INTERIM REPORT

to the

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM
(NCHRP)

Project NCHRP 09-54

Long-Term Aging of Asphalt Mixtures for Performance Testing and Prediction

from

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Introduction

Background

The characterization of asphalt pavement materials is increasingly important as mechanistic-empirical pavement design and performance prediction methods are implemented. Materials characterization for aging is a requirement for such mechanistic analysis and research is warranted to improve current practice. Current pavement performance prediction models have different levels of sophistication for numerically simulating the increased stiffness from aging (e.g., the Global Aging System in Pavement ME Design) and the competing phenomena of accumulated damage and deterioration manifesting as a reduction in modulus (e.g., CalME). A prominent shortcoming in the materials technology supporting the use of these models is using an accelerated laboratory procedure to accurately characterize the long-term field condition of asphalt pavements due to oxidative aging. The long-term procedure in AASHTO R 30, Mixture Conditioning of Hot Mix Asphalt (HMA), prescribes aging compacted mixtures at 85°C for 5 days, a time and temperature combination that the original Strategic Highway Research Program (SHRP) research estimated—based on limited field calibration—to reflect a critical duration of field exposure as little as 5 or 7 years or as much as 10 years. This single time-temperature combination may not be applicable for all the different climates found throughout the United States. To address this issue, research is needed to develop a calibrated and validated procedure to simulate long-term aging of asphalt mixtures for performance testing and prediction.

Objective

The objective of this research is to develop a procedure calibrated and validated with field data to simulate long-term aging of asphalt mixtures for performance testing and prediction.

This research will provide a basis for future development of a methodology for integrating the effects of long-term aging in Pavement ME Design and other mechanistic design and analysis systems and using the methodology to enable consideration of long-term aging in full-scale and accelerated pavement testing (APT) results.

The research shall be limited to asphalt-aggregate mixture aging procedures because these will inherently take air voids (permeability) and asphalt-aggregate chemical interaction into account.

During the development of this procedure, consideration shall be given to (1) different types of cracking distress which originate towards the top or bottom of the asphalt pavement layers and are impacted by aging and (2) the potential differential aging within an asphalt pavement layer.

Research Approach

Phase I Develop a Calibrated, Validated Procedure to Simulate Long-Term Aging of Asphalt Mixtures for Performance Testing and Prediction

Task 1. Prepare a critical review of the literature to fully understand and appreciate the following topics, at a minimum:

- Mechanisms governing the long-term aging of asphalt mixtures in in-service pavements
- Material properties that are representative of and sensitive to different levels of aging in in-service pavements
- Types and effects of in situ variables that affect the governing mechanisms during long-term aging
- Laboratory aging equipment and procedures with emphasis on their rationales, efficiency, costs, and validation
- Comparison of the different aging behavior between hot mix asphalt and warm mix asphalt and between virgin and reclaimed asphalt pavement mixes
- Diffusion and heat transfer models appropriate to asphalt mixtures in in-service pavements
- Algorithms to capture the effects of binder oxidation and its effects on mixture behavior for implementation in performance prediction programs such as DARWin-ME

Task 2. Prepare a detailed work plan for a coordinated laboratory and field experiment to (1) identify key aging index properties of asphalt mixtures, (2) use these index properties to define a reliable long-term aging procedure that mimics field aging conditions, and (3) provide a basis for future development of a methodology for incorporating the effects of long-term aging in analyses made with DARWin-ME and other mechanistic design and analysis systems.

Candidate aging index properties include carbonyl absorbance, carbonyl plus sulfoxide absorbance, dynamic shear crossover modulus, and viscosity. In addition, the work plan will consider potential variables such as project climate and service life, mixture density (air voids), and test specimen geometry, as well as the type and location of cracking distresses of interest.

Submit the work plan and the Task 1 critical literature review in an interim report to NCHRP. Meet with NCHRP approximately 1 month later to review the work plan and receive approval to proceed with Task 3.

Task 3. Conduct the approved Task 2 work plan in the following sequence of subtasks:

1. Acquire the necessary original materials (asphalt binders and aggregate) and field cores.
2. Evaluate various aging procedures identified in Task 1 and select candidate procedures for further testing and development.
3. Determine requisite aging index properties from original materials and cores from in-service pavements.
4. Conduct a preliminary assessment and sensitivity analysis of promising aging procedures.
5. Develop a final long-term aging protocol and conduct a field calibration.

6. Evaluate the effects of aging on cracking in asphalt pavements and develop a future research plan to implement the long-term aging procedure and associated models in Pavement ME Design.
7. Prepare a proposed AASHTO standard procedure for long-term aging of asphalt mixtures for performance testing and prediction.
8. Conduct an analysis of the cost and benefit associated with the replacement the long-term aging procedure in AASHTO R 30 with the proposed procedure from this research.

Phase II Reporting

Task 4. Submit a final report that documents results, summarizes findings, draws conclusions, and presents (1) the proposed procedure to simulate long-term aging of asphalt mixtures for performance testing and prediction in AASHTO standard format, (2) the proposed plan for future research; and (3) the cost and benefit analysis. An appendix to the report shall include electronic files of all test data and results collected.

Summary of Work to Date

To date, Tasks 1 through Task 3.2 have been completed, culminating in the establishment of an asphalt mixture long-term aging procedure. The report herein provides a summary of the experimental work conducted thus far that has led to the selection of the optimal aging procedure.

The literature review conducted in Task 1 was used to identify preliminary aging procedures for evaluation. These procedures included the temperature conditioning of loose mixtures and compacted specimens with and without pressure. For the compacted specimens, two geometries were considered: standard large specimens, 100 mm in diameter, and small specimens, 38 mm in diameter. The 38 mm diameter geometry was suggested by the Federal Highway Administration (FHWA) in its forensic evaluation of Accelerated Loading Facility (ALF) pavements (Mbarki et al. 2012) and further developed by the North Carolina State University research team for the forensic study of fatigue cracking of pavements in North Carolina (Park and Kim 2013, Park et al. 2014).

In order to evaluate candidate procedures, preliminary aging trials were conducted on a typical North Carolina mix with 9.5 mm nominal maximum aggregate size (NMAS) and PG 64-22 binder, hereinafter referred to as the 'NC mix'. The integrity of the specimens following aging, the rate of oxidation quantified using AIPs of the extracted binder, versatility, and the cost of the various procedures were compared in order to select the most promising aging procedure. The selected procedure was then applied to a FHWA ALF styrene-butadiene-styrene (SBS) modified mixture, which is known to be highly susceptible to hardening with oxidation and difficult to compact, in order to verify that the procedure would not degrade the specimen integrity. Aging trials on the SBS mix included laboratory aging to match the oxidation level of the surface of an eight-year-old field core obtained from McLean, Virginia. Figure 1 presents a depiction of the overall work plan for Task 3.2. Subsequent sections discuss Subtasks 3.2.1 and 3.2.2 in detail.
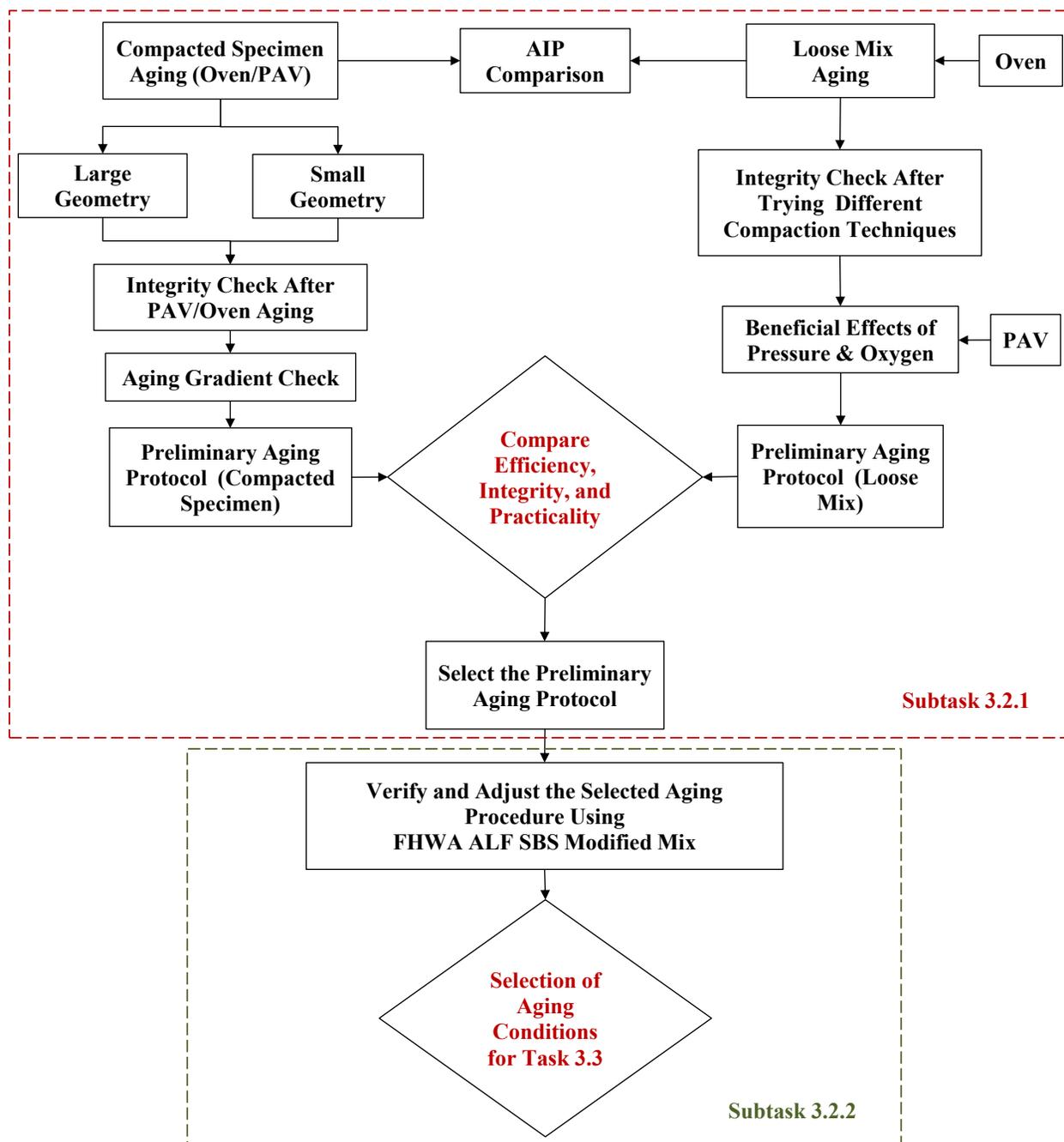
Figure 1. Flowchart for Task 3.2: Establishment of the preliminary aging procedure for field materials.

Subtask 3.2.1: Establishment of Candidate Aging Procedures

Based on the literature review, two candidate aging methods were identified: oven aging and pressurized aging. For the preliminary evaluation of these two aging procedures, a standard binder pressure aging vessel (PAV) was utilized for the pressurized aging trials. Both oven and pressurized aging methods were applied to both loose mix and compacted specimens. Therefore, the preliminary aging procedures were divided into two subtasks on the basis of compacted and loose mixtures, because the potential for integrity problems associated with the two specimen types could differ.

Preliminary Study on Aging of Compacted Specimens

Trials for aging the compacted specimens were conducted using both the oven and PAV. The current standard procedure for asphalt mixture laboratory aging, AASHTO R 30, consists of aging compacted specimens in the oven at 85°C for five days. However, two specimen integrity issues have been found using this procedure in previous research work:

(1) Distortion: Changes in air void content and geometry due to compression under self-weight have been reported when using AASHTO R 30 (Reed 2010). To overcome this problem, the NCHRP 9-23 protocol recommends wrapping specimens in metal wire mesh secured with three clamps to prevent the samples from geometry distortion (Houston et al. 2005). However, this approach has been reported only to reduce, but not eliminate, specimen distortion during aging (Reed 2010).

(2) Oxidation gradient: The NCHRP 9-23 project (2005) demonstrated that the long-term oven aging of compacted specimens leads to both radial and vertical oxidation gradients in mixture specimens, which is a concern for its use in performance testing because properties throughout a specimen differ (Houston et al. 2005).

To overcome these specimen integrity issues, two potential remedial approaches were tried in this study:

(1) Application of pressure to increase the diffusion of oxygen and, hence, potentially reduce oxidation gradients.

(2) Use of small specimens, 38 mm in diameter and 100 mm in height, to reduce the diffusion path distances and reduce slump under self-weight.

To evaluate compacted specimen aging as rigorously as possible, various procedures were tried, including pressurized and oven aging of both the large and small specimens. All specimens were fabricated using the NC mix. To prepare the specimens, mixtures were first prepared using component materials and subjected to short-term oven aging. Then, the mixtures were compacted in a Superpave Gyratory Compacter (SGC) to fabricate Ø150 mm × 178 mm specimens. Subsequently, large specimens for aging were obtained through coring to obtain Ø100 mm × 178 mm specimens. The ends of the cored large specimens were not sawed before aging because of the high probability of an aging gradient that could affect the performance test results. To fabricate the small specimens, Ø38 mm cylindrical specimens were

cored from initial specimens (Ø150 mm × 178 mm) horizontally. Then, the ends were sawed to obtain
Ø38 mm × 100 mm specimens.

For the oven aging trials of the large specimens, wire mesh supports were utilized to minimize distortion
under self-weight. A single aging temperature, 85°C (as specified by AASHTO R 30), was used for the
aging trials. A pressure level of 300 kPa was selected for the PAV aging trials, because higher pressure
levels had been found to damage specimens upon pressure release in the SHRP project (Bell et al. 1994).
In addition, in order to reduce the stress on the large specimens under self-weight in the PAV, a wire
mesh hammock-like support was developed to allow the specimen weight to be distributed over a larger
area on its sides than if it were positioned vertically, as shown in Figure 2.

Figure 2. Simple set-up for holding large specimens during aging in the PAV.

Three criteria were used to evaluate the integrity of the specimens that were subjected to compacted
specimen aging:

(1) Initial integrity check: Specimen integrity was evaluated initially by visual inspection, dimension
     measurements, and air void content comparisons before and after aging to determine if the specimen
     was damaged during the laboratory aging process. If an aging procedure was found to disturb
     specimen integrity, it was eliminated from further consideration.

(2) Performance testing: Performance test data were analyzed to detect any integrity issues that were not
     related to measurable geometry changes (e.g., microcracking). Dynamic modulus tests (AASHTO TP
     79-12) and cyclic direct tension fatigue tests (AASHTO TP 107-14) were conducted, and the results
     were compared to the short-term aged mixture properties to determine if specimen integrity was
     affected during aging (e.g., dynamic modulus decreases upon aging).

(3) Oxidation gradient: Oxidation gradients in the aged specimens were evaluated through Fourier
     Transform Infrared Spectroscopy (FTIR) and Dynamic Shear Rheometer (DSR) testing of binders
     extracted and recovered from locations in an aged specimen that varied in terms of distance from the

specimen periphery. Differences in the rheology and chemical compositions, along with the distance from the specimen periphery, were used to detect the presence (if any) of an aging gradient.

The outcome of this subtask is an assessment of the feasibility of compacted specimen aging and associated preliminary recommendations for the compacted specimen aging procedure, including specimen size and pressure (Oven if 0, and PAV if pressure other than 0 is selected), at 85°C.

Preliminary Study on Aging of Loose Mixtures

The aging of loose mixtures provides another potential solution to overcome the issues associated with the AASHTO R 30 procedures. Geometry distortion is not a concern because loose mix specimens are compacted following aging. In addition, aging gradients are not a problem, because the loose mix is aged as a single layer of coated aggregate particles and, thus, oxygen and heat can circulate easily throughout the mix. Also, the increased surface area of the binder film that is exposed to oxygen is expected to accelerate aging in loose mixtures compared to compacted specimens. However, the compaction of aged loose mix for performance testing is a potential specimen integrity concern because aged binder is very stiff and, thus, is expected to be less compactable than unaged material. A past study on the loose mix aging of an asphalt rubber friction course (ARFC) indicated that significantly more effort is required to compact long-term aged loose mix than short-term aged loose mix (Reed 2010). However, it is important to note that an ARFC represents an extreme case with rubber-modified asphalt and relatively thick asphalt films. It has also been found that the increased force/effort required to reach target air void contents when using compacted aged loose mixtures may cause degradation in the aggregate structure and alter the mixture properties (Gatchalian 2006). Also, the compactability of aged loose mix can potentially be improved by increasing the compaction temperature or by the addition of a compaction aid such as zeolite.

For this study, preliminary loose mix aging trials consisted of both oven and PAV aging of the NC mix at 85°C. Prior to all the long-term aging trials, the loose mix was first subjected to short-term aging.

The oven aging of the loose mix was accomplished by separating the mix into several pans such that each pan had a relatively thin layer of loose mix (approximately equal to the NMAS of the aged mix), as shown in Figure 3. The loose mix was agitated several times during oven aging, and the pans in the oven were rotated systematically to minimize any effects of an oven temperature gradient and/or draft on the degree of aging.

Figure 3. Loose mix separated into pans in thin layers for long-term aging in oven.

After long-term aging, the materials were taken out of the oven and mixed together in order to obtain a uniform mixture, and then the mixture was left to cool to room temperature. The loose mixture was then reheated to the compaction temperature and left for 75 minutes. Specimens were compacted following aging at two temperatures: 144°C (consistent with specifications for short-term aged material) and 157°C to determine if the increased temperature aided the compactability of the mix. The latter temperature is the recommended temperature for compacting less workable mixtures fabricated with high PG binders following the equiviscosity and equiphase angle concepts presented in a study conducted by the National Center for Asphalt Technology (NCAT) (West et al. 2010) that used the SGC to produce 178 mm tall specimens.

The PAV aging trials on the loose mix utilized the standard binder PAV pressure of 2.1 MPa, because pressure was not anticipated to induce any integrity concerns regarding the loose mixture samples since compaction follows the aging process. The specimen set-up is shown in Figure 4. The loose mix was dispersed in thin layers, consistent with oven aging. The size of the binder PAV prohibited aging a large quantity of mix efficiently and, thus, any gain in the oxidation rate had to be balanced with the amount of material that could be aged at one time or, conversely, the associated costs in developing a mixture-specific pressure aging device. Due to the capacity constraints of the PAV, the long-term aging trials of the loose mix in the PAV were limited to simply assessing how much pressure would expedite the oxidation of the loose mix. Insufficient quantities of material were aged to produce compacted specimens. However, extracted binder was tested, which allowed the extent of the oxidation to be determined and, hence, allowed an assessment of the efficiency gains due to the pressure in oxidizing the loose mix.

Figure 4. Aging rack developed for long-term aging of loose mix in PAV.

Two criteria were used to evaluate the integrity of the specimens compacted following loose mix aging:

(1) Initial integrity check: The number of gyrations required to meet the target air void content was compared with that of the short-term aged mix in order to assess compactability. Air void content measurements were used to verify that the desired compaction level was met. In addition, digital imaging processing software was used to analyze the internal coarse aggregate structure of the compacted short-term and long-term aged loose mixes to determine if the aggregate structure was degraded by compacting the mixes following long-term aging.

(2) Performance testing: Performance tests, including dynamic modulus tests (AASHTO TP 79-12) and simplified continuum damage (S-VECD) fatigue tests (AASHTO TP 107-14), were conducted on specimens that were compacted following loose mix aging to assess any further potential integrity problems (e.g., dynamic modulus decrease upon aging).

The outcome of this subtask is the assessment of the feasibility of loose mixture aging. Recommendations for the long-term aging of loose mixtures are established, including guidelines for appropriate compaction techniques for aged loose mixtures.

Selection of Preliminary Aging Procedure

The ultimate outcome of Subtask 3.2.1 was the selection of the most promising aging procedure to utilize for further consideration. To select the most promising aging procedure, compacted and loose mix aging procedures were compared based on the following criteria:

(1) Specimen integrity: Specimen integrity, as related to compacted and loose mix aging, as previously discussed, is important for reliable performance evaluation.

(2) Efficiency: The relative rate of oxidation achieved in each procedure as evaluated through comparisons of chemical and rheological AIPs, was quantified using attenuated total reflectance (ATR) FTIR and DSR temperature-frequency sweep testing, respectively.

(3) Practicality and versatility: The relative cost and availability of the required equipment were considered in selecting the most promising aging procedure. Furthermore, the versatility of the specimen geometries that can be produced for performance testing was an important consideration.

The outcome of this subtask is the selection of loose mix versus compacted specimen aging. Preliminary recommendations for aging procedure conditions (e.g., temperature, duration, and pressure level) are also defined.

Subtask 3.2.2: Preliminary Evaluation of Selected Aging Procedure

The selected procedure needed to be verified for an additional mixture, which posed potential concerns regarding specimen integrity. For this purpose, the FHWA ALF SBS-modified mixture was selected, because loose mixture aging was the eventual outcome of Subtask 3.2.1 and because the FHWA ALF SBS mix is known to be both difficult to compact and highly susceptible to hardening with oxidation. Asphalt binder was extracted and recovered from a field core obtained after eight years in service at the FHWA ALF in McLean, VA for comparison to the loose mix aging trial results. Loose mix aging trials were conducted at 70°C, 85°C, and 95°C to determine the time required to match the level of oxidation of the surface of the field core at varying depths. To evaluate the integrity of the specimens that were compacted following loose mix aging, two laboratory aging conditions were considered: eight days at 85°C, consistent with Subtask 3.2.1, and 21 days at 95°C, which was found to match the level of oxidation of the binder extracted from the surface of the field core. Note that this latter condition is thought to represent an 'extreme' level of oxidation, as oxidation levels dissipate drastically with the depth of the pavement. To evaluate the integrity of the aged loose mix, the aged mix was compacted with no adjustment to the short-term aging compaction temperature and then subjected to dynamic modulus and fatigue (S-VECD) performance testing. The number of gyrations required for compaction and the performance test results were compared to the results of the short-term aged specimens in order to assess the integrity of the specimens that were compacted after loose mix aging.

The outcome of this subtask is the verification of the procedure selected in Subtask 3.2.1 with establishment of preliminary aging conditions for Subtask 3.3.1.

Summary of Experimental Plan

Table 1 provides a summary of the experiments conducted within Subtask 3.2 in order to establish the selected aging protocol.

Table 1 Summary of Aging Trials and Naming Scheme Description

Mixture	Material		Aging Method	Temp. (°C)	Duration	Air Pressure (kPa)	Sample ID	Performance Testing*
NCS9.5B	Binder		RTFO	163	85 min	-	RTFO-NC	--
	Binder		PAV	100	20 hr	2100	PAV-NC	--
	Loose Mix		STA	135	4 hr	-	S-NC	Yes
	Loose Mix		Oven	85	8 days, Compacted at 144°C	-	L-O-85-8D-NC-(C144)	Yes
	Loose Mix		Oven	85	8 days, Compacted at 157°C	-	L-O-85-8D-NC-(C157)	Yes
	Loose Mix		PAV	85	2 days	2100	L-P21-85-2D-NC	No
	Compacted Specimen	Small	PAV	85	1 day	300	C-P3-85-1D-NC-S	No
		Small	PAV	85	3 days	300	C-P3-85-3D-NC-S	No
		Small	Oven	85	8 days	-	C-O-85-8D-NC-S	No
		Large	PAV	85	1 day	300	C-P3-85-1D-NC-L	Yes
		Large	Oven	85	8 days	-	C-O-85-8D-NC-L	Yes
FHWA ALF-SBS-LG	Binder		RTFO	163	85 min	-	RTFO-SBS	--
	Binder		PAV	100	20 hr	2100	PAV-SBS	--
	Loose Mix		STA	135	4 hr	-	S-SBS	Yes
	Loose Mix		Oven	70	35 days	-	L-O-70-35D-SBS	No
	Loose Mix		Oven	85	8 days	-	L-O-85-8D-SBS	Yes
	Loose Mix		Oven	85	10 days	-	L-O-85-10D-SBS	No
	Loose Mix		Oven	95	21 days	-	L-O-95-21D-SBS	Yes

*Performance testing was conducted only for a select set of aged specimens.

Establishment of Candidate Aging Procedure (Subtask 3.2.1)

Results

Initial Integrity Check Results

Compacted Specimen Aging

Initial integrity checks of the compacted specimens included visual inspection, air void content, and dimensions of the specimens. In cases where integrity issues were encountered, remedial strategies were developed to eliminate air void content and dimensional integrity problems. These strategies are detailed in Table 2.

Table 2 Summary of Findings from Level 1 Integrity Check of Compacted Specimen Long-Term Aging

Material State	Temperature	Pressure	Recommendation to Avoid Integrity Problems
Compacted Large Specimen	85°C	-	Wire mesh support be used for specimens
Compacted Large Specimen	85°C	0.30 MPa	Specimen to be placed on a hammock-like support on its side
Compacted Small Specimen	85°C	-	Specimen be placed in the oven on its side on a flat surface
Compacted Small Specimen	85°C	0.30 MPa	Controlled air pressure application be considered and specimen be placed on its side on a flat surface

The comparison of specimen air voids contents before and after aging are shown in Figure 5 for the aging trials that utilized the strategies detailed in Table 2. The results indicate that very minor air void changes occurred during the aging of both the small and large specimens with and without pressure. Note that the initial integrity checks for the small specimens aged in the oven at 85°C for eight days indicate that no wire mesh was needed to avoid geometry distortion due to the relatively low weight of the small specimens.

However, visual changes were observed for all the specimens that were subjected to oven and PAV aging. A representative example of such visual change is shown in Figure 6. It can be seen that the exposed aggregates particles appear largely to be coated in asphalt after aging. Although the reason for this visual change is not fully understood, it is thought to be related to the absorption of the binder by the aggregate at the elevated temperatures that were used during aging and/or bleeding of the asphalt binder to the surface of the mix. This visual change has also been reported by other researchers (e.g., Tarbox 2010).
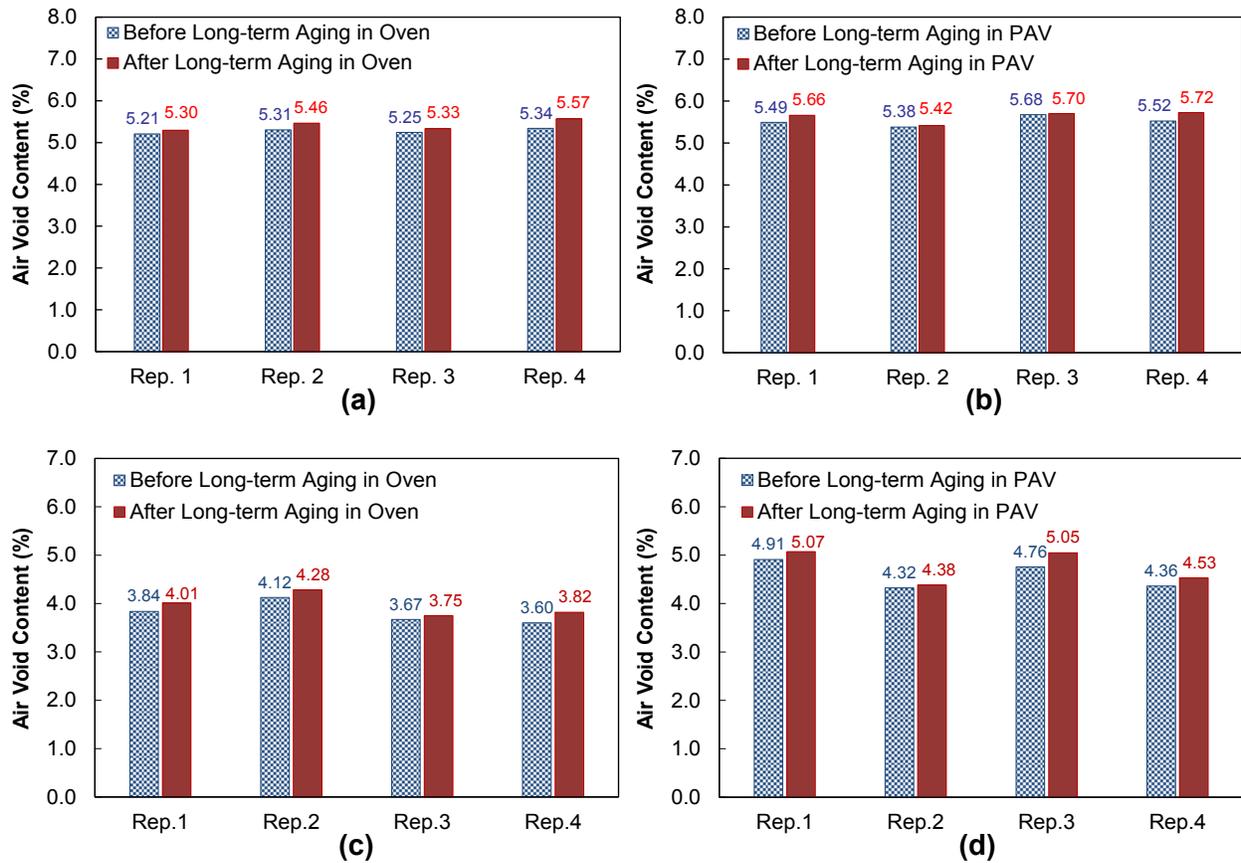
Figure 5. Air void measurements for (a) large specimens (100 mm × 178 mm) before and after aging in the oven at 85°C for 8 days, (b) large specimens (100 mm × 178 mm) before and after aging in the PAV at 85°C, 300 kPa air pressure for 24 hours, (c) small specimens (38 mm × 100 mm) before and after aging in the oven at 85°C for 8 days, and (d) small specimens (38 mm × 100 mm) before and after aging in the PAV at 85°C, 300 kPa air pressure for 24 hours.

Figure 6. NC mix specimen before (left) and after (right) long-term aging in the oven.
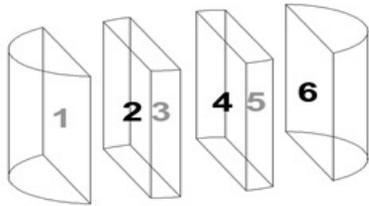
Loose Mix Aging

The number of gyrations needed to reach the target air void contents and analysis of the coarse aggregate structure were used as initial integrity checks for loose mix aging because the primary integrity concern was the ability to compact aged material for performance testing. Two compaction temperatures were tried: 144°C and 157°C. The number of gyrations required to reach the target air void contents for both the short-term and long-term aged materials is shown in Figure 7 (a). The results indicate no significant difference in the compaction effort required for the short-term and long-term aged materials. The results indicate that it is possible to compact aged loose mix with no adjustment to the compaction temperature.

As an additional check of specimen integrity, the coarse aggregate structures of the specimens that were compacted following the short-term aging and long-term aging (with compaction at 144°C) were analyzed using the image processing software, iPas, developed at the University of Wisconsin-Madison and Michigan State University. To apply iPas, the samples were cut vertically to form four sections, as depicted in Figure 7 (b). Using a scanner, two-dimensional images of the faces (numbers 2, 3, 4 and 5 shown in Figure 7 (b)) were obtained and used as inputs for the iPas software. The iPas software outputs several quantities that can be used to quantify the aggregate structure, most notably the number of aggregate particle contacts and the contact length. A contact point is regarded as any point where two aggregate particles are in contact. The contact length is the length between the aggregate particle contacts. The iPas main output summary is shown in Figure 7 (c). The results indicate no reduction in the number of contact points or contact length for the compacted aged material, indicating that there are no integrity problems associated with compacting aged loose mix.
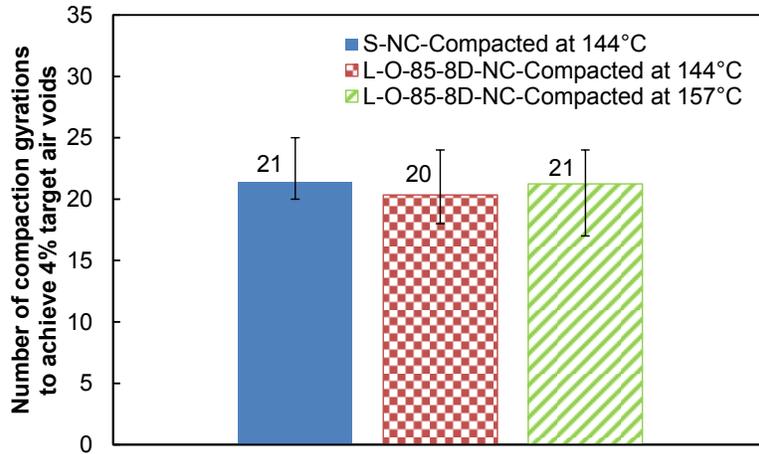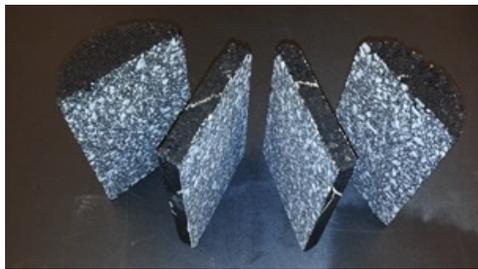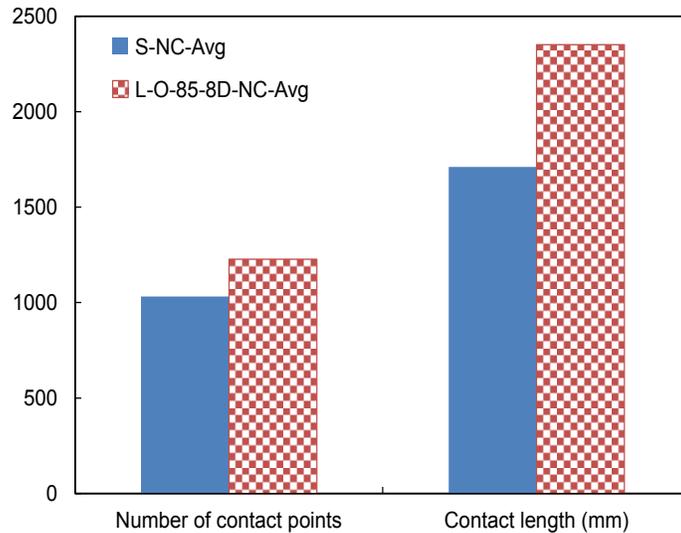
Figure 7. Integrity assessment of long-term aging trials performed on loose mix (NCS9.5B mix): (a) number of compaction gyrations needed to achieve target air voids, (b) SGC sample prepared for scanning, and (c) iPas main outputs summary.

Performance Testing

Following the initial integrity checks, the specimen integrity of the aged mixtures was assessed using performance testing. Only a limited number of aging conditions were selected for performance testing due to the time constraints detailed in Table 1. For specimens that were aged using compacted specimen aging, the strategies detailed in Table 2 were utilized to minimize integrity issues.

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Dynamic modulus testing results

The dynamic modulus mastercurves are shown in Figure 8. The results presented in Figure 8 correspond to the average values of two replicates. No meaningful difference is evident between the dynamic modulus values of the short-term aged and PAV-aged compacted specimens, indicating that either (a) no significant aging occurred or (b) the application of pressure damaged the specimens. The specimens aged using other methods show a significant increase in dynamic modulus values. Loose mix aging appears to lead to slightly higher dynamic modulus values than compacted specimen aging in the oven for the same duration, indicating that aged loose mix can be compacted for performance testing. In addition, these results suggest that higher levels of oxidation are achieved using loose mix aging compared to compacted specimen aging, given the same temperature and duration of conditioning in an oven. The compaction temperature utilized for the aged loose mixes had little effect on the dynamic modulus.

(a) (b)
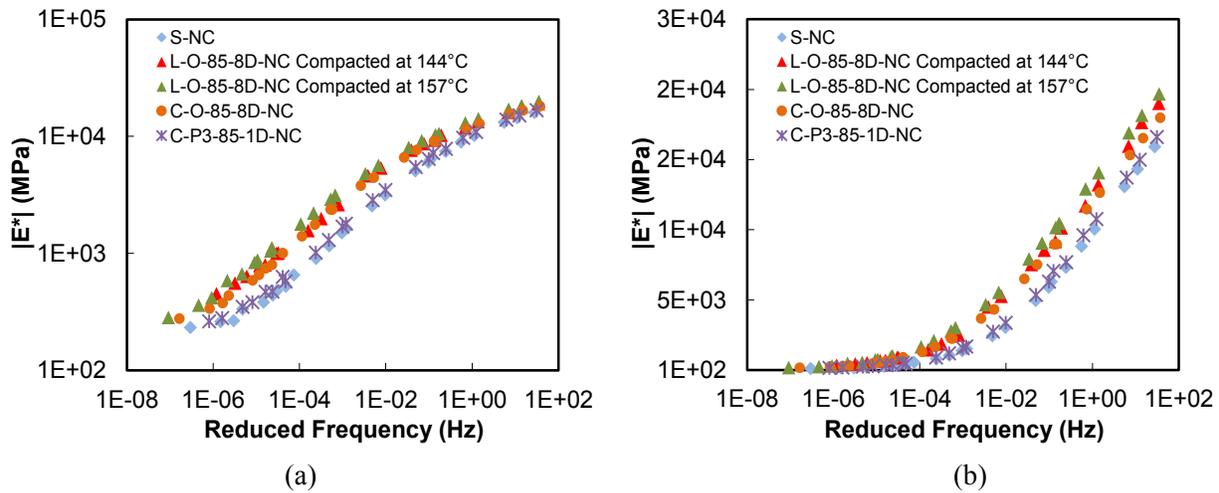
Figure 8. Dynamic modulus test results: (a) log-log scale and (b) semi-log scale.

Fatigue performance testing (S-VECD) results

Figure 9 presents the damage characteristic curves obtained from the S-VECD analysis of the cyclic direct tension test results for both the short-term and long-term aged materials. Typically, damage characteristic curves are used to describe the relationship between material integrity and damage and are path-independent (i.e., independent of loading and thermal history). The curves presented in Figure 9 represent the average of the curves obtained from three different cross-head displacement amplitudes used in the tests. The damage characteristic curves of the stiffer materials usually are higher than the damage characteristic curves of the softer mixtures, as demonstrated also in Hou et al. (2010) and Norouzi et al. (2015). Because aging is expected to increase the stiffness of asphalt mixtures, it is expected that the damage characteristic curves of the long-term aged mixtures would be higher than those of the short-term aged mixtures, unless an integrity problem existed in the specimen. The results demonstrate that all the oven-aged specimens (both aged loose mix and aged compacted specimens) have higher damage characteristic curves than the short-term aged specimens, indicating no integrity issues. In other words, the compaction of aged loose mix does not appear to lead to integrity problems. Furthermore, the results of the long-term aged loose mixture trials show similar damage characteristic curves regardless of the

compaction temperature, indicating that specimen integrity can be achieved without elevating the compaction temperature. In addition, the results indicate that the oven-aged loose mix specimens have slightly higher damage characteristic curves than the oven-aged compacted specimens, which is consistent with the dynamic modulus test results.

Figure 9. Comparison of damage characteristic curves from the NC mixtures subjected to different aging conditions.

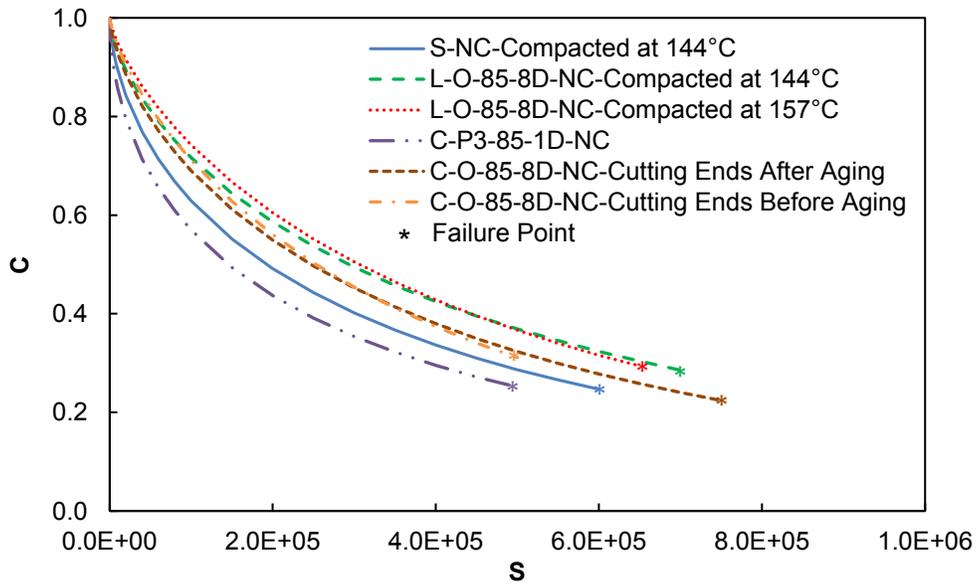The research team compared two sets of specimens for the compacted specimens that were subjected to oven aging: aged 178-mm tall specimens, whereby the specimen ends were cut following aging to reduce the height to 130 mm for testing, and 130-mm tall specimens aged in the oven following cutting the ends of the specimens. The damage characteristic curves were similar for the two sets of samples. However, the specimens that were aged at a height of 130 mm (i.e., ends cut before aging) demonstrated a high propensity for end failure, indicating a higher level of oxidation at the ends of the specimen and, hence, a testing concern. The damage characteristic curves of the PAV-aged compacted specimens lie below those of the short-term aged specimen, indicating that the specimens were damaged by the application and/or release of pressure during aging. Thus, the application of pressure when aging compacted specimens should be avoided.

Figure 10 depicts the G^R energy-based failure criterion plots. G^R represents the average rate of the pseudo strain energy that is released per cycle up to the point of failure. Sabouri and Kim (2014) have demonstrated that a unique relationship exists between G^R and fatigue life (N_f), which is both temperature-independent and loading history-independent and thus represents a valuable failure criterion, which when coupled with the S-VECD model allows for the accurate prediction of fatigue life under any loading history of interest. For severely aged materials, it is anticipated that the failure criterion curves will fall below those of the short-term aged materials due to the loss of fatigue resistance associated with embrittlement imposed by oxidation. However, the lack of a strong relationship between G^R and N_f or an unusually low curve could also indicate integrity problems. The failure criterion line is expected to fall

beneath that of the less aged material. Thus, the failure criterion results of the PAV-aged compacted specimens potentially indicate an integrity problem, as the dynamic modulus results do not indicate an elevated modulus values compared to those derived from short-term aging. All the other failure criterion lines fall close to that of the short-term aged materials, which does not indicate integrity problems.
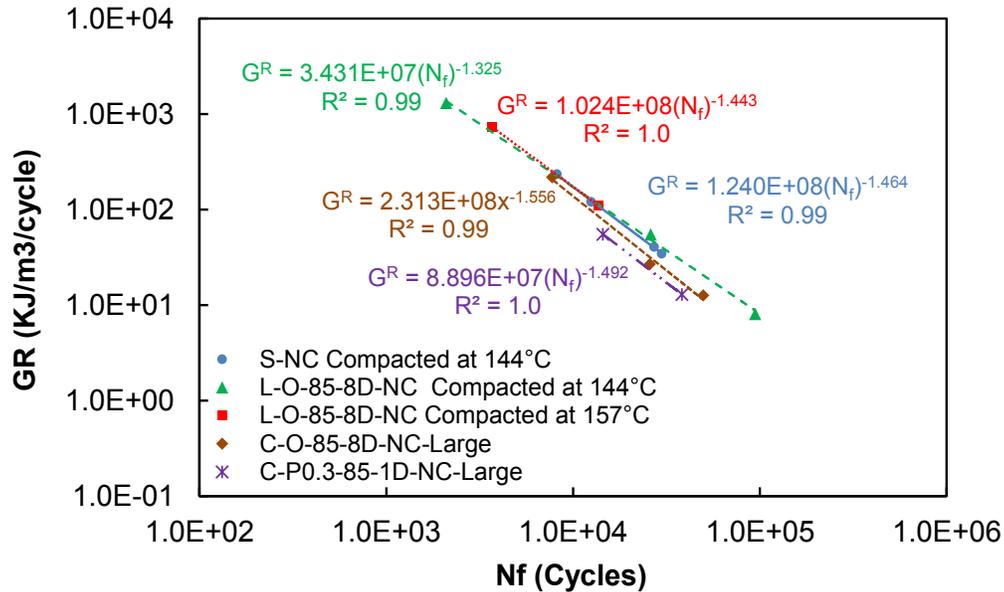

Figure 10. Comparison of failure criterion lines of NC mixtures subjected to different aging conditions.

Evaluation of Extracted and Recovered Asphalt Binder Aging Index Properties (AIPs)

The extracted and recovered binder chemical and rheological data obtained from the different aging trials were compared using aging index properties (AIPs). Binder also was extracted from the short-term aged loose mix and tested in order to assess the oxidation that was induced during the long-term aging. In addition, the AIPs of binders that were aged using standard rolling thin-film oven (RTFO) aging and RTFO plus PAV aging (i.e., RTFO + PAV) were measured to provide a reference, as it is known that the binder PAV is expected to simulate five to ten years of aging in the field. The chemical and rheological AIPs presented herein are the carbonyl plus sulfoxide peak absorbance and the binder dynamic shear modulus value (G* at 64°C and 10 Hz), respectively. The carbonyl plus sulfoxide absorbance peak was found to be the FTIR parameter that was most sensitive to oxidation level. The rheological AIPs considered also include the zero shear viscosity (ZSV) and the cross-over modulus (G*$_c$). The ZSV and G*$_c$ have an advantage in that they are temperature- and loading frequency-independent. However, their determination is based on curve fitting, whereas G* at 64°C and 10 Hz loading frequency can be determined directly and, thus, is a parameter that is not sensitive to the optimization approach used to model the mastercurve. Figure 11 presents the correlations between the rheology-based AIPs and the carbonyl plus sulfoxide absorbance peaks (C+S) for the binders extracted and recovered from the NC mixes aged in the oven. The results indicate a strong relationship between each rheological AIP and carbonyl plus sulfoxide absorbance and thus suggest that both rheology and chemistry can be used as oxidation level indicators. The parameter G* at 64°C and 10 Hz loading frequency is used as the

rheological AIP in forthcoming discussions both for simplicity and due to the known sensitivity of the mixture's dynamic modulus to changes in the binder dynamic shear modulus, which have yet to be resolved for ZSV and the cross-over modulus. Table 3 summarizes the naming scheme used for the different components of the small, large specimens and loose mix.

Table 3 Naming Scheme Description for Aging Gradient Study

Material	Aging Method	Temp. (°C)	Duration	Air Pressure	Component	Naming Scheme
Loose Mix	Oven	135	4 hr	-	-	STA-NC-UC
Compacted Specimen - Small	PAV	85	3 days	300 kPa	Core	C-P3-85-3D-NC-S-C
					Outer Segment	C-P3-85-3D-NC-S-O
	Oven	85	8 days	-	Core	C-O-85-8D-NC-S-C
					Outer Segment	C-O-85-8D-NC-S-O
Compacted Specimen - Large	Oven	85	8 days	-	Core	C-O-85-8D-NC-L-C
					Mid-Layer	C-O-85-8D-NC-L-M
					Outer-Layer	C-O-85-8D-NC-L-O
Loose Mix	Oven	85	8 days	-	-	L-O-85-8D-NC

(a)

(b)

(c)
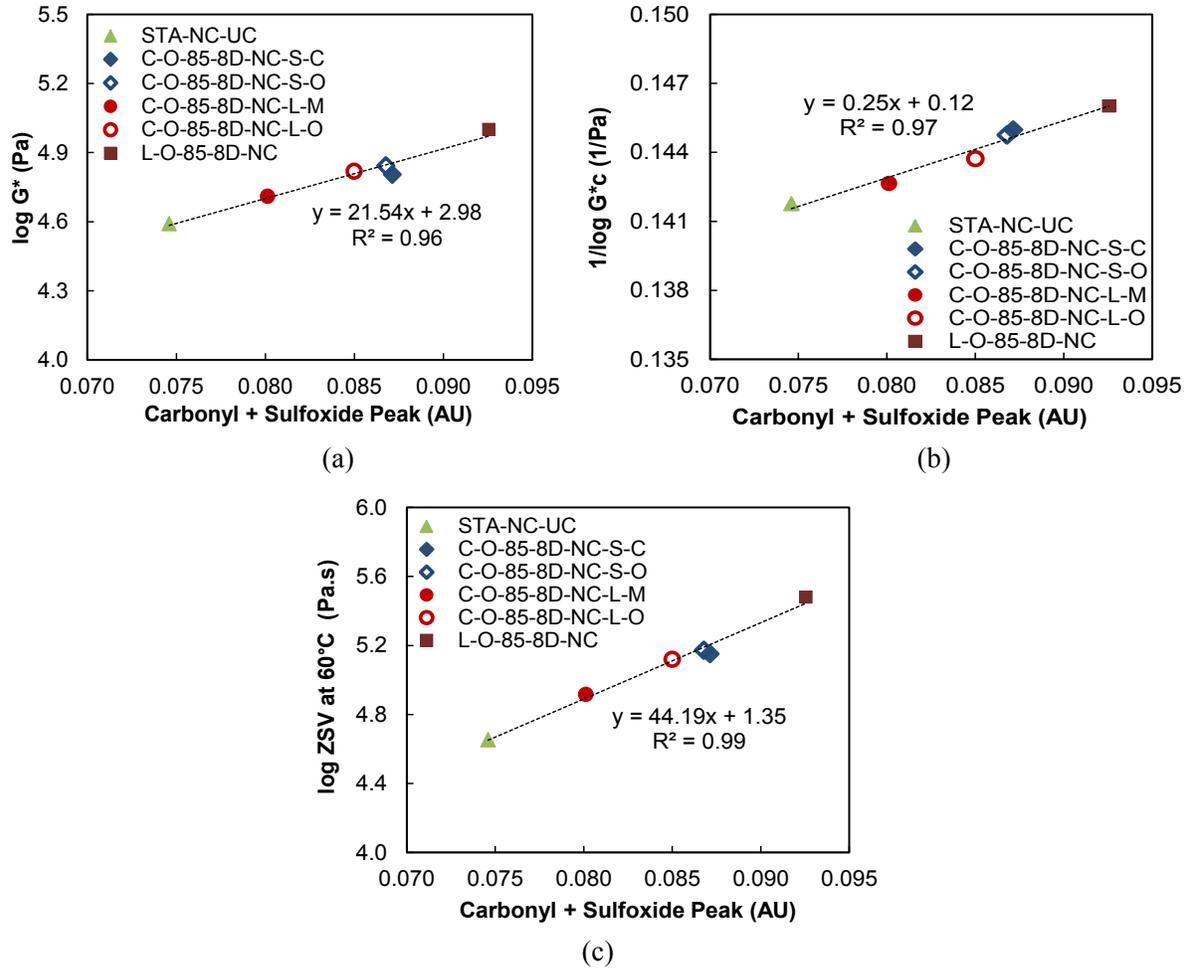
Figure 11. Correlations between different rheology-based AIPs and carbonyl plus sulfoxide absorbance peaks for binders extracted and recovered from aged NC mix: (a) log G* versus C+S, (b) 1/log G*c versus C+S, and (c) log ZSV versus C+S.

In order to evaluate the significance of the different test results and draw solid conclusions, the sensitivity of the mixtures' performance to the binder AIP parameters was evaluated as part of the sensitivity study subtask (Subtask 3.3.2). Details of this study will be presented in a separate report. Based on the sensitivity study results, a 2% change in the carbonyl + sulfoxide absorbance and a 15% change in the binder complex modulus both correspond to approximately a 10% change in the mixtures' dynamic modulus values. A 10% change in the dynamic modulus value is considered a reasonable threshold of significance and, hence, a 2% change in the carbonyl + sulfoxide absorbance and 15% change in G* at 64°C and 10 Hz were used as threshold for detecting significant differences when interpreting the AIP results.

Evaluation of Aging Gradient in Compacted Specimen Aging

In compacted specimen aging, the oxygen diffusion from the periphery to the specimen center is impeded by the binder film and aggregate, thus leading to a high possibility of an oxidation gradient within specimens aged in a compacted state. The extraction and recovery of binder from differing distances from

the periphery of compacted specimens following long-term aging allows for the assessment of aging gradients. This assessment was accomplished in this study by first slicing and coring the specimens into slices from which the binder was recovered. For the small specimens, the outer segments were obtained by slicing the specimens vertically, as depicted in Figure 12. The large specimens were cored using a 38-mm core bit and 75-mm core bit to obtain radial slices, as shown in Figure 13. Binder extraction and recovery was carried out only for the outer layer, middle layer, and core of the oven-aged large specimen.
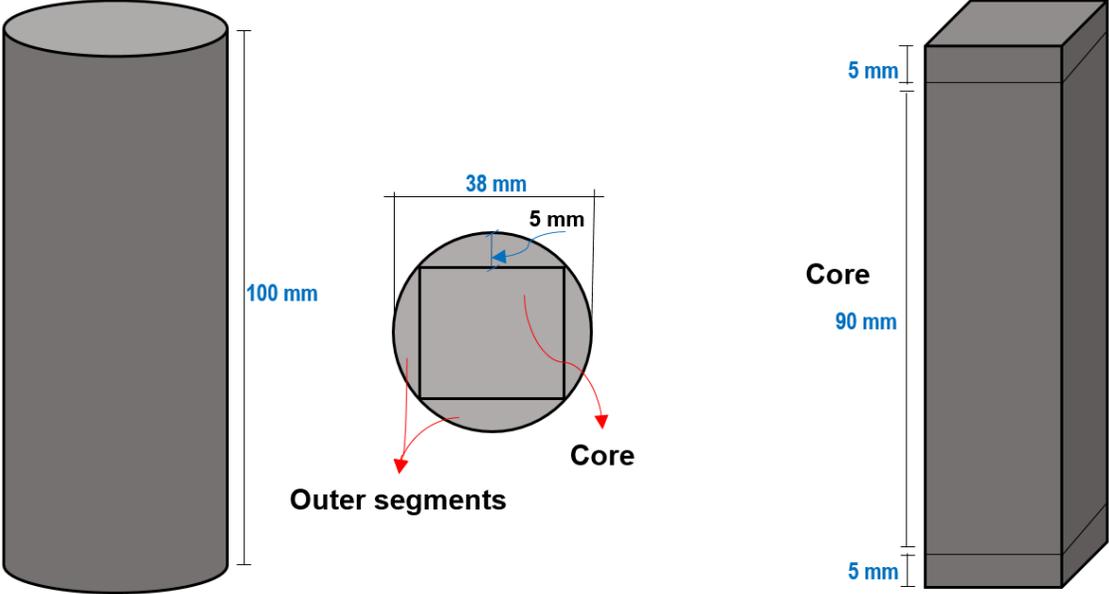

Figure 12. Schematic of components of small specimen (38 mm × 100 mm) used to evaluate oxidation gradients.
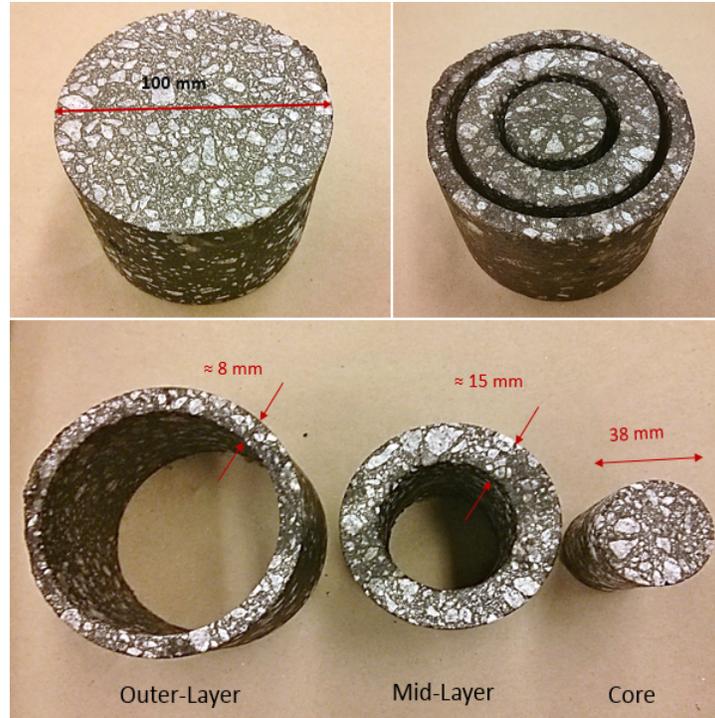
Figure 13. Schematic of components of large specimen (100 mm × 150 mm) used to evaluate oxidation gradients.

The results of the AIP tests of the different specimen components for all the compacted specimen aging trials are shown in Figure 14. (Note that the logs of the dynamic shear modulus results are presented to facilitate the comparison to the carbonyl plus sulfoxide absorbance results.) Considering the two percent threshold for significant changes in carbonyl + sulfoxide absorbance, the results indicate that significant oxidation occurred during all the compacted aging trials, as evident by the increase in the carbonyl + sulfoxide absorbance and dynamic shear modulus values between the long-term and short-term aged materials (uncompacted S-NC-UC); however, the extent of aging that was achieved is slightly less than for the RTFO+PAV binder. The AIP measurements for the binders that were extracted and recovered from the different layers of the large specimens that were long-term aged in the oven (8 days at 85°C) reveal significant changes between the cores and outer portions of the specimens in terms of both rheological and chemical AIPs, thereby indicating the existence of an aging gradient within the specimens. The small specimens aged in the oven exhibited levels of oxidation that were similar to those of the large specimens, based on the AIP values. However, the AIP values for the binders extracted and recovered from the outer segments and from the cores of the small specimens that were long-term aged in the oven (8 days at 85°C) indicate no significant aging gradient, thus confirming that shorter diffusion paths can mitigate oxidation gradient concerns. The small specimens aged in the PAV showed a higher level of oxidation than the oven-aged specimens, based on the binder dynamic shear modulus values and IR spectra, indicating that pressure does expedite the oxidation of the mixtures, as these PAV specimens were aged for only three days at 85°C compared to oven-aged specimens that were conditioned for eight days. However, for the small specimens aged in the PAV (3 days at 85°C and 300 kPa), a significant aging gradient can be observed based on the chemical and rheological AIPs, indicating that pressure does not alleviate the effects of an oxidation gradient.
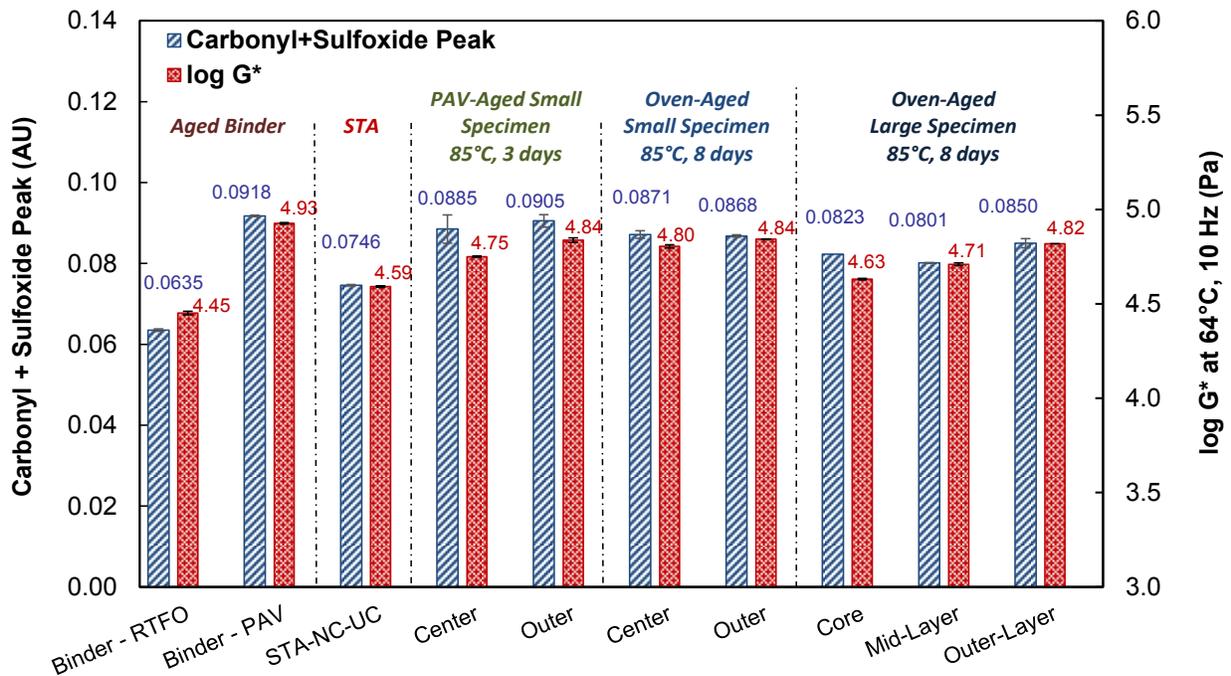
Figure 14. Comparison between carbonyl+sulfoxide absorbance peaks and log G* at 64°C and 10 Hz for extracted and recovered binders from different slices of aged NC compacted specimens and aged NC binders.

Evaluation of Aging Efficiency of Loose Mix and Compacted Specimen Aging With and Without Pressure

In addition to evaluating the aging gradients in the compacted specimens, the AIP measurements of the binders extracted from both the aged loose mix and compacted specimens were used to assess the relative rate at which the different procedures oxidize the binder. The AIP results of all the long-term aging trials in addition to those of the short-term aged mix and the asphalt binder aged using standard methods are provided in Figure 15. The results first demonstrate that the level of oxidation in the short-term aged mixtures surpasses the level of oxidation produced by the RTFO-aged binder. As discussed, the oven aging of the compacted specimens, both large and small, at 85°C for eight days (i.e., AASHTO R 30 long-term aging level 3) led to oxidation levels that were somewhat lower than for the binder PAV. The application of pressure to the compacted specimens during aging expedited the oxidation process, as discussed, but led to integrity problems in terms of both aging gradient and the damaging effects that affect performance test results. The long-term aging of the loose mix in an oven for eight days at 85°C led to a level of oxidation based on chemical and rheological AIPs that exceeded that of the oven aging of the compacted specimens for the same duration and also exceeded the level of RTFO+PAV binder aging. Thus, aging loose mix appears to expedite oxidation significantly compared to aging compacted specimens. The long-term aging of the loose mix in the PAV for two days at 85°C and 2.1 MPa led to a level of oxidation similar to that of the loose mix oven aging for eight days at the same temperature. These results suggest that the addition of pressure can greatly expedite aging almost four times faster than a conventional oven for aging. However, it is important to note that the standard binder PAV does not

allow sufficient space for aging sufficient quantities of material for performance testing in a single trial. Thus, if PAV aging of loose mix were to be adopted for this project, a new (larger) PAV would have to be developed.
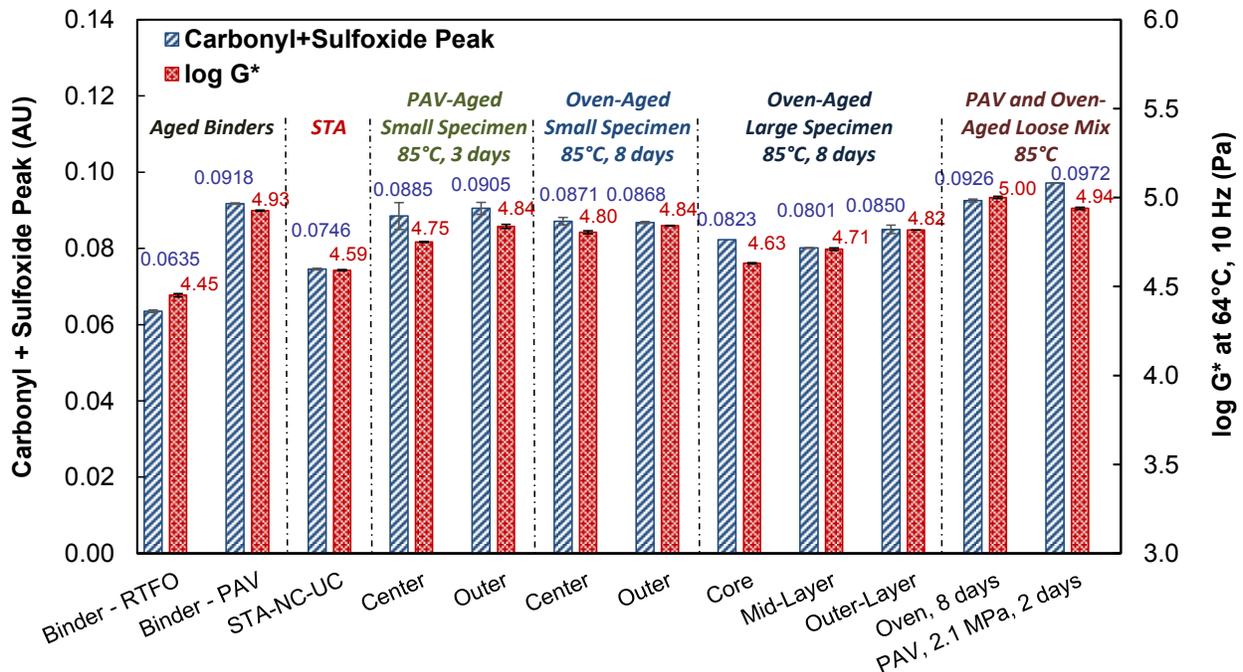
Figure 15. Comparison between carbonyl+sulfoxide absorbance peaks and log G* at 64°C and 10 Hz for extracted and recovered binders from different compacted specimen aging processes, loose mix aging trials, and aged binders.

Summary

Compacted Specimen Aging

Although no integrity issues in terms of changes in air void content or specimen dimensions were encountered with the AASHTO R 30 protocol, the aging of large (100-mm diameter) compacted specimens with wire mesh support in an oven at 85°C led to the development of an aging gradient within the specimens. This lack of uniform properties throughout the specimen is of concern for performance testing and was observed directly through a high rate of end failure at the end locations where oxidation was most significant in the cyclic direct tension fatigue tests. However, the high rate of end failure could be overcome by aging specimens 178 mm in height and then trimming the ends to produce a 130-mm tall specimen for testing. The aging gradient observed in the large compacted specimens subjected to oven aging was eliminated by using small specimens (38-mm diameter with 100-mm height) due to decreased diffusion paths.

The application of pressure in compacted specimen aging was found to expedite aging. However, oxidation gradients were observed in pressure-aged specimens. In addition, although no changes in air void contents or specimen dimensions were induced by pressurized aging, the performance test results

indicate that the application and/or release of pressure can damage specimens. Therefore, the results indicate that the most promising method for aging compacted specimen is to age small specimens in an oven without pressure.

Loose Mix Aging

The primary concern associated with loose mixture aging is the ability to compact the material after long-term aging. However, in this study, the compaction of the NC mix after eight days of oven conditioning at 85°C was possible with no adjustment to the compaction temperature. A similar number of compaction gyrations was required for both the short-term aged and long-term aged loose mixes. The image analysis of the aggregate structure also indicated comparable compaction of both the short- and long-term aged loose materials. Furthermore, the performance tests indicated a significant increase in the dynamic modulus values of the long-term aged material compared to those of the short-term aged material, and the fatigue performance tests indicated no integrity concerns. In addition, loose mix aging exposes a large surface area of the binder to oxygen, and thus, a faster rate of oxidation was observed in loose mix oven aging compared to compacted specimen aging based on the measured asphalt binder chemical and rheological aging indices. The application of pressure also was found to expedite the oxidation of the loose mix. However, only 500 g of loose mix could be aged at one time in the binder PAV. One SGC specimen requires the preparation of 7000 g to 8000 g of loose mix. Thus, the binder PAV would need to be run approximately 15 times to generate enough loose mix to prepare a compacted specimen for performance testing, which is inefficient and therefore was deemed impractical. If the pressure aging of loose mix is selected, then a new, larger PAV would need to be developed.

Preliminary Selection of Aging Procedure

Based on the aforementioned summary of the compacted and loose mix aging trials with and without pressure, the research team recommends that oven aging of loose mix should be selected as the optimal aging procedure. To avoid specimen integrity issues, the only option for the oven aging of compacted specimens is to age small specimens in an oven. This specimen geometry allows for only dynamic modulus and direct tension testing. Other tests (e.g., permanent deformation tests) would not be possible under this scenario. Loose mix aging is more versatile than compacted specimen aging in that any specimen geometry can be produced using aged loose mix (e.g., slabs or beams). In addition, loose mix aging leads to faster oxidation than compacted specimen aging and therefore has efficiency gains. As discussed, the PAV aging of loose mix would require the development of a new, large mixture-specific PAV, which would be costly. Thus, given that aging loose mix can be accomplished relatively quickly in an oven using multiple pans, this method is considered a more practical approach. Currently, the research team is using a conventional oven with inner chamber dimensions of 36 in. × 24 in. × 19 in. (W × H × D). Using only six shelves, 18 pans can fit inside the oven. Loose mix spread in four pans is sufficient for the preparation of one SGC-compacted specimen that is 150 mm in diameter and 178 mm in height. Preliminary results indicate that the compaction of aged loose mix can be accomplished using the same temperature that is required to compact short-term aged material.

Preliminary Evaluation of Selected Aging Procedure (Subtask 3.2.2)

To verify the findings of the loose mix aging trials for the NC mix, the FHWA ALF SBS mixture was subjected to loose mix oven aging trials at 70°C, 85°C, and 95°C. Small samples were removed periodically from the oven and subjected to extraction and recovery to determine the binder AIPs. In order to compare the level of oxidation achieved in the laboratory to that found under field conditions, the binder extracted from the aged loose mix was compared to the asphalt binder extracted from the top lift of a field core extracted after eight years in service, using AIPs. The results were used to approximate the oven conditioning time needed for the loose mix to reach the oxidation level of the field core at varying depths. Two aging procedures were used to evaluate the integrity of the specimens that were compacted after loose mix aging: eight days of conditioning at 85°C (consistent with the NC mix aging trials) and 21 days of conditioning at 95°C, which was found to correspond to the same oxidation level as the surface of the eight-year-old field core. The conditioning temperature of 95°C was selected because it can expedite aging faster than 85°C but is not expected to lead to volatilization or degradation of the polymers (Petersen 2009). Note that the asphalt binder oxidation level of the surface of the field core is thought to represent an 'extreme' level of aging, as the surface of the field core was found to be severely oxidized compared to samples extracted from deeper within the pavement. Following compaction, the aged loose mix was evaluated using the same framework utilized for the NC mix, which included an assessment of compactability and performance testing.

Results

Evaluation of Loose Mix Aging Conditions Required to Match Oxidation Level of Eight-Year-Old Field Core

The eight-year-old field core obtained from the FHWA ALF was cut (sawn) to obtain three half-inch thick slices, as shown in Figure 16. The asphalt binder was extracted and recovered from the field core slices, and the AIPs were determined. The results were used to evaluate the oxidation level of the field core in terms of depth for comparison to the oxidation levels of the laboratory-aged samples. The carbonyl plus sulfoxide absorbance and G* at 64°C and 10 Hz frequency results are shown in Figure 17. The results demonstrate that a significant oxidation gradient was found within the field core, with the surface of the field core being more severely oxidized than deeper within the pavement.
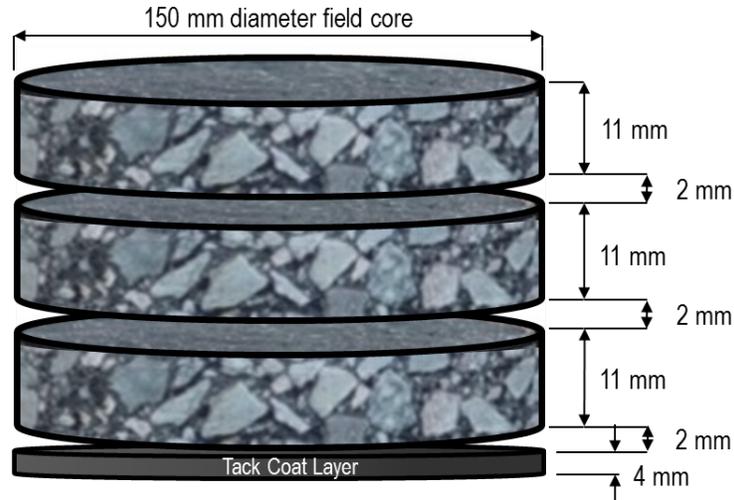
Figure 16. ALF-SBS field core: top layer slicing details.
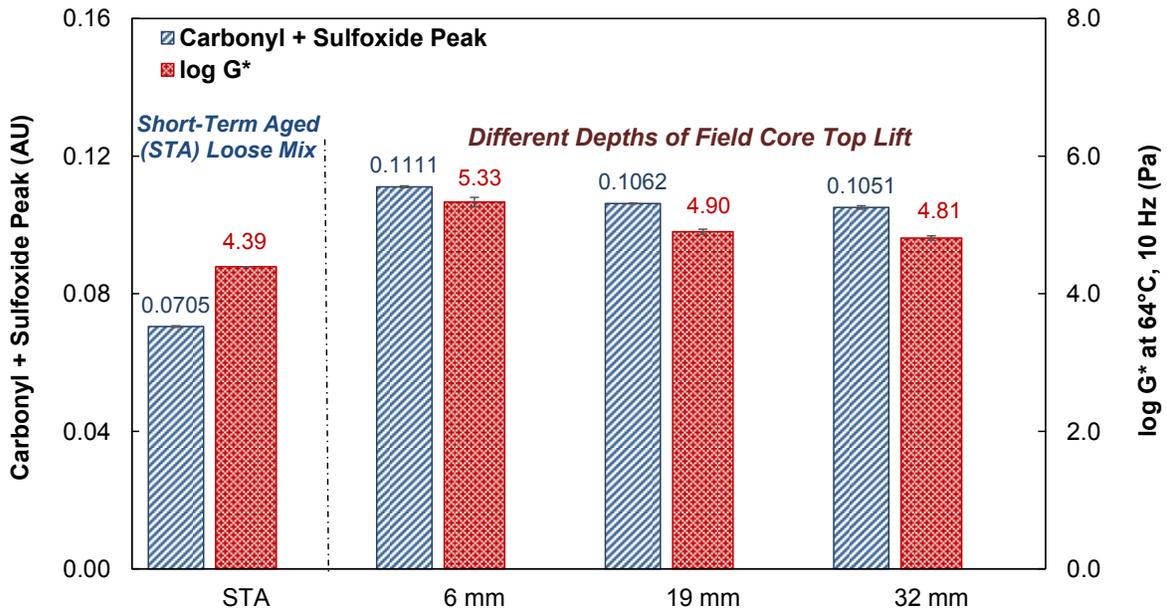
Figure 17. Chemical and rheological AIP results of field core aging gradient after eight years of service in Mclean, VA.

Carbonyl plus sulfoxide absorbance was used as the AIP to compare the lab- and field-aged materials in order to select laboratory aging conditions that correspond to those of the field core. Samples subjected to extraction and recovery after varying durations of oven conditioning at three different aging temperatures, 70°C, 85°C, and 95°C, were used to establish the laboratory oxidation rates by linear fitting and to determine the oven conditioning time required to match the oxidation level of the field core. The linear fitting was deemed reasonable, as only data points following the initial oxidation 'spurt' were utilized. The results of the laboratory aging trials are presented in Figure 18. These results demonstrate that, as the temperature decreased, oxidation occurred at a slower rate, as expected. Table 4 shows the aging

durations for each temperature that are required to meet the oxidation level of each field core slice. For example, the results indicate that at the conditioning temperature of 85°C, 41 days of oven conditioning are required to match the level of aging of the surface of the field core. These results, although limited, indicate that the AASHTO R 30 protocol, which specifies five days of oven conditioning for compacted specimens, greatly underestimates field aging, especially considering the fact that compacted specimen aging leads to substantially lower oxidation rates than loose mix aging. The results at 70°C and 85°C indicate that unreasonable durations of oven conditioning would be required to match the field core conditions. Thus, aging at 95°C appears to be the most reasonable conditioning temperature and is not anticipated to alter the oxidation reactions, lead to volatilization, or degrade the polymers, which can occur if temperatures that exceed 100°C are used.
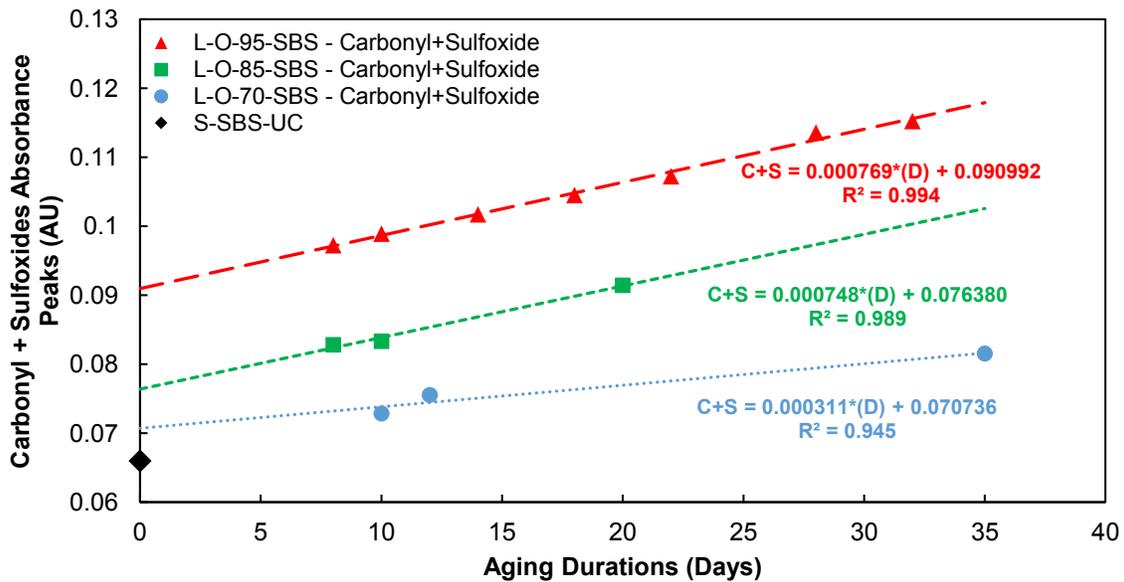
Figure 18. Constant (slow) rate fitting of loose mix aging at different aging temperatures based on carbonyl + sulfoxides absorbance peaks.

Table 4 Required Aging Durations at Different Temperatures to Meet Field Aging Levels at Different Depths

Field core slice (average depth from surface)	Target C+S (AU)	Target C+S before reheating for compaction	Required aging durations to meet field aging level (days)		
			95°C	85°C	70°C
T1 (6 mm)	0.11112	0.10712	21	41	117
T2 (19 mm)	0.10622	0.10222	15	35	101
T3 (32 mm)	0.10512	0.10112	13	33	97

The estimated oxidation levels for loose mix aging at 95°C that are needed to match the level of oxidation of the field core at different depths are presented graphically in Figure 19. Even at 95°C, 21 days of oven conditioning are needed to match the level of oxidation of the surface of the field core. However, it is worth noting that the smallest sample utilized in the performance testing is 38 mm in diameter. Thus, if one considers that in order to extract horizontally a small specimen Ø38 mm × 100 mm for the performance testing of field cores, which would comprise the smallest specimen utilized, the representative aging level for a depth of 38 mm would be close to the oxidation level at a depth of 19 mm. This outcome would indicate that 15 days are required for loose mix aging to match the age level of an eight-year-old field core in VA. Additionally, for structural modeling and analysis purposes (e.g., using the LVECD program), typically the averaged properties of each layer are used as inputs. Therefore, for this study, laboratory-prepared samples will be aged in order to meet the average level of aging of each layer (in this case, 15 days of aging at 95°C). Based on these results, the oxidation level of the surface is considered to be a severe condition, because oxidation greatly dissipates with depth. Thus, the research team assessed loose mix aged at 95°C for 21 days as an 'extreme' condition for evaluating the compactability and integrity of aged loose mix.
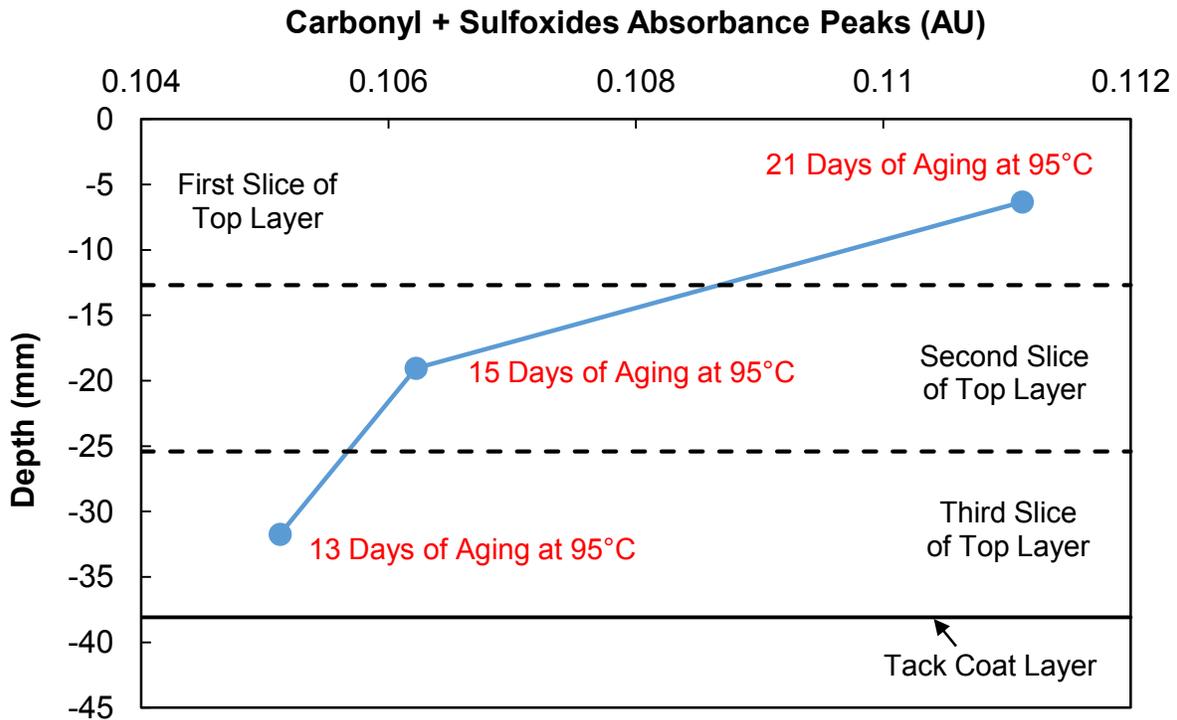
Figure 19. Comparison between field core aging gradient with respect to depth and long-term aging of loose mix in oven at 95°C.

Figure 20 shows the comparisons of degree of aging, using the carbonyl plus sulfoxide absorbance peaks and G* AIPs, among the aged loose mix used for the compacted specimen integrity assessment, the short-term aged mix, and binders aged by RTFO and PAV. The results demonstrate that 21 days of loose mix conditioning at 95°C greatly exceeds the oxidation level of the binder PAV, which is comparable to eight days of loose mix aging at 85°C.

Figure 20. Comparisons between carbonyl + sulfoxide absorbance peaks and log G* at 64°C and 10 Hz for extracted and recovered binders from different loose mix aging trials, field core top layer surface slices, and aged binders (SBS mixture).
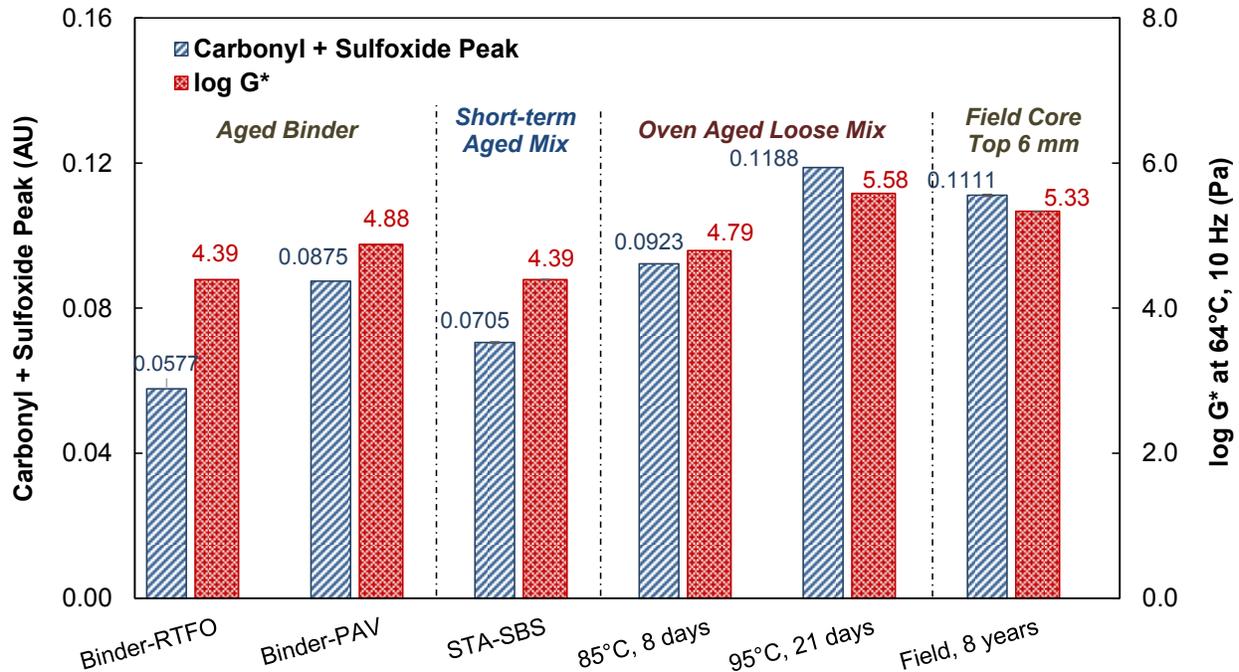
Figure 21 shows the correlation between the three rheology-based AIPs (i.e., G* at 64°C and 10 Hz, G^*_c, and ZSV) and the chemically-based AIP, i.e., carbonyl plus sulfoxide absorbance peak, for the binders extracted and recovered from the ALF-SBS-LG mix field core and from the loose mix aging trials in the oven at two different temperatures. Based on the limited results presented in Figure 21, the dynamic shear modulus shows the strongest aging temperature-independent relationship between the carbonyl plus sulfoxide absorbance peaks and all the rheological-based AIPs, with the field core extracted data points falling relatively close to the laboratory aging trial data points. The relationship between the cross-over modulus and carbonyl plus sulfoxide absorbance peaks appears to break down for extremely high age levels. The field core data appear to deviate from the laboratory-aged mix data when the ZSV is compared to the carbonyl plus sulfoxide absorbance peaks. It is speculated that these findings are related to the fact that the ZSV and G^*_c parameters are determined based on model fitting of the mastercurves, whereas G* is measured directly. The research team will continue to evaluate all three rheological AIPs in future analyses.
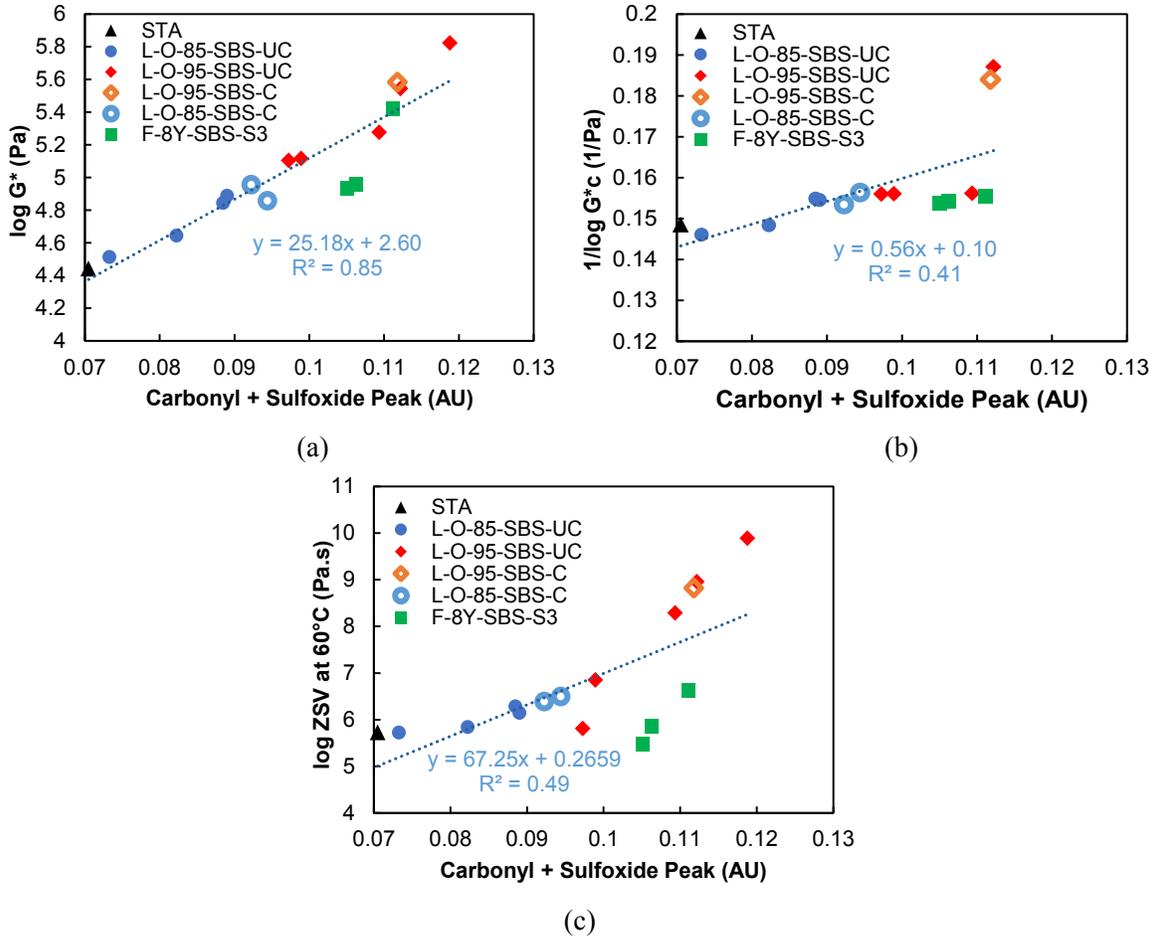
Figure 21. Correlation between different rheology-based AIPs and carbonyl plus sulfoxide absorbance peaks for binders extracted and recovered from aged ALF-SBS-LG mix: (a) log G* versus C+S, (b) 1/log G*c versus C+S, and (c) log ZSV versus C+S.

Initial Integrity Check

The compactability of the long-term aged FHWA ALF SBS mix was evaluated as an initial specimen integrity check by comparing the number of gyrations needed to reach the target air void content to the number needed for short-term aged materials. The results are shown in Figure 22. The number of gyrations needed to reach the target air void contents was similar for both the short-term aged and the two levels of long-term aged loose mixture (8 days at 85°C and 21 days at 95°C) with no adjustment of the compaction temperature. Thus, the compaction of the long-term aged loose mix was not problematic.

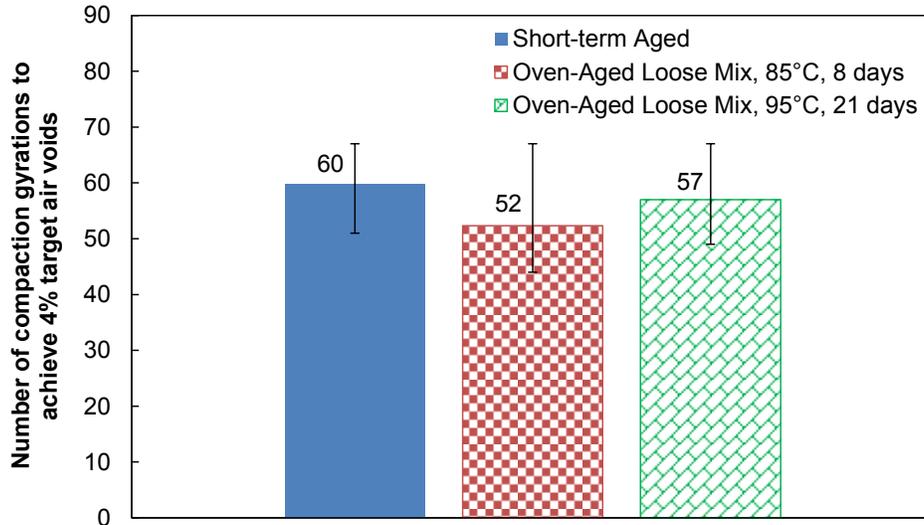**Figure 22. Number of compaction gyrations required to achieve the target air voids.**

Performance Testing

Performance testing was utilized as an additional means to evaluate the integrity of the FHWA ALF SBS specimens that were compacted following long-term loose mix aging. Comparisons between the dynamic modulus and S-VECD damage characteristic curves of the short-term aged material and the long-term aged material were used to evaluate the specimen integrity of the compacted long-term aged material based on adherence to expected trends with increased aging.

Dynamic modulus testing results

The dynamic modulus mastercurves are shown in Figure 23. The mastercurves represent the averaged values of two replicates. The results indicate that the oven-aged loose mix specimens have higher dynamic modulus values than the short-term aged specimens. Furthermore, the results suggest that the specimens that were compacted after 21 days of oven aging at 95°C have significantly higher dynamic modulus values than the specimens compacted after eight days of oven aging at 85°C, as was expected based on the AIPs. If severe integrity problems had been present in the long-term aged specimens, then the dynamic modulus values would not be significantly higher than those of the short-term aged specimens, regardless of the aging level (because damage in the specimen reduces the dynamic modulus value), and thus, no integrity problems were detected in the dynamic modulus test results.
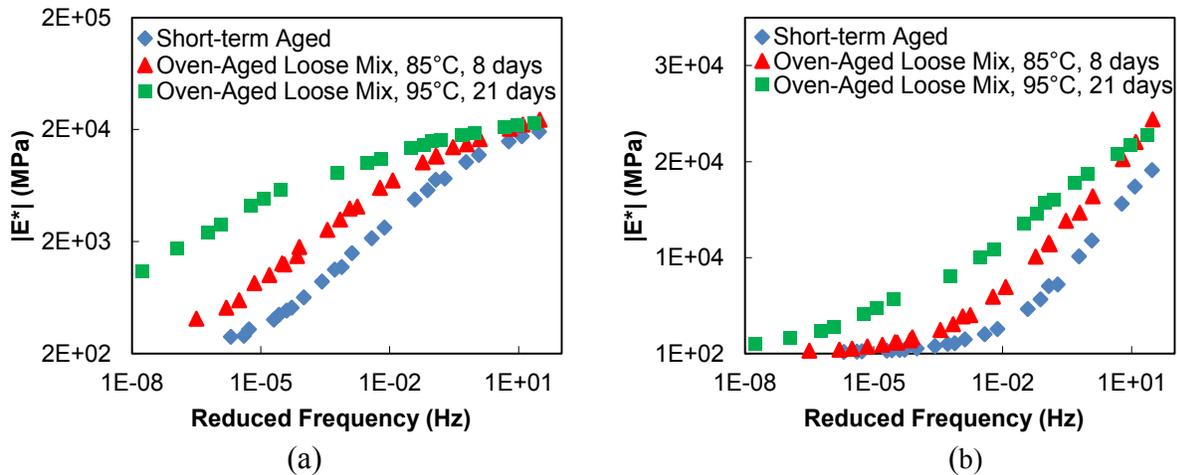
Figure 23. Dynamic modulus test results: (a) log-log scale and (b) semi-log scale.

In order to further evaluate the integrity of the specimens that were compacted following long-term loose mix aging, binder samples were extracted and recovered from the tested specimens, and the dynamic shear modulus values of these binder samples were input into existing asphalt concrete dynamic modulus prediction models to determine, as an additional means of integrity assessment, if the measured mixture dynamic modulus values were in the expected range based on the asphalt binder dynamic shear modulus values. The modified Witczak model (Bari et al. 2006), Hirsch model (Christensen et al. 2003), and the North Carolina State University Artificial Neural Network (NCSU ANN) model (Sakhaei Far 2011) were used to accomplish this task. Figure 24 shows the comparisons between the model predictions and the measured dynamic modulus values at 20°C and 10 Hz frequency. The results demonstrate that the measured dynamic modulus values of the long-term aged material are within the range of the model predictions based on the binder properties, thereby indicating that the results are reasonable. The research team surmises that if the long-term aged specimens had had an integrity problem, the measured dynamic modulus values of these specimens would have been lower than the expected values commonly used in predictive models.
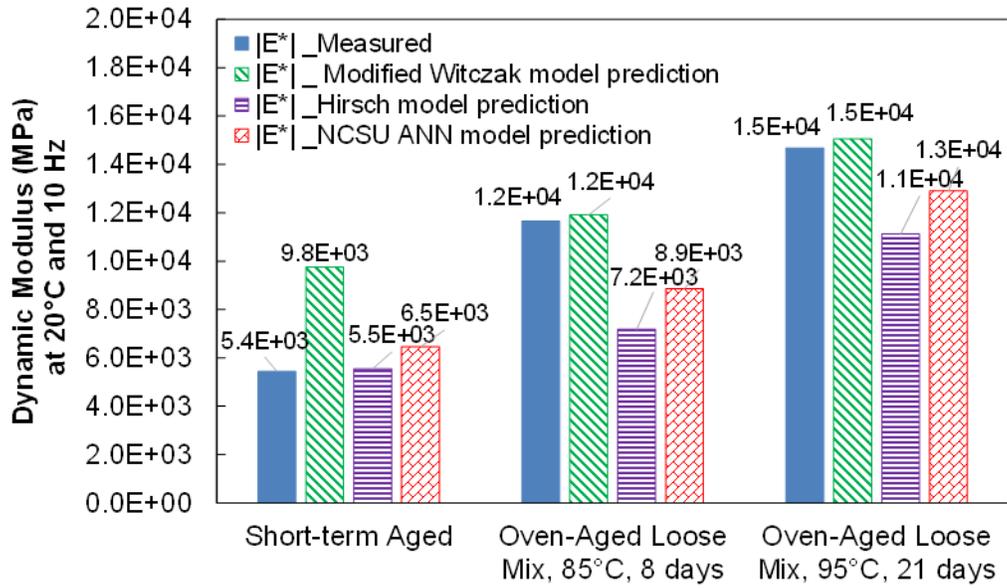
Figure 24. Comparison of predictive model results and measured data.

Fatigue performance testing (S-VECD model) results

The S-VECD model characteristic curves for the short- and long-term aged material are shown in Figure 25. These curves define how damage grows in a material and represent the averaged results of three tests that were conducted using various cross-head displacement amplitudes. The long-term aged specimens have higher damage characteristic curves than the short-term aged specimen, which follows expected trends. Thus, the performance test results indicate that no integrity issues are associated with the compaction of the aged loose mix.

Figure 25. Comparison of damage characteristic curves from FHWA ALF SBS mixtures subjected to different aging conditions.

Figure 26 shows the G^R energy-based failure criterion for the SBS mix. The failure criterion line for the specimens that were compacted following long-term aging for 21 days at 95°C falls significantly lower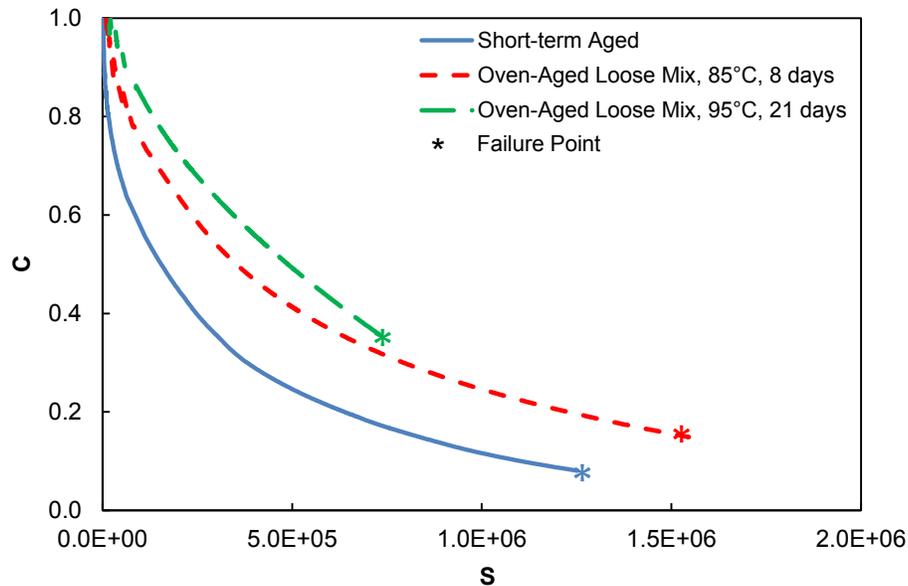 than the failure criterion lines of the short-term aged specimens and the specimens aged for eight days at 85°C. This outcome suggests that the severe level of aging led to embrittlement and consequently degraded the resistance to fatigue and, hence, suggests no integrity problems.
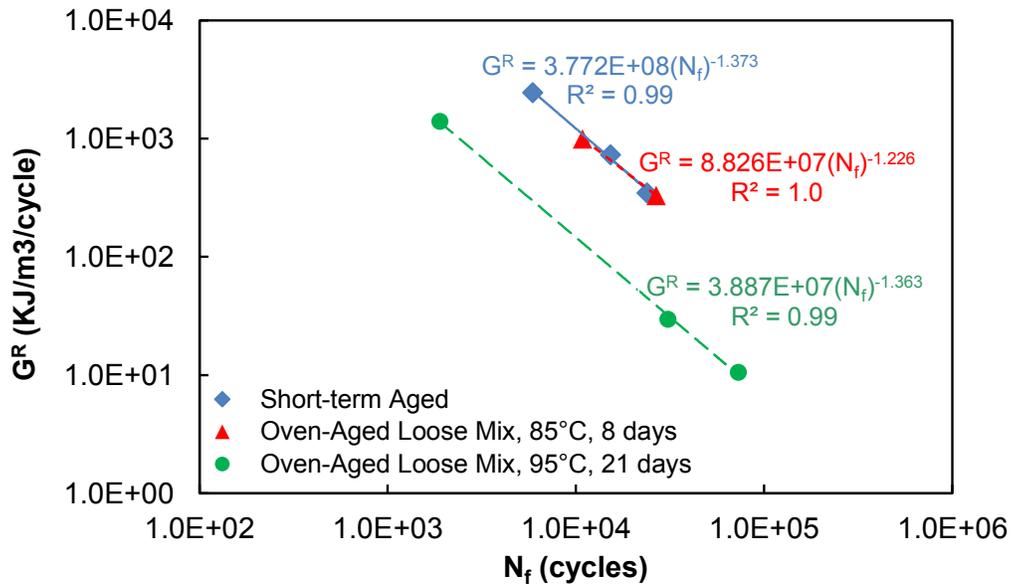
$G^R = 3.772E+08(N_f)^{-1.373}$
$R^2 = 0.99$

$G^R = 8.826E+07(N_f)^{-1.226}$
$R^2 = 1.0$

$G^R = 3.887E+07(N_f)^{-1.363}$
$R^2 = 0.99$

G^R (KJ/m3/cycle)

N_f (cycles)

◆ Short-term Aged
▲ Oven-Aged Loose Mix, 85°C, 8 days
● Oven-Aged Loose Mix, 95°C, 21 days

Figure 26. Comparison of failure criterion lines.

Summary

The findings for the loose mixture aging testing using the FHWA ALF SBS mix were consistent with those for the NC mix. The compaction of long-term aged loose mix is possible with no adjustment to the compaction temperature, based on both the number of compaction gyrations required to reach the target air void contents and the performance test results. The long-term aged loose mix that was aged at 95°C for 21 days had an oxidation level that was equivalent to that of the surface of an eight-year-old field core in McLean, VA. This level is assumed to represent an extreme oxidation level that nonetheless allows compaction of the mix. The results indicate that loose mix aging at 95°C is the optimal condition for the long-term aging of asphalt concrete for performance testing. Aging at lower temperatures precludes long-term oxidation within a reasonable timeframe.

Conclusions

The conclusions are summarized as follows:

- The current standard procedure for the long-term aging of asphalt mixtures (AASHTO R 30), which consists of conditioning large 100-mm diameter compacted specimens in an oven at 85°C, leads to the development of an oxidation gradient from the specimen center to the periphery. The lack of uniform properties throughout the specimen is of concern for performance testing, which

was observed directly through a high rate of end failure at specimen locations where oxidation was most significant in cyclic direct tension fatigue tests.

- The application of pressure in the compacted specimen aging process expedites oxidation. However, the performance test results indicate that the application and/or release of pressure damages specimens.

- The aging gradient observed in the large compacted specimens that were subjected to oven aging was eliminated by the use of small specimens (38-mm diameter with 100-mm height) due to the latter's decreased diffusion paths. Therefore, oven aging of small compacted specimens is the most promising compacted specimen aging procedure, as no integrity issues were observed.

- Aging asphalt mixtures in a loose mix state expedites oxidation compared to compacted specimen aging under the same conditions.

- The compactive effort required to compact long-term aged loose mixes is comparable to that required for short-term aged mixes, with no adjustment to the compaction temperature based on the results for two mixtures, PG 64-22 and PG 70-28 SBS-modified, the latter of which is known to be difficult to compact.

- The performance test results indicate no problems with loose mixtures compacted after long-term aging.

- Pressure expedites the aging of loose mix. However, the size of the standard binder PAV prohibits the generation of enough aged material for performance testing. If the pressure aging of loose mix were to be selected, a larger PAV would need to be developed.

- Based on the aforementioned conclusions, loose mix aging in an oven is the most promising aging procedure to produce mixture specimens for performance testing in terms of efficiency and integrity without the need to develop costly new equipment. In addition, any specimen geometry (e.g., beams) can be produced using aged loose mix, also making this procedure the most versatile option.

- The results indicate that loose mix aging at 95°C is the optimal procedure for the long-term aging of asphalt concrete for performance testing. Aging at lower temperatures precludes reaching field levels of oxidation within a reasonable timeframe.

Remaining Work

Plans for remaining work are summarized as follows:

- Efforts will proceed with loose mix aging trials primarily at 95°C using ALF, NCAT, Long-Term Pavement Performance (LTPP), WesTrack, and Manitoba materials. The overall approach that will be followed for each material is depicted in Figure 27. The field cores will be sliced and

subjected to extraction and recovery to determine the AIPs at selected depths and to allow for the prediction of AIPs at any given depth of interest (Step 1). Loose mix aging trials will first consist of aging a single pan of loose mix in the oven. Samples will be removed periodically and subjected to extraction and recovery, after which the binder AIPs will be measured (Step 2). The rate of oven oxidation will then be determined and used to determine the time required to match the target field AIP (Step 3). Then, enough loose mix for performance testing will be aged for the duration that is required to match the field conditions and then will be subjected to performance testing. Small specimens laterally extracted from field cores also will be performance tested in order to develop the calibration factors for the factors, other than oxidation (e.g., moisture), that differ between the lab and the field.
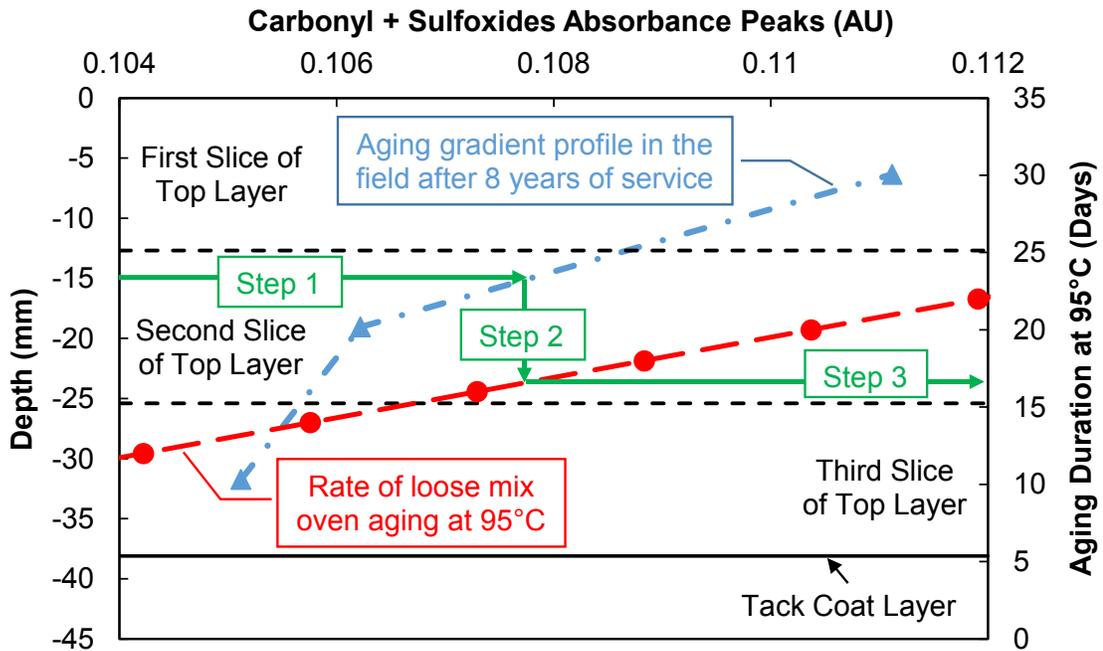

Figure 27. Prediction of the required aging duration of loose mix at 95°C to meet the field aging level at a given depth and age.

- Initially, a subset of the selected field sections included in the experimental plan will be subjected to loose mix aging at three temperatures in order to evaluate the modeling of oxidation kinetics with various temperatures. Preliminary studies conducted by the Western Research Institute (WRI) suggest that the Glaser-Petersen fundamental parallel model can account for the temperature dependence of oxidation through the measurement of oxidation kinetics at a single temperature, which will be evaluated using this initial experimental plan. If the findings demonstrate that only one temperature is needed, additional trials will be conducted only at 95°C.

- The field cores that correspond to the initial subset of materials that are to be subjected to loose mix aging at multiple temperatures will be sliced relatively thinly throughout the core depth; the slices will be subjected to extraction and recovery for subsequent AIP determination. This initial assessment will be used to determine the optimal thickness of the slices in order to obtain a

representative model of the oxidation gradient with depth. Following the initial assessment, a revised plan for slicing the field cores to evaluate the oxidation gradient with depth will be developed. Caution will be taken to avoid the inclusion of a tack coat or prime coat when slicing the cores.

- The measured oxidation gradients with depth obtained from the field cores will be coupled with climatic and mixture volumetric information in order to assess and refine the diffusion models (e.g., the GAS model or Transport model) to allow for linking the lab aging conditions to the corresponding field age level.

- The research team anticipates that the final aging protocol will consist of subjecting loose mix to long-term oven aging at 95°C, with the duration to be determined as a function of the climatic performance grade (PG) determined from LTPPBind. That is, the kinetics-diffusion model results will be used to estimate three durations of laboratory aging to correspond to three approximate field age levels. The team recognizes that some approximation and variability will be involved in the actual level of the corresponding field aging, given the binder-specific oxidation kinetics, variations in mixture volumetrics, and variations in pavement structure. Therefore, as 'back-end' analysis, other tools that are utilized and developed as part of the project will allow users to better determine the level of aging achieved in the laboratory through the measurements of the required binder kinetics parameters and diffusion model inputs.

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