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Validation of Loose Mix Aging Procedures for Cracking Resistance Evaluation in Balanced Mix Design

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16. Abstract (Limit: 250 words)

This project aimed to validate loose mix aging procedures for cracking resistance evaluation of asphalt mixtures in balanced mix design (BMD) with a broad range of field projects covering various mixture components, pavement ages, and climatic conditions. To that end, a two-phase research approach was followed, with Phase I focusing on a literature review, research gap analysis, and development of Phase II work plan. The literature review topics included development and preliminary field validation of existing loose mix aging procedures; the impact of loose mix aging on asphalt binder and mixture properties; and effects of silo storage, mix hauling, mix reheating, specimen storage, and asphalt weathering on asphalt binder and mixture properties. The literature was then critically reviewed to identify research gaps that might hinder the implementation of loose mix aging for cracking resistance evaluation in BMD, including lab-to-field aging correlation, applicability to asphalt mixtures containing additives, selection of laboratory tests and parameters to assess loose mix aging, and implementation of loose mix aging into BMD. Finally, a Phase II work plan was developed to address the knowledge gaps identified through the literature review and research gap analysis, which include two major tasks: 1) further validation of 95°C loose mix aging maps, and 2) conversion of different loose mix aging procedures based on a kinetics aging model.

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Executive Summary

The project aimed to validate loose mix aging procedures for cracking resistance evaluation of asphalt mixtures in balanced mix design (BMD) with a broad range of field projects covering various mixture components, pavement ages, and climatic conditions. A two-phase research approach was used to accomplish the objective of the project. Phase I sought to: (1) critically review existing studies on the development, evaluation, and validation of candidate loose mix aging procedures; (2) synthesize the existing binder and mixture test results and identify research gaps for further implementation of loose mix aging for BMD; and (3) develop an experimental plan for Phase II. Phase II will focus on executing the experimental plan to address the research gaps by leveraging existing aging data and field projects on the Minnesota Road Research Facility (MnROAD), the National Center for Asphalt Technology (NCAT) Test Track, and those in the National Road Research Alliance (NRRA) states.

Phase I started with a comprehensive literature review on existing loose mix aging procedures for simulating the long-term aging of asphalt mixtures and their impacts on the performance properties of asphalt binders and mixtures, and the findings are summarized as follows. The temperature of the existing aging procedures varies from 85°C to 135°C, and the duration varies from hours to weeks depending on the targeted level of field aging. The two most studied aging procedures are loose mix aging at 95°C and 135°C. In general, loose mix aging at 95°C is considered a more accurate procedure in terms of its ability to predict the properties of asphalt binders and mixtures for pavement performance prediction purposes. Loose mix aging at 135°C, on the other hand, is considered a more practical procedure for use with mixture performance testing for asphalt mix design and production. In addition to these two aging procedures, loose mix aging for 20 hours at 100 to 125°C has shown promising results and is considered laboratory operations-friendly. The kinetics model developed in the National Cooperative Highway Research Program (NCHRP) project 9-54 has the potential to correlate loose mix aging procedures at different temperatures, but its validity and applicability to asphalt mixtures with various components and mix design variables need further investigation. Most of the asphalt binder and mixture performance tests used in previous asphalt aging research show good sensitivity to loose mix aging and thus can discriminate asphalt mixtures with different loose mix aging conditions. Finally, several studies have demonstrated the impacts of silo storage, mixing hauling, mix reheating, specimen storage, and asphalt weathering on the aging of asphalt binders and mixtures, highlighting the need to consider these factors in future asphalt aging research.

A research gap analysis was then conducted to analyze the literature review findings to identify gaps that might hinder the implementation of loose mix aging for cracking resistance evaluation in BMD. The analysis had four focuses: 1) determining the correlations between different loose mix aging procedures and field aging for various climatic conditions and locations in the pavement structure; 2) assessing the effects of loose mix aging on the performance properties of specialty asphalt mixtures and the corresponding extracted asphalt binders containing recycling agents, recycled plastics, and crumb rubber; 3) selecting appropriate binder and mixture performance tests and parameters to assess loose mix aging; and 4) recommending loose mix aging procedures for use in mix design approval and production acceptance for BMD. Among the existing loose mix aging procedures, only the 95°C

procedure developed in the NCHRP project 9-54 has undergone reasonable field validation, while the others have no or very limited lab-to-field validation data. Most of the existing loose mix aging procedures have been successfully used to evaluate asphalt mixtures with reclaimed asphalt pavement, recycled asphalt shingle, rejuvenator, and polymer modified asphalt, but it remains unknown whether they are applicable to mixtures containing recycled plastics, recycled tire rubber, and synthetic fiber, and how these non-traditional asphalt additives affect the established lab-to-field aging correlations. The majority of the laboratory tests and their associated test parameters used in previous aging studies have reasonable sensitivity to loose mix aging and thus, have the potential to discriminate different aging procedures and determine their correlation to field aging. Finally, advantages and disadvantages associated with the existing loose mix aging procedures for use in BMD are determined. The 95°C aging procedure is recommended for highway agencies interested in using BMD cracking tests to predict pavement performance for high-profile projects when high accuracy in the prediction results is desired from the risk management perspective. Conversely, the 100-125°C and 135°C aging procedures are suggested for highway agencies interested in using BMD cracking tests to screen and eliminate poor-performing mixes from mix design and production while desiring a quick turnaround of test results for decision making.

Finally, a Phase II work plan to address knowledge gaps from the gap analysis was developed. The work plan includes two major tasks: 1) further validating the 95°C aging maps with additional lab-to-field aging data, including asphalt mixtures containing non-traditional additives; and 2) assessing and refining the conversion of different loose mix aging procedures based on the kinetics model developed in the NCHRP project 9-54. For each task, an experimental plan including potential field projects and laboratory testing matrix is suggested. Furthermore, the anticipated approach of implementing loose mix aging in cracking resistance evaluation for BMD based on the Phase II research efforts is provided.

Chapter 1: Introduction

Over the last two decades, cracking has become the primary mode of distress in asphalt pavements in the United States. To address the cracking issues, many state transportation agencies (STAs) have made modifications to the Superpave volumetric mix design system to improve the cracking resistance and durability of asphalt mixtures. However, the overall effectiveness of these modifications was not very satisfactory because of inherent limitations associated with the volumetric analysis. Recently, balanced mix design (BMD) has been developed as a new asphalt mix design system that relies on performance testing in addition to (or sometimes in place of) volumetric analysis for mix design approval and production acceptance. Because BMD addresses many of the limitations associated with the volumetric mix design system, it has the potential to yield asphalt mixtures with good performance.

Although the concept of BMD has gained significant attention among STAs and the asphalt pavement industry, developing and implementing a robust BMD specification has challenges. One of them is selecting appropriate long-term mix aging procedure(s) for use with the BMD cracking tests so that the mixture can be tested at a representative field aging condition. Addressing long-term aging is critical for the evaluation of cracking resistance for several reasons. First, cracking does not occur immediately after construction; instead, it typically develops after several years in-service because of mix aging and embrittlement, which reduces the mixture's ability to resist damage from traffic and climatic stressors. Second, because of the different crude oil sources and refining processes, asphalt binders do not age at the same rate or to the same extent, with some being more susceptible to aging than others. Furthermore, the use of recycled asphalt materials, including reclaimed asphalt pavements (RAP) and recycled asphalt shingles (RAS), as well as asphalt additives such as polymers, recycling agents, warm mix asphalt, and liquid anti-strip additives, could significantly affect the aging susceptibility of asphalt binders and mixtures. Therefore, a robust BMD specification requires an appropriate laboratory aging procedure for conditioning asphalt mixtures prior to cracking tests. This is particularly important for evaluating surface mixtures to ensure adequate long-term pavement cracking performance.

Over the years, asphalt researchers and practitioners have developed and evaluated different long-term aging procedures. Most notably, the AASHTO R 30 procedure requires aging compacted specimens for 5 days at 85°C, which was originally developed in the Strategic Highway Research Program (SHRP) program to simulate 7 to 10 years of field aging in the United States (Bell et al., 1994). However, the National Cooperative Highway Research Program (NCHRP) project 9-52 found that this aging procedure was not severe enough for asphalt mixtures used nowadays because it could only simulate up to 3 years of field aging (Newcomb et al., 2015). Similar findings have also been reported by Islam et al. (2015) and Howard and Doyle (2015). Furthermore, the compacted specimen aging procedure has limitations, including the presence of aging gradient within the mixture specimen and the inability to accommodate elevated aging temperatures due to specimen distortion concerns. More recently, numerous studies have explored loose mix aging as an alternative, yet accelerated, method to simulate the field aging of asphalt pavements. The temperature of these procedures ranges from 85 to 135°C and the duration varies from hours to weeks. Although the loose mix aging procedures show promising results in correlating to field aging, their development has been based on a limited number of field projects and component materials. Therefore, this project was initiated with the overall objective of validating these procedures with a broader range of field projects with various mixture components, pavement ages, and climatic conditions.

A two-phase research approach was used to accomplish the objective of the project. Phase I sought to: (1) critically review existing studies on the development, evaluation, and validation of candidate loose mix aging procedures; (2) synthesize the existing binder and mixture test results and identify research gaps for further implementation of loose mix aging for BMD; and (3) develop an experimental plan for Phase II. Phase II will focus on executing the experimental plan to address the research gaps by leveraging existing aging data and field projects, especially those containing asphalt additives such as recycling agents, recycled plastics, and crumb rubber on the Minnesota Road Research Facility (MnROAD) and the NCAT Test Track as well as those in the National Road Research Alliance (NRRA) states.

This report serves as the final report of the Phase I study, which consists of four chapters. Chapter 1 introduces the background and overall objectives of the project, as well as the structure of the Phase I final report. Chapter 2 presents the literature review findings on loose mix aging. Chapter 3 discusses the research gap analysis on implementing loose mix aging for cracking resistance evaluation in BMD. Finally, Chapter 4 presents the proposed Phase II work plan to address the research gaps identified in the Phase I study.

Chapter 2: Literature Review

This chapter presents the literature review findings from the Phase I study. It is organized into four sections. Section 2.1 discusses the development of various loose mix aging procedures and their preliminary correlations to field aging. Section 2.2 discusses the impact of loose mix aging on the performance properties of asphalt mixtures and extracted asphalt binders evaluated using different laboratory tests. Section 2.3 synthesizes existing studies on the effects of silo storage, mix hauling, mix reheating, specimen storage, and asphalt weathering on the properties of asphalt binders and mixtures. Finally, Section 2.4 provides a summary of the significant literature review findings.

2.1 Development and Preliminary Field Validation of Existing Loose Mix Aging Procedures

2.1.1 Loose Mix Aging at 85°C

In NCHRP project 9-52A, a limited laboratory experiment was conducted to explore the use of loose mix aging for 5 days at 85°C as an alternative to the long-term aging procedure in AASHTO R 30 (Newcomb et al., 2019). Four mixtures from a field project in South Dakota were used in the experiment, which included a hot mix asphalt (HMA) mixture and three warm mix asphalt (WMA) mixtures containing different technologies (Table 1). Each mixture was tested with the Resilient Modulus (Mr) test for stiffness characterization with and without subjection to the 5-day, 85°C loose mix aging procedure. The Mr stiffness results of the loose mix aged samples were then divided by those of the corresponding short-term aged specimens (i.e., without loose mix aging) to calculate a Mr stiffness ratio for the 5-day, 85°C loose mix aging procedure. The Mr stiffness ratios of the four mixtures were then averaged and plotted against the Mr stiffness ratio-versus-field aging curve developed in NCHRP project 9-52 (Newcomb et al., 2015), as shown in Figure 1, to determine the equivalent field aging condition for the 5-day, 85°C loose mix aging procedure. Note that in NCHRP projects 9-52 and 9-52A, field aging was quantified using the cumulative degree days (CDD) parameter, which was defined as the accumulation of the daily high temperature above freezing for all the days being considered from the time of construction to the time of coring (Yin et al., 2014).

Table 1. Summary of Asphalt Mixtures used for the Evaluation of 85°C Loose Mix Aging in NCHRP Project 9-52A (Newcomb et al., 2019)

Mix ID	Mix 1	Mix 2	Mix 3	Mix 4
Mixture Type	HMA	WMA	WMA	WMA
Aggregate Type	Quartize	Quartize	Quartize	Quartize
Nominal Maximum Aggregate Size (NMAS)	12.5 mm	12.5 mm	12.5 mm	12.5 mm
Virgin Binder	PG 58-34	PG 58-34	PG 58-34	PG 58-34
Reclaimed Asphalt Pavement (RAP)	20%	20%	20%	20%
Recycled Asphalt Shingle (RAS)	-	-	-	-
Additive	-	Foaming	Evotherm	Advera

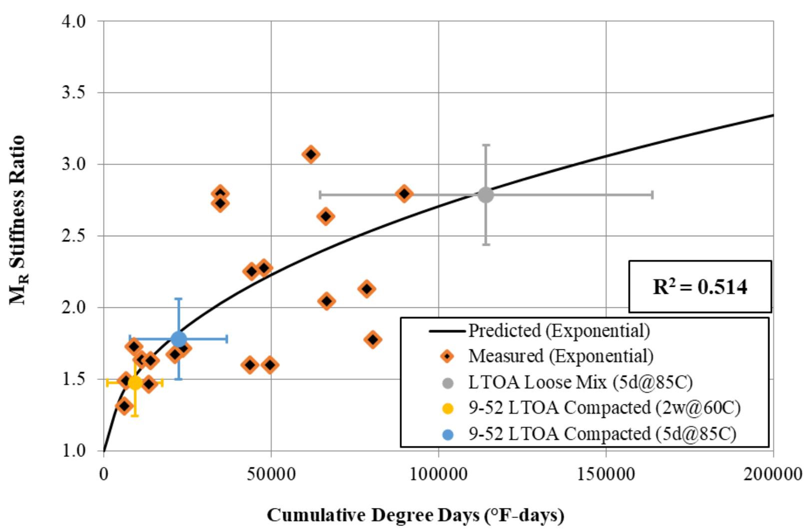


Figure 1. Mr Stiffness Ratio Correlation between Field Aging and Various Laboratory Long-term Aging Procedures (Newcomb et al., 2019)

As shown in Figure 1, based on the limited Mr stiffness results collected in NCHRP project 9-52A, the 5-day, 85°C loose mix aging procedure was expected to simulate approximately 114,000 CDD of field aging on average, which corresponds to 7 to 10 years for warmer climates (e.g., Florida, New Mexico, and Texas) and 12 to 14 years for cooler climates (Indiana, Iowa, South Dakota, and Wyoming). For the other two long-term aging procedures evaluated in NCHRP projects 9-52 and 9-52A, aging compacted specimens for 2 weeks at 60°C and 5 days at 85°C was only expected to simulate 9,000 CDD and 23,000 CDD of field aging, respectively, which was significantly less severe than the 5-day, 85°C loose mix aging procedure.

2.1.2 Loose Mix Aging at 95°C

NCHRP project 9-54 recommended using loose mix aging at 95°C for the long-term aging of asphalt mixtures for performance testing and prediction (Kim et al., 2017; Kim et al., 2021). The project included three phases, with Phase I and Phase II completed in 2015 and Phase III completed in 2021. The overall objective of the first two phases was to develop a calibrated and validated procedure to simulate the long-term aging of asphalt mixtures for performance testing and prediction. To that end, a comprehensive experimental design was executed, which consisted of six major tasks: 1) sensitivity evaluation to asphalt binder oxidation; 2) selection of aging index properties (AIP); 3) selection of optimum long-term aging method; 4) determination of project-specific aging durations; 5) climate-based determination of predefined aging durations; and 6) development of pavement aging model. Tasks 1, 2, and 6 are beyond the scope of this NRRA project and thus are not discussed here.

In Task 3 of the Phase I and II studies, three major factors were considered in selecting the optimum long-term aging method: state of the material to use for aging (i.e., compacted specimen aging versus loose mix aging), pressure level (i.e., oven aging versus pressurized aging), and aging temperature (i.e., 95°C versus 135°C). Note that the latter two factors only applied to the loose mix aging method. The compacted specimen versus loose mix aging was evaluated based on considerations of specimen integrity (i.e., susceptibility to specimen distortion during aging), efficiency, practicality, and versatility. Evaluation results indicated that aging compacted specimens for 5 days at 85°C per AASHTO R 30 did not cause specimen integrity issues, but it introduced an aging gradient within 100 mm-diameter gyratory specimens along the diametrical direction, which raised concerns for performance testing due to lack of specimen uniformity. Loose mix aging, on the other hand, did not cause specimen integrity, nonuniformity, or compactability issues. Furthermore, loose mix aging was more effective in accelerating oxidative aging than compacted specimen aging. Based on these findings, loose mix aging was recommended over compacted specimen aging for further evaluation in NCHRP project 9-54 as a more robust and efficient method to simulate the long-term aging of asphalt mixtures in the laboratory.

Compared to oven aging, pressurized aging using the pressure aging vessel (PAV) significantly intensified the severity of loose mix aging. However, using PAV for pressurized loose mix aging had major practicality concerns because of the limited amount of loose mix samples that could fit in the PAV. Alternatively, a larger mixture-scale pressurized oven could be used, but such a device was not readily available or practical for implementation in the asphalt pavement industry. Therefore, oven aging was recommended as a more appropriate method for loose mix aging of asphalt mixtures.

The last factor considered in Task 3 was the selection of loose mix aging temperature. Two candidates were considered for aging temperatures: 95°C and 135°C. 95°C was selected based on the literature that indicated the oxidation reaction mechanism of asphalt binders can change when the temperature exceeds 100°C (Peterson, 2009). 135°C was selected based on previous studies that showed reasonably promising results with loose mix aging at 135°C (Braham et al., 2009; Blankenship et al., 2010). Three asphalt mixtures were included for evaluating loose mix aging at 95°C versus 135°C. The mixtures used the same aggregates but different asphalt binders. One mixture used a styrene-butadiene-styrene (SBS) modified binder while the other two used unmodified binders with distinctly different chemistry (referred to as the SHRP AAD binder and SHRP AAG binder, respectively). The evaluation started with selecting the durations of loose mix aging at 95°C and 135°C that yielded an equivalent level of asphalt aging based on the complex shear modulus (|G*|) at 64°C and 10Hz of the extracted binders, as shown in Figure 2. The target |G*| at 64°C and 10 Hz was selected to be four times the |G*| of the corresponding PAV-aged binder as represented by the dashed line in the figure.

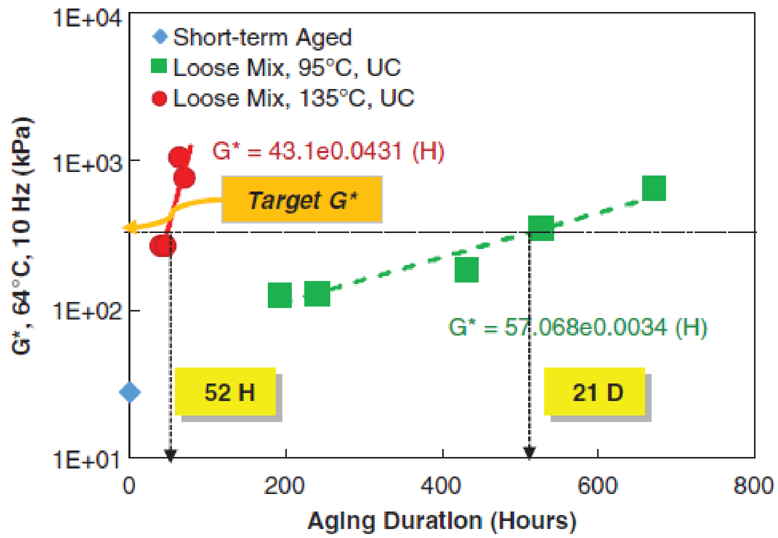


Figure 2. Example to Illustrate the Selection of Equivalent Aging Time for Loose Mix Aging at 95°C versus 135°C (Kim et al., 2017)

After selecting the equivalent aging durations, mixture specimens were prepared using loose mixes aged at 95°C and 135°C, which were then tested with the Dynamic Modulus (E*) and Direct Tension Cyclic Fatigue (DTCF) tests. Furthermore, short-term aged mixture specimens without loose mix aging were also tested for comparison purposes. Figure 3 through Figure 5 present the E* master curve and DTCF C-versus-S curve of the three mixtures containing different binders. As shown, for both the FHWA ALF-SBS mixture (Figure 3) and the SHRP AAG mixture (Figure 5), loose mix aging at 95°C and 135°C at their corresponding equivalent aging time yielded similar E* and DTCF test results, which indicated that the two loose mix aging temperatures selected did not affect their stiffness and fatigue damage resistance. However, a different trend was observed for the SHRP AAD mixture in Figure 4. As shown, the two loose mix aging procedures exhibited notably different E* master curves and DTCF C-versus-S curves, which indicated that loose mix aging at 135°C detrimentally affected the stiffness and fatigue damage resistance of the mixture, possibly due to chemical changes of the highly structured (and highly aging-susceptible) SHRP AAD binder. Based on these results, loose mix aging at 95°C was recommended over 135°C as a more conservative approach to simulate the long-term aging of asphalt mixtures for performance testing and prediction in the laboratory.

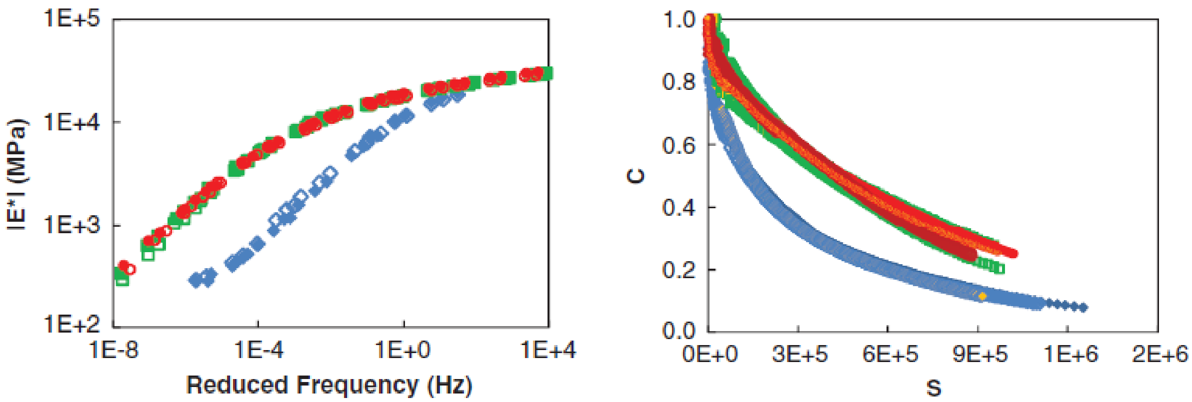


Figure 3. E* Master Curves (left) and DTCF C-versus-S Curves (right) of FHWA ALF-SBS Mixture with Short-term Aging (Blue), Loose Mix Aging at 95°C (Green) and Loose Mix Aging at 135°C (Red) (Kim et al., 2017)

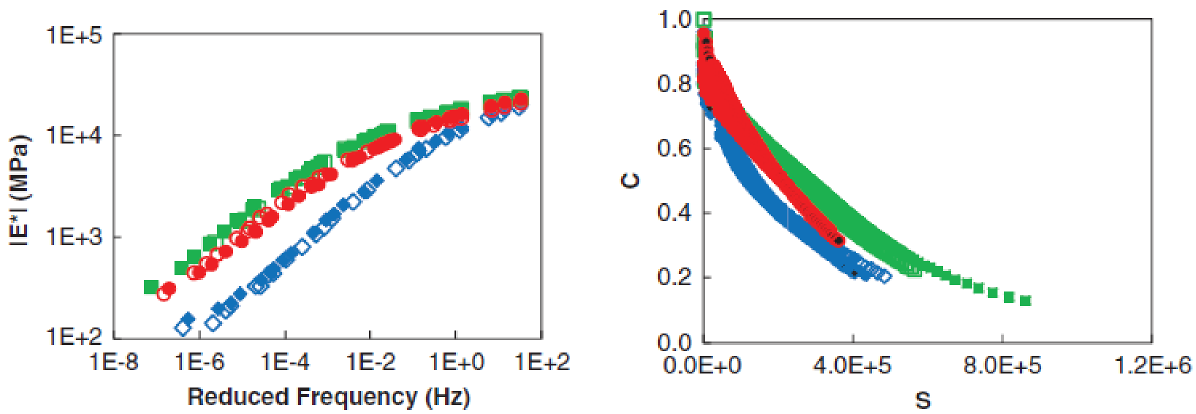


Figure 4. E* Master Curves (left) and DTCF C-versus-S Curves (right) of SHRP AAD Mixture with Short-term Aging (Blue), Loose Mix Aging at 95°C (Green) and Loose Mix Aging at 135°C (Red) (Kim et al., 2017)

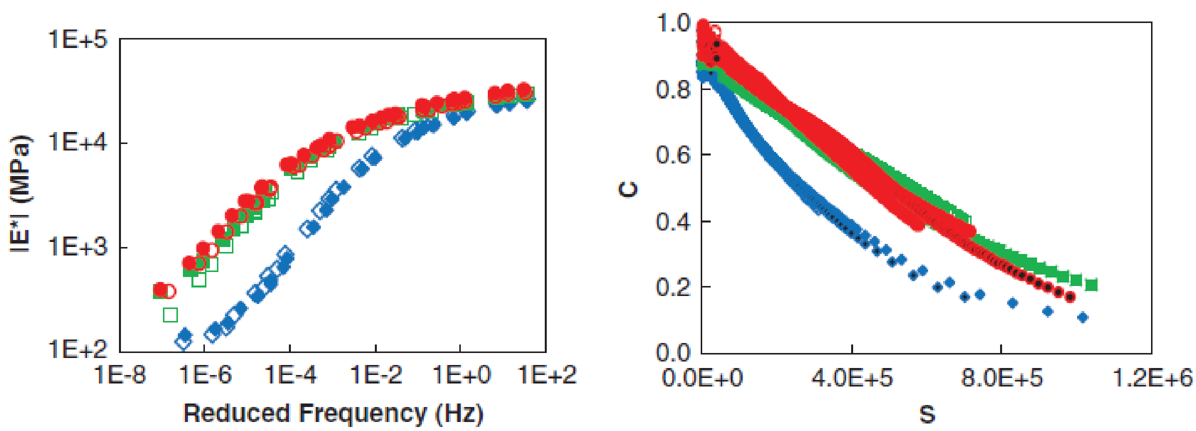


Figure 5. E* Master Curves (left) and DTCF C-versus-S Curves (right) of SHRP AAG Mixture with Short-term Aging (Blue), Loose Mix Aging at 95°C (Green) and Loose Mix Aging at 135°C (Red) (Kim et al., 2017)

After selecting the optimum long-term aging method in Task 3, research efforts were devoted to correlating loose mix aging at 95°C with field aging in Task 4 of the Phase I and II studies. To that end, a rheological-based kinetics model was developed based on existing chemistry-based kinetics models and rheological AIP results collected in the study. The developed kinetics model was based on the binder |G*| at 64°C and 10 rad/s, as shown in Equation 1. The model allowed the prediction of long-term aged |G*| as a function of long-term aging time (t), the short-term aged |G*| of the binder ($|G_0^*|$), two universal reaction parameters (k_f and k_c), and a mixture-specific aging kinetics parameter (M).

$$\log(|G^*|) = \log(|G_0^*|) + M\left(1 - \frac{k_c}{k_f}\right)\left(1 - e^{(-k_f t)}\right) + k_c M t \qquad \text{Equation 1}$$

The model was first calibrated and validated with ten mixtures under an isothermal aging condition and showed promising results. It was then calibrated to confirm its applicability to non-isothermal loose mix aging conditions using two selected mixtures. This finding highlighted the feasibility of using the kinetics model to predict the evolution of binder |G*| over field aging based on the pavement temperature history and more importantly, to correlate loose mix aging in the laboratory with field aging, as illustrated in Equation 2. As shown, the duration of loose mix aging required to match a given level of field aging is mixture independent as the equation does not include mixture-specific parameters, $|G_0^*|$ and M; instead, it is only based on universal reaction parameters (k_c and k_f) and the temperature history for lab aging versus field aging.

$$\log G^*_{lab} = \log G^*_{o,lab} + M\left[\left(1 - \frac{k_c}{k_f}\right)(1 - \exp(-k_f t)) + k_c t\right]_{lab}$$

$$\log G^*_{field} = \log G^*_{o,\text{field}} + M\left[\left(1 - \frac{k_c}{k_f}\right)(1 - \exp(-k_f t)) + k_c t\right]_{field}$$

$$\cancel{\log G^*_{o,\text{field}}} + \cancel{M}\left[\left(1 - \frac{k_c}{k_f}\right)(1 - \exp(-k_f t)) + k_c t\right]_{field} \qquad \text{Equation 2}$$

$$= \cancel{\log G^*_{o,\text{lab}}} + \cancel{M}\left[\left(1 - \frac{k_c}{k_f}\right)(1 - \exp(-k_f t)) + k_c t\right]_{lab}$$

$$\left[\left(1 - \frac{k_c}{k_f}\right)(1 - \exp(-k_f t)) + k_c t\right]_{field} = \left[\left(1 - \frac{k_c}{k_f}\right)(1 - \exp(-k_f t)) + k_c t\right]_{lab}$$

Due to practicality considerations, Equation 2 was simplified with the use of a climatic aging index (CAI). As shown in Equation 3, CAI is expressed as a function of the rate of reaction (k), reaction time (t), and pavement depth correction factor (*D*), which serves as an empirical correction factor to account for the differences in oxygen partial pressure with pavement depth. By integrating Equation 3 into Equation 2, the duration of loose mix aging required to match a given level of field aging can be determined using Equation 4.

$$CAI = D * A * e^{\left(-\frac{E_a}{RT}\right)} * t \qquad \text{Equation 3}$$

$$t_{oven} = CAI = \sum_{i=1}^{N} D * A * e^{\left(-\frac{E_a}{RT_i}\right)}/24 \qquad \text{Equation 4}$$

Where,

t_{oven} = required laboratory aging duration at 95C to match field aging (day),
CAI = climatic aging index,
D = depth correction factor,
A = frequency factor
E_a = activation energy (kJ/mol),
R = universal gas constant (kJ/mol.K), and
T = hourly pavement temperature obtained from EICM at the depth of interest (Kelvin).

Figure 6 presents the measured 95°C loose mix aging durations and the predicted CAI of ten mixtures using Equation 4. As shown, a good correlation (with a R^2 of 0.71) existed, which demonstrated the potential of Equation 4 in reasonably correlating loose mix aging at 95°C with field aging.

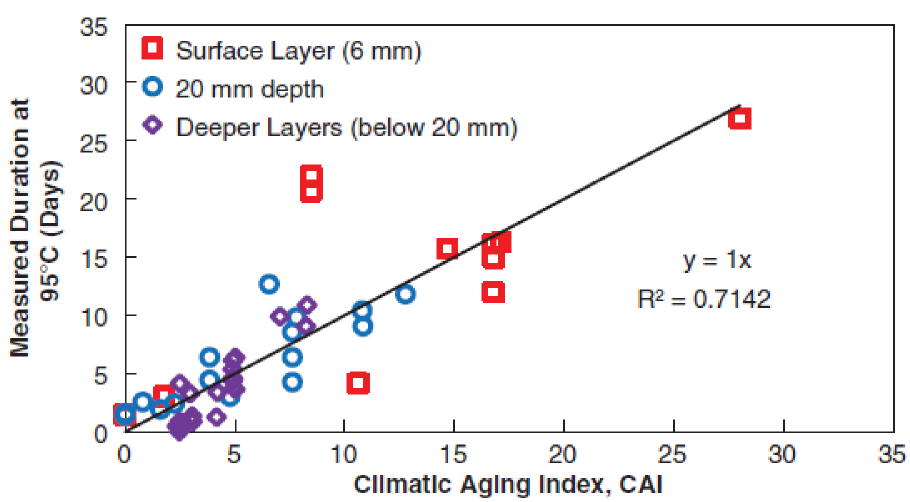


Figure 6. Correlation between Measured Duration of Loose Mix Aging at 95°C and CAI (Kim et al., 2017)

Based on the lab-to-field aging correlation described in Equation 4, a series of field aging maps were developed in Task 5 of the Phase I and II studies, as shown in Figure 7 through Figure 9. These maps provide the estimated duration of loose mix aging at 95°C (in days) that is required to simulate 4, 8, and 16 years of field aging at various pavement depths (6, 20, and 50 mm below pavement surface) for pavement locations across the United States.

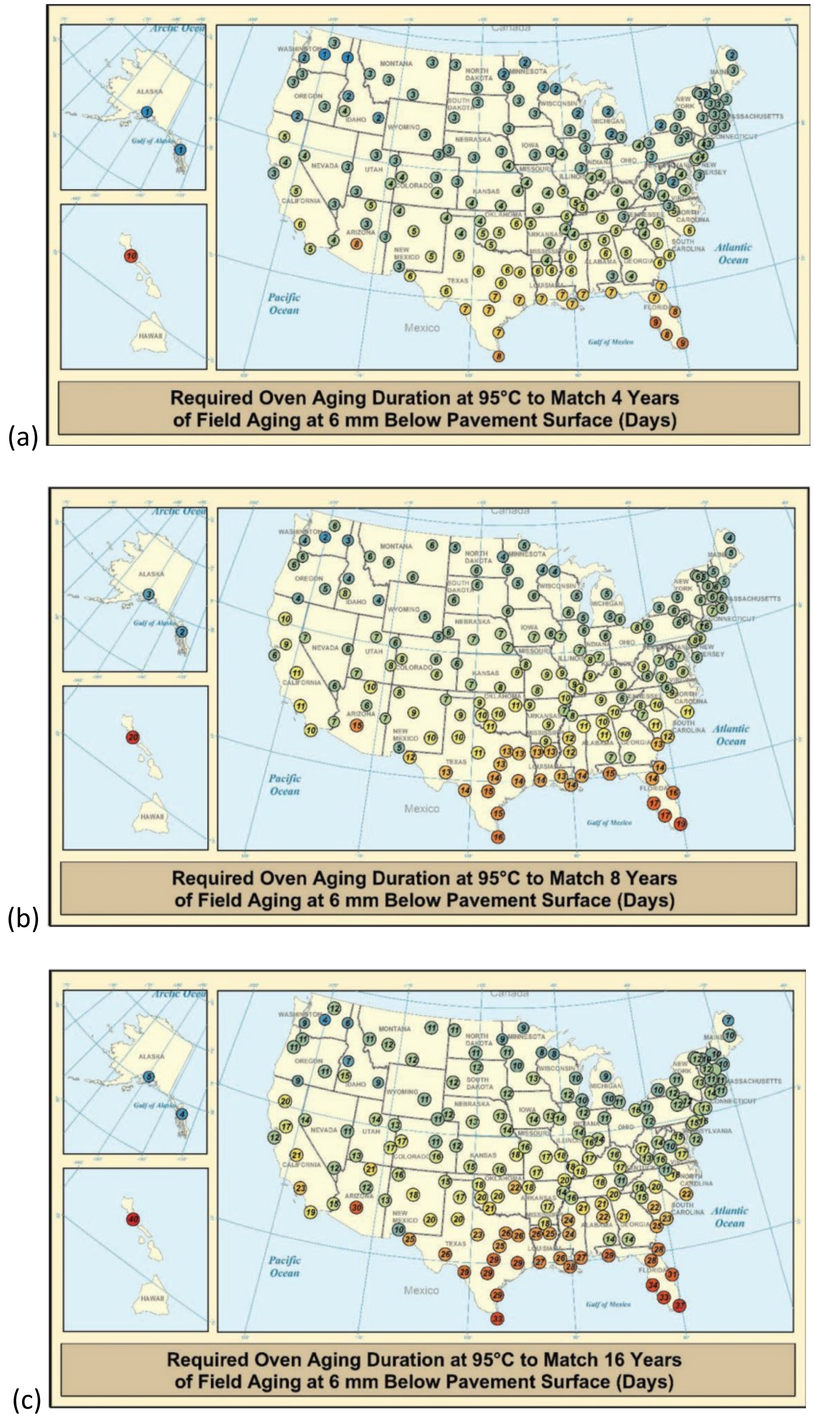
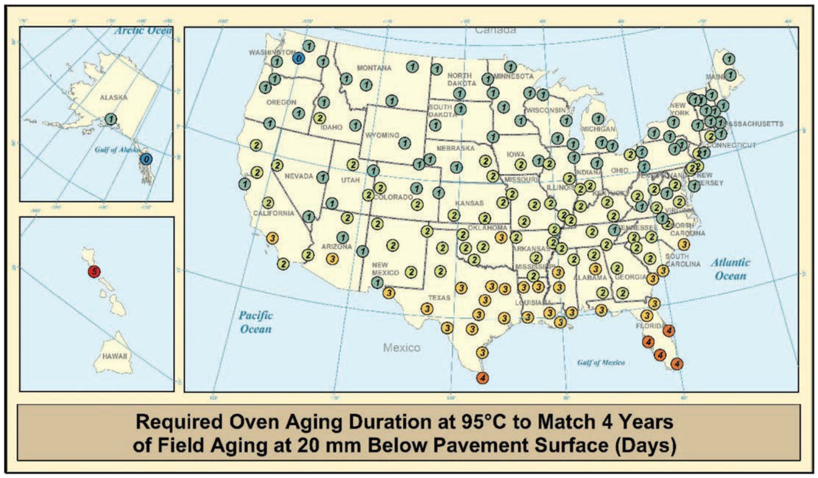
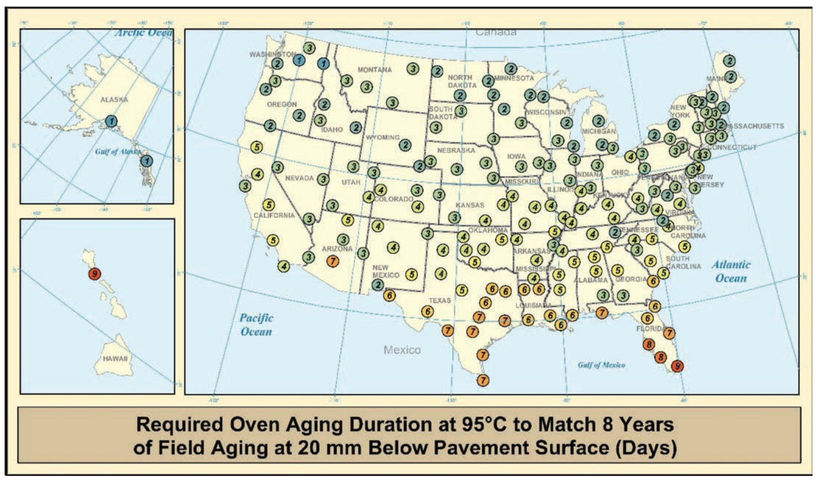


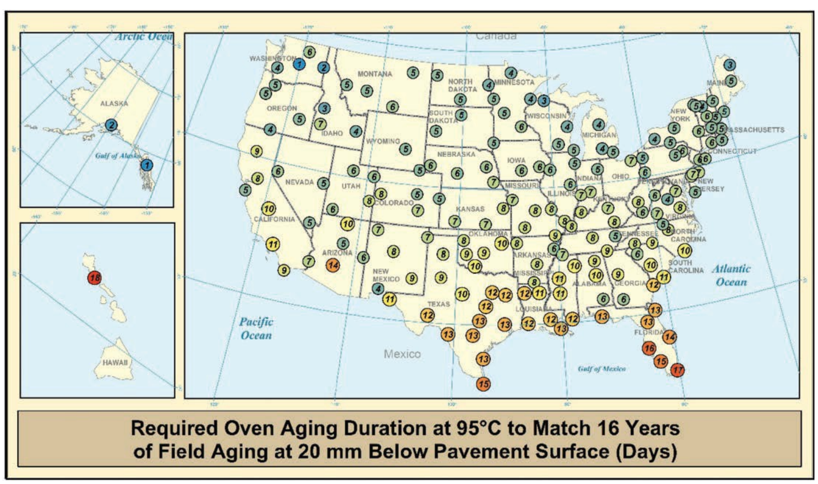
Figure 7. Field Aging Maps of Estimated Loose Mix Aging Duration (in Days) at 95°C to Match (a) 4 Years, (b) 8 Years, and (c) 16 Years of Field Aging at 6 mm below Pavement Surface (Kim et al., 2017)



(a)



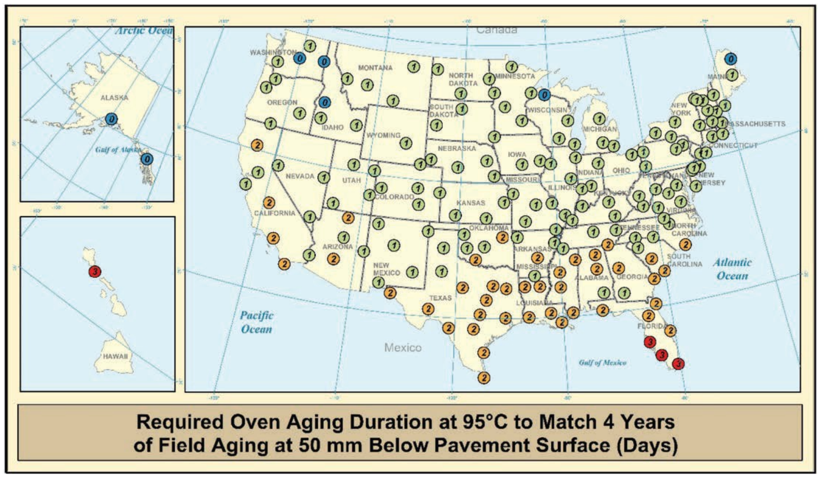
(b)



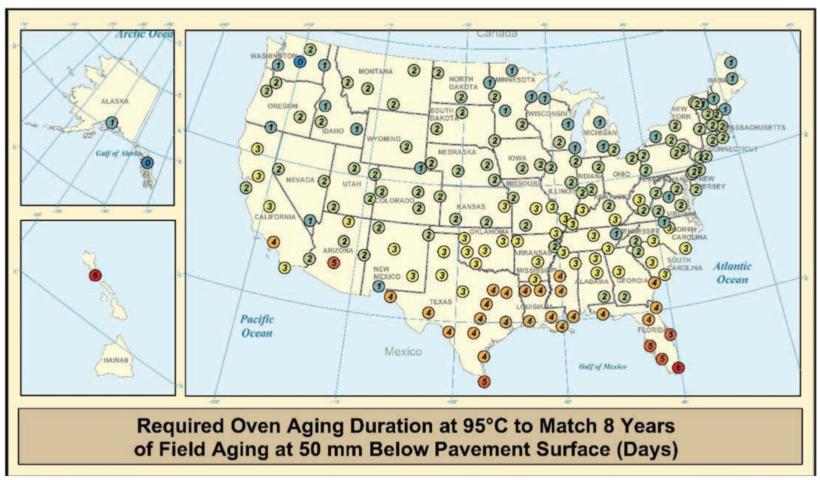
(c)

Figure 8. Field Aging Maps of Estimated Loose Mix Aging Duration (in Days) at 95°C to Match (a) 4 Years, (b) 8 Years, and (c) 16 Years of Field Aging at 20 mm below Pavement Surface (Kim et al., 2017)

(a)



(b)



(c)

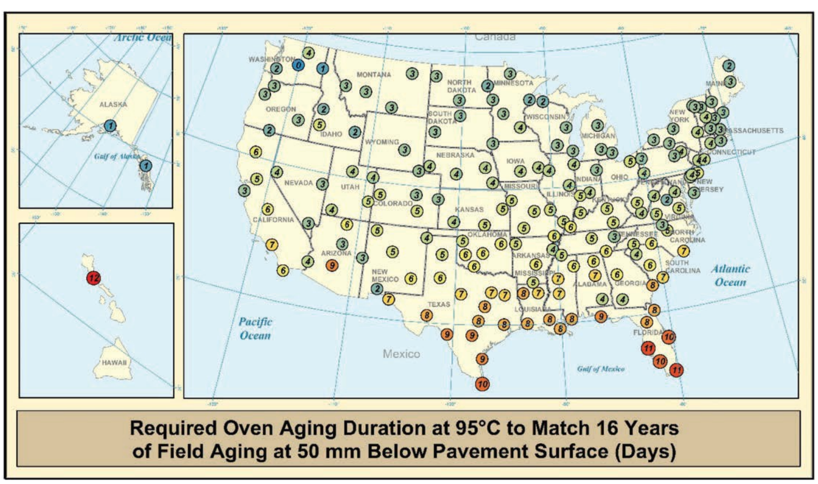


Figure 9. Field Aging Maps of Estimated Loose Mix Aging Duration (in Days) at 95°C to Match (a) 4 Years, (b) 8 Years, and (c) 16 Years of Field Aging at 50 mm below Pavement Surface (Kim et al., 2017)

Phase III of the NCHRP project 9-54 was conducted as a follow-up to Phase I and Phase II. One of the primary objectives of the Phase III study was to refine the previously developed laboratory aging procedure by including WMA and asphalt mixtures containing polymer-modified asphalt (PMA) and RAP. To that end, 30 mixtures from ten field projects across the U.S. and Canada were used to recalibrate the CAI parameters in Equation 4, which significantly improved the prediction accuracy of CAI for HMA, WMA, and PMA mixtures. However, the prediction for RAP mixtures was not as reliable as virgin mixtures and thus was recommended for further investigation.

Equation 5 presents the recalibrated CAI expression, which was derived from Equation 4 by inputting the parameter *D* as an exponential function of depth instead of using arbitrary depth correlation factor values; setting the parameter *A* to a value of 1 to reduce the variables in the CAI expression; and dividing the parameter E_a by *R* to simplify the CAI expression.

$$t_{oven} = CAI = \sum_{i=1}^{N} 0.0437 * d^{-0.426} * e^{\left(-\frac{1601.167}{T_i}\right)} \qquad \text{Equation 5}$$

Where,

d = depth from the pavement surface (cm), and

T_i = hourly pavement temperature (Kelvin).

Using the recalibrated CAI parameters, the previously developed field aging maps for loose mix aging at 95°C (Figure 7 through Figure 9) were updated and are presented in Figure 10 through Figure 12.

(a)
(b)
(c)

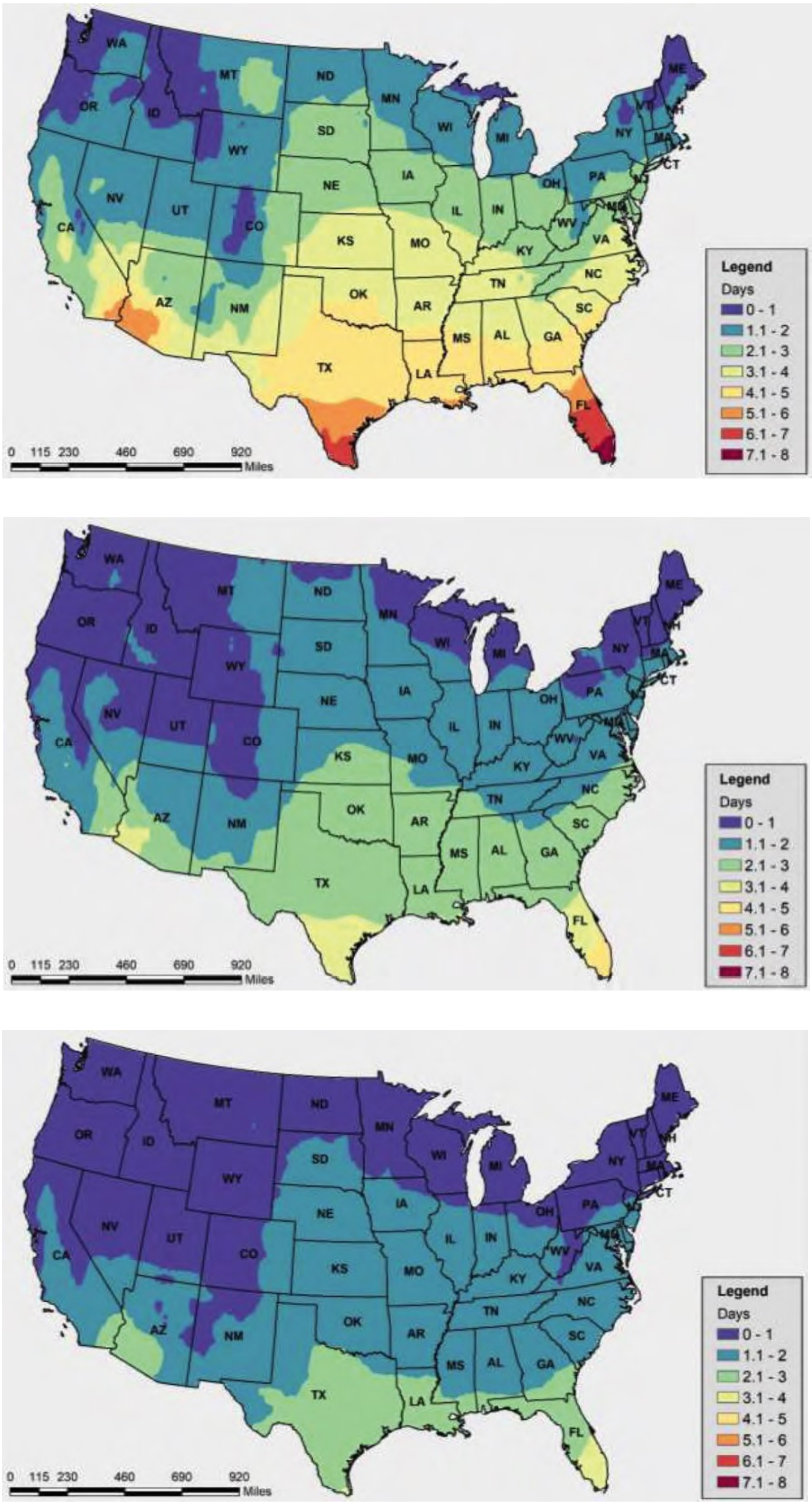
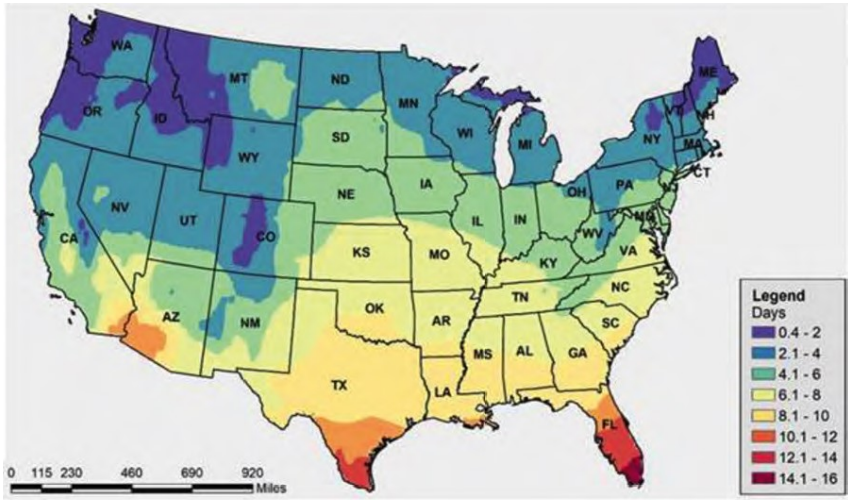
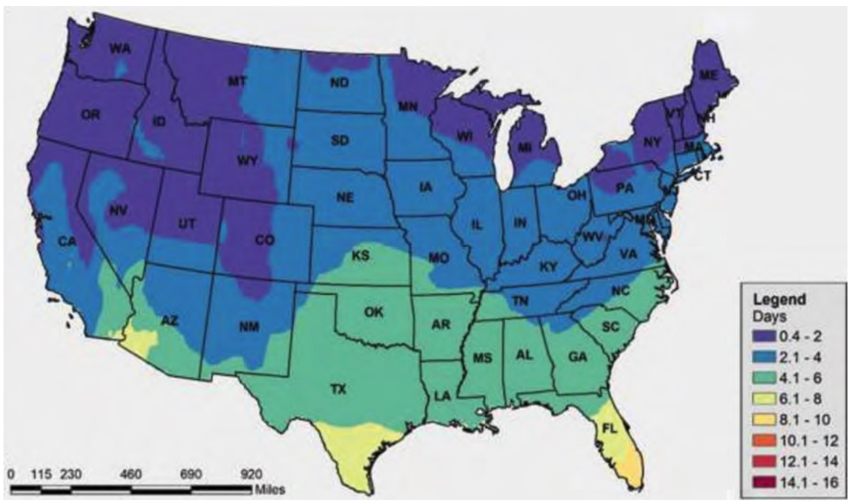


Figure 10. Updated Field Aging Maps of Estimated Loose Mix Aging Duration (in Days) at 95°C to Match 4 Years of Field Aging at (a) 6 mm, (b) 20 mm, and (c) 30 mm below Pavement Surface (Kim et al., 2021)

(a)



(b)



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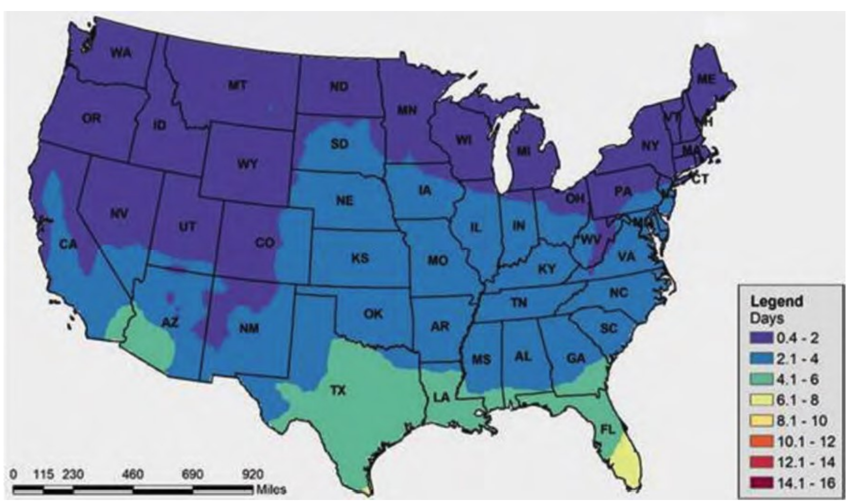


Figure 11. Updated Field Aging Maps of Estimated Loose Mix Aging Duration (in Days) at 95°C to Match 8 Years of Field Aging at (a) 6 mm, (b) 20 mm, and (c) 30 mm below Pavement Surface (Kim et al., 2021)

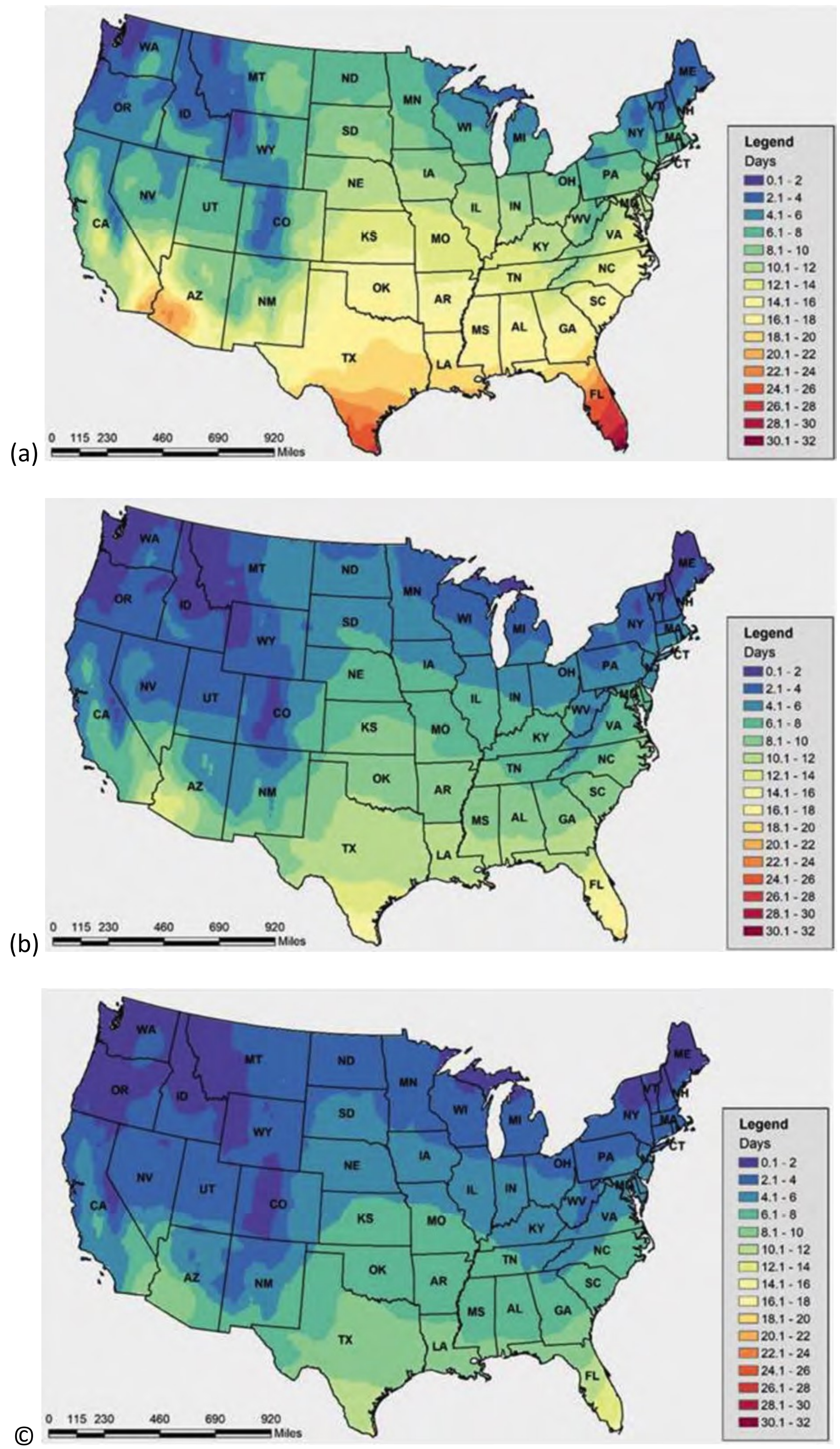


Figure 12. Updated Field Aging Maps of Estimated Loose Mix Aging Duration (in Days) at 95°C to Match 16 Years of Field Aging at (a) 6 mm, (b) 20 mm, and (c) 30 mm below Pavement Surface (Kim et al., 2021)

Zhang et al. (2019) at UNH compared the E* test results of 4-year-old field cores and laboratory-aged specimens for two plant-produced surface asphalt mixtures in New Hampshire summarized in Table 2. Three loose mix aging procedures were evaluated: 5 days at 95°C, 12 days at 95°C, and 24 hours at 135°C. According to the modulus and phase angle results in Figure 13, loose mix aging for 5 days at 95°C appeared to simulate approximately 4 years of field aging at 20 mm below the pavement surface in New Hampshire, while the other two aging procedures yielded a considerably more severe level of asphalt aging. This limited lab-to-field aging equivalency relationship differed from the field aging maps in the NCHRP project 9-54, which indicates that loose mix aging for 5 days at 95°C is equivalent to approximately 7 years of field aging in New Hampshire at a depth of 20 mm.

Table 2. Summary of Asphalt Mixtures used in the UNH Study by Zhang et al. (2019)

Mix ID	5234LM	5234LL
Mixture Type	HMA	HMA
Aggregate Type	Unknown	Unknown
NMAS	12.5 mm	12.5 mm
Virgin Binder	PG 52-34	PG 52-34
Recycled Binder Replacement	18.9%	28.3%
Additive	-	-

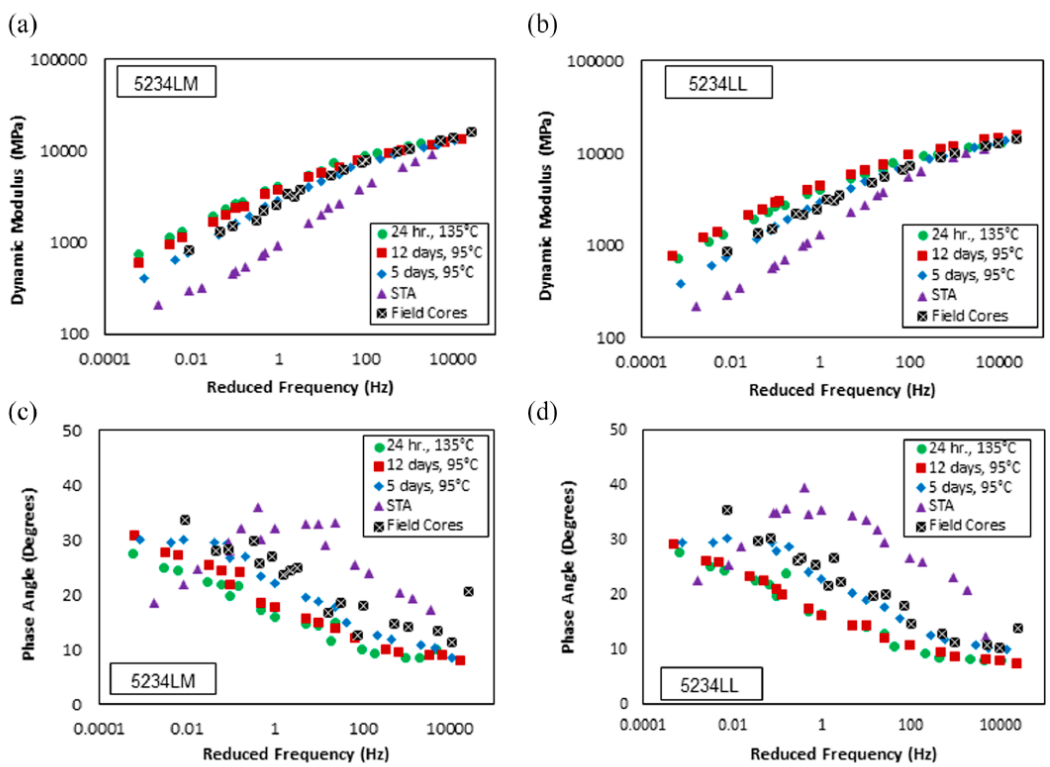


Figure 13. Comparison of E* Results of Laboratory-aged Specimens and 4-year Field Cores for Two Plant-produced Surface Asphalt Mixtures in New Hampshire (Zhang et al., 2019)

2.1.3 Loose Mix Aging at 100-125°C

Loose mix aging for 20 hours at 100-125°C was recommended by Zhou et al. (2022) at TTI for evaluating the fatigue and low-temperature cracking resistance of asphalt mixtures in different climate regions. This aging procedure was found to be approximately equivalent to the 6-day, 95°C loose mix aging in terms of their impact on the cracking resistance of asphalt mixtures evaluated using the Indirect Tensile Asphalt Cracking Test (IDEAL-CT), the Illinois Flexibility Index Test (I-FIT), and the Overlay Test (OT). Different from previous studies, this study opted to fix the aging duration at 20 hours but varied the loose mix aging temperature. The 20-hour aging duration was selected because it is convenient for laboratory operations in an 8-hour daily working schedule and has been used for the PAV aging of asphalt binders over the last three decades.

The experimental plan of the study started by determining the equivalent aging temperature of the 20-hour aging procedure to match loose mix aging at 95°C. Seven mixtures with a range of material components were used, as shown in Table 3. Five loose mix aging procedures were evaluated, including 20 hours at 100°C, 20 hours at 115°C, 20 hours at 125°C, 3 days at 95°C, and 6 days at 95°C. Each mixture was tested in the IDEAL-CT after being subjected to the selected loose mix aging procedures, and the results were analyzed to determine the equivalent aging temperature of the 20-hour aging procedure that best simulated loose mix aging for 3 and 6 days at 95°C.

Table 3. Summary of Asphalt Mixtures used in the TTI Study by Zhou et al. (2023)

Mix ID	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Mix 6	Mix 7
Mixture Type	HMA	HMA	HMA	HMA	HMA	HMA	HMA
Aggregate	Igneous	Igneous	Igneous	Igneous	Igneous	Igneous	Granite
NMAS	9.5 mm	9.5 mm	9.5 mm	9.5 mm	9.5 mm	9.5 mm	9.5 mm
Virgin Binder	PG 64-22 (Source 1)	PG 64-22 (Source 2)	SHRP AAG	SHRP AAD	PG 76-22 (Source 3)	PG 76-28 (Source 4)	PG 64-28 (Source 5)
RAP	-	-	-	-	-	-	15%
RAS	-	-	-	-	-	-	-
Additive	-	-	-	-	-	-	-

Figure 14 presents the IDEAL-CT results of Mix 1 as an example to illustrate the determination of the equivalent 20-hour loose mix aging temperature. In this case, based on interpolation of the IDEAL-CT results, 20 hours of loose mix aging at 112°C was found to be equivalent to 3 days of loose mix aging at 95°C while 20 hours of loose mix aging at 120°C was equivalent to 6 days of loose mix aging at 95°C. Table 4 summarizes the equivalent aging temperatures for all the mixtures evaluated. As shown, the equivalent 20-hour aging temperature for the 3-day, 95°C loose mix aging was either 110 or 112°C, while that for the 6-day, 95°C loose mix aging was 120°C. These results indicate that the equivalent aging temperature is not mixture specific. The aging equivalency relationships in Table 4 were also validated by the I-FIT and OT results of two mixtures containing a highly polymer-modified asphalt (HiMA) binder.

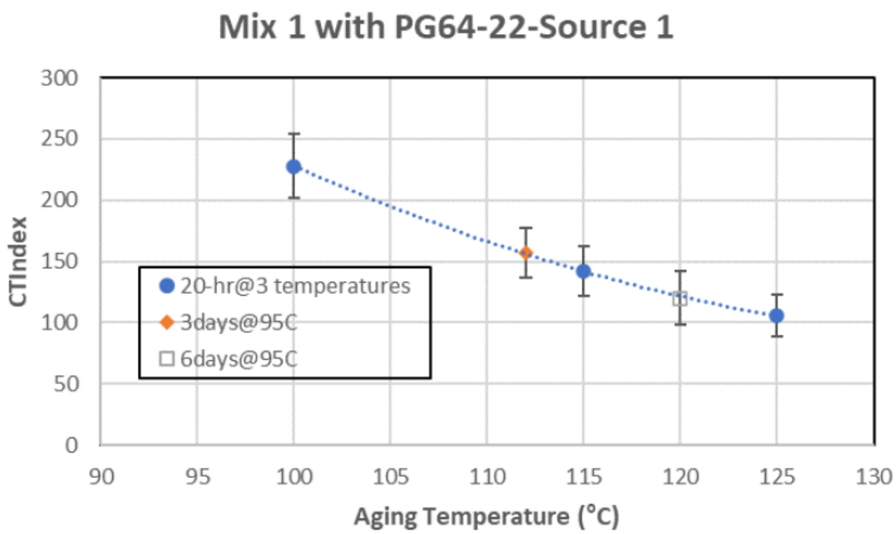


Figure 14. Determination of Equivalent 20-hour Loose Mix Aging Temperature for Mix 1 (Zhou et al., 2022)

Table 4. Summary of Equivalent 20-hour Loose Mix Aging Temperature (Zhou et al., 2022)

Mix ID	Equivalent Aging Temperature for 3-day at 95°C (°C)	Equivalent Aging Temperature for 6-day at 95°C (°C)
Mix 1	112	120
Mix 2	110	120
Mix 3	112	120
Mix 4	110	120
Mix 5	112	120
Mix 6	112	120
Mix 7	112	120

Upon completing the laboratory testing, a correlation between the 95°C loose mix aging procedure (at various times) and the 20-hour loose mix aging procedure (at various temperatures) was developed, shown in Figure 15. Data in yellow markers represent the “theoretical” prediction results based on the kinetics model developed in NCHRP project 9-54, while data in blue markers represent the “corrected” prediction results based on the IDEAL-CT results of this study and a previous study by Zhou et al. (2021). Using the “corrected” prediction results, a 20-hour loose mix aging map was developed, as shown in Figure 16. The map is color coded to indicate the recommended oven aging temperature for the 20-hour aging procedure that is required to simulate 12 years of field aging at 50 mm below pavement surface. This field aging condition was selected because it represents a critical pavement in-service time and location in the pavement structure for the evaluation of bottom-up fatigue cracking in asphalt pavements.

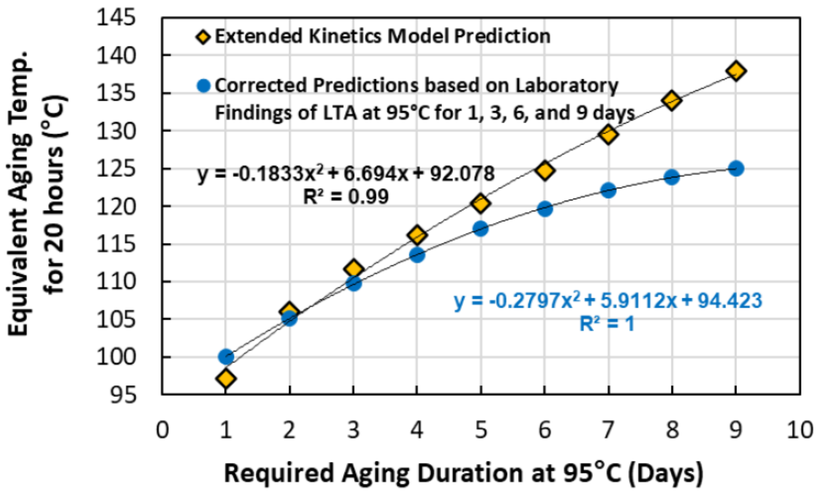


Figure 15. Correlation between Loose Mix Aging at 95°C and 20-hour Loose mix Aging (Zhou et al., 2022)

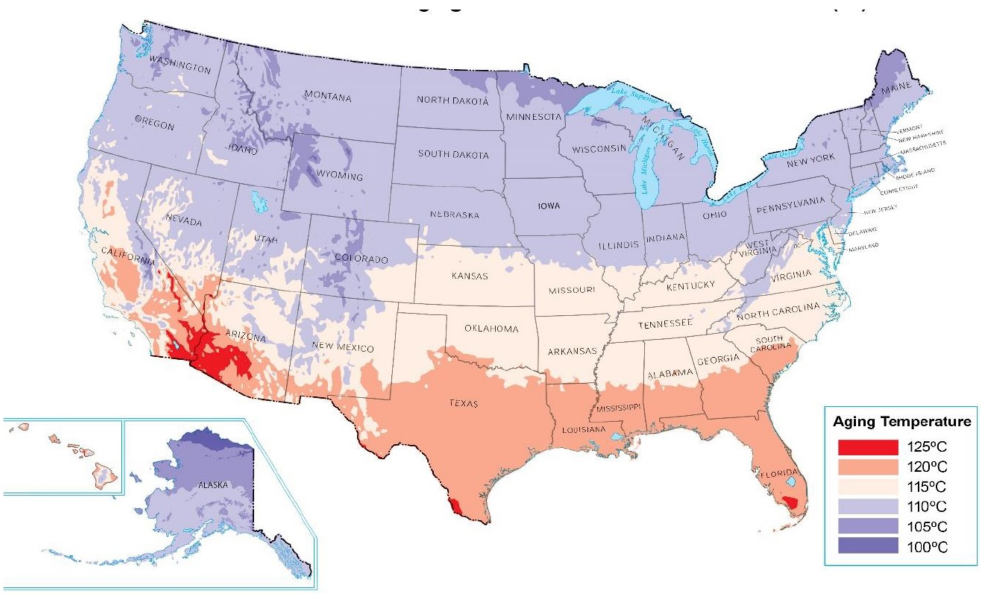


Figure 16. Field Aging Map of Proposed 20-hour Loose Mix Aging Temperature to Match 12 Years of Field Aging at 50mm below Pavement Surface (Zhou et al., 2022)

2.1.4 Loose Mix Aging at 135°C

Braham et al. (2009) is arguably the first documented study on using loose mix aging at 135°C for long-term aging of asphalt mixtures. They evaluated the impact of loose mix aging at 135°C for 6 to 48 hours on the Disc-shaped Compact Tension (DCT) fracture energy (G_f) of an asphalt mixture from MnROAD. The mixture was a 12.5mm NMAS virgin mix with an unmodified PG 58-28 binder. In addition to the lab-aged specimens, field cores after 6 years in-service were also collected and tested to represent field-aged samples of the mixture. Figure 17 presents the DCT G_f results of the laboratory- and field-aged samples. As shown, loose mix aging for 24 hours at 135°C was representative of approximately 6 years of field aging in Minnesota in terms of their impacts on the thermal cracking resistance of the mixture.

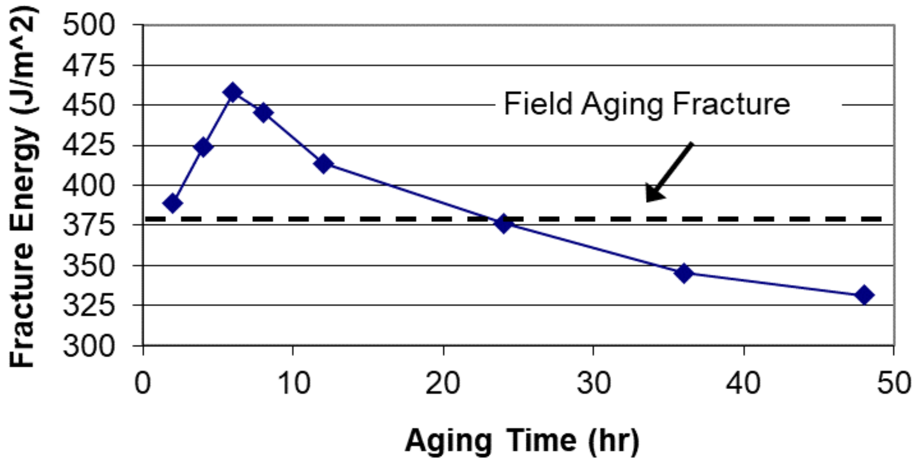


Figure 17. DCT G_f Result of Laboratory- and Field-Aged Samples for an Asphalt Mixture from MnROAD (Braham et al., 2009)

Three additional virgin mixtures from MnROAD were tested with the DCT to further verify this lab-to-field aging relationship. These mixtures, referred to as M3, M4, and M5, used the same aggregates (i.e., gravel) with an identical gradation structure but varied in the asphalt binder grade. One of them used an unmodified PG 58-28 binder, while the other two used SBS modified binders with a PG 58-34 and PG 58-40 grade, respectively. Each mixture was tested with the DCT at three laboratory aging conditions: unaged (i.e., reheating only), compacted specimen aging for 5 days at 85°C per AASHTO R 30, and loose mix aging for 24 hours at 135°C. Furthermore, the 6-year-old field cores of these mixtures were also tested to represent the field aging sample. Figure 18 presents the DCT G_f results of the three mixtures at various aging conditions. For mixtures M3 and M5, loose mix aging for 24 hours at 135°C was approximately equivalent to 6 years of field aging in Minnesota, while for mixture M4, the loose mix aging procedure was found to be more severe than the 6-year field aging in Minnesota as indicated by a significantly lower DCT G_f result.

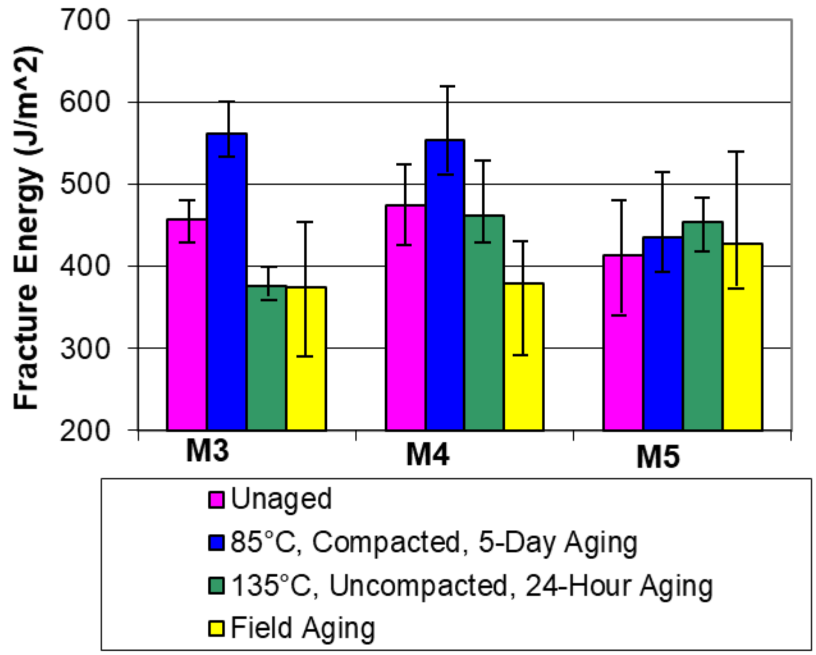
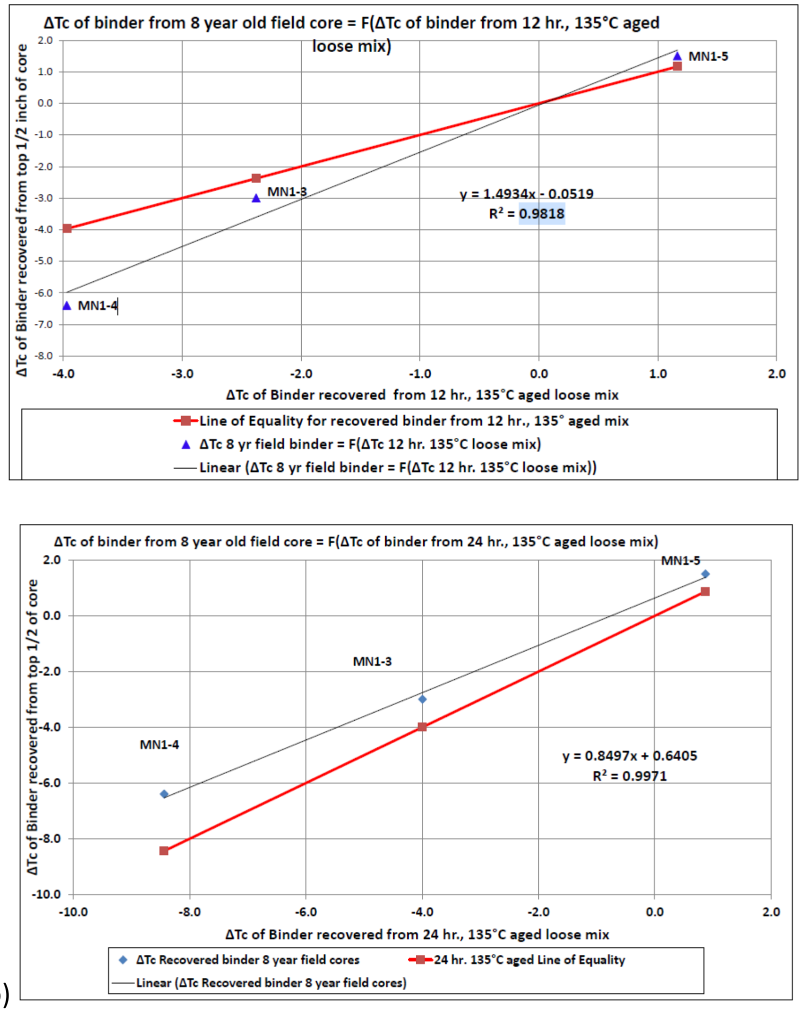


Figure 18. DCT G_f Results of Laboratory- and Field-Aged Samples for Three Asphalt Mixtures from MnROAD (Braham et al., 2009)

In addition to the DCT test, asphalt binders were extracted and recovered from the three mixtures and tested with the Double Edge Notched Tension (DENT), Direct Tension (DTT), and Bending Beam Rheometer (BBR) tests for binder rheological characterization. However, the binder results disagreed with the mixture DCT G_f results in comparing the various aging conditions. Although there was no consistent trend among the binder results, in most cases, loose mix aging for 24 hours at 135°C overpredicted the level of asphalt aging compared to 6 years of field aging in Minnesota. Based on these results, the study concluded that it might be very difficult to develop a highly accelerated aging procedure that could yield laboratory samples with binder and mixture properties that are representative of field samples.

In a study by Reinke et al. (2015), three asphalt mixtures from MnROAD (denoted as MN 1-3, 1-4, and 1-5) were subjected to loose mix aging for 12 and 24 hours at 135°C. All three mixtures used a PG 58-28 binder but from different sources. One of them was modified with re-refined engine oil bottom (REOB) while the other two were unmodified binders. After loose mix aging, asphalt binders were extracted and recovered from these mixtures and then tested with BBR to determine the ΔTc. As shown in Figure 19, asphalt binders recovered from the 24-hour, 135°C loose mix aged samples had consistently the lowest (i.e., most negative) ΔTc values, followed by those recovered from the top ½ inch of the 6-year field core, and those recovered from 12-hour, 135°C loose mix aged samples. These results indicated that loose mix aging for 24 hours at 135°C was more severe than 6 years of surface field aging in Minnesota, but loose mix aging for 12 hours at 135°C was not as severe as the 6-year field aging.



(a) (b)

Figure 19. ΔTc Results of Extracted and Recovered Asphalt Binders from Laboratory- and Field-aged Samples for Three Asphalt Mixtures from MnROAD; (a) Loose Mix Aging for 12 Hours at 135°C, (b) Loose Mix Aging for 24 Hours at 135°C (Reinke et al., 2015)

As part of the 2015 Top-down Cracking Group Experiment on the NCAT Test Track, Chen et al. (2018) at NCAT evaluated four loose mix aging procedures for five plant-produced mixtures from field projects in Alabama, Michigan, and Washington. These aging procedures included 5 days at 95°C, 6 hours at 135°C, 12 hours at 135°C, and 24 hours at 135°C. Table 5 summarizes the mixture type and material components of the five mixtures. For each mixture, the plant mix sampled during construction of the field project was long-term aged in accordance with the selected aging procedures. After aging, asphalt binders were extracted and recovered from the loose mix samples and tested to determine their rheological and chemical properties using the Dynamic Shear Rheometer (DSR), BBR, and Fourier-transform Infrared Spectroscopy (FTIR). Testing was also conducted on asphalt binders extracted and recovered from the field cores to represent field aging samples. The age of the field cores varies from 6 to 14 years among the five mixtures.

Table 5. Summary of Asphalt Mixtures used in the NCAT Study by Chen et al. (2018)

Mix ID	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5
Location	Rapid River, Michigan	Walla Walla, Washington	Auburn, Alabama	Auburn, Alabama	Auburn, Alabama
Mixture Type	HMA	HMA	HMA	HMA	HMA
Aggregate Type					
NMAS	12.5 mm	12.5 mm	9.5 mm	12.5 mm	12.5 mm
Virgin Binder	PG 52-34	PG 64-28	PG 76-22 (SBS)	PG 67-22	PG 67-22
RAP	17%	20%	-	20%	-
Additive	-	-	-	-	-

Test results indicated that loose mix aging temperature did not significantly change the oxidation kinetics of the extracted asphalt binders according to the Glower-Rowe Hardening Susceptibility (*G-R HS*) parameter, which was defined as the ratio of change in the logarithm of the Glover-Rowe parameter over the change in the FTIR carbonyl area with aging (Yin et al., 2017). Among the different aging procedures evaluated in the study, loose mix aging for 24 hours at 135°C yielded the most severe level of aging, followed by aging for 12 hours at 135°C, 5 days at 95°C, and 6 hours at 135°C, respectively. Furthermore, the 5-day, 95°C and 8-hour, 135°C aging procedures were found to be equivalent, in terms of their impacts on the high-temperature continuous grade, the Glower-Rowe parameter, and FTIR carbonyl area of the extracted asphalt binders.

Regarding the lab-to-field aging correlation, both the 5-day, 95°C and 8-hour, 135°C aging procedures were expected to simulate approximately 70,000 CDD of field aging. According to the field cracking data for over 80 pavement sections in NCHRP project 9-49A (Shen et al. 2017), 70,000 CDD represented a critical field aging condition for evaluating top-down cracking in asphalt pavements. Figure 20 presents a map showing the number of years required for different states to reach 70,000 CDD based on the 2016 climate data. As shown, states with warm climates typically need 4 to 5 years to achieve 70,000 CDD while states with cold climates require up to 10 years.

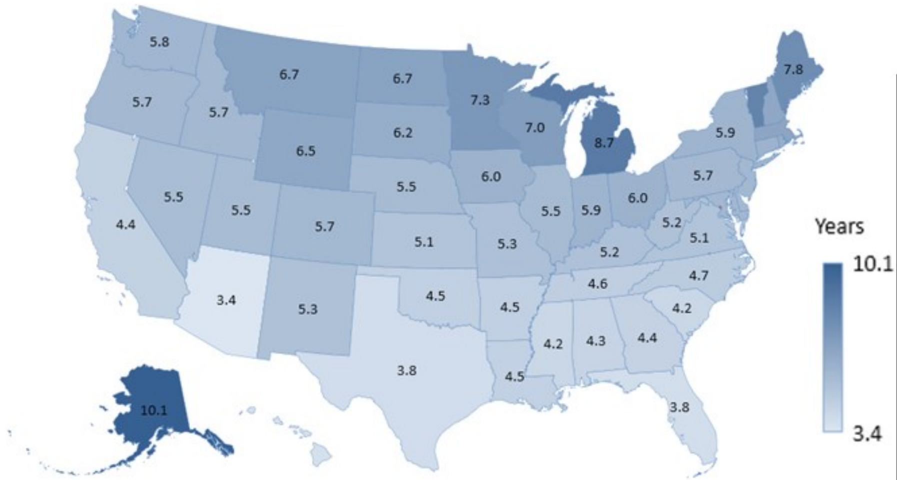


Figure 20. Map of Field Aging Time required to Reach 70,000 CDD (Chen et al., 2018)

A follow-up study by Chen et al. (2020), based on collaboration between NCAT and FHWA's Turner-Fairbank Highway Research Center (TFHRC), sought to validate the two aging procedures (i.e., 8 hours at 135°C and 5 days at 95°C) recommended in the 2015 Top-down Cracking Group Experiment. Four surface mixtures on the NCAT Test Track were included in this validation study, which are summarized in Table 6. For each mixture, PMLC specimens with three different aging conditions (i.e., unaged, 8-hour, 135°C loose mix aged, and 5-day, 95°C loose mix aged) were tested with the I-FIT, IDEAL-CT, and small-specimen DTCF tests. Furthermore, asphalt binders were extracted and recovered from the PMLC specimens at different loose mix aging conditions and up to 4-year-old field cores, and then tested for rheological characterization using the DSR, BBR, and DENT tests.

Table 6. Summary of Asphalt Mixtures used in the NCAT-TFHRC Study by Chen et al. (2020)

Mix ID	N1	N8	S5	S6
Mixture Type	HMA	HMA	HMA	HMA
Aggregate Type				
NMAS	9.5 mm	9.5 mm	9.5 mm	9.5 mm
Virgin Binder	PG 67-22	PG 67-22	PG 58-28 (SBS)	PG 94-22 (HiMA)
RAP	20%	20%	35%	20%
RAS	-	5%	-	-
Additive	-	-	-	-

Test results indicated that the comparison between the 5-day, 95°C and 8-hour, 135°C loose mix aging procedures varied among the different binder and mixture properties evaluated in the study. Specifically, the two aging procedures yielded similar I-FIT and IDEAL-CT results. The DTCF and DENT test results, however, identified more significant deterioration in the fatigue and cracking resistance of Mix S6 (with a HiMA binder) when aged at 135°C than at 95°C. These results raised the concern that the 135°C loose mix aging procedure might not be appropriate for use with HiMA mixtures due to the potential thermal degradation of SBS at such an elevated temperature. Finally, the two loose mix aging procedures were found to yield a more severe level of asphalt aging than 4 years of surface field aging (for the top 1.0 to 1.5 inches of asphalt pavements) on the NCAT Test Track. According to the most recently obtained I-FIT results in Figure 21, loose mix aging for 8 hours at 135°C or 5 days at 95°C is representative of approximately 85,000 CDD of field aging, which corresponds to slightly over 5 years in Alabama.

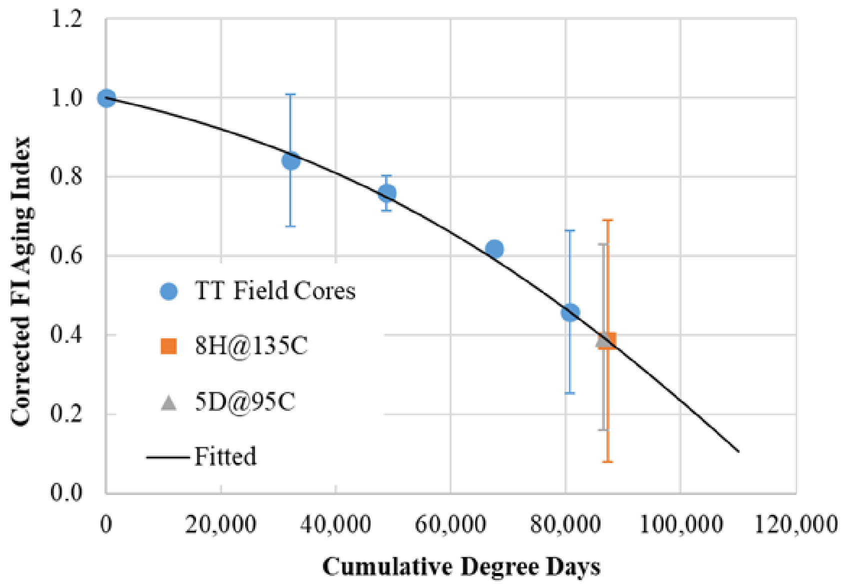


Figure 21. Correlation of Field Aging on the NCAT Test Track to Laboratory Loose Mix Aging for 8 Hours at 135°C and 5 Days at 95°C

2.1.5 Comparison of Loose Mix Aging at 95°C versus 135°C

As discussed in the previous sections, loose mix aging at 95°C and 135°C have been the two most used aging procedures for simulating the long-term aging of asphalt mixtures among the literature. In general, loose mix aging at 95°C is considered a more accurate procedure in terms of its ability to predict the properties of asphalt binders and mixtures for pavement performance prediction purposes. Loose mix aging at 135°C, on the other hand, is considered a more practical procedure for use with mixture performance testing for asphalt mix design and production. Over recent years, several studies have evaluated these two loose mix aging procedures and compared their impacts on the performance properties of asphalt mixtures and in some cases, the rheological and chemical properties of the extracted asphalt binders. Major findings of these studies are summarized in Table 7.

Table 7. Summary of Existing Studies on Loose Mix Aging at 95°C versus 135°C

Reference	Mixture Tests and Properties Measured	Binder Tests and Properties Measured	Major Findings on Comparison Level of Asphalt Aging)
Chen et al. (2018)	-	PG grade, ΔTc, Glover-Rowe (*G-R*) parameter, FTIR carbonyl area	6 hours at 135°C < 5 days at 95°C < 12 hours at 135°C < 24 hours at 135°C
Rahbar-Rastegar et al. (2018)	E*, DCT, I-FIT	-	5 days at 95°C < 12 hours at 135°C < 24 hours at 135°C
Rahbar-Rastegar et al. (2019)	E*, DTCF, I-FIT	PG grade, ΔTc, *G-R* parameter, R-value	5 days at 95°C < 12 hours at 135°C ≈ 24 hours at 135°C
Chen et al. (2020)	IDEAL-CT, I-FIT	-	5 days at 95°C ≈ 8 hours at 135°C
Li et al. (2020)	E*	-	7 days at 95°C < 24 hours at 135°C
Ningappa and Suresha (2020)	DSR temperature, frequency, and time sweep tests (FAM mixture)	-	5 days at 95°C < 6 hours at 135°C < 12 hours at 135°C < 24 hours at 135°C ≈ 12 days at 95°C
Zhang (2020)	E*	Linear viscoelastic properties	12 days at 95°C ≈ 24 hours at 135°C
	DCT, I-FIT	-	12 days at 95°C < 24 hours at 135°C
Elwardany et al. (2021)	DTCF	-	3 days at 95°C < 8 hours at 135°C
	IDEAL-CT, I-FIT	-	3 days at 95°C > 8 hours at 135°C
Epps Martin et al. (2021)	IDEAL-CT		3 days at 95°C ≈ 6 hours at 135°C
Elwardany et al. (2022)	E*, IDEAL-CT, I-FIT, DTCF	DENT	3-4 days at 95°C ≈ 8 hours at 135°C
Screedhar and Coleri (2022)	I-FIT	-	12 hours at 95°C < 1 day at 95°C < 3 days at 95°C ≈ 6 hours at 135°C < 12 hours at 135°C

Elwardany et al. (2021) applied the kinetics model developed in NCHRP project 9-54 to correlate loose mixture aging procedures at 95°C and 135°C, and the results are summarized in Table 8. As shown, to achieve the same level of aging, significantly shorter aging times are required for loose mix aging at 135°C than 95°C. For example, the kinetics model predicts an approximate aging equivalency between 5 days at 95°C and 8 hours at 135°C. In general, the predicted aging equivalency relationships based on the kinetics model agree reasonably with the research findings in Table 7. Nevertheless, the predicted aging equivalency among the different loose mix aging procedures should be interpreted with caution as it could vary for asphalt mixtures with different components and mix design variables, especially those containing RAP, RAS, and/or additives.

Table 8. Predicted Equivalent Aging Times for Loose Mixture Aging at 95°C versus 135°C (Elwardany et al., 2021)

Loose Mixture Aging Time at 95°C (days)	Loose Mixture Aging Time at 135°C (hours)
1	1
2	2
3	4
4	6
5	8
6	11
7	15
8	19
9	23
10	27

2.2 Impact of Loose Mix Aging on Asphalt Binder and Mixture Properties

2.2.1 Impact of Loose Mix Aging on Properties of Asphalt Mixtures

This section synthesizes existing studies that evaluate the impact of loose mix aging on the performance properties of asphalt mixtures using different mixture performance tests.

2.2.1.1 Intermediate-Temperature Cracking Resistance

Zhou et al. (2021) used the IDEAL-CT to evaluate the intermediate-temperature cracking resistance of 13 overlay mixes from Texas and Massachusetts at different aging conditions. Each mixture was short-term aged for 2 hours at compaction temperature and then subjected to four loose mix aging procedures: 20 hours at 100°C, 24 hours at 95°C, 72 hours at 95°C, and 144 hours at 95°C. As shown in Figure 22(a), for all the mixtures, loose mix aging had a detrimental impact on the mixture cracking resistance as indicated by lower cracking tolerance index (CT_{Index}) values. The reduction in the average CT_{Index} from short-term aging to loose mix aging ranged from 20% to 80% among the different mixtures and different aging procedures. These results indicated that the CT_{Index} parameter was able to discriminate the intermediate-temperature cracking resistance of asphalt mixtures subjected to different loose mix aging procedures.

In a different study, Zhou et al. (2023) conditioned seven dense-graded mixtures using five different loose mix aging procedures: 72 hours at 95°C, 144 hours at 95°C, and 20 hours at 100°C, 115°C, and 125°C. The intermediate-temperature cracking resistance of these mixtures was evaluated using the IDEAL-CT. As shown in Figure 22(b) for one of the selected mixtures, the CT_{Index} parameter was able to discriminate the various loose mix aging procedures. Furthermore, the CT_{Index} decreased as the aging temperature increased among the 20-hour aging procedures, which indicated a proper sensitivity to aging temperature.

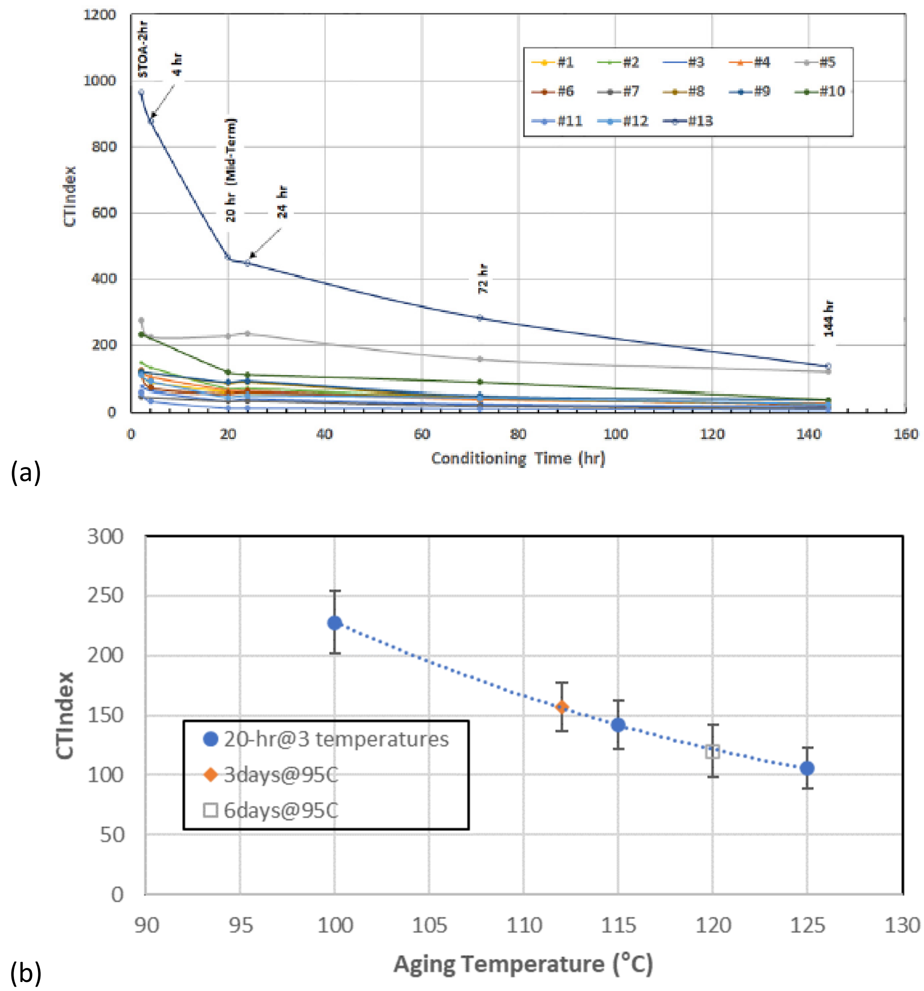


Figure 22. Effect of Loose Mix Aging on IDEAL-CT Results (Zhou et al., 2021; Zhou et al., 2022)

Chen et al. (2020) used the IDEAL-CT to evaluate the effect of loose mix aging on the intermediate-temperature cracking resistance of four plant-produced mixtures on the NCAT Test Track. Two loose mix aging procedures were included: 5 days at 95°C and 8 hours at 135°C. For all the mixtures evaluated, loose mix aging yielded significantly reduced CT_{Index} results, indicating a detrimental impact on the mixture cracking resistance. Mensching et al. (2022) reported similar conclusions based on the IDEAL-CT testing of five plant-produced mixtures conditioned with two loose mix aging procedures: 3 days at 95°C and 8 hours at 135°C.

Sreedhar and Coleri (2022) used the I-FIT to evaluate the impact of loose mix aging on the intermediate-temperature cracking resistance of asphalt mixtures. In the first part of the study, six laboratory-prepared mixtures containing two binder types and three RAP contents were conditioned with seven loose mix aging procedures at three temperatures: 120 hours at 85°C; 12, 24, and 72 hours at 95°C; and 6, 12, and 24 hours at 135°C. As shown in Figure 23(a), the flexibility index (FI) of these mixtures generally decreased as the loose mix aging time increased, but the mixtures containing the PG 76-22 virgin binder and 30% or 40% RAP had similar FI results among the different aging procedures at 135°C. In the second part of the study, five plant-produced mixtures were conditioned with five selected loose mix aging procedures prior to being tested in I-FIT; these aging procedures included 6 and 12 hours at 135°C; and 12, 24, and 72 hours at 95°C. As shown in Figure 23(b), for all the mixtures, longer aging procedures at the same temperature yielded reduced cracking resistance as indicated by lower FI values. Overall, this study indicated that the FI parameter from the I-FIT was sensitive to loose mix aging and was able to discriminate asphalt mixtures conditioned with different aging procedures.

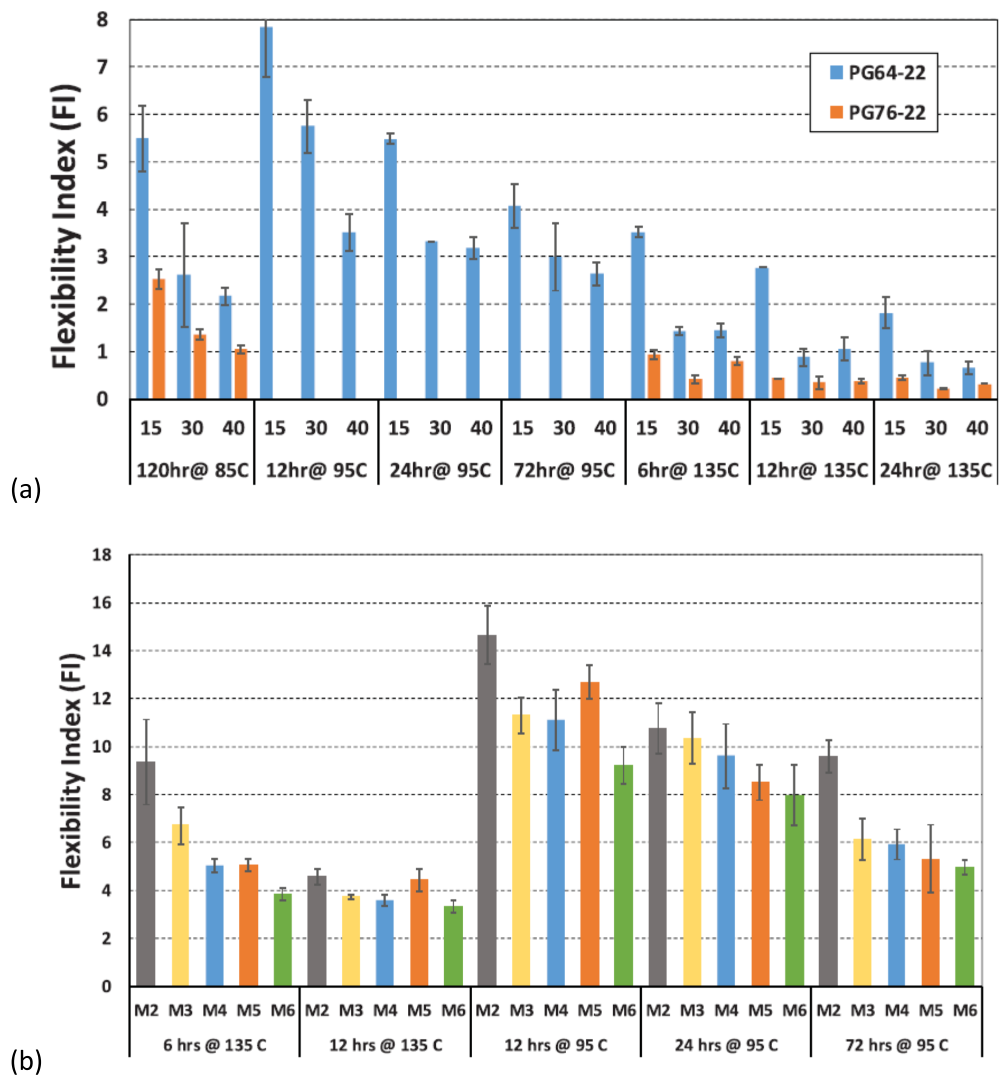


Figure 23. Effect of Loose Mix Aging on I-FIT Results (Sreedhar and Coleri, 2022)

Zhou et al. (2022) used the I-FIT to evaluate the effect of loose mix aging at 135°C on the cracking resistance of 12 dense-graded mixtures containing different binder types, RAP contents, and rejuvenator dosage levels. Test results consistently showed that the FI decreased (indicating reduced cracking resistance) as the aging time and RAP content increased. Other studies evaluating the impact of loose mix aging at 95°C and 135°C on the I-FIT results of plant-produced mixtures also reported similar conclusions that the FI decreased as the loose mix aging time and/or temperature increased (Yin et al., 2017; Rahbar-Rastegar et al., 2018; Rahbar-Rastegar et al., 2019; Chen et al., 2020; Zhang, 2020; Zhou et al., 2020; Mensching et al., 2022).

Besides the IDEAL-CT and I-FIT, asphalt researchers have also used the OT, the Energy Ratio (ER) test, and the Louisiana Semi-Circular Bend (LA-SCB) test to evaluate the impact of loose mix aging at 135°C on the intermediate-temperature cracking resistance of asphalt mixtures (Blankenship, 2015; Hanz et al., 2017; Chen, 2020). In general, these studies showed that the OT was sensitive to loose mix aging at 135°C, while the LA-SCB and ER tests were not.

2.2.1.2 Low-temperature Cracking Resistance

Blankenship and Zeinali (2016) used the DCT to evaluate the low-temperature cracking resistance of laboratory-prepared asphalt mixtures from Kentucky with asphalt binders from different sources. All the mixtures were subjected to four loose mix aging procedures for up to 48 hours at 135°C prior to being tested in DCT at three test temperatures. Test results showed that the G_f of the mixtures generally decreased as the loose mix aging time increased, but for a few mixtures, the G_f increased for up to 4 hours of loose mix aging at 135°C and then decreased afterwards. Similar observations were also reported by Braham et al. (2009) based on the DCT testing of a 12.5 mm NMAS dense-graded mixture conditioned with loose mix aging for up to 48 hours at 135°C.

Rahbar-Rastegar et al. (2018) used the DCT to evaluate the effect of loose mix aging on the low-temperature cracking resistance of ten plant-produced mixtures from New Hampshire. Three loose mix aging procedures were included: 5 days at 95°C, 12 days at 95°C, and 24 hours at 135°C. Test results indicated that the G_f and fracture strain tolerance (FST) of the mixtures decreased (indicating reduced low-temperature cracking resistance) as the severity of the aging procedures increased. Similar findings were also reported by Blankenship (2015), Hanz et al. (2017), and Zhang (2020) based on the DCT testing of asphalt mixtures conditioned with various loose mix aging procedures at 95°C and 135°C.

Mensching et al. (2017) used the Thermal Stress Restrained Specimen Test (TSRST) to evaluate the low-temperature cracking resistance of four laboratory-prepared asphalt mixtures at various REOB contents. The mixtures were tested at two loose mix aging conditions: short-term aging for 4 hours at 135°C and long-term aging for 24 hours at 135°C. Test results showed that the 24-hour, 135°C aging reduced the low-temperature cracking resistance of the mixtures as indicated by higher fracture temperature results.

Sahebzamani et al. (2020) used the Low-temperature Semi-Circular Bend (LT-SCB) test to evaluate the low-temperature cracking resistance of asphalt mixtures and found that loose mix aging at 95°C had a detrimental impact as the specimens after aging had lower failure deformation results than the specimens before aging.

2.2.1.3 Cyclic Fatigue Resistance

Saleh et al. (2020) used the DTCF test to evaluate the cyclic fatigue resistance of 11 laboratory-prepared mixtures after short-term aging for 4 hours at 135°C and long-term aging for up to 21 days at 95°C. Test results showed that all the long-term aged specimens had reduced fatigue resistance compared to the short-term aged specimens based on the fatigue damage capacity index (S_{app}), and that the fatigue resistance of the mixtures decreased as the duration of the 95°C loose mix aging procedures increased.

Mensching et al. (2022) used the DTCF test to evaluate the cyclic fatigue resistance of five plant-produced mixtures conditioned with two loose mix aging procedures: 3 days at 95°C and 8 hours at 135°C. For all the mixtures evaluated, the specimens after aging had lower S_{app} values than the reheated specimens, which indicated that the S_{app} parameter was sensitive to loose mix aging at 95°C and 135°C. Similar conclusions were also obtained by Chen et al. (2020) based on the DTCF testing of four plant-produced mixtures conditioned with loose mix aging for 5 days at 95°C and 8 hours at 135°C.

Mensching et al. (2017) and Jia et al. (2022) used the DTCF test to evaluate the cyclic fatigue resistance of laboratory-prepared mixtures containing REOBs and fibers, respectively, and found that loose mix aging at 95°C and 135°C had a negative impact on the fatigue resistance of the mixtures as indicated by lower number of cycles to failure (N_f).

Rahbar-Rastegar et al. (2019) and Zhang (2020) used the D^R parameter from the DTCF test to evaluate the cyclic fatigue resistance of plant-produced mixtures conditioned with loose mix aging for 24 hours at 135°C, 5 days at 95°C, and 12 days at 95°C, where D^R was defined as the average reduction in pseudo stiffness up to the failure point. Both studies found that for the same mixtures, the specimens corresponding to more severe aging procedures generally had lower average D^R values (indicating poorer fatigue resistance), but the differences were not statistically significant if the test variability was considered.

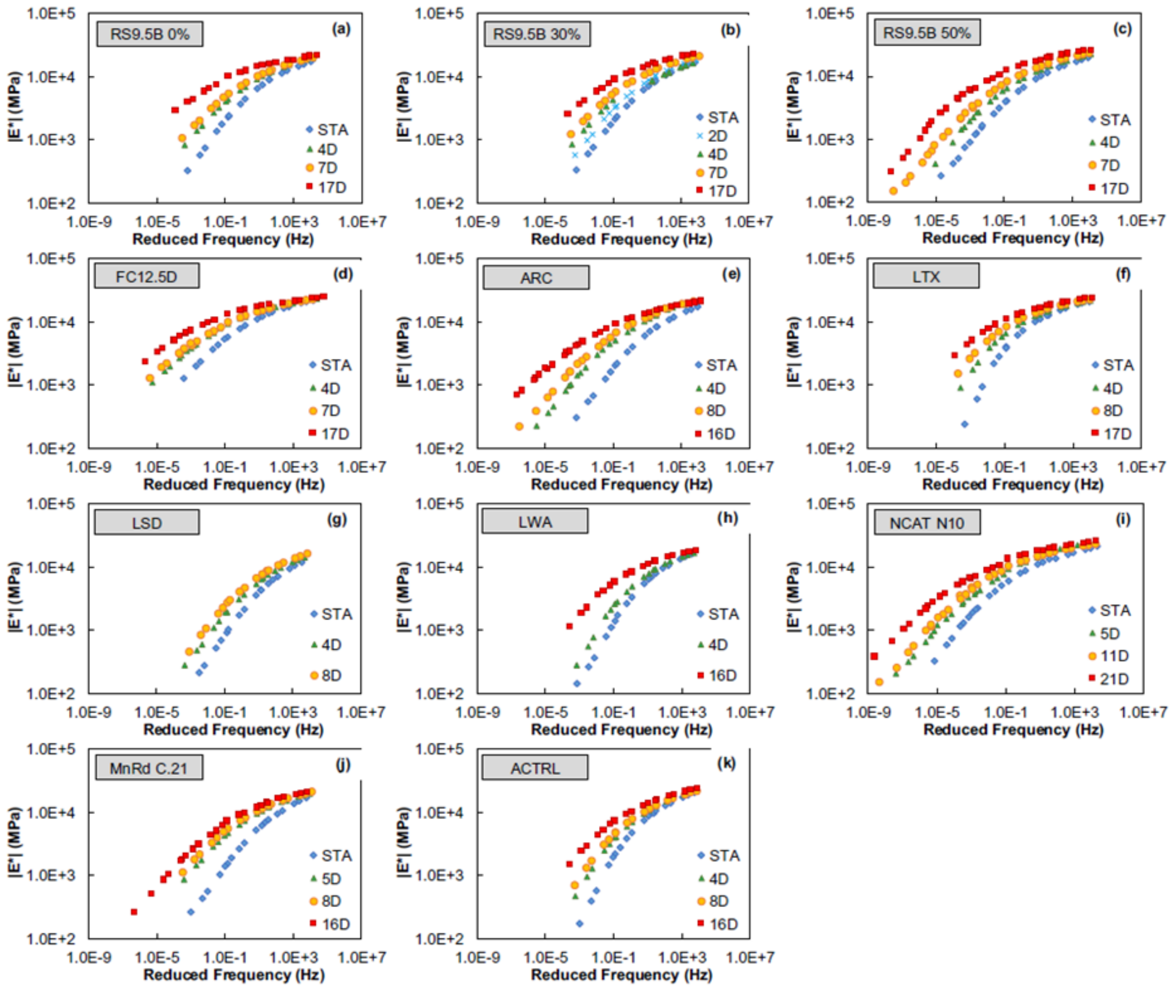
Islam and Tarefder (2015) used the Bending Beam Fatigue (BBF) test to assess the impact of loose mix aging on the cyclic fatigue resistance of a Superpave dense-graded mixture. The mixture was subjected to loose mix aging for up to 100 hours at 135°C prior to being tested. Test results showed that the flexural stiffness of the mixture increased dramatically as the aging time increased. In addition, loose mix aging at 135°C significantly reduced the fatigue life of the mixture, which was consistent with the findings of Blankenship (2015) based on the BBF testing of asphalt mixtures conditioned with loose mix aging for up to 24 hours at 135°C.

Diab et al. (2019) used the Diametral Fatigue test to evaluate the effects of polymer modification and loose mix aging on the cyclic fatigue resistance of 13 laboratory-prepared asphalt mixtures. The mixtures were prepared using a Marshall mix design and with six polymer modifiers at various contents. Each mixture was tested at two loose mix aging conditions: short-term aging for 4 hours at 160°C and long-term aging for 16 hours at 160°C. Test results showed that loose mix aging at 160°C had a detrimental effect on the fatigue resistance of the mixtures, as indicated by lower cycles to failure.

Arega et al. (2013) used the Dynamic Mechanical Analyzer (DMA) Fatigue test to assess the effect of loose mix aging for 30 days at 60°C on the cyclic fatigue resistance of fine aggregate matrix (FAM) mixtures. Twelve FAM mixtures were prepared with five WMA additives and two binder types. Test results showed that loose mix aging at 60°C did not significantly affect the fatigue life of the FAM mixtures, which highlighted the potential lack of sensitivity of the DMA Fatigue test to loose mix aging.

2.2.1.4 Rheological Properties

Saleh et al. (2020) used the E* test to assess the stiffness and viscoelasticity properties of 11 laboratory-prepared asphalt mixtures with a wide range of mixture components and mix design variables. Prior to testing, the mixtures were short-term aged for 4 hours at 135°C followed by long-term loose mix aging for up to 21 days at 95°C. As shown in Figure 24, for all the mixtures evaluated, the E* stiffness increased, and the phase angle (δ) decreased as the 95°C loose mix aging time increased. The impact of loose mix aging on the E* test results at low reduced frequencies was more pronounced than those at high reduced frequencies. This trend was expected because mixture stiffness at low reduced frequencies depended more on the stiffness of the asphalt binder, which was highly susceptible to aging. Several other studies reported similar findings that loose mix aging at 85°C to 160°C had a stiffening impact on asphalt mixtures as indicated by higher E* and lower δ results (Mensching et al., 2017; Li et al., 2020; Sirin et al., 2020; Jia et al., 2022; Sahebzamani et al., 2020).


RS9.5B 0%
(a)
STA
4D
7D
17D
RS9.5B 30%
(b)
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RS9.5B 50%
(c)
STA
4D
7D
17D
FC12.5D
(d)
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4D
7D
17D
ARC
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4D
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4D
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4D
8D
LWA
(h)
STA
4D
16D
NCAT N10
(i)
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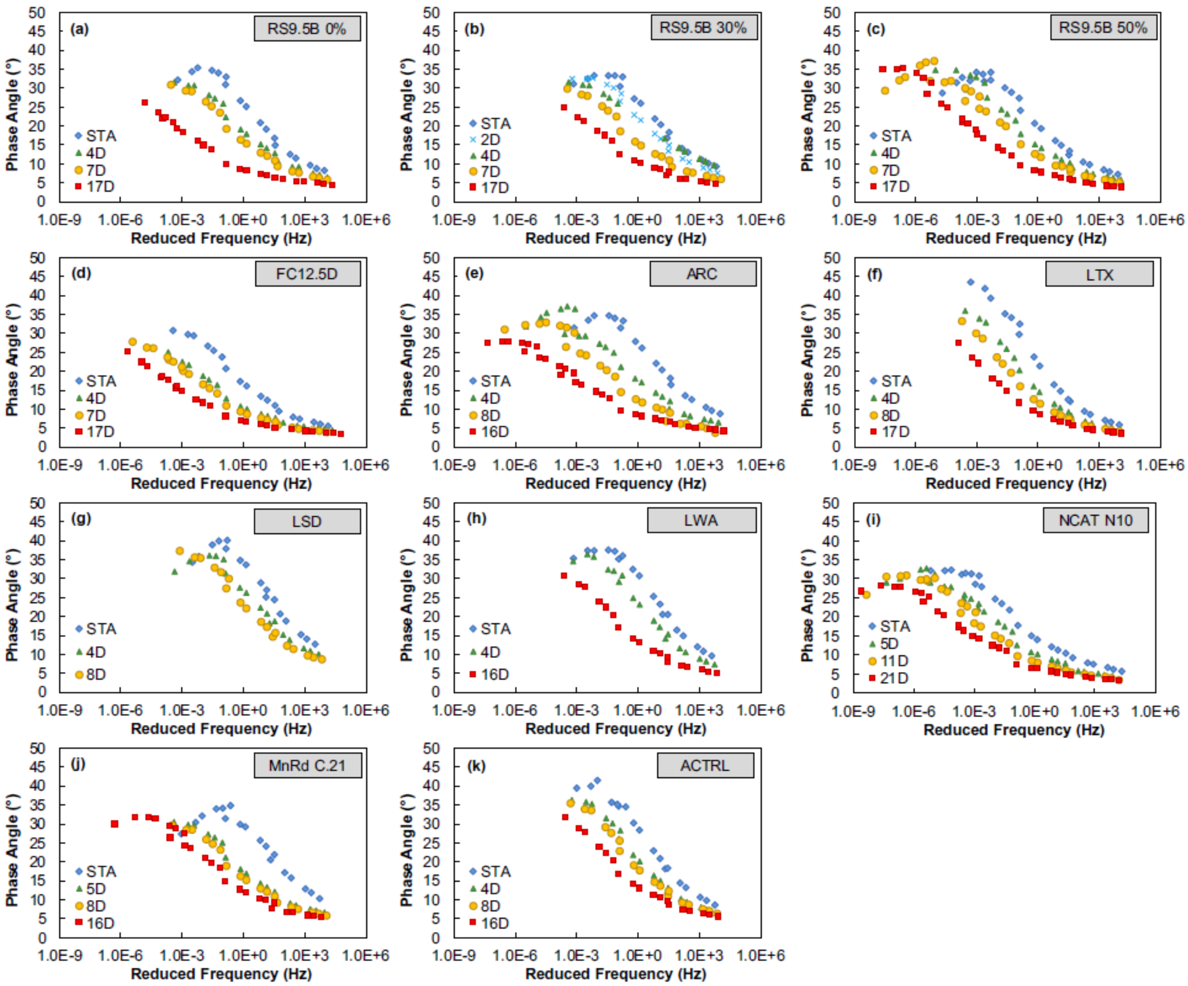
5D
11D
21D
MnRd C.21
(j)
STA
5D
8D
16D
ACTRL
(k)
STA
4D
8D
16D
|E*| (MPa)
1.0E+2
1.0E+3
1.0E+4
1.0E+5
Reduced Frequency (Hz)
1.0E-9
1.0E-5
1.0E-1
1.0E+3
1.0E+7

(a)



(b)

Figure 24. Effect of Loose Mix Aging at 95°C on E* Test Results; (a) Dynamic Modulus, (b) Phase Angle (Saleh et al., 2020)

Mensching et al. (2022) used the |E*|/sin(δ) parameter from the E* test to evaluate the stiffness properties of five plant-produced mixtures and found that loose mix aging for 3 days at 95°C and 8 hours at 135°C significantly increased the stiffness and brittleness of the mixtures as indicated by higher |E*|/sin(δ) results.

Rahbar-Rastegar et al. (2018), Rahbar-Rastegar et al. (2019), and Zhang (2020) used the Mixture Glover-Rowe ($G\text{-}R_m$) parameter from the E* test to characterize the stiffness and brittleness behavior of several plant-produced mixtures conditioned with loose mix aging at 95°C and 135°C. The $G\text{-}R_m$ parameter was calculated based on the E* and δ results at 20°C and 5 Hz, where a higher $G\text{-}R_m$ value indicated higher mixture stiffness and brittleness and potentially higher susceptibility to block cracking. Test results showed that the $G\text{-}R_m$ parameter was sensitive to loose mix aging and was able to discriminate different aging procedures at 95°C and 135°C.

2.2.1.5 Indirect Tensile Strength and Modulus

Diab et al. (2019) used the Indirect Tensile (IDT) Strength test to evaluate the strength properties of 13 laboratory-prepared mixtures at two loose mix aging conditions: short-term aging for 4 hours at 160°C and long-term aging for 16 hours at 160°C. The mixtures were prepared with six polymer modifiers at various dosages. Test results showed that loose mix aging at 160°C significantly increased the IDT strength of the mixtures. Similar conclusions were also reported by Blankership (2015), Sahebzamani et al. (2020), and Durmaz et al. (2021) based on the IDT strength testing of asphalt mixtures conditioned with loose mix aging for up to 10 days at 85°C and 95°C, and for up to 24 hours at 135°C. However, Islam et al. (2015) reported a different trend that the IDT strength of a plant-produced dense-graded mixture increased with loose mix aging at 135°C for up to 40 hours but then decreased as the aging time further increased to 100 hours, as shown in Figure 25.

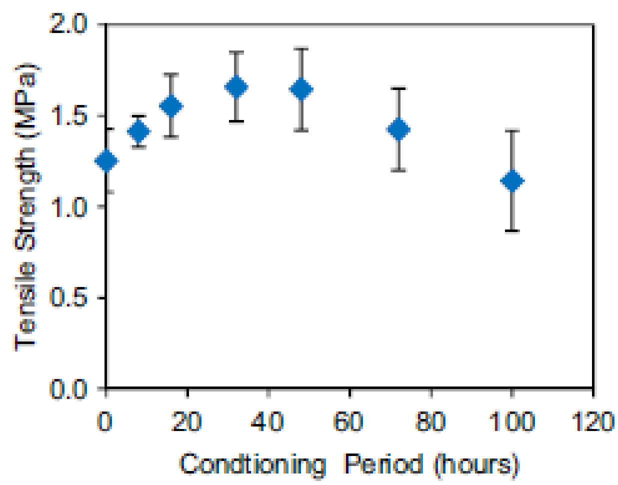


Figure 25. Effect of Loose Mix Aging at 135°C on IDT Strength Results (Islam et al., 2015)

Casado-Barrasa et al. (2022) used the IDT Stiffness Modulus test to evaluate the effect of loose mix aging on the stiffness properties of four laboratory-prepared mixtures containing polymer modified binders and rejuvenators. The mixtures were conditioned at 85°C for up to 19 days prior to being tested. Test results showed that loose mix aging at 85°C significantly stiffened the mixtures as indicated by an increase in the stiffness modulus and that the stiffening effect was more pronounced for the first 9 days of aging.

2.2.2 Impact of Loose Mix Aging on Properties of Extracted Asphalt Binders

This section synthesizes existing studies that evaluate the impact of loose mix aging on the rheological, consistency, and physicochemical properties of extracted asphalt binders.

2.2.2.1 Rheological Properties

Superpave Performance Grading Tests

Chen et al. (2018) determined the PG of asphalt binders extracted from five plant-produced mixtures conditioned with four loose mix aging procedures: 5 days at 95°C, and 6, 12, and 24 hours at 135°C. Test results showed that loose mix aging at 95°C and 135°C had an overall stiffening effect on the extracted asphalt binders as indicated by an increase in both the high- and low-temperature PG. Similar conclusions were also reported by Rahbar-Rastergar et al. (2019) and Zhang (2020) based on the performance grading of asphalt binders extracted from several plant-produced mixtures conditioned with loose mix aging at 95°C and 135°C.

Hanz et al. (2017) and Sirin et al. (2020) determined the PG of asphalt binders extracted from several laboratory-prepared mixtures after loose mix aging for up to 4 days at 135°C and found that both the high- and intermediate-temperature PG of the extracted asphalt binders increased as the loose mix aging time increased.

Mensching et al. (2017) applied loose mix aging for up to 24 hours at 135°C to four mixtures containing REOB and determined the PG of the extracted binders at various aging conditions. It was found that loose mix aging at 135°C significantly stiffened the extracted asphalt binders as indicated by an increase in the PG. Furthermore, the stiffening effect from loose mix aging was found to be more pronounced for mixtures at higher REOB contents, which was attributed to the higher sensitivity of REOB to oxidative aging at 135°C.

Besides the PG, the ΔT_c parameter derived from the BBR test results had also been found to be sensitive to loose mix aging. Previous studies consistently showed that loose mix aging at 95°C and 135°C had a detrimental impact on the ΔT_c parameter of the extracted asphalt binders, which indicated reduced relaxation properties and increased susceptibility to block cracking and other durability-related cracking distresses (Hanz et al., 2017; Mensching et al., 2017; Chen et al., 2018; Rahbar-Rastergar et al., 2019; Chen et al., 2020; Zhang, 2020).

Multiple Stress Creep Recovery (MSCR) Test

Sirin et al. (2020) conditioned four plant-produced mixtures with loose mix aging for up to 4 days at 135°C and conducted the MSCR test on the asphalt binders extracted from the aged mixtures. Test results showed that loose mix aging at 135°C significantly stiffened the extracted asphalt binders as indicated by lower non-recoverable creep compliance (J_{nr}) results.

DSR Frequency Sweep Test

Rahbar-Rastegar et al. (2019) used the DSR Frequency Sweep test to evaluate the effect of loose mix aging on the rheological properties of asphalt binders extracted from five plant-produced mixtures conditioned with loose mix aging for 24 hours at 135°C and up to 12 days at 95°C. Test results indicated that the G* of the extracted binders increased while the phase angle (δ) decreased as the severity of the loose mix aging procedures increased. This indicated that loose mix aging had an overall stiffening and embrittlement effect on the asphalt binders. Similar conclusions were also reported by Zhou et al. (2021) and Sreedhar and Coleri (2022) based on the DSR Frequency Sweep testing of several laboratory-prepared mixtures conditioned with loose mix aging for up to 6 days at 95°C, 100°C, and 135°C.

Ding et al. (2022) also used the DSR Frequency Sweep test to assess the rheological properties of asphalt binders extracted from several laboratory-prepared FAM and Marshall mixtures conditioned with loose mix aging for up to 12 days at 95°C and 24 hours at 135°C. Test results indicated that the G* increased as the loose mix aging level increased, which agreed with the findings of Roche et al. (2009) and Mensching et al. (2017) that evaluated loose mix aging for up to 35 days at 70°C, 85°C, and 95°C.

In addition to the G* and δ, several other parameters derived from the DSR Frequency Sweep test results have been used to evaluate the impact of loose mix aging on the rheological properties of asphalt binders. These parameters include the *G-R* parameter, R-value, and crossover frequency, etc. Rahbar-Rastegar et al. (2019) and Zhang (2020) conditioned several plant-produced mixtures with different loose mix aging procedures at 95°C and 135°C and conducted the DSR Frequency Sweep test to characterize the aging severity of asphalt binders extracted from the mixtures. Test results showed that the extracted asphalt binders corresponding to more severe loose mix aging procedures had higher *G-R* parameter and R-value results, which agreed with the findings of Chen et al. (2018), Chen et al. (2020), and Ding et al. (2022). Furthermore, Ding et al. (2022) found that the crossover frequency of the extracted asphalt binders decreased as the severity of the loose mix aging procedures increased.

2.2.2.2 Fatigue and Fracture Resistance

DSR Linear Amplitude Sweep (LAS) Test

Chen et al. (2020) conducted the LAS test to determine the effect of loose mix aging on the fatigue resistance of asphalt binders extracted from four plant-produced mixtures conditioned with loose mix aging for 5 days at 95°C and 8 hours at 135°C. Test results indicated that both aging procedures significantly reduced the fatigue resistance of the extracted asphalt binders as indicated by higher LAS-|B| values.

Zhang (2020) also used the LAS test to evaluate the fatigue resistance of asphalt binders extracted from five plant-produced mixtures but found that loose mix aging for up to 12 days at 95°C did not have a consistent impact on the LAS A and |B| parameters. To address this limitation, three new LAS parameters were developed: average reduction in integrity up to failure (I^R), strain tolerance up to failure (ε_T), and strain energy tolerance (E_f). Different with the traditional LAS parameters (A and |B|), the three new parameters showed a consistently decreasing trend as the severity of the loose mix aging procedures increased, which indicated their effectiveness in capturing the sensitivity of binder fatigue resistance to loose mix aging.

Double-edge-notched Tension (DENT) Test

Chen et al. (2020) evaluated the sensitivity of the DENT test to loose mix aging for 5 days at 95°C and 8 hours at 135°C for four plant-produced mixtures. For all the mixtures evaluated, the asphalt binders extracted from the 95°C and 135°C aged specimens had significantly lower critical tip opening displacement (CTOD) values, indicating higher susceptibility to ductile failure than those extracted from the specimens without loose mix aging. Similar conclusions were also reported by Mensching et al. (2017) based on the DENT testing of asphalt binders extracted from four REOB-modified mixtures conditioned with loose mix aging for up to 24 hours at 135°C.

2.2.2.3 Consistency Properties

Roche et al. (2009) conditioned several plant-produced and lab-prepared mixtures with loose mix aging for up to 9 days at 85°C and determined the penetration and softening point of the extracted asphalt binders. Test results showed that the penetration of the extracted asphalt binders decreased, and the softening point increased with loose mix aging at 85°C. Similar conclusions were also reported by Huang et al. (2022). In a different study, Sirin et al. (2020) conditioned four plant-produced mixtures with loose mix aging for up to 4 days at 135°C and found that loose mix aging significantly increased the viscosity of the extracted asphalt binders.

2.2.2.4 Physicochemical Properties

Ding et al. (2022) utilized FTIR to compare the oxygen-containing functional groups of asphalt binders extracted from mixtures conditioned with loose mix aging for up to 12 days at 95°C and up to 24 hours at 135°C. Test results indicated that both the carbonyl index and sulfoxide index (defined as the ratio between the area of carbonyl peaks and area of reference peaks, and the ratio between the area of sulfoxide peaks and area of reference peaks, respectively) were sensitive to loose mix aging. Furthermore, the extracted asphalt binders corresponding to more severe loose mix aging procedures had higher carbonyl index and sulfoxide index values than those with less severe aging procedures. Similar conclusions were also reported by Roche et al. (2009) based on the FTIR carbonyl index results of asphalt binders extracted from mixtures conditioned with loose mix aging for up to 9 days at 85°C.

Chen et al. (2018) utilized the FTIR carbonyl area (CA) (defined as the integrated peak area for the wavelength range from 1,820 to 1,659 cm^{-1}) to evaluate the aging of asphalt binders extracted from five plant-produced mixtures at various loose mix aging conditions: 5 days at 95°C, and 6, 12, and 24 hours at 135°C. Test results showed that the CA increased as the severity of the loose mix aging procedures increased, which indicated the formation of more oxygen-containing functional groups.

Elwardany et al. (2017) utilized the sum of FTIR carbonyl and sulfoxide peaks to characterize the aging severity of asphalt binders extracted from mixtures conditioned with loose mix aging for up to 35 days at 70°C, 85°C and 95°C. They found that the carbonyl-plus-sulfoxide peak absorbance value increased linearly with the duration of the aging procedures at the same temperature.

Ding et al. (2022) used the Atomic Force Microscope (AFM) to characterize the effect of loose mix aging on the nanoscopic properties of extracted asphalt binders and found that loose mix aging for up to 12 days at 95°C and for up to 24 hours at 135°C did not affect the morphological maps of the extracted asphalt binders, but significantly reduced their adhesive force and Derjaguin-Muller-Toporov modulus.

Roche et al. (2009) investigated the effect of loose mix aging on the asphaltene content of asphalt binders extracted from mixtures conditioned with loose mix aging for up to 4 days at 135°C and found that the asphaltene content increased as the loose mix aging time increased.

2.2.3 Summary

Table 9 and Table 10 summarize the impacts of loose mix aging on the asphalt mixture performance test results and the extracted asphalt binder test results, respectively, from the existing literature. As shown, the majority of the tests and their associated test parameters are sensitive to loose mix aging and thus, have the potential to be used to discriminate different loose mix aging procedures and determine their correlation to field aging.

Table 9. Impact of Loose Mix Aging on Asphalt Mixture Performance Test Results from Literature Review

Mixture Property	Mixture Test	Test Parameter	Impact of Loose Mix Aging
Intermediate-temperature Cracking Resistance	IDEAL-CT	CT_{Index}	Decreases with loose mix aging
	I-FIT	FI	Decreases with loose mix aging
	LA-SCB	J_c	No consistent trend with loose mix aging
	ER Test	ER	No consistent trend with loose mix aging
Low-temperature Cracking Resistance	DCT	G_f	Generally, decreases with loose mix aging (although several studies showed that G_f increased first but then decreased with loose mix aging)
		FST	Decreases with loose mix aging
	TSRST	Fracture Temperature	Increases with loose mix aging
	Low-Temperature SCB	Deformation at the Peak Load	Decreases with loose mix aging
Cyclic Fatigue Resistance	DTCF	S_{app}	Decreases with loose mix aging
		N_f	Decreases with loose mix aging
		D^R	No consistent trend with loose mix aging
	BBF	Flexural Stiffness	Increases with loose mix aging
		N_f	Decreases with loose mix aging
	OT	N_f	Decreases with loose mix aging
		CPR (β)	Increases with loose mix aging
	DMA Fatigue Test	N_f	No consistent trend with loose mix aging
	Diametral Fatigue Test	N_f	Decreases with loose mix aging
Rheological Properties	E*	E*	Increases with loose mix aging
		δ	Decreases with loose mix aging
		$\|E^*\|/\sin(\delta)$	Increases with loose mix aging
		$G\text{-}R_m$	Increases with loose mix aging
Indirect Tensile Strength and Modulus	ITS Test	IDT Strength	Generally, decreases with loose mix aging (although several studies showed that the IDT strength increased first but then decreased with loose mix aging)
	IDT Stiffness Modulus Test	Stiffness Modulus	Increases with loose mix aging

Table 10. Impact of Loose Mix Aging on Extracted Asphalt Binder Test Results from Literature Review

Binder Property	Binder Test	Test Parameter	Impact of Loose Mix Aging
Rheological Properties	Performance Grading	PG	Increases with loose mix aging
		ΔTc	Decreases with loose mix aging
	Frequency Sweep	G*	Increases with loose mix aging
		δ	Decreases with loose mix aging
		G-R Parameter	Increases with loose mix aging
		R-value	Increases with loose mix aging
		Crossover Frequency	Decreases with loose mix aging
	MSCR	J_{nr}	Decreases with loose mix aging
Fatigue and Fracture Resistance	LAS	A	No consistent trend with loose mix aging
		|B|	No consistent trend with loose mix aging
		I^R	Decreases with loose mix aging
		ε^T	Decreases with loose mix aging
		E_f	Decreases with loose mix aging
	DENT	CTOD	Decreases with loose mix aging
Consistency Properties	Penetration	Penetration	Decreases with loose mix aging
	Softening Point	Softening Point	Increases with loose mix aging
	Viscosity	Viscosity	Increases with loose mix aging
Physicochemical Properties	FT-IR	$I_{C=O}$	Increases with loose mix aging
		$I_{S=O}$	Increases with loose mix aging
		Carbonyl Area	Increases with loose mix aging
		Carbonyl plus Sulfoxide Peak Absorbance	Increases with loose mix aging
	AFM	Adhesive Force	Decreases with loose mix aging
		DMT Modulus	Increases with loose mix aging
	Asphaltene Content	Asphaltene Content	Increases with loose mix aging

2.3 Effects of Silo Storage, Mix Hauling, Mix Reheating, Specimen Storage, and Asphalt Weathering on Asphalt Binder and Mixture Properties

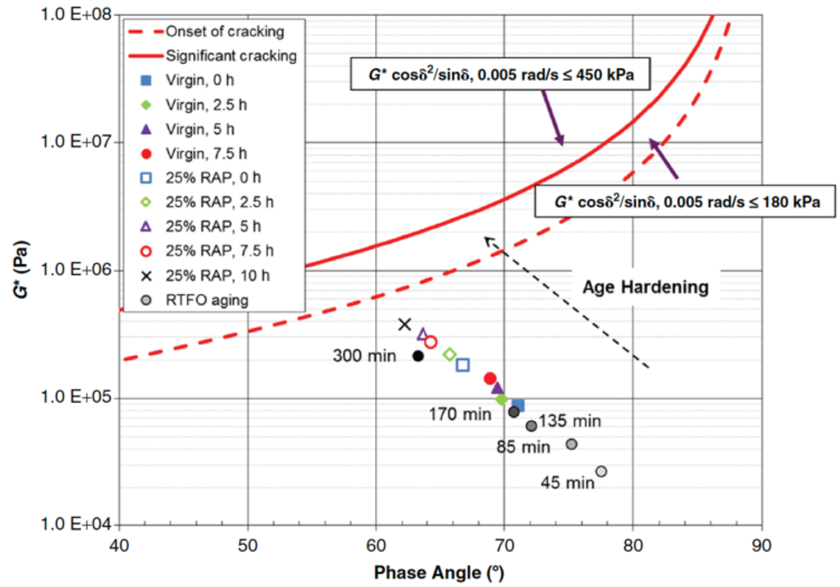
2.3.1 Silo Storage

At many asphalt plants, the loose asphalt mix is stored in silos before being transported to the construction site, which could affect the short-term aging of the mixture. Storage time is typically not controlled and can vary widely based on the construction region, silo type, mix size, and truck schedule (Jacques et al., 2016).

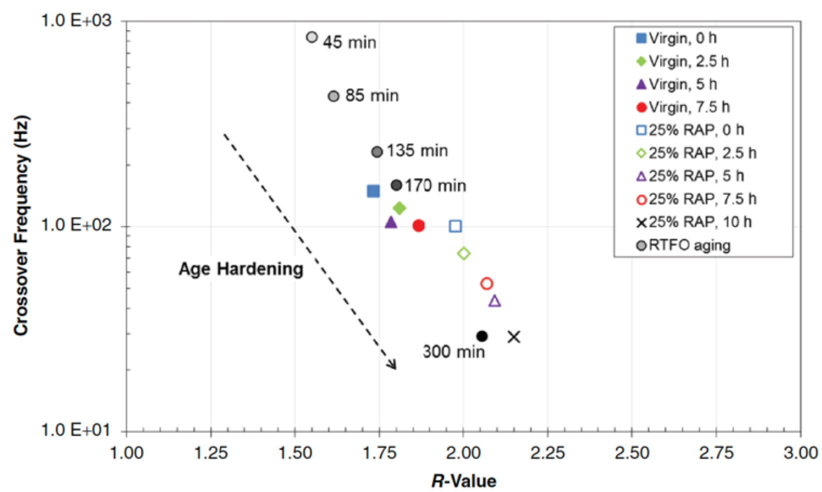
Garrick and Nunna (1992) indicated that silo storage for 5 and 10 days resulted in increased viscosity and penetration of the extracted asphalt binders, where factors such as the type of atmosphere in the silo, source of the asphalt binder, additives, aggregate type and gradation, temperature of the silo appeared to influence the observed changes. In most cases, hardening of asphalt binders and mixtures occurred within the first 24 to 48 hours of storage. Furthermore, silo storage increased the IDT strength of the mixtures but did not significantly affect their compactability.

Jacques et al. (2016) evaluated a virgin mixture and a 25% RAP mixture at different silo storage times. The virgin mixture used a PG 64-22 binder and was sampled after being stored in the silo for 0, 2.5, 5, and 7.5 hours after production. The 25% RAP mixture used the same PG 64-22 binder and was sampled after silo storage for 0, 2.5, 5, 7.5, and 10 hours after production. The properties of the mixtures at different silo storage times were characterized using the DTCF and TSRST tests. The DTCF test results were input into Layered Viscoelastic Critical Distresses (LVECD) simulations to determine the effect of silo storage on the predicted cracking performance of asphalt pavements. Additionally, the asphalt binders were extracted and recovered from loose mix sampled from the asphalt plant for binder characterization testing. The recovered asphalt binder was considered as an asphalt binder that had been short-term aged in a rolling thin film oven (RTFO). The virgin binder was also aged in the RTFO at five conditioning times (i.e., 45, 85, 135, 170, and 300 min) to evaluate if RTFO aging could simulate the plant production and storage time associated with the virgin mixture. Performance grading, R-value, crossover frequency, and the *G-R* parameter were used to evaluate the rheological properties of the extracted binders.

The high-temperature PG results indicated an increase of 0.39°C/h of silo storage time for the binder extracted and recovered from the virgin mixtures, and 0.53°C/h for the binder extracted and recovered from the RAP mixtures. The intermediate-temperature PG showed an increase of 0.20°C/h for the virgin mixtures, while the RAP mixtures had no measurable trend. The low-temperature PG increased by 0.14°C/h and 0.21°C/h for the virgin and RAP mixtures, respectively. The ΔT_c results showed that the extracted binders became more m-controlled (with more negative ΔT_c) as the silo storage time increased beyond 5 hours. The binder recovered from the RAP mixtures experienced greater increases in ΔT_c than the binder recovered from the virgin mixtures, suggesting that the virgin asphalt binder had undergone less aging during production and silo storage. The *G-R* parameter, crossover frequency, and R-value results in Figure 26 of the extracted binders indicated trends associated with age hardening, suggesting that asphalt aging occurred during silo storage. Overall, the binders extracted from the RAP mixtures showed greater changes in the rheological indexes than the extracted virgin binders. The results of the RTFO aging at five conditioning times indicated that the specified time of 85 min per AASHTO T 240 was not sufficient to simulate the aging that occurred to the virgin mixtures during plant production and silo storage. An extended RTFO aging time of 170 min was required to yield similar $|G^*|$, δ, crossover frequency, and R-value results as the extracted virgin binder with no silo storage.



(a)



(b)

Figure 26. Effects of Silo Storage Time and RTFO Conditioning on Extracted Asphalt Binder Properties; (a) *G-R* Parameter in Black Space Diagram, (b) Crossover Frequency versus R-value (Jacques et al., 2016)

The E* test results showed that increased silo storage time caused an increase in stiffness for both the virgin and 25% RAP mixtures. Statistically, the virgin mixtures stored for 0, 2.5, and 5 hours had similar E* stiffness, while the mixture with 7.5-hour silo storage had statistically higher E* stiffness than those with 0- and 2.5-hour silo storage. The RAP mixtures sampled after 7.5 and 10 hours of silo storage had significantly higher E* stiffness than the mixture without silo storage. Overall, the RAP mixtures experienced greater changes in E* stiffness than the virgin mixtures as silo storage time increased. The authors suggested that this difference could imply that the RAP mixtures experienced additional blending or diffusion between the RAP and virgin binders in the silo in addition to short-term aging experienced with the virgin mixtures, while differences in the specimen air voids could also contribute to the more significant stiffening of the RAP mixtures. The DTCF test results in terms of the relationship between failure criterion (G^R) and N_f in Figure 27 indicated that the virgin mixture with 7.5 hours of silo storage was most susceptible to fatigue cracking, which agreed with the predicted pavement cracking performance from LVECD simulations. Lastly, the TSRST results (Figure 28) indicated that the virgin mixture with 5 hours of silo storage had a statistically warmer critical cracking temperature (indicating higher susceptibility to low-temperature cracking) than the other virgin mixtures, and that the RAP mixture with 7.5 hours of silo storage had a statistically warmer critical cracking temperature than those with other silo storage times.

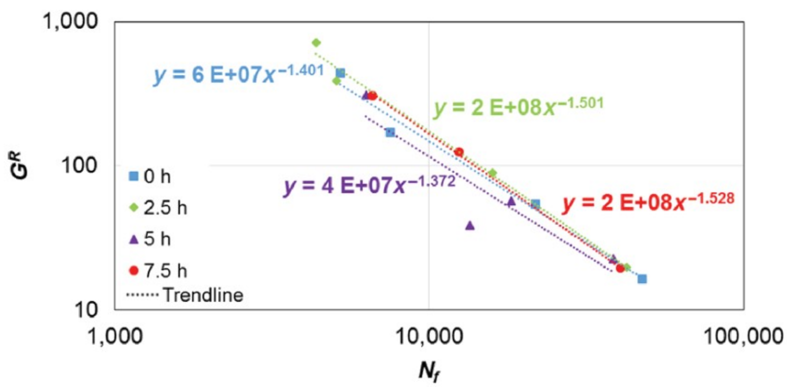


Figure 27. DTCF Test Failure Criterion Results for Virgin Mixtures at Different Silo Storage Times (Jacques et al., 2016)

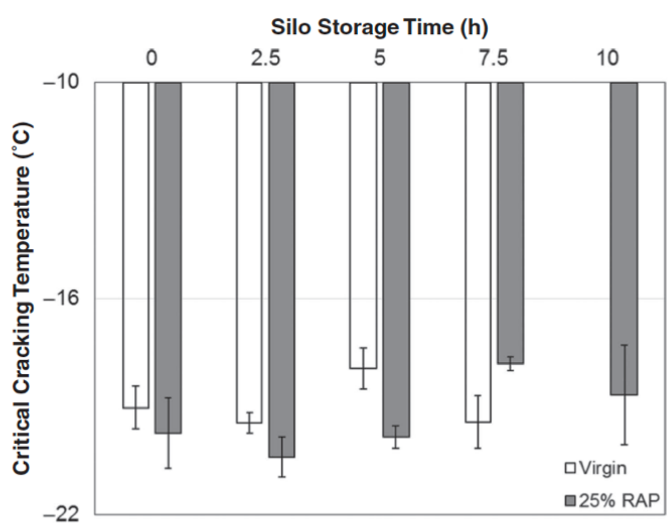


Figure 28. TSRST Critical Cracking Temperatures for Virgin and RAP Mixtures at Different Silo Storage Times (Jacques et al., 2016)

Kadhim and Baaj (2018) evaluated the effect of silo storage time on the thermal cracking resistance of asphalt mixtures containing RAP. The study sampled mixtures with 15% and 30% RAP from an asphalt plant after different silo storage times (i.e., 1, 4, 8, and 12 hours). The thermal cracking resistance of the mixtures was evaluated using the TSRST. Test results indicated that the mixtures collected after 8 and 12 hours of silo storage had better resistance to thermal cracking than the ones without silo storage, which was possible due to the occurrence of more homogeneous blending between the virgin and RAP binders during silo storage. Based on these results, it was suggested that extended silo storage could potentially improve the blending between the virgin and RAP binders and consequently, improve the low-temperature cracking resistance of the resultant RAP mixture.

Pirzadeh et al. (2021) investigated the effect of silo storage to expedite diffusion between the virgin and RAP binders. Several surface (HL-3) and base (HL-8) mixtures produced at two asphalt plants using different sources and contents of RAP (15% and 30% RAP for Plant 1, and 20% and 40% RAP for Plant 2) and two virgin binder grades (PG 58-28 and PG 52-34 virgin binders for the surface and base mix, respectively) were evaluated. The mixture samples were collected after 0, 1, 4, 8, and 12 hours of silo storage times at both plants, while the 24-hour silo storage samples were collected at Plant 2 only. The E* test results showed that significant mixture stiffening occurred after 24 hours of silo storage, indicating that an optimum silo storage time would occur between 8 and 12 hours for the mixtures evaluated in the study. Rutting resistance of the mixtures was evaluated with the Hamburg Wheel Tracking Test (HWTT), and the results showed that the rut depth decreased (indicating improved rutting resistance) as the silo storage time increased. Based on the E* and HWTT results, the authors concluded that diffusion between the RAP and virgin binders approached completion within 12 hours of silo storage. Asphalt binders extracted from the mixtures collected at different silo storage times were evaluated in terms of high- and low-temperature PG, SARA (saturates, aromatics, resins, asphaltenes) fractions, and FTIR. Test results indicated that significant asphalt aging did not appear to occur during the optimum silo storage time of 8 to 12 hours.

2.3.2 Mix Hauling

Howard et al. (2013) investigated the changes in the properties of asphalt binders with no additive, foaming, and a WMA chemical additive with haul time after mixture production. In the study, plant-produced materials were hauled from 1.0 to 10.5 hours, with loose mixture sampled before hauling (pre-haul) and after hauling (post-haul) to evaluate the potential impact of long haul on the volumetric and workability of the mixtures as well as the rheological and chemical properties of the extracted binders. The parameters utilized for these evaluations included changes in the maximum specific gravity (G_{mm}) of the mixture caused by asphalt absorption; PG and FTIR spectrum of virgin binder in comparison to the recovered binders from pre-haul and post-haul mixture samples; and workability and repeated creep of pre-haul versus post-haul mixture samples; Test results showed that haul time for up to 8 hours did not significantly affect the asphalt absorption, G_{mm}, workability, and creep properties of the mixtures. Furthermore, mix hauling had no significant impact on the aging and PG of the extracted asphalt binders. However, the extracted asphalt binders containing a WMA chemical additive had slightly better low-temperature properties than those corresponding to the foamed and HMA mixtures.

Based on these results, the study concluded that transport and placement of asphalt mixtures within an 8-hour period would have no detrimental effects on pavement performance.

Bocci et al. (2020) investigated the aging that occurred during mix hauling and observed that the compactability [evaluated using the air voids content (V_m)], stiffness [evaluated using the indirect tensile stiffness modulus (ITSM)], strength [evaluated using the indirect tensile strength (ITS)], and intermediate-temperature cracking resistance (evaluated using the CT_{Index}) of asphalt mixtures containing various RAP contents and rejuvenators did not change significantly within up to 3 hours (180 minutes) of mix hauling after production, as shown in Figure 29.

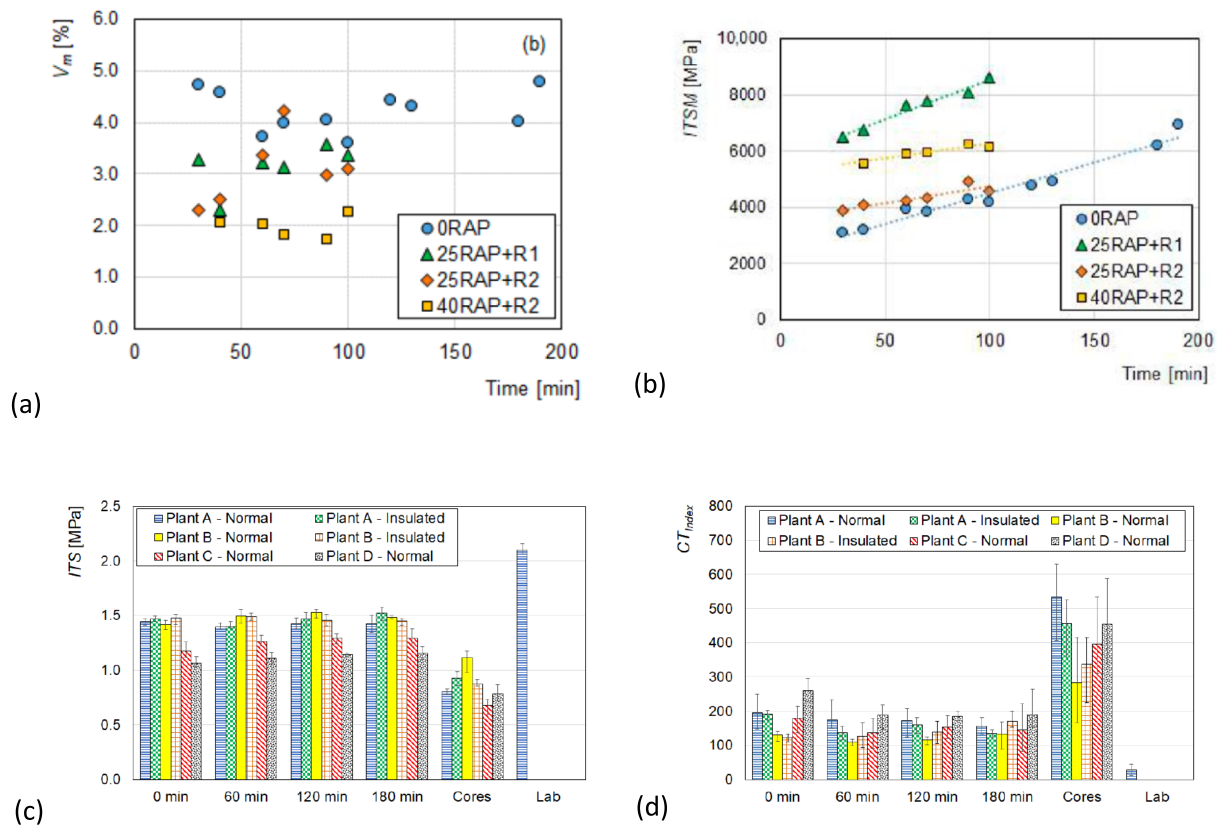


Figure 29. Impact of Mix Hauling Time on (a) V_m, (b) ITSM, (c) ITS, and (d) CT_{Index} Results (Bocci et al., 2020)

2.3.3 Mix Reheating

Lemke et al. (2019) investigated the influence of sample size and preparation, mix reheating, and aging temperature on the properties of a plant-produced mixture from Wisconsin. The mixture used a PG 58S-28 asphalt binder and had a total binder content of 5.4% and a RAP binder replacement ratio of 26%. The study first evaluated the time required to reheat boxed and unboxed loose mixtures, as shown in Figure 30. After 2 hours of reheating in an oven, the unboxed sample reached 215°F (102°C), whereas the boxed sample only reached 135°F (57°C). At 215°F (102°C), the unboxed sample could be broken apart and split into smaller batch sizes.

Figure 30. Reheating of Boxed versus Unboxed Loose Mixture Samples (Lemke et al., 2019)

The study then investigated whether, after splitting a sample into pans, covered or uncovered samples would reach a target aging temperature [i.e., 135°C] at the same time. The reheated sample was remixed and placed into two stainless-steel pans (11" x 9" x 2.5") with a thickness of 1.25 inches. One pan was covered with aluminum foil, and the other was left uncovered in the middle rack of the oven, preheated to 135°C (Figure 31). The uncovered sample took approximately 25% less time to reach the desired temperature relative to the covered sample, as shown in Figure 31. The study also found that the uncovered sample placed in the upper-center location of the oven returned to a pre-stir temperature in about 38 minutes. In contrast, the uncovered sample placed at the bottom of the oven took 51 minutes.

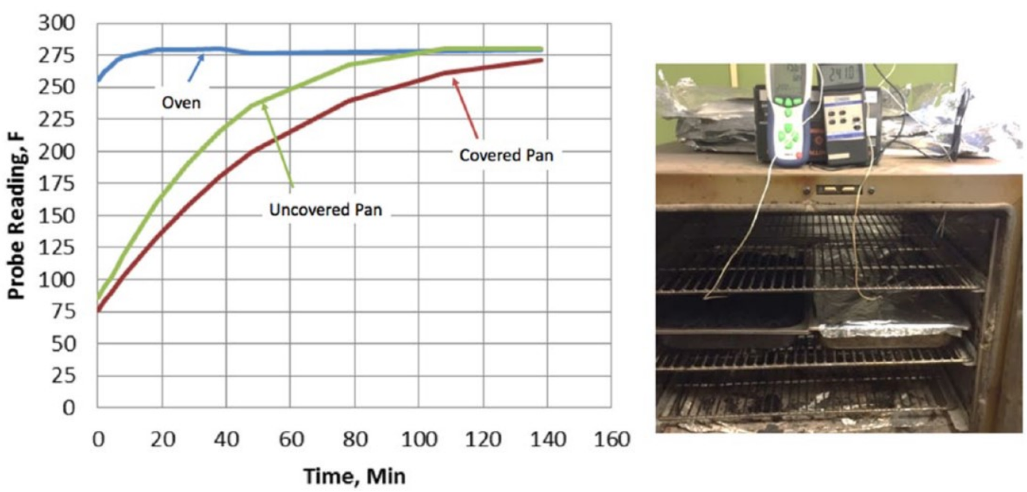


Figure 31. Monitoring Temperature of Covered versus Uncovered Loose Mixture Samples (Lemke et al., 2019)

Lastly, the study investigated the effect of mix reheating temperature on the volumetric properties and rutting resistance of the resultant compacted mixture specimens. Six mixture samples were prepared in pans for reheating at two temperatures: 132°C and 140°C. The results indicated that mix reheating temperature affected the air voids of the compacted specimens but did not affect their G_{mm} and HWTT results.

2.3.4 Specimen Storage

Al-Qadi et al. (2019) evaluated the impact of shelf storage of compacted specimens using canvas bags in a non-climate-controlled environment and found that shelf storage for more than one month during the summer season in Illinois significantly reduced the I-FIT results while shelf storage during the winter season had no significant impact. In a different study, Newcomb et al. (2021) studied the effect of specimen storage and found that the time between sample fabrication and testing could vary up to two weeks (at ambient temperature) without significantly affecting the IDEAL-CT results.

2.3.5 Asphalt Weathering

Aging of asphalt binders is caused by volatilization (i.e., evaporation of the light fractions of asphalt), thermal and ultraviolet (UV) oxidation, and other chemical processes while being affected by moisture acting upon exposed surfaces and interconnected voids. Thus, asphalt researchers and practitioners have developed an accelerated pavement weathering system (APWS) for simulating the aging and weathering of asphalt binders and mixtures in the laboratory, as shown in Figure 32. The accelerated weathering system for asphalt materials is standardized as ASTM D4798, which is also known as the Xenon-Arc method per weatherometer. The APWS chamber has controllable cycles to simulate various environmental conditions, including rain, relative humidity, sunlight, temperature, and a combination of the above; thus, it can mimic the long-term exposure of asphalt pavement materials to moisture, heat, and ultraviolet light simultaneously.

It is worth noting that oven aging and APWS weathering expose the asphalt binder to different aging mechanisms, as indicated below: 1) when considering thermal oxidation, as simulated in ovens, the increase in the hardening of the asphalt binder is caused by the introduction of polar chemical functionality, which increases the molecular interactions. This process does not cause significant mass loss of the material; 2) UV radiation only occurs at the material surface. Furthermore, when considering UV radiation, the primary effect of this aging mechanism is component loss, primarily loss of the oily fractions (i.e., maltenes), which has a hardening impact on the asphalt binder. The water spray applied during APWS weathering will wash away the water-soluble asphalt degradation products, thereby continually exposing a new surface of the asphalt binder for weathering, which will further increase the mass loss of the material; and 3) the rate of UV oxidation is insensitive to temperature. On the other hand, the thermal oxidation rate increases dramatically with temperature due to the compounding effects of the molecules' increased kinetic energy and the breakup of the microstructure.

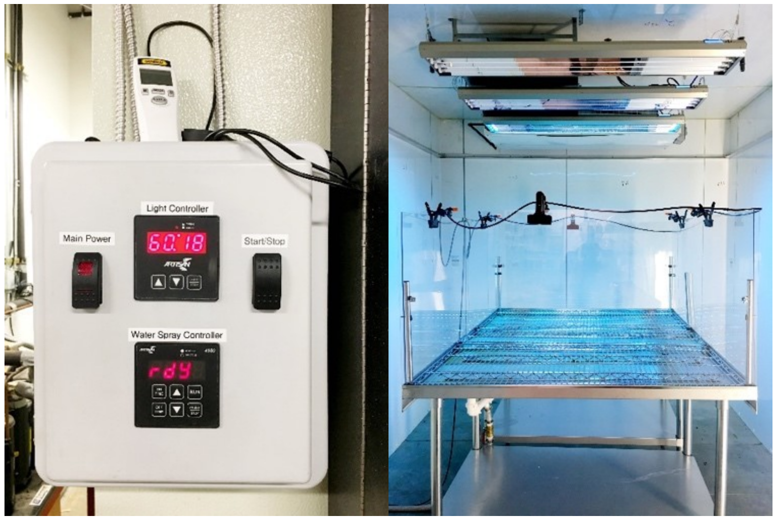


Figure 32. APWS Device at NCAT

Li et al. (2020) investigated the exposure of a loose asphalt mixture to UV radiation (without moisture) at different times (i.e., 7, 14, and 28 days). The mixture utilized was a dense-graded AC-13 mixture with basalt and limestone aggregates and a 60/80 penetration asphalt binder. In the UV chamber (Figure 33), the UV light radiation was kept to 21 W/m^2 at a temperature of 50°C, and the loose mixture was stirred every 24 hours. The SARA fraction results indicated a decrease in the colloidal stability of the recovered binders as the UV radiation time increased. Physical properties evaluated by the penetration, softening point, and ductility tests indicated that UV radiation had a stiffening impact on the recovered binders. This finding was also supported based on the DSR testing of the recovered binders at different UV radiation times.

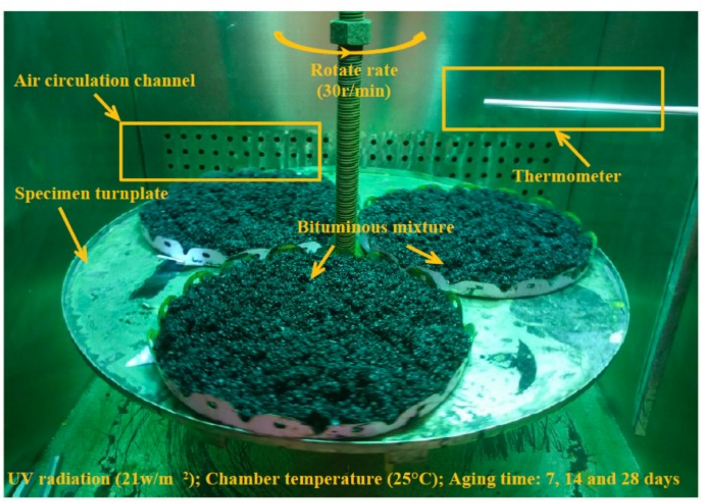


Figure 33. UV Chamber for Weathering of Asphalt Loose Mixture (Li et al., 2020)

Huang et al. (2021) investigated the impact of UV aging (without moisture) on asphalt mixtures using both loose mix samples and compacted specimens. Both the samples and specimens were aged at 60°C for six days in a UV aging vessel with a mercury lamp of 500 W and a target UV radiation of 8 W/m^2. Test results showed that asphalt binders extracted from the loose mix samples had consistently lower penetration, higher softening point, and higher viscosity than those extracted from the compacted specimens, which indicated that the loose mix samples were more exposed to UV radiation than the compacted specimens.

2.4 Summary of Literature Review Findings

A comprehensive literature review was conducted on existing loose mix aging procedures for simulating the long-term aging of asphalt mixtures and their impacts on the performance properties of asphalt mixtures and extracted asphalt binders. The aging temperature of these procedures varies from 85°C to 135°C, and the duration varies from hours to weeks depending on the targeted level of field aging. The two most studied aging procedures are loose mix aging at 95°C and 135°C, and they both have advantages and limitations. In general, loose mix aging at 95°C is considered a more accurate procedure in terms of its ability to predict the properties of asphalt binders and mixtures for pavement performance prediction purposes. Loose mix aging at 135°C, on the other hand, is considered a more practical procedure for use with mixture performance testing for asphalt mix design and production. In addition to these two aging procedures, loose mix aging for 20 hours at 100 to 125°C has shown promising results and is considered laboratory operations-friendly. The kinetics model developed in NCHRP project 9-54 has the potential to correlate loose mix aging procedures at different temperatures, but its validity and applicability to asphalt mixtures with various components and mix design variables need further investigation. Most of the asphalt binder and mixture performance tests used in previous asphalt aging research show good sensitivity to loose mix aging and thus can discriminate asphalt mixtures with different loose mix aging conditions. Finally, several studies have demonstrated the impacts of silo storage, mixing hauling, mix reheating, specimen storage, and asphalt weathering on the aging of asphalt binders and mixtures, highlighting the need to consider these factors in future asphalt aging research.

Chapter 3: Research Gap Analysis

The research gap analysis was aimed at identifying research gaps that might hinder the implementation of loose mix aging for cracking resistance evaluation in BMD. The analysis included four objectives:

1) Determine the correlations between different loose mix aging procedures and field aging for various climatic conditions and locations in the pavement structure.
2) Assess the effects of loose mix aging on the performance properties of specialty asphalt mixtures and the corresponding extracted asphalt binders containing recycling agents, recycled plastics, and crumb rubber.
3) Select appropriate binder and mixture performance tests and parameters to assess loose mix aging.
4) Recommend loose mix aging procedures for use in mix design approval and production acceptance for BMD.

3.1 Lab-to-Field Aging Correlation

Table 11 summarizes the existing lab-to-field correlation efforts of the four existing loose mix aging procedures identified in the literature. Comparatively, the 95°C aging procedure is the most robust as it was developed and validated with more than 35 sets of lab-to-field aging data from 10 field projects across the United States (shown in Figure 34). Furthermore, the 95°C aging maps developed in the NCHRP project 9-54 (Kim et al., 2017; Kim et al., 2021) enable the correlation of this aging procedure to field aging for various combinations of pavement location, age, and location within the pavement structure.

Table 11. Existing Lab-to-field Correlation Efforts of Different Loose Mix Aging Procedures

Loose Mix Aging Procedure	Number of Mixtures with Lab-to-field Aging Data	Number of Field Projects with Lab-to-field Aging Data
Aging at 85°C	4	1
Aging at 95°C	Over 35	10
Aging at 100-125°C	None	None
Aging at 135°C	12	5

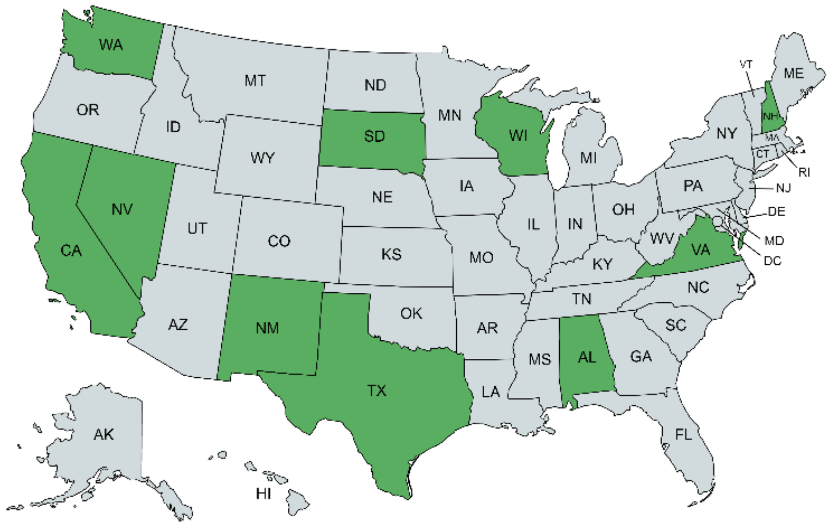


Figure 34. Map of Field Projects Used to Develop and Validate the 95°C Loose Mix Aging Procedure

The 135°C aging procedure has been evaluated with 12 sets of lab-to-field aging data from 5 field projects in Alabama, Michigan, Minnesota, and Washington. The limited field validation data at the NCAT Test Track indicated that loose mix aging for 8 hours at 135°C represents approximately 5 to 6 years of field aging in Alabama for the top 1 inch of the asphalt pavement (Chen et al., 2020). The 85°C aging procedure was developed with only four sets of lab-to-field aging data from a field project in South Dakota. The limited data indicated that loose mix aging for 5 days at 85°C can simulate approximately 114,000 CDD of field aging, which corresponds to 7 to 10 years for states in warm climates and 12 to 14 years for states in cold climates (Newcomb et al., 2019). The 100-125°C aging procedure was developed purely based on correlations with the 95°C aging procedure and thus has no field validation data available (Zhou et al., 2022). In summary, among the four existing loose mix aging procedures, only the 95°C procedure has undergone reasonable field validation, while the other procedures have no, or very limited, lab-to-field validation data.

3.2 Applicability to Asphalt Mixtures Containing Additives

The asphalt pavement industry has a long history of using asphalt additives to enhance the performance of asphalt mixtures. More recently, there has been increasing interest in using innovative additives due to sustainability considerations; these additives include but are not limited to recycling agents, recycled plastic, and recycled tire rubber (RTR). Despite the potential environmental benefits of using these additives, STAs desire to ensure that the resulting mixtures perform better or at least comparably to the unmodified mixtures. Furthermore, many of these additives could have a substantial impact on the aging behavior of asphalt binders and mixtures; therefore, incorporating aging into the cracking resistance evaluation of asphalt mixtures containing additives is crucial for product approval and asphalt mix design purposes.

Table 12 summarizes the different types of asphalt additives evaluated in published loose mix aging studies. As shown, all four aging procedures have been used to assess asphalt mixtures containing RAP, RAS, and PMA. The 85°C and 95°C aging procedures have also been used to evaluate asphalt mixtures with WMA, while the 135°C aging procedure has been used to assess mixtures with REOB. Several recent studies have successfully used loose mix aging at 95°C, 100-125°C, and 135°C to evaluate RAP/RAS mixtures with rejuvenators. However, only limited loose mix aging studies have evaluated recycled plastics, RTR, and synthetic fiber; therefore, it remains unknown whether the existing procedures apply to asphalt mixtures containing these additives and how they would affect the established lab-to-field aging correlations.

Table 12. Summary of Asphalt Additives Evaluated in Published Loose Mix Aging Studies

Loose Mix Aging Procedure	WMA	RAP/RAS	PMA	REOB	Rejuvenator	Recycled Plastic	RTR
Aging at 85°C	X	X	X				
Aging at 95°C	X	X	X		X		
Aging at 100-125°C		X	X		X		
Aging at 135°C		X	X	X	X	X (limited)	X (limited)

3.3 Selection of Laboratory Tests and Parameters to Assess Loose Mix Aging

As previously discussed in Chapter 2, the literature review indicates that the majority of the laboratory tests (and their associated test parameters) used in previous aging studies are sensitive to loose mix aging and thus have the potential to discriminate different aging procedures and determine their correlation to field aging. These tests and parameters are summarized in Table 13 and Table 14, which will be considered for use in the Phase II work plan with priority given to those with data available in existing aging studies at NCAT, UNH, and TTI.

Table 13. Asphalt Mixture Tests and Parameters Suitable for Assessing Loose Mix Aging

Mixture Property	Mixture Test	Test Parameter
Intermediate-temperature Cracking Resistance	IDEAL-CT	CT_{Index}
	I-FIT	FI
Low-temperature Cracking Resistance	DCT	G_f, FST
	TSRST	Fracture Temperature
	Low-Temperature SCB	Deformation at the Peak Load
Cyclic Fatigue Resistance	DTCF	S_{app}, N_f
	BBF	Flexural Stiffness, N_f
	OT	N_f, CPR (β)
	Diametral Fatigue Test	N_f
Rheological Properties	E*	E*, δ, |E*|/sin(δ), $G\text{-}R_m$
Indirect Tensile Strength and Modulus	ITS Test	IDT Strength
	IDT Stiffness Modulus Test	Stiffness Modulus

Table 14. Asphalt Binder Tests and Parameters Suitable for Assessing Loose Mix Aging

Binder Property	Binder Test	Test Parameter
Rheological Properties	Performance Grading	PG, ΔT_c
	Frequency Sweep	|G*|, δ, G-R, R-value, Crossover Frequency
	MSCR	J_{nr}
Fatigue and Fracture Resistance	LAS	N_f, I^R, ε^T, E_f
	DENT	CTOD
Consistency Properties	Penetration	Penetration
	Softening Point	Softening Point
	Viscosity	Viscosity
Physicochemical Properties	FT-IR	$I_{C=O}$, $I_{S=O}$, Carbonyl Area, Carbonyl plus Sulfoxide Peak Absorbance
	AFM	Adhesive Force, DMT Modulus
	Asphaltenes Content	Asphaltenes Content

3.4 Implementation of Loose Mix Aging into BMD

Table 15 summarizes the advantages and disadvantages of the different loose mix aging procedures in terms of their potential for implementation into BMD for asphalt mix design and production acceptance. The 85°C aging procedure is similar to the existing long-term aging procedure in AASHTO R 30, as they both require aging for 5 days at 85°C. However, the long duration of the 85°C loose mix aging procedure is a potential challenge for use in BMD, especially during production when a quick turnaround of test results is desired for quality control and acceptance purposes. Another major limitation of the 85°C aging procedure is the lack of field validation, as it was developed based on only four mixes from a field project in South Dakota.

Table 15. Advantages and Disadvantages of Different Loose Mix Aging Procedures for Implementation into BMD System

Loose Mix Aging Procedure	Advantages	Disadvantages
Aging at 85°C	Similar to AASHTO R 30	1) Long duration 2) Very limited field validation
Aging at 95°C	Robust field validation	Long duration
Aging at 100-125°C	1) Short duration 2) Lab operations-friendly	1) Potential chemistry change 2) No field validation
Aging at 135°C	Short duration	1) Potential chemistry change 2) Very limited field validation

As discussed previously, the 95°C aging procedure is the most robust in terms of field validation. The aging maps developed in the NCHRP project 9-54 allow STAs to target different field aging conditions while considering the impacts of pavement location, age, and location within the pavement structure. Similar to the 85°C aging procedure, the 95°C aging procedure has a limitation of long durations. In some cases, the aging procedure may take up to weeks to complete, significantly delaying the turnaround of test results for performance evaluation of asphalt mixtures in BMD.

On the other hand, the 100-125°C and 135°C aging procedures have the advantage of being efficient and practical and having good implementation potential due to accelerated aging at elevated temperatures. Both procedures typically allow the turnaround of test results within two days, which is beneficial to STAs and asphalt contractors. Compared to the 135°C procedure, the 100-125°C procedure is more laboratory operation-friendly as it fits the 8-hour work schedule better. However, both procedures have a limitation with aging at elevated temperatures above 100°C, which could cause changes in the asphalt chemistry associated with oxidative aging for certain asphalt binders. These changes in asphalt chemistry could be problematic if the intent of implementing BMD is to use performance tests to predict pavement performance for high-profile projects when high accuracy in the prediction results is desired from the risk management perspective. However, if the intent of implementing BMD is to use performance tests as a tool to screen and eliminate poor-performing mixes from mix design and production, the 100-125°C and 135°C aging procedures would be acceptable, provided that they can effectively discriminate mixes with different field cracking performance, which has been found promising in the literature (West et al., 2021; Podolsky et al., 2022). Another limitation of these two procedures is the lack of field validation, as the 135°C procedure was only validated with four mixes at the NCAT Test Track, while the 100-125°C procedure was developed based on correlations with the 95°C aging procedure with no field aging data.

Chapter 4: Proposed Phase II Work Plan

The overall objective of the Phase II work plan is to address research gaps associated with implementing loose mix aging for cracking resistance evaluation in BMD. Specifically, the work plan consists of three tasks:

- Task 1 seeks to further validate the 95°C aging maps with additional lab-to-field aging data, including asphalt mixtures containing non-traditional additives such as recycling agents, recycled plastic, and RTR.
- Task 2 aims to assess and refine the conversion of different loose mix aging procedures based on the kinetics model developed in the NCHRP project 9-54.
- Task 3 focuses on the implementation of research findings and recommendations.

4.1 Further Validation of 95°C Aging Maps (Task 1)

As previously discussed in Chapter 3, the 95°C loose mix aging procedure is the most robust in terms of field validation, which has been evaluated with more than 35 sets of lab-to-field aging data from 10 field projects across the United States. Nevertheless, this procedure needs to be further validated with additional lab-to-field aging data from projects in different states other than those in Figure 34. Furthermore, most of the existing data associated with the 95°C aging procedure is limited to asphalt mixtures with WMA, RAP/RAS, and PMA; thus, it remains unknown if the 95°C lab-to-field aging maps apply to mixtures containing non-traditional additives such as recycling agents, recycled plastic, and RTR. To address these gaps, an experimental plan is proposed to validate the 95°C aging procedure by leveraging several ongoing aging studies at NCAT, UNH, and TTI.

As shown in Table 16, the proposed experimental plan includes seven potential field projects, five in states not covered in Figure 34 (i.e., Illinois, Minnesota, and Missouri), and four using specialty mixtures with recycling agents, recycled plastic, and RTR. Post-construction field cores will be collected and tested for each field project to establish field aging as the reference. Furthermore, plant mixes sampled during production will be tested after being subjected to the 95°C aging procedure to develop the lab aging data. The proposed testing of field cores and plant mixes includes the |G*| at 64°C and 10 Hz, IDEAL-CT, and possibly I-FIT, DCT, or DTCF (depending on material and funding availability). The |G*| is included because it was the primary aging index property (AIP) used to develop the 95°C aging procedure in the NCHRP project 9-54 (Kim et al., 2017). The IDEAL-CT is included because it can assess the aging condition of the mixture, especially those containing dry-process additives, and it is the most popular cracking test among STAs.

Figure 35 conceptualizes the lab-versus-field aging data analysis for project-specific extracted binder and mixture results. The field aging data will be used as the target to determine the representative duration of the 95°C aging procedure (i.e., measured $t_{95°C}$), which will then be compared against the predicted duration based on the 95°C aging maps from the NCHRP project 9-54 (i.e., predicated $t_{95°C}$). Finally, the aggregated measured-versus-predicted $t_{95°C}$ results across all the field projects will be used to validate or adjust, if necessary, the 95°C aging maps based on the additional lab-to-field aging data.

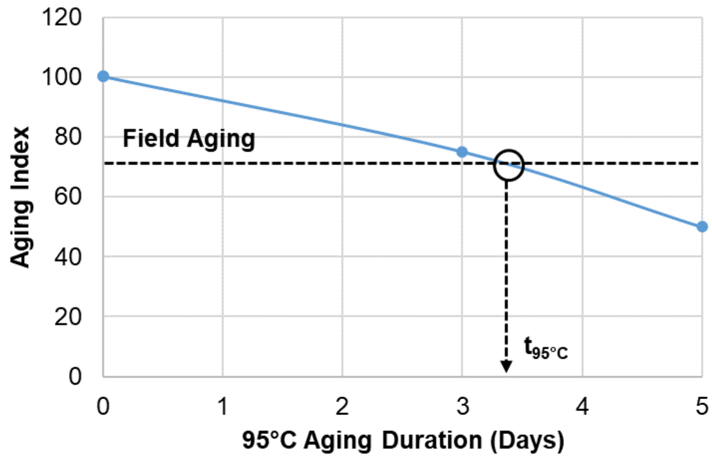


Figure 35. Conceptual Illustration of Lab-versus-Field Aging Data Analysis for Task 1

Table 16. Potential Field Projects for Further Validation of 95°C Aging Maps in Task 1

Location	Year Constructed	Still In-place?	# Mix	Virgin Binder	RAP/RAS	Additive	Loose Mix Aging Procedures	Existing Aging Data
Minnesota (MnROAD)	2016	No	6	PG 64S-22, PG 52S-34, PG 58H-34	10 to 30% RAP, 0 to 5% RAS	None	6h@135°C	IDEAL-CT, DCT
Minnesota (Emily)	2019	Yes	10	PG 58S-28	30% RAP, 40% RAP	Rejuvenator	7d@95°C, 6h@135°C	PG, ΔTc, FS, FTIR, IDEAL-CT, DCT, DTCF
Missouri (St. Louis)	2020	Yes	1	PG 46-34	30% RAP + 3% RAS	None	None	None
Texas (Arlington)	2020	Yes	7	PG 64-22, PG 64-28, PG 70-22	0, 15, and 25% RAP; some with 2% RAS	Rejuvenator	1/3/6d@95°C, 20h@100°C	IDEAL-CT
Alabama (NCAT Test Track)	2021	Yes	6	PG 76-22	20% RAP	Plastic (wet & dry), Rubber (wet & dry), Aramid Fiber	8h@135°C	IDEAL-CT
Illinois (Chicagoland)	2021	Yes	1	PG 58-28	22% RAP +2.5% RAS	None	None	None
Minnesota (MnROAD)	2022	Yes	7	PG 46-34, PG 58-34	20% RAP	Plastic (wet & dry), Rubber (wet & dry), Aramid Fiber	6h@135°C	IDEAL-CT, DCT

4.2 Conversion of Different Loose Mix Aging Procedures (Task 2)

Although the 95°C aging procedure has the most robust lab-to-field correlation data, its long duration makes it an undesirable option in assessing the cracking resistance of asphalt mixtures for BMD. Comparatively, the 100-125°C and 135°C aging procedures are more practical options because they can be completed within a reasonably short time. However, as discussed in the research gap analysis, these two aging procedures have no, or limited, field validation data. One potential approach to address this limitation is to use the kinetics model developed in the NCHRP project 9-54 to convert the 100-125°C and 135°C aging procedures to the 95°C aging procedure, which can then be correlated with field aging using the established 95°C aging maps. This approach is promising because the preliminary conversions between the 95°C and 135°C aging procedures in Elwardany et al. (2021) agree reasonably with the laboratory test results in existing aging studies, as previously discussed in Chapter 2.

Table 17 summarizes the potential field projects for assessing and refining the conversion of different loose mix aging procedures in Task 2. These projects are selected for several reasons: first, they have plant mixes available from production, which can be used to simulate a wide range of laboratory aging conditions using different loose mix aging procedures; second, they cover asphalt mixtures containing non-traditional additives, including recycling agents, recycled plastic, and RTR; and finally and most importantly, they have aging data available associated with one or two loose mix aging procedures that can be leveraged for further testing. Three loose mix aging procedures are proposed to be included: 95°C, 100-125°C, and 135°C. The 85°C aging procedure is not considered because it is impractical for implementation into BMD due to the long duration (i.e., 5 days) and lack of field validation data. The anticipated testing plan for each aging procedure includes the DSR (i.e., PG grading, Delta Tc, and Frequency Sweep) and FTIR testing of the extracted binder and the IDEAL-CT, I-FIT, DCT, and/or DTCF, depending on material and funding availability. These tests are selected because they are sensitive to loose mix aging, as shown in Table 13 and Table 14, and they have been included in ongoing aging studies at NCAT, UNH, and TTI.

Table 17. Potential Field Projects for Conversion of Different Loose Mix Aging Procedures in Task 2

Location	Year Constructed	Still In-place?	# Mix	Virgin Binder	RAP/RAS	Additive	Loose Mix Aging Procedures	Existing Aging Data
Alabama (NCAT Test Track)	2015	No	4	PG 67-22, PG 64-28, HiMA	20% RAP, 35% RAP, 20% RAP + 5% RAS	None	5d@95°C, 8h@135°C	PG, ΔTc, FS, FTIR, IDEAL-CT, I-FIT, DTCF
Minnesota (MnROAD)	2016	No	6	PG 64S-22, PG 52S-34, PG 58H-34	10 to 30% RAP, 0 to 5% RAS	None	6h@135°C	IDEAL-CT, DCT
Minnesota (Emily)	2019	Yes	10	PG 58S-28	30% RAP, 40% RAP	Rejuvenator	7d@95°C, 6h@135°C	PG, ΔTc, FS, FTIR, IDEAL-CT, DCT, DTCF
Missouri (St. Louis)	2020	Yes	1	PG 46-34	30% RAP + 3% RAS	None	None	None
Texas (Arlington)	2020	Yes	7	PG 64-22, PG 64-28, PG 70-22	0, 15, and 25% RAP; some with 2% RAS	Rejuvenator	1/3/6d@95°C, 20h@100°C	IDEAL-CT
Texas (Marshall)	2020	Yes	3	PG 64-22, PG 64-28	20% RAP	None	1/3/6d@95°C, 20h@100°C	IDEAL-CT
Alabama (NCAT Test Track)	2021	Yes	6	PG 76-22	20% RAP	Plastic (wet & dry), Rubber (wet & dry), Aramid Fiber	8h@135°C	IDEAL-CT
Illinois (Chicagoland)	2021	Yes	1	PG 58-28	22% RAP + 2.5% RAS	None	None	None
Minnesota (MnROAD)	2022	Yes	7	PG 46-34, PG 58-34	20% RAP	Plastic (wet & dry), Rubber (wet & dry), Aramid Fiber	6h@135°C	IDEAL-CT, DCT

Figure 36 presents a conceptual illustration of the extracted binder and mixture results associated with different loose mix aging procedures for data analysis. For each field project, the 95°C aging data will be used as the target to determine the equivalent aging time at 135°C ($t_{135°C}$) or the equivalent aging temperature of the 20-hour, 100-125C aging procedure (T_{20hr}) based on interpolation of the results. The aggregated measured $t_{135°C}$ or T_{20hr} results across all projects will then be used to validate or adjust the kinetics model developed in the NCHRP project 9-54. It should be noted that the adjustments to the kinetics model may vary among different tests (and their associated test parameters) because they may have different sensitivity levels to loose mix aging. The data analysis will also identify tests and parameters that are susceptible to changes in asphalt chemistry associated with aging at elevated temperatures above 100°C.

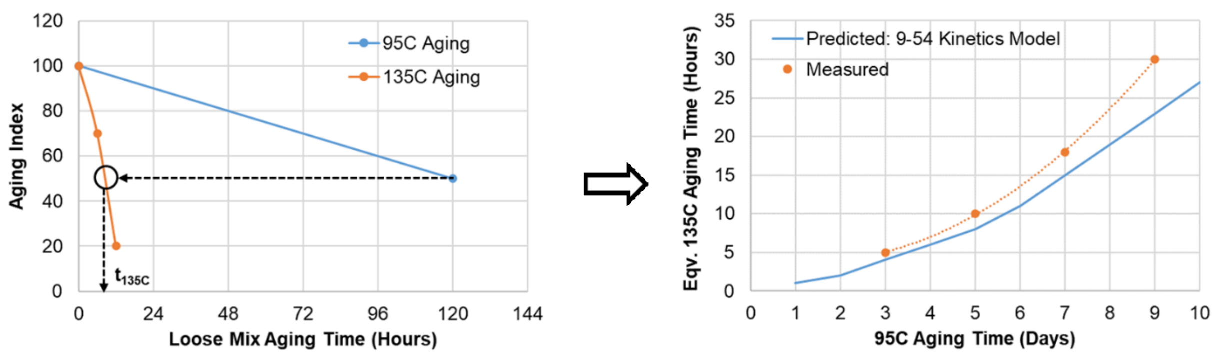


Figure 36. Conceptual Illustration of Aging Conversion Data Analysis for Task 2 (Example of 95°C versus 135°C Aging Conversion)

Figure 37 presents the anticipated approach of implementing loose mix aging in cracking resistance evaluation for BMD. First, a target field aging condition must be specified, including the pavement location, age, and location within the pavement structure (for example, 8 years of field aging 6mm below pavement surface for a pavement at MnROAD). Then, the representative 95°C loose mix aging procedure can be selected based on the 95°C aging maps developed in the NCHRP project 9-54 with additional field validation data collected in Task 1 of the Phase II work plan (for example, 3 days at 95°C). If there is a desire to use an accelerated aging procedure at 100-125°C or 135°C, $t_{135°C}$ or T_{20hr} can then be selected based on the conversion relationships established in Task 2 of the Phase II work plan (for example, 6 hours at 135°C or 20 hours at 110°C).

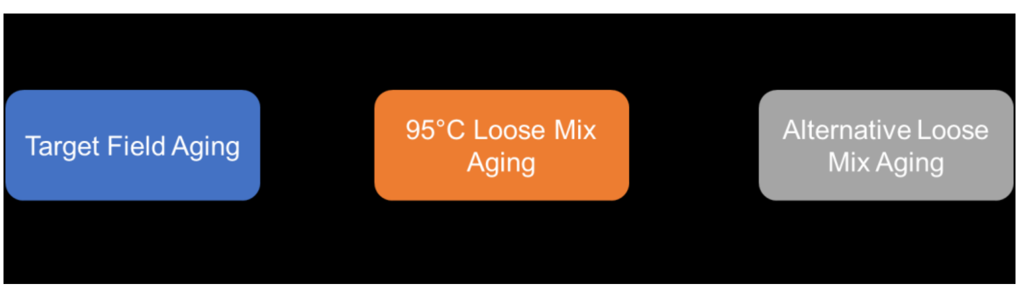


Figure 37. Anticipated Approach of Implementing Loose Mix Aging in Cracking Resistance Evaluation for BMD

4.3 Research Implementation (Task 3)

A final report will be prepared, and an NRRA webinar will be conducted to broadcast the research findings and recommendations of the Phase II study. Depending on funding availability, web software incorporating the 95°C aging maps and the conversion relationships of different loose mix aging procedures can be developed to assist STAs in selecting representative loose mix aging procedures for any target field aging conditions.

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