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Simulating Plant Produced Material in the Laboratory to Replicate Rheological and Fatigue Properties

As part of an effort by agencies and industry to move towards performance-based design to evaluate mixtures in the laboratory at a smaller scale before moving to full scale operation, laboratory protocols exist to simulate the aging that occurs as a material is produced. However, recent research has shown that these existing protocols may not accurately represent the changes a material experiences in a plant. Moreover, due to the focus of previous studies on the ability of the current method to replicate mixture characteristics and performance in an undamaged state, there is a lack of information as it relates to the damaged state. This paper presents a concise description of a study undertaken on a particular mixture to evaluate the differences in the behaviour of a standard asphalt concrete mixture produced in the laboratory and in the plant to assess the anticipated field performance at the mixture design stage. The results, in terms of the rheological properties of binders extracted and recovered from laboratory and plant produced mixtures as well as rheological, repeated cyclic fatigue, and cracking performance evaluation of the asphalt mixtures, have shown the ability of a short-term oven aging protocol to replicate plant produced material in the laboratory.

Keywords: asphalt concrete; short-term oven aging (STOA); rheological properties; plant production; laboratory production; cracking

Introduction

When an asphalt mixture is produced in a hot mix plant, the asphalt is heated to reduce its viscosity and then mixed with hot aggregate to facilitate proper coating of the aggregate particles. During this process at elevated temperatures, the asphalt undergoes aging (hardening) primarily associated with the loss of volatile components and oxidation of the asphalt. Age hardening has two effects: it increases the load bearing capacity and permanent deformation resistance of the pavement by producing a stiffer material while at the same time it reduces pavement flexibility and relaxation capacity resulting in greater susceptibility to the development of fatigue cracks that may lead to total failure (Vallerga, 1981).

The design of asphalt mixtures is performed in the laboratory at a smaller scale before moving to full scale plant operations. In addition to volumetric mix design, many agencies and asphalt producers are moving towards performance-based design methodologies that incorporate additional binder or mixture characterization tests to evaluate potential performance in the field. To be effective in selecting appropriate materials for a particular field application, these tests must also be performed on laboratory produced mixtures during the design stage.

The conditions and processes that materials are exposed to in the plant cannot be exactly replicated in the laboratory. Therefore, laboratory protocols to simulate the aging that occurs in a plant (short-term oven aging, STOA) are used. Thin film oven aging to age the asphalt in an accelerated manner (e.g. thin film oven test, rolling thin film oven test) is typically used for evaluation of the asphalt itself. Recently a new thin film (300μm) short term aging test was developed by Farrar et al., (2012) as an alternative to the standard thin film and rolling thin film oven test. For mixtures, a protocol was developed under the SHRP-A-003A project and is based on the work done by Von Quintus et al. (1988). The procedure requires loose mixtures, prior to compaction, to be aged in a forced draft oven for 4 hours at 135°C (AASHTO PP2) and was found to represent the aging occurring during mixing and placing and effectively represents the condition of pavements in the first two years (Bell et al., 1994; Monismith et al., 1994).

Recent research has shown that these existing protocols may not accurately represent the changes that a material experiences in a plant (Jacques et al., 2016). Several researchers (Rahbar and Daniel, 2016; Xiao et al., 2014; Mogawer et al., 2012, Johnson et al., 2010) have conducted studies that showed the absence of a consistent trend between laboratory and plant produced mixtures and the differences depend on mixture characteristics as well as plant operations.

Reheating plant produced mixtures in the laboratory during the process of specimen fabrication has also been shown to impact the measured material properties with the significance of differences dependent upon mixture characteristics (Mogawer et al. 2012).

This paper presents a concise description of the results of a targeted study to develop a laboratory conditioning protocol to replicate the aging that occurs in a plant for one particular mixture. The protocol is evaluated to ensure that the rheological characteristics of both the asphalt and mixture are similar along with the fatigue characteristics of the mixture. Pavement evaluation is performed to predict the relative performance of the different mixtures in a typical pavement structure under representative traffic and climatic conditions. The new understanding obtained from this paper by performing mixture fatigue characterization and pavement performance evaluation enables researchers to understand the ability of the current method to replicate the performance/characteristics of mixtures under high stress and strain levels where damage occurs as opposed to the undamaged state.

Materials

The asphalt mixture chosen for this study was a 20 mm dense, heavy duty and high modulus binder course asphalt concrete complying with BS EN 13108-1 (2012) with an EN 13108 designation 'AC 20 HDM binder'. The asphalt mixture was designed with a target binder content of 4.6% using 40/60 penetration grade asphalt and produced through a standard asphalt batching plant.

To produce the identical material (same gradation and volumetric properties) in the laboratory, a sample of the plant produced (loose) material was subjected to a compositional analysis according to BS EN 12697-28 (2001) and the actual binder content and the detailed aggregate gradation were determined. The individual aggregate bin sizes (16/24mm, 12/16mm, 8/12mm, 4/8mm, 0/4mm and filler) used to produce the plant material were then batched together with a target binder content of 5.0% using the 40/60 pen asphalt to produce the identical grading and binder content obtained from the compositional analysis of the plant material to produce the laboratory asphalt mixture.

Approach to Determine Short-term Aging Protocol

The asphalt from the plant mixture was recovered using BS EN 12697-4 (2005) and subjected to a range of conventional and more detailed rheological testing. The conventional properties included penetration at 25°C (BS EN 1426: 2007) and Ring & Ball softening point (BS EN 1427: 2007). The detailed rheological properties consisted of frequency sweep measurements (0.1 to 10 Hz) of complex modulus (G*) and phase angle (δ) using a Dynamic Shear Rheometer (DSR) over a range of temperatures from 0 to 80°C within the binder's linear viscoelastic (LVE) response range. The same binder tests were also performed on the virgin 40/60 penetration grade asphalt used to produce the AC 20 HDM binder mixture.

Based on research undertaken as part of RILEM TC-ATB-TG5, 15kg of loose mixture was placed in a standard steel box with dimensions 300mm by 300mm by 80mm deep and held in an oven at 135°C for different periods of time (4 hours, 5 hours and 5.5 hours) with the mixture stirred manually after each hour. At the end of each period (4, 5 and 5.5 hours), asphalt was recovered from the mixture and its conventional and rheological properties compared with those of the recovered asphalt from the plant produced mixture. The flow chart in Figure 1 illustrates the short-term aging approach undertaken for binders and mixtures as part of this study.

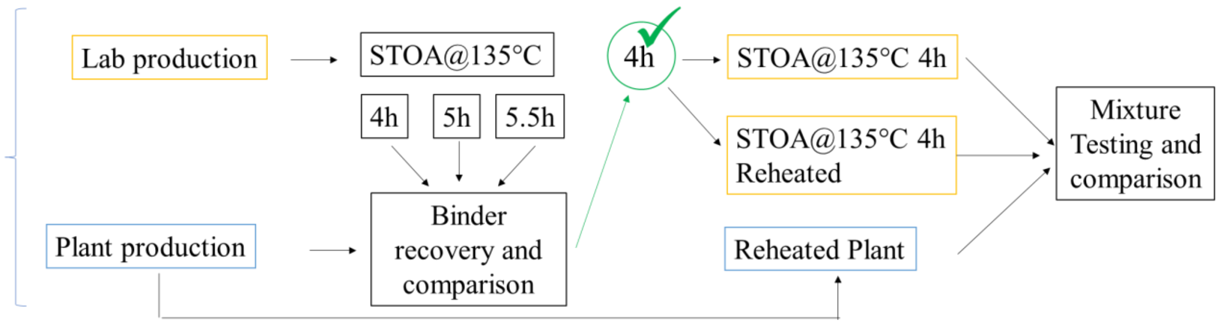

Figure 1. Short-term Aging Approach for Binders and Mixtures

Table 1 shows the results of penetration and softening point of the virgin 40/60 pen asphalt, asphalt recovered from the plant mixture and asphalt recovered from the laboratory produced mixture with and without different time periods of STOA at 135°C. In addition to the measured penetration and softening point, the DSR complex modulus results at 0.4Hz and 25°C have been used to calculate a predicted penetration value using the correlation proposed by Gershkoff (1991). A predicted softening point value has also been calculated (interpreted) from the temperature associated with a G* value of 10 MPa at 1.6 Hz and/or a G* value of 1 MPa at 0.16 Hz (Gershkoff, 1991).

Although there are differences in the measured and predicted values, both sets of data clearly show the ability of the 4 hours STOA @ 135°C protocol to replicate the conventional binder properties of the plant produced mixture. Extended oven aging (5 and 5.5 hours) produced further decreases in penetration and increases in softening point.

Table 1. Conventional Binder Properties of Plant and Laboratory Recovered Binders

Binder	Measured properties		Predicted properties	
	Penetration @ 25°C (dmm)	Softening Point (°C)	Penetration @ 25°C (dmm)	Softening Point (°C)
40/60 pen (virgin)	53.0	50.2	40.0	50
Lab mixing	44.7	52.6	36.2	53
Lab mixing + 4h@135°C	**38.6**	**54.8**	**30.4**	**55**
Plant mixing	**39.0**	**54.4**	**33.4**	**55**
Lab mixing + 5h@135°C	-	-	28.6	57
Lab mixing + 5.5h@135°C	-	-	27.4	58

Figure 2 (a) and (b) show the complex modulus master curves and Black space plots produced for the asphalts (virgin and recovered) at a reference temperature of 25°C. The master curves provide a clear indication of the increase in stiffness (complex modulus) of the binders after both plant and laboratory production relative to the unaged virgin 40/60 pen asphalt. The results indicate that the rheological properties of the asphalt recovered from the plant produced material and that from the laboratory produced 4 hours STOA material are similar.

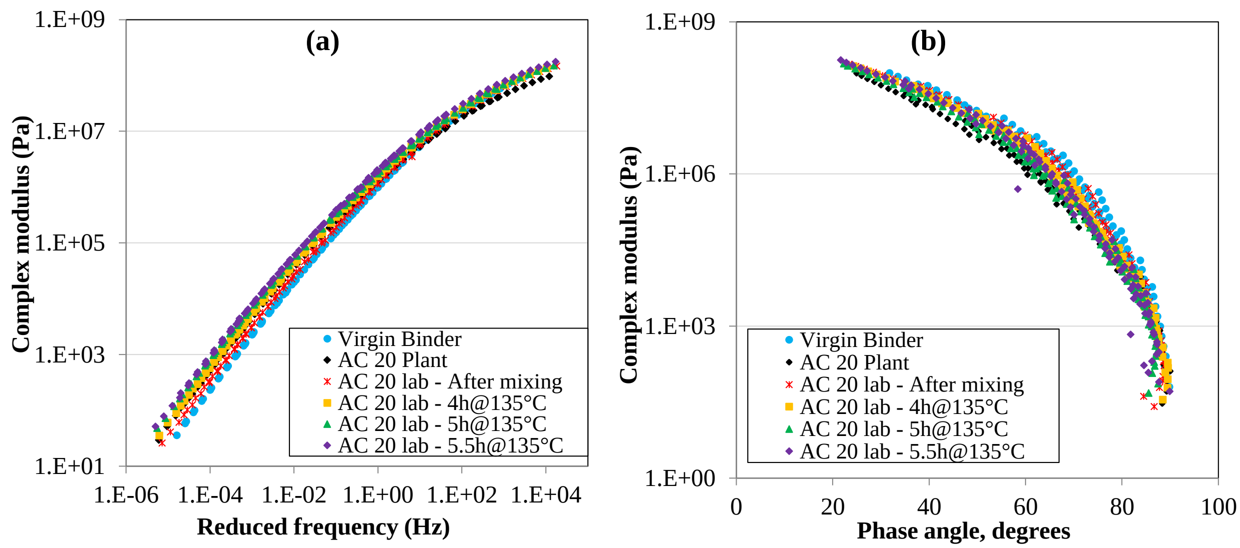

Figure 2. (a) Complex Modulus Master Curves (b) Black Space Diagrams for Virgin 40/60 Pen Asphalt and Binder Recovered from Plant and Laboratory Produced Mixtures

Asphalt Mixture Specimen Production

Compacted specimens for subsequent mixture testing were produced using the three materials from reheated plant produced mixture, laboratory produced mixture (with 4 hours STOA @ 135°C) and reheated laboratory produced mixture (with 4 hours STOA @ 135°C).

The reheating procedure used for both the ‘cold’ plant produced material and the ‘cold’ laboratory produced material consisted of 2.5 hours of heating @ 135°C followed by 20 seconds of mixing in the mechanical mixer and then a further 1.5 hours @ 135°C (total 4 hours reheating). The philosophy was that the STOA protocol simulates the aging that the plant material experienced during production, but additional aging occurs during the reheating process in the lab to fabricate specimens. By reheating the laboratory produced mixture, both the plant and laboratory produced materials are exposed to the same conditions. This also allows for the evaluation of the impact of the reheating on the mixture properties.

Two compaction processes were used to produce the asphalt mixture test specimens with a target air void content of 6% ± 1%. A gyratory compactor was used to produce cylindrical specimens that were cut and cored to produce final test specimens for complex modulus and uniaxial fatigue testing. Roller compaction was used to produce 300mm by 300mm by 80mm slabs that were then cored to produce specimens for indirect tensile testing.

Mixture Testing Methods

Two approaches were used to determine the stiffness of the plant and laboratory produced asphalt mixtures: indirect tension to cylindrical specimens (IT-CY) method described in BS EN 12697-26 (2012) was performed on 100mm diameter by 40mm thick cores and complex modulus testing was performed on 100mm diameter by 150mm cylindrical specimens as described in AASHTO TP 79 (2015).

To describe the cracking behaviour of the mixtures, the indirect tensile fatigue test (ITFT) and the simplified viscoelastic continuum damage (S-VECD) fatigue tests were carried out. The ITFT was run according to the BS DD ABF (2003) standard. The S-VECD fatigue testing was carried out on specimens following the test procedure in AASHTO TP 107 (2016). Fatigue performance of mixtures in a pavement structure was predicted using Layered Viscoelastic Pavement Analysis for Critical Distresses (LVECD) analysis. The pavement structure considered for this analysis comprises a 20cm asphalt concrete (AC) layer, a 15cm base layer and a subgrade. A 0.5 million axle load per year and an 80 km/h design speed was used to obtain the total traffic loading over a design period of 20 years. The linear viscoelastic characterization for the AC layer was performed by producing dynamic modulus master curves and shift factors from measured dynamic modulus data. The S-VECD analysis is used to calculate the damage growth in the asphalt mixture. The output from LVECD analysis includes the N/N_f ratio defined as the damage distribution factor, where N is the number of cycles at a given time and N_f is the number of cycles to failure. When the damage factor becomes 1.0, the asphalt mixture element is considered to be completely cracked.

Results and Discussion

Stiffness

The average values and standard deviation from IT-CY test for the three asphalt mixtures are presented in Figure 3. The results show that the average IT-CY stiffness at 20°C with a loading rise-time of 124ms for the reheated plant produced and reheated lab produced mixtures are very similar and approximately 15% higher than that found for the lab produced mixtures. A paired-samples t-test showed no significant difference at a confidence level of 95% between the reheated plant produced and reheated lab produced mixtures. However, there was a significant difference between the reheated plant produced and lab produced (not reheated) mixtures.

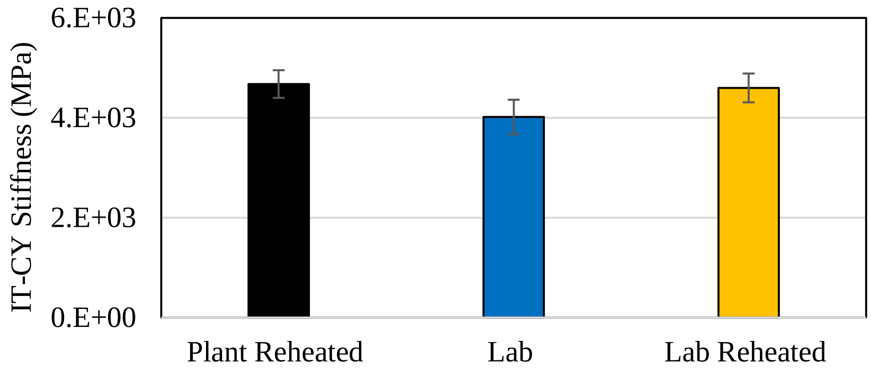

Figure 3. IT-CY Stiffness Results of Plant and Laboratory Produced Mixtures

Figure 4 (a) shows the |E*| master curves for the three different mixtures at a reference temperature of 20°C. A paired-samples t-test indicates no significant difference at a confidence level of 95% between the |E*| of the reheated plant produced and reheated lab produced mixtures or between the two lab produced mixtures. However, a significant difference is observed between the reheated plant produced and lab produced (not reheated) mixtures at intermediate and high temperatures. Observation of the Black space diagram (Figure 4(b)) indicates that the plant reheated, lab and lab reheated mixtures have similar stiffness and viscoelastic properties at higher frequencies whereas differences were observed at lower frequencies.

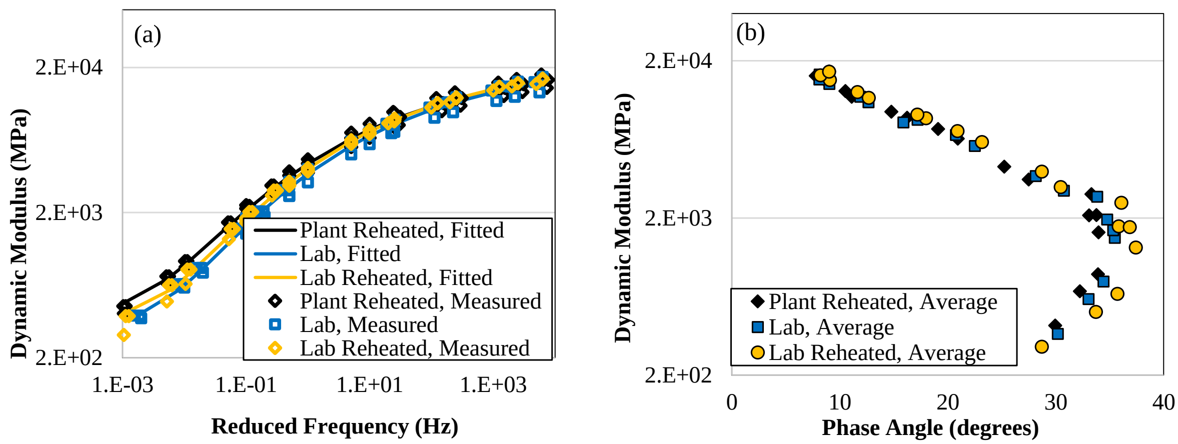

Figure 4. (a) Dynamic Modulus Master Curves (b) Black Space Diagrams for Different Mixtures

Fatigue Performance Evaluation

The strain and cycles to failure relationship obtained from ITFT is displayed in Figure 5 for plant reheated, lab and lab reheated mixtures. Although not considered a pure fatigue test but rather a damage or 'torture' test, the ITFT is still able to rank and compare the fatigue (or cyclic damage) response of the different mixtures. Based on the results, similar fatigue characteristics were observed between lab reheated and plant reheated mixtures at higher cycles to failure (lower strain levels) and lab reheated and lab mixtures at lower cycles to failure (higher strain levels). The results also showed that plant reheated and lab mixtures plots exhibited similar slopes indicating similar sensitivity to fatigue life due to changes in strain level. However, the lab reheated mixture displayed a steeper slope as compared to the other two mixtures indicating higher sensitivity of fatigue life for changes in strain level.

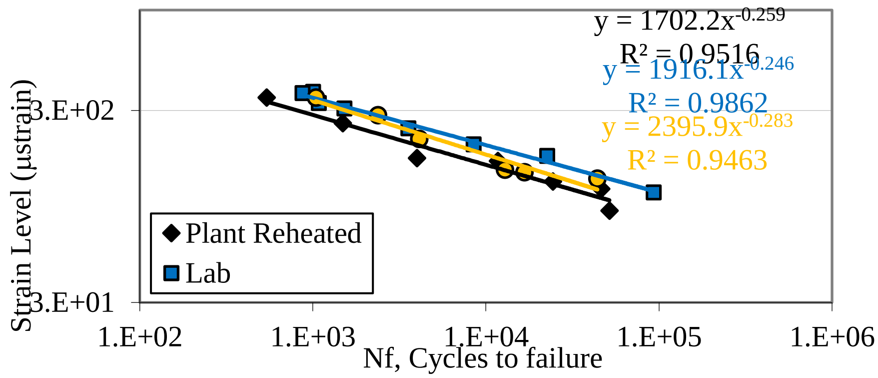

Figure 5. Strain vs N_f Plot from ITFT for Different Mixtures

Figures 6 (a) and (b) display the G^R vs N_f and predicted strain level vs N_f plots for plant reheated, lab and lab reheated mixtures from the S-VECD analysis. The results from both plots showed the overlap of plant reheated and lab reheated curves demonstrating the ability of lab reheated mixture to replicate the expected fatigue characteristics of plant reheated mixture. The lab produced (not reheated) mixture exhibited a slightly better fatigue behaviour indicating a potential negative effect of reheating on lab and plant mixtures. Moreover, all mixtures displayed similar slopes indicating similar changes in G^R for a change in strain level or for a change in failure cycles.

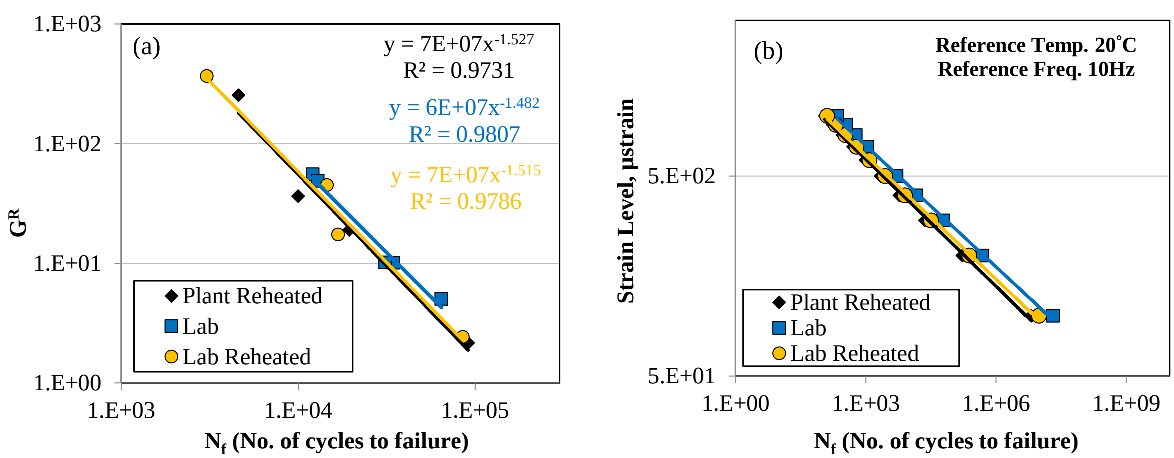

Figure 6. (a) G^R vs N_f (b) Predicted Strain vs N_f Plot for Different Mixtures

Pavement Evaluation

The predicted N/N_f ratio along the pavement cross section after 20 years of service determined from the LVECD analysis is presented as contours in Figure 7. The number of failure points versus time plot was produced by counting the failure points (N/N_f = 1) over time from the contour plots to determine the total number of failure points. The lab produced (not reheated) mixture exhibited different number of failure points as compared to the lab reheated and plant reheated mixtures indicating a difference in fatigue performance. The failure points for plant reheated and lab reheated mixtures were comparable indicating the ability of reheated lab mixture to replicate the expected field fatigue performance of reheated plant mixture. Moreover, the lab (not reheated) exhibited less failure points as compared to the reheated mixtures which confirms the negative effect of the reheating on fatigue performance.

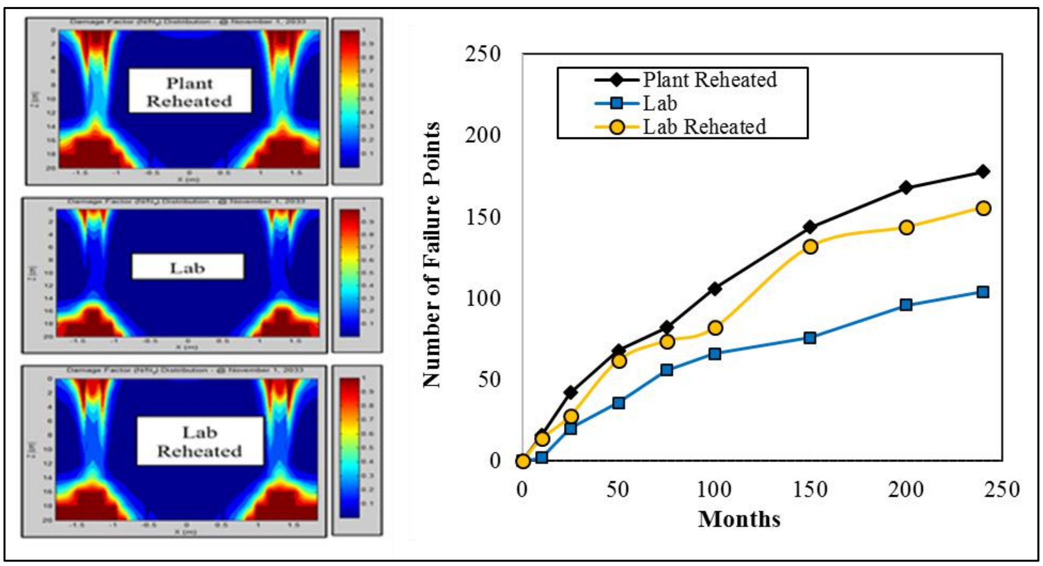

Figure 7. Number of Failure Points Over Time Due to Total Cracking

Summary and Conclusions

The evaluation of a short-term laboratory aging protocol to replicate the aging that occurs in a plant in the laboratory for one particular mixture is described. The effectiveness of the protocol is evaluated by comparing the rheological characteristics of both the asphalt and asphalt mixture as well as the fatigue characteristics of the mixture for plant and laboratory produced materials. In addition, pavement evaluation was conducted to predict the relative performance of the different mixtures in a typical pavement structure under representative traffic and climatic conditions. The following key conclusions can be drawn from the study:

- The use of a STOA protocol of 4 hours aging of loose asphalt mixture @ 135°C was found to simulate the degree of aging experience in an asphalt plant for a standard asphalt concrete (AC 20 HDM binder).
- The conventional asphalt properties of penetration and softening point as well as the rheological properties of complex modulus and phase angle were found to be similar for binder recovered from plant produced and STOA laboratory produced AC 20 HMB binder mixtures.
- The asphalt mixture rheological evaluation of plant and laboratory produced asphalt mixtures were found to be similar for reheated plant produced and reheated laboratory produced asphalt mixture specimens using both indirect tensile as well as uniaxial stiffness testing configurations.
- The S-VECD fatigue testing and the LVECD pavement performance analysis both showed the close correlation between the reheated plant produced and reheated laboratory produced asphalt mixture. Reheating can therefore be considered to have an impact that is measurable although it may not always be statistically significant.

This study contributes to a better understanding of the differences in the behaviour of asphalt mixtures produced in the laboratory and in the plant to assess anticipated differences in field performance at the mixture design stage. The simulative aging and testing protocols have the potential to be used to aid the understanding of the performance of asphalt mixtures. In the future, the study should be extended to mixtures with varying mix properties such as different percentages of RAP, modifiers, warm mix asphalt, binder type and source, production type and temperature to evaluate the validity of the conclusions drawn from this study and subsequently modify the procedure as needed to present a comprehensive aging protocol that can be used for a wide set of mixtures. It is also critical to verify the lab test results with other tests that are not evaluated as part of this study such as Hamburg wheel track (for rutting), disk shaped compact tension test (for thermal cracking) and indirect tension test for moisture susceptibility as well as field performance data.

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