigue testing. A characteristic relationship, which is found to exist in both RAP and non-RAP mixtures, can be derived between the rate of change of the averaged released pseudo strain energy during fatigue testing (G^R) and the final fatigue life or number of cycles to failure (N_f). The equation to calculate G^R is as follows:

$$G^R = \frac{\frac{1}{2}\int_0^{N_f} \left(\varepsilon^R{}_{0,ta}\right)_i^2 (1-F_i)}{N_f{}^2} \tag{4}$$

where,

$(\varepsilon^R{}_{0,ta})_i$ = pseudo strain amplitude at cycle i

F_i = pseudo stiffness at cycle i

Pavement Fatigue Life Evaluation

The layered viscoelastic critical distresses (LVECD) program was used to predict the long-term fatigue performance of pavements under traffic loading. Eslaminia et al. (*19*) developed the layered viscoelastic structural program with the material level continuum damage model to calculate the required stresses and strains for the fatigue behavior prediction using three-dimensional viscoelastic calculations under moving loads. The LVECD simulations were performed for both thin and thick pavement structures using the required parameters including design time, structural layout, traffic, and climate. The thin pavement structure had an asphalt layer of 100 mm and aggregate base of 200 mm; the thick pavement had an asphalt layer of 300 mm with the same base. The aggregate base and the subgrade were modeled using the linear elastic properties with the modulus values of 350 MPa and 100 MPa, respectively.

Two climates were evaluated: Boston, Massachusetts and Raleigh, North Carolina using pavement temperatures obtained from the Enhanced Integrated Climate Model (EICM). Also, a single tire with the standard loading of 80 kN at the center of pavement was utilized. The average annual daily truck traffic (AADTT) was assumed to be 2,000.

For fatigue cracking resistance evaluation, LVECD calculates the damage growth and the damage factor based on Miner's law (Equation 5). If the damage factor is equal to zero, the element does not experience any damage, while a damage factor of one indicates total failure of the element.

$$\sum_{i=1}^{T} D_i = \frac{N_i}{N_{fi}} \tag{5}$$

where,

D = damage

T = total number of periods

N_i = traffic for period i

N_{fi} = allowable failure repetitions under the conditions that prevail in period i

TSRST

In order to assess the low temperature cracking suscpetibility, each mixture was tested in the Thermal Stress Restrained Specimen Test (TSRST) device in accordance with AASHTO TP10-93. TSRST testing was performed on loose mixture that was reheated in the laboratory. Three replicate gyratory specimens 150 mm in diameter by 185 mm tall were fabricated for the virgin and RAP mixtures. Specimens were then cored and cut to 54 mm in diameter by 160 mm tall. The air voids of the final cut specimens were 6.5±1.0%.

RESULTS AND DISCUSSION

Binder Testing

Performance Grading

The general trend in PG grade results (Table 1) shows an increase in high temperature PG grade of 0.39°C/hr and 0.53°C/hr of silo storage time for the binder extracted and recovered from the virgin and RAP mixes, respectively. An increase in intermediate temperature PG grade of 0.20°C/hr was observed for the virgin mix while the RAP mix had no measurable trend. The low temperature PG grade increased 0.14°C/hr and 0.21°C/hr for virgin and RAP mixtures, respectively, with the low temperature grade being m-slope dependent for both. The results also show a general trend of the BBR ΔT_{cr} remaining relatively constant and then negatively increasing (i.e. greater difference between S and m-slope critical low temperature) after 5 hours of storage time. The recovered binder from the virgin mixture consistently has a smaller ΔT_{cr} than the 25% RAP mixture, indicating that the virgin asphalt binder has undergone less aging.

TABLE 1 Performance grade results for extracted/recovered asphalt binders.

Virgin Mix										
Silo Storage Time (Hrs)	Performance Grade (^{o}C)					Rheological Indices				
	High Temp (RTFO)	Intermediate Temp	Low Temperature			R-value	Crossover Fequency	Glover-Rowe Analysis (15° C, 0.005 rad/s)		
			Stiffness (S)	m-slope	BBR ΔT_{crit}			G* (Pa)	δ (degrees)	G-R (kPa)
0 Hrs	72.1	22.7	-25.1	-24.8	-0.3	1.732	149.1	8.78E+04	71.1	9.8
2.5 Hrs	73.8	23.3	-25.0	-24.6	-0.4	1.808	123.4	9.84E+04	69.8	12.5
5 Hrs	73.4	24.1	-24.9	-24.7	-0.2	1.784	105.5	1.22E+05	69.5	16.0
7.5 Hrs	75.5	24.1	-25.1	-23.6	-1.5	1.866	101.2	1.43E+05	68.9	19.8

25% RAP Mix										
Silo Storage Time (Hrs)	Performance Grade (^{o}C)					Rheological Indices				
	High Temp (RTFO)	Intermediate Temp	Low Temperature			R-value	Crossover Fequency	Glover-Rowe Analysis (15° C, 0.005 rad/s)		
			Stiffness (S)	m-slope	BBR ΔT_{crit}			G* (Pa)	δ (degrees)	G-R (kPa)
0 Hrs	73.9	24.6	-25.9	-24.9	-1.0	1.977	100.2	1.83E+05	66.8	31.0
2.5 Hrs	76.2	22.6	-25.4	-22.8	-2.6	2.002	74.2	2.20E+05	65.8	40.7
5 Hrs	77.9	24.5	-24.9	-23.4	-1.5	2.094	43.5	3.19E+05	63.6	70.2
7.5 Hrs	77.3	23.6	-25.2	-22.7	-2.5	2.070	52.6	2.77E+05	64.3	58.0
10 Hrs	80.0	24.1	-24.8	-22.3	-2.5	2.150	29.0	3.78E+05	62.2	93.1

Glover-Rowe Parameter and Rheological Indices

The Glover-Rowe Parameter analysis, shown in Figure 1(a), illustrates that as silo storage time increases, the extracted asphalt binder becomes more aged and migrates to areas where potential, non-load associated cracking is a concern. The results also show that the 25% RAP mixture initiates and moves closer to the threshold values than the asphalt binder from the virgin mixture. The measured crossover frequency and R-value shown in Figure 1(b) clearly indicates that a change in the CAM rheological indices occurs due to longer silo storage times, indicating that aging is occurring over time. The binder extracted from the RAP mixture shows larger changes than the extracted virgin binder.

The results of the RTFO aging for various times are also shown in Figure 1. These results indicate that using the specified time of 85 minutes in the RTFO does not simulate the aging that occurred during plant production and silo storage for the virgin mixtures. In fact, it can be seen that RTFO conditioning does not show similar stiffness (G* and δ) and CAM rheological indices to 0 hours of silo storage time until approximately 170 minutes, which is twice the amount specified in AASHTO T240. This clearly indicates that current laboratory conditioning methods do not necessarily simulate asphalt plant production. The large differences in this case are likely a result of the relatively high (175°C) production temperatures that would have aged the asphalt binder, especially under extended silo storage times.

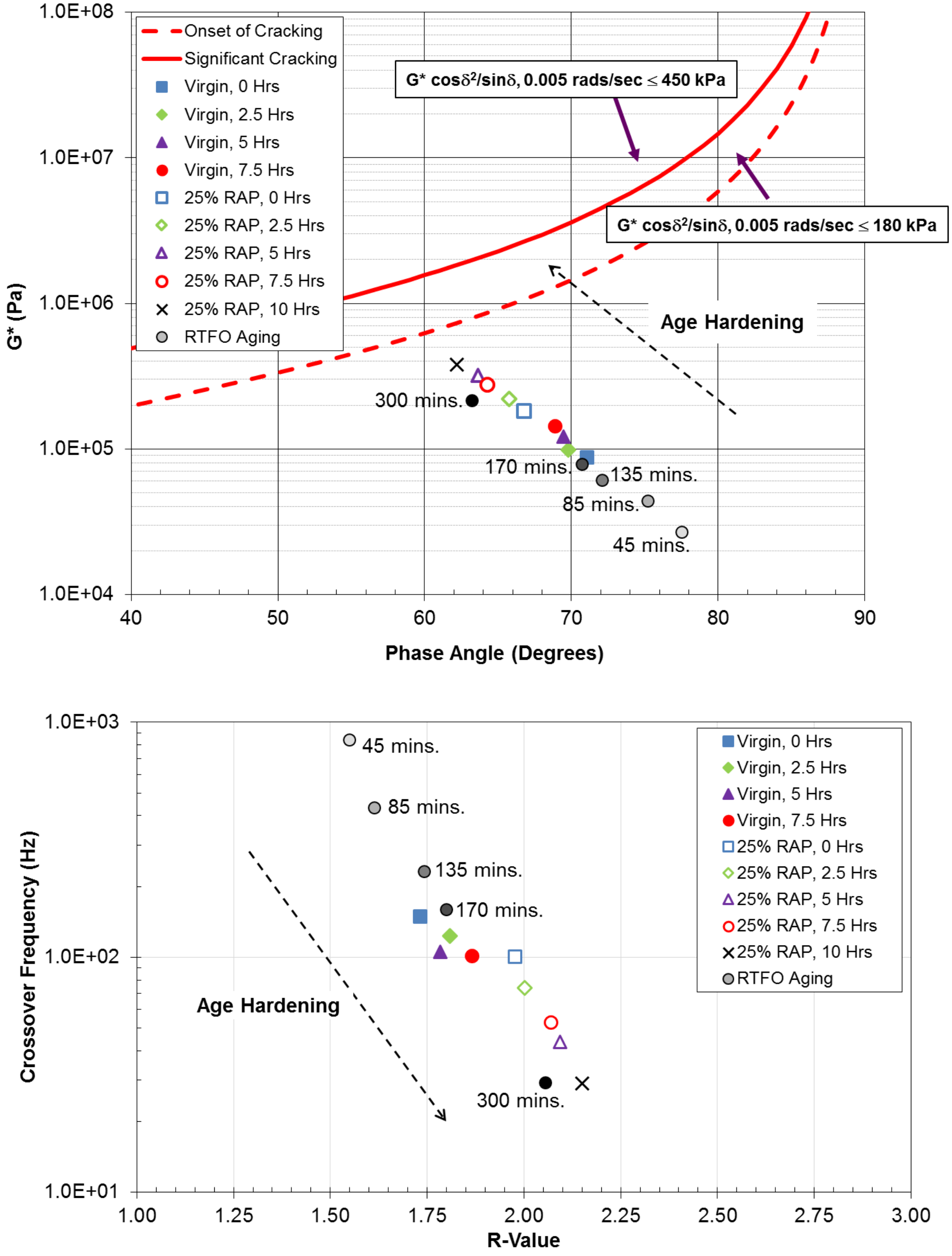


FIGURE 1 Effect of silo storage time and RTFO conditioning on retained asphalt binder: a) Black Space plot and b) Crossover frequency – R-value space.

Mixture Testing

Dynamic Modulus

Dynamic modulus master curves were constructed for varying silo storage times as shown in Figure 2(a) and (b) for the virgin and 25% RAP mixtures, respectively. Average air void content of the test specimens, determined in accordance with AASHTO T166, is also shown. Each master curve represents the fitted sigmoidal function from the average of three replicate specimens. Both the virgin and RAP mixtures show an increase in dynamic modulus as the mixtures remain in the silo for longer periods. The RAP mixture shows greater increases with storage time than the virgin mixtures.

Figure 2(c) and (d) shows Black Space plots for the virgin and RAP mixtures. In Black Space, lower phase angles at similar modulus values indicate that the mixture may be more prone to cracking. At higher stiffness values, the silo storage time has little effect on the phase angle for both mixtures. At lower stiffness values and near the inflection point, there is a decrease in phase angle with longer storage times. The virgin mixture shows larger differences near the inflection point and the RAP mixture shows larger differences at the low stiffness values.

A statistical analysis was also conducted on the raw data using independent sample t-tests with a confidence interval of 95%. Statistically, the 0, 2.5, and 5 hours mixtures are all similar for the virgin material. The 7.5 hours virgin mixture is statistically different from the 0 and 2.5 hours storage times. The RAP mixture at 7.5 and 10 hours shows significant differences from 0 hours. Phase angle results generally show little statistical significance.

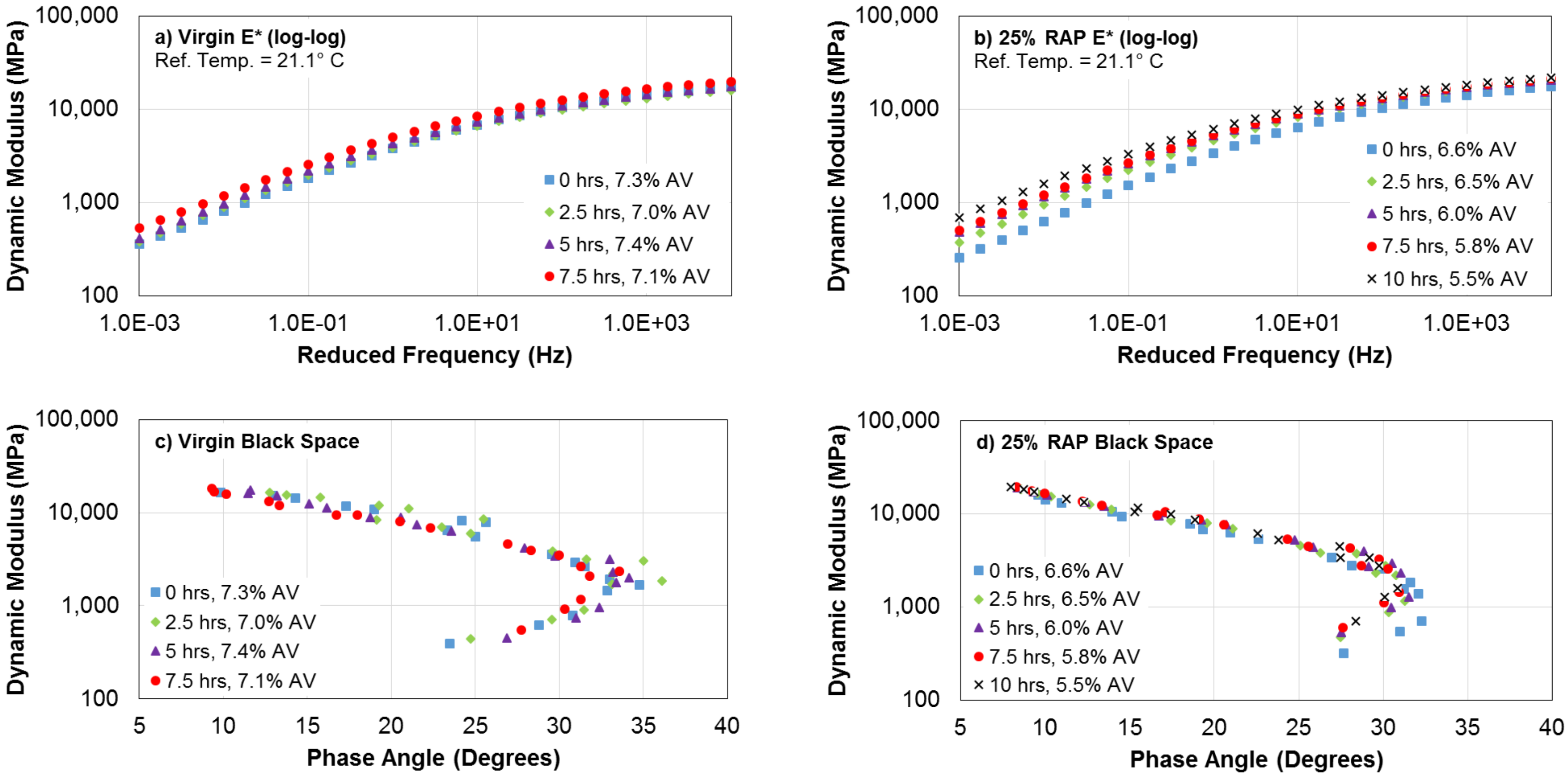
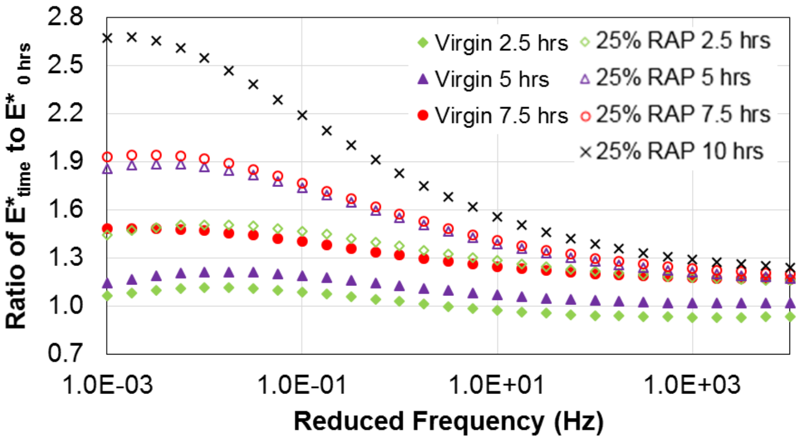


FIGURE 2 Complex modulus testing results: Dynamic modulus master curves (a, b) and Black Space plots (c, d) for virgin and 25% RAP mixtures.

Using the sigmoidal fit master curves, dynamic modulus ratios were calculated comparing each mixture to its respective 0 hours value. Figure 3(a) shows the ratio of dynamic modulus values with respect to the 0 hours master curve across all frequencies. The average of all these values are then summarized in Figure 3(b). The virgin mixtures show a slightly higher ratio in the lower frequencies, and the ratio increases with storage time. On average, the 7.5 hours virgin mixture is approximately 1.3 times stiffer than the 0 hours mixture. Stiffening of the virgin mixtures implies that there is short-term aging or additional binder absorption occurring within the silo, particularly at longer storage times such as 7.5 hours.

The RAP mixtures show higher ratios and larger differences across the frequency range than the virgin mixtures. The RAP mixture at 2.5 hours has a similar ratio to the virgin mixture at 7.5 hours. It is clear that the RAP mixture experiences greater stiffness changes than the virgin mixture as silo storage time increases. This could imply that there is blending or diffusion between RAP and virgin binders in the silo, in addition to short-term aging that is experienced with the virgin mixture. The differences in air void contents could also be contributing to some of the stiffening observed.



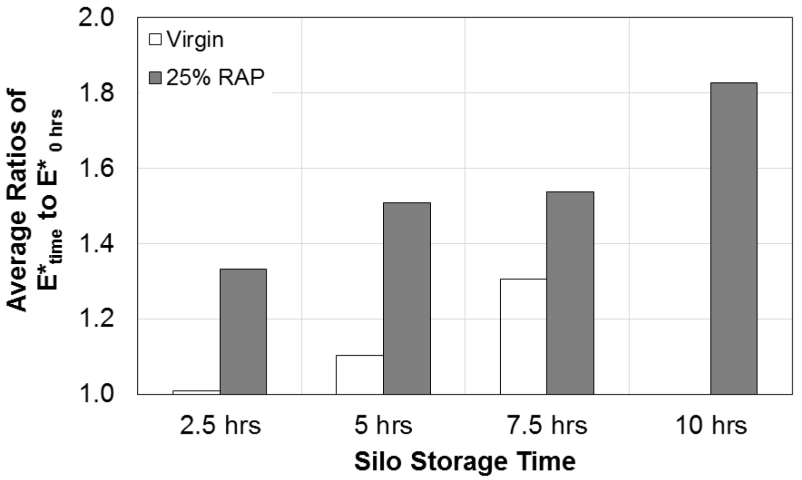


FIGURE 3 Dynamic modulus ratios for a) all frequencies and b) overall average.

S-VECD Fatigue Cracking

The results from the S-VECD testing and analysis on the virgin mixtures are shown in Figure 4. Fatigue data for the 25% RAP mixtures was not available due to lack of materials. For the damage characteristic curves shown in Figure 4 (a), a clear increase in pseudo-stiffness is observed with an increase in silo storage time. Figure 4 (b) shows the relationship between the failure criterion G^R, a parameter that characterizes damage accumulation, and number of cycles to failure, N_f. Typically, mixtures with similar slopes and that are closer to the upper right corner of G^R-N_f space indicate better fatigue resistance. There appears to be little distinction between the mixtures, but it is observed that the 7.5 hours mixture has the largest slope (-1.528) which may indicate more susceptibility to fatigue cracking. It is important to keep in mind that the fatigue performance in the field also depends on the location within the pavement structure and loading conditions.

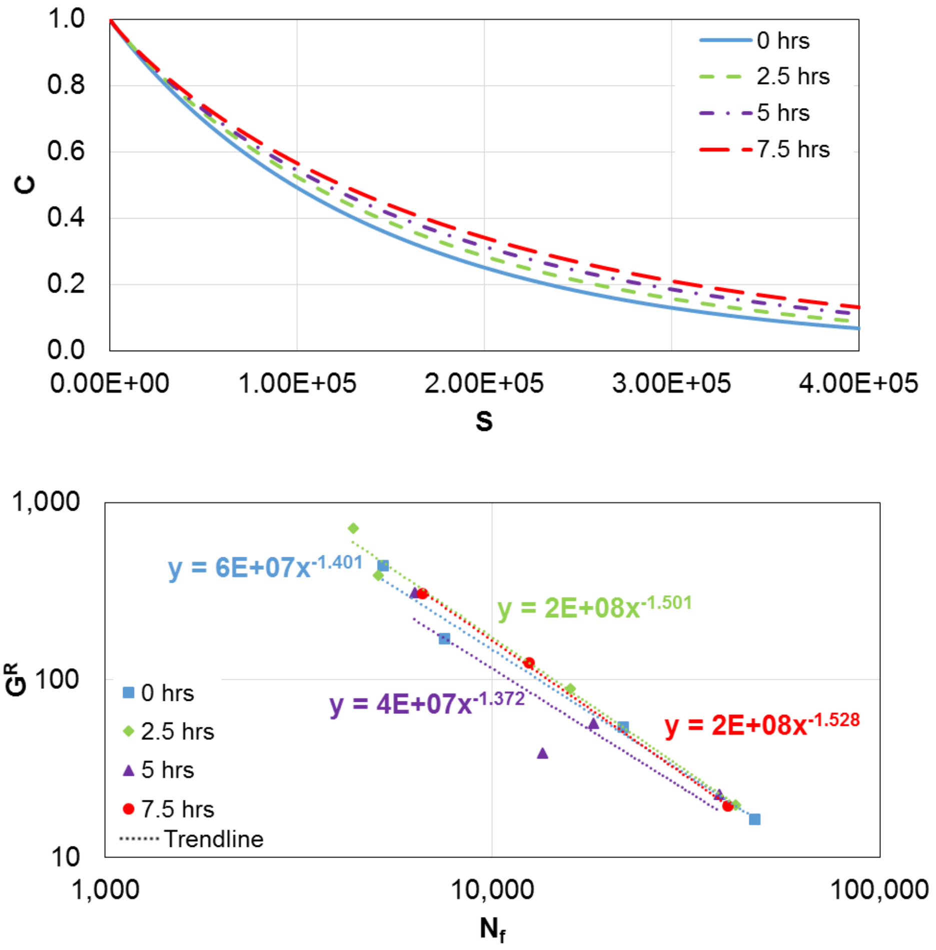


FIGURE 4 S-VECD virgin mixture results: a) damage characteristic curves and b) fatigue failure criterion.

Pavement Fatigue Life Evaluation

Figure 5 presents the results from LVECD analysis for virgin mixtures among two climate conditions for thin and thick pavements. Although LVECD was verified by several researchers (*20, 21*) for various conditions, this software has not been fully calibrated, and the transfer function to convert the predicted damage obtained from LVECD to cracking area in the field is still under development. Therefore, predictions presented in this paper are for relative comparisons; they use the number of elements that experienced more than 20% damage ($N/N_f > 0.20$) to evaluate the relative effects of silo storage time on the pavement performance. Figure 5 shows that an increase in silo storage time causes increases in fatigue damage for both types of pavements and climates, with increases of approximately 40% from 0 to 7.5 hours storage times for the thin pavements and tripling of the damage for thick pavements (although magnitude of damage in thick pavements is much lower).

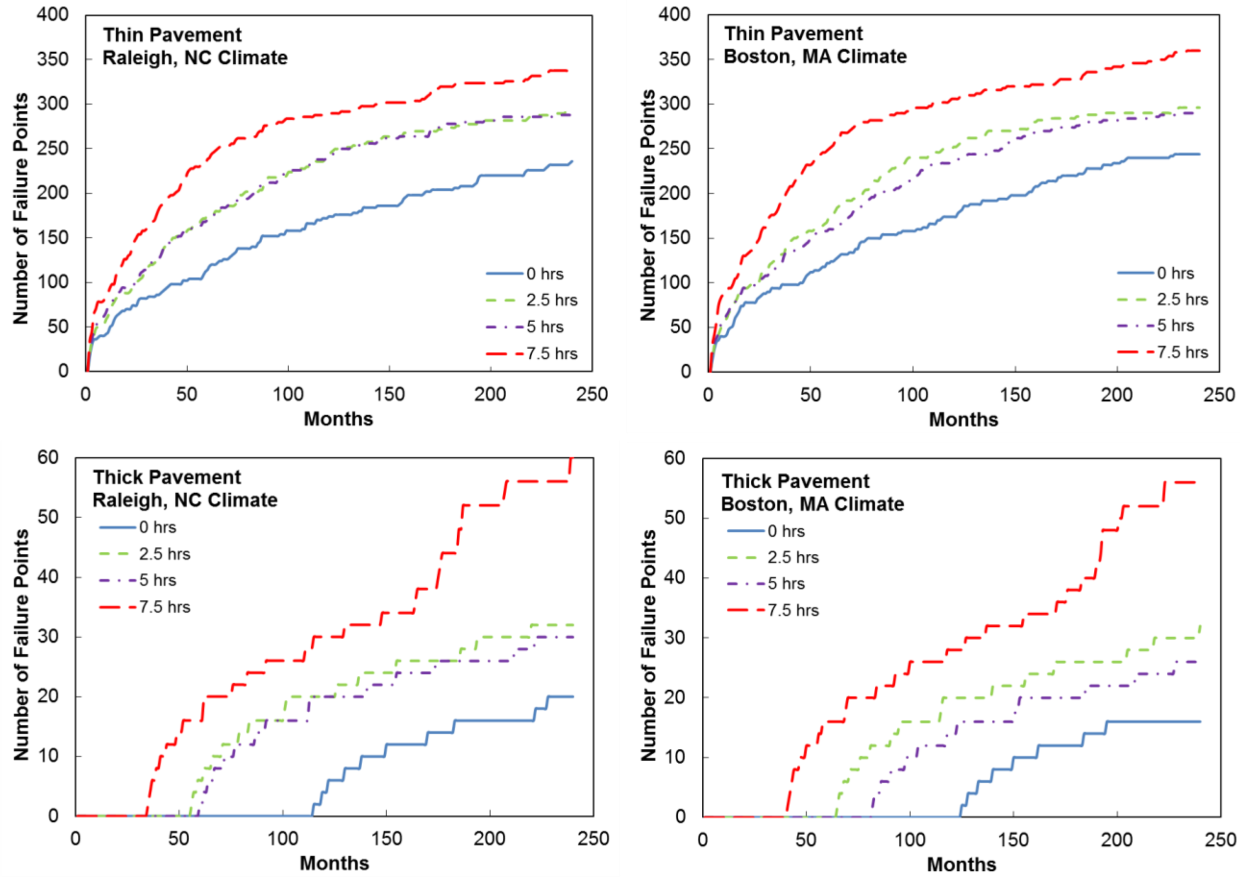


FIGURE 5 Comparison of fatigue resistance for virgin mixture using LVECD thick/thin pavements and two climate conditions.

TSRST

Results from the thermal stress restrained specimen test (TSRST) are shown in Figure 6. Error bars represent one standard deviation from the mean. Warmer critical cracking temperatures from TSRST results can indicate susceptibility to thermal cracking. While most results are within a few degrees of each other, warmer temperatures were observed with statistical significance for the virgin mixture at 5 hours and for the RAP mixture at 7.5 hours.

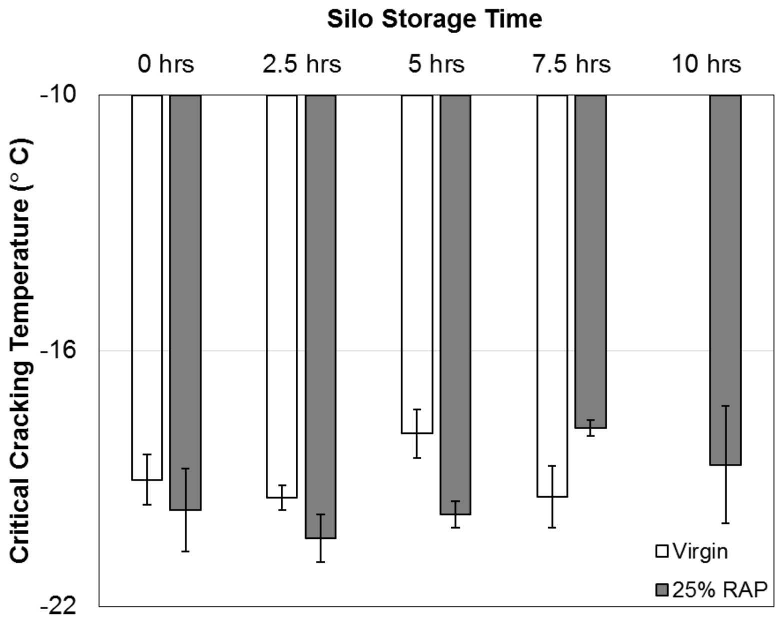


FIGURE 6 Critical cracking temperatures (TSRST) among virgin and RAP mixtures.

SUMMARY AND CONCLUSIONS

In this study, the effect of silo storage time on virgin and RAP mixtures was evaluated. Binders were evaluated using performance grading, rheological indices, and the Glover-Rowe parameter. Mixtures were evaluated with complex modulus, S-VECD fatigue, pavement life evaluation with LVECD, and TSRST. Testing was performed at incremental silo storage times up to 7.5 hours for the virgin mixture and 10 hours for the 25% RAP mixture. The following observations were made based on the results and analysis:

- Binder results showed an increase in both high and low grades with longer silo storage times. Larger increases were observed for the high temperatures and in the RAP mixtures. ΔT_{cr} analysis showed that the binders became more m-controlled as silo storage time increased, particularly after 5 hours, and the RAP mixtures experienced greater increases.
- Recovered binders showed a clear change in rheological indices (CAM model) and in the Glover-Rowe parameter. The binders of the virgin and RAP mixtures experienced trends associated with age hardening as silo storage increased, indicating short-term aging occurring within the silo.
- RTFO aging of the virgin tank binder showed that current laboratory conditioning times do not necessarily simulate asphalt plant production. In this study, it was not until 170 minutes of RTFO conditioning that properties similar to the 0 hours extracted virgin binder were obtained.
- Dynamic modulus testing on the mixtures showed that an increase in silo storage time caused an increase in stiffness for both virgin and RAP mixtures, and this difference was statistically significant at a storage time of 7.5 hours. The RAP material clearly experienced a greater increase in stiffness with storage time than the virgin mixture. This may be a result of the decreasing air void content of the RAP mixture or an indication of blending/diffusion within the silo.

- S-VECD fatigue testing was only performed for the virgin mixtures. An increase in silo storage time resulted in an increase in pseudo-stiffness using the damage characteristic curve. Analysis in the G^R-N_f plot showed little distinction between storage times, but identified 7.5 hours as the most susceptible to fatigue cracking.
- Fatigue life evaluation using the LVECD analysis showed that the 7.5 hours virgin mixture was much more susceptible to fatigue cracking than the 0 hours mixture, while the 2.5 and 5 hours mixtures were similar. This fatigue life evaluation showed similar trends among thin and thick pavements and in two different climates.
- TSRST results indicated warmer critical cracking temperatures for the 5 hours virgin mixture and 7.5 hours RAP mixture, but there were no other statistically significant differences

Results from several tests clearly indicate that the mixtures undergo stiffening, likely due to aging, as silo storage time increases. Both virgin and RAP mixtures experienced changes as a result of being stored in the silo, but the RAP mixture may have experienced larger changes. This indicates that there may be a combination of short-term aging within the silo and a blending or diffusion process occurring with the RAP mixture. The larger changes among the RAP mixture may also have been affected by the decreasing air void content.

The primary objective of this study was to gain a better understanding of the relation between production parameters, particularly silo storage time, and mixture performance. This study indicates that silo storage time can have a significant impact on field performance. RTFO aging also showed that current laboratory conditioning methods do not necessarily simulate plant production. Similar to other production parameters, the length of silo storage time is not typically controlled and depends on several factors. There are many situations whereby plants will need to vary production parameters, such as temperature and silo storage times. It is important to recognize that control of these parameters is currently not practical and existing laboratory conditioning methods may not accurately capture what occurs in the field. However, it is also important to understand the impacts of plant production variations on the properties of the asphalt mixture.

Future work is needed to gain a more complete understanding of production variations and silo storage time in particular. Different PG grades and RAP contents, binder absorption, and other material properties should be explored in future testing. The relation to haul time must also be considered as both processes expose the mixtures to elevated temperatures for relatively long durations. Additional work would be beneficial to further explore the effects of production parameters mixture properties.

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