LONG-TERM TESTING AND ANALYSIS ON ASPHALT MIX REJUVENATOR FIELD SECTIONS

MnDOT Contract 1036343

TPF-5(341) National Road Research Alliance

Task 2: Summary of Construction Information and Binder Testing Results

Prepared by:

Runhua Zhang (Postdoctoral Researcher)
Zheng Wang (Graduate Student)
Jo E. Sias (PI)
Eshan V. Dave (Co-PI)
Department of Civil and Environmental Engineering
University of New Hampshire

Gerald Reinke
Andrew Hanz
MTE Services, Inc

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CHAPTER 1: Introduction And Scope

Asphalt rejuvenators or recycling agents (RAs) are intended to be used to incorporate higher amounts of Reclaimed Asphalt Pavement (RAP) in asphalt mixtures without detrimentally impacting the long-term performance of the pavement. Recycling agents are relatively new in the asphalt industry and there are many different products marketed to transportation agencies. However, most of these products have limited field and laboratory test data available to support their effectiveness over time. Several recent research efforts have shown that some products, while effective immediately after production, show rapid decrease in effectiveness with aging (Mohammadafzali et al., 2017; Ziari et al., 2019; Sias et al., 2019; Christensen et al., 2019; Al-Badr et al. 2021). Therefore, there is a need for a better understanding of how various RAs perform over time through both laboratory and field evaluations to help guide engineers on appropriate usage of these materials.

The National Road Research Alliance (NRRA) constructed field test sections as part of a mill and overlay project on Trunk Highway 6 (TH6) located in Emily, MN in August of 2019. These field sections include wearing courses with 40% RAP that incorporate seven different RA products, with the dosage determined by the supplier to meet a target extracted and recovered performance grade (PG) of XX-34. In addition to the RA test sections, there are control sections with 40% RAP and 30% RAP (the maximum level allowed on the remainder of this project). Mixtures and binders were sampled at the time of production and one set of field cores was taken shortly after construction. Mixture and binder tests on the plant produced mixtures are being conducted by NRRA members and the research team, and MnDOT is monitoring the performance of the field sections over time.

The objective of this research project is to evaluate the effectiveness of the seven RA products over time and evaluate their performance as compared to the control mixtures. This will be accomplished through a combination of binder and mixture characterization and performance testing using different laboratory aging levels, field core testing, and performance monitoring of the field sections over time. The outcome of this project is anticipated to provide NRRA with guidelines for assessment and adoption of RAs for routine usage in asphalt mixtures.

This report serves as the Task-2 deliverable which summarizes the construction information and presents the binder testing results for the sampled virgin and blended binders as well as the binders extracted and recovered from the plant-produced mixtures. Chapter 2 provides the summary of available construction information for the project sections. Chapter 3 introduces the different binder tests and the corresponding test parameters included in this study. Chapter 4 presents the results of the in-line sampled binders, while Chapter 5 discusses the results of binders extracted and recovered from the study mixtures. Chapter 6 presents a summary of the major findings from the binder tests.

CHAPTER 2: Materials And Construction Information

Ten test sections including seven RA mixtures (6001-6007) and three control (RAP) mixtures (6010-6012) were constructed on Trunk Highway 6 near Emily, MN on August 28 and 29, 2019. The top 2 inches of the existing total 5-inch asphalt layer was milled and replaced, then a 1.5 inch wearing course containing the different project mixtures was placed as the overlay. Three control mixtures include a 40% RAP mixture that was produced during the two days of production (6011 on day 1; 6012 on day 2) and a 30% RAP mixture (6010) that was produced the day before the test sections (day 0). The 30% RAP mixture is the standard mixture that was designed based on the traffic and environment at the project location. The detailed mix design information for the 30% RAP and 40% RAP mixtures is included in the Appendix. All mixes were produced at the same hot-mix plant and constructed by the same paving contractor.

RA suppliers received samples of the base binder (PG 58S-28) and the RAP material (PG 75-23 continuous binder grade) and determined the amount of their RA additive that needed to be added to the base binder to result in PG low temperature (PGLT) of -34°C for a 40% RAP mixture. No constraints were placed on the PG high temperature (PGHT) of the RA blended binders. For the seven RA sections, each RA supplier provided their additive to the contractor who then injected the amount of additive as directed by the RA supplier. Six products (6001-6006) were added in-line at the plant, while one (6007) was blended at the terminal. Section 6004 was constructed at a lower temperature (WMA temperature) as compared to others. Samples of the blended binders and the mixtures produced with each RA additive were obtained during production. The virgin PG 58S-28 binder from each day of production and mixtures from the three control sections were also sampled.

Table 2-1 below presents the detailed information of the project sections/mixtures. Virgin Binder O1 is the base binder used during the first day of production, while O2 is the one used during the second day of production. Binder N is the base binder specifically used to blend with the RA used in section 6007. The base binder for the 30% RAP mixture was not sampled for testing.

Table 2-1 Information for Project Sections/Mixtures

Mixture/Section ID	6001	6002	6003	6004	6005	6006	6007	6010	6011	6012
Virgin Binder	O1	O1	O1	O2	O2	O2	N	N/A	O1	O2
RAP Content (%)	40%	40%	40%	40%	40%	40%	40%	30%	40%	40%
Production Day	D1	D1	D1	D2	D2	D2	D2	D0	D1	D2
RA Supplier	Cargill	Poet	US Soybean	Ingevity	Kraton	Asphalt and Wax Innovations	Georgia Pacific	--	--	--

CHAPTER 3: Binder Testing Methods

3.1 RHEOLOGICAL PROPERTIES

The rheological properties of asphalt binders were measured using a Dynamic Shear Rheometer (DSR) with the 25 mm, 8 mm and 4 mm plates (Sui et al., 2011). This test covers a wide range of temperatures and frequencies, by using the appropriate strain level at each combination of test temperature and frequency. The isotherm tests are conducted from the coldest to the warmest temperature and from the highest to the lowest frequencies. The complex shear modulus master curve is constructed at 25°C in this study, and fit by the Christensen-Anderson-Marasteanu model (CAM, as shown in **Equations 1 and 2**) using the RHEA software.

$$G^*(w) = \frac{G_g}{\left[1+(w_0/w)^{\beta}\right]^{k/\beta}} \quad (1)$$

$$\beta = log2/R \quad (2)$$

Where,
$G^*(w)$: complex shear modulus at a given frequency (Pa);
G_g: glassy asymptote (modulus) (Pa);
w: frequency (rad/s);
w_0: crossover frequency (rad/s);
k: fitting coefficient;
R: difference between the logarithmic glassy modulus and the logarithmic equilibrium modulus of the binder, simplified as Log |G*| at glassy asymptote (approximately 1E9 Pa) minus Log |G*| at the crossover frequency.

The ΔTc parameter can be then calculated from the DSR measurements (Sui et al., 2011). ΔTc is defined as the difference between the temperature at which the S(t) and m-value critical criteria from the BBR testing are met, as shown in **Equation 3**.

$$\Delta T_c = T_{(stiffness)} - T_{(m\text{-}slope)} \quad (3)$$

Where,
$T_{(stiffness)}$: critical low temperature at which S(60) =300 MPa;
$T_{(m\text{-}slope)}$: critical low temperature at which m(60) = 0.300.

When the ΔTc value is positive, the binder grade is controlled by the creep stiffness (S-controlled); when the ΔTc value is negative, the binder grade becomes m-controlled. S-controlled binders typically have better stress relaxation capability and are therefore typically less prone to cracking. Asphalt Institute (Al-Badr et al., 2021; Christensen et al., 2019) suggests using ΔTc = -2.5°C and ΔTc = -5.0°C as threshold values for crack warning and cracking limit, respectively.

The complex modulus master curve from the DSR test can be used to calculate the binder Glover-Rowe parameter as well (Christensen et al., 2019). The binder G-R parameter is generally calculated at the temperature and frequency combination of 15°C and 0.005rad/sec, as shown in **Equation 4**. A lower G-R parameter indicates better capability to resist durability cracking. A limiting value of 180 kPa is proposed as a crack warning limit, a second value of 600 kPa is suggested for the development of significant cracking (block cracking).

$$G - R = \frac{|G^*|(cos\delta)^2}{sin\delta} \tag{4}$$

Where,
δ: phase angle of the binder.

3.2 ASPHALT FRACTIONATION

Classifying and understanding the chemical composition of asphalt binders has been of significant focus in asphalt research for many decades (Oyekunle et al., 2006; Paliukaite et al., 2014; Mansourkhaki et al., 2020). Various methods have been proposed and used for separating asphalt into its chemical building blocks, or "fractionation". Such methods often rely on one or a combination of methods such as solvent solubility, separation by molecular size or polarity through various size exclusion or column separation methods, and thin layer chromatography such as with an Iatroscan (Christensen et al., 2019). Most commonly, asphalt is split into four fractions in terms of solvent affinity (polarity and molecular weight): Saturate, Aromatic, Resin and Asphaltene, also known as "SARA fractionation". Based on the measured fractions of the binder, the Colloidal Index (CI) can be calculated as shown in **Equation 5** below.

$$CI = \frac{A_R + R}{A_S + S} \tag{5}$$

where,

A_S = denotes the asphaltene content;
S = saturate content;
R = resin content; and
A_R = Aromatic content.

3.3 FOURIER-TRANSFORM INFRARED (FTIR) SPECTROMETER

A Fourier-transform infrared spectrometer emits infrared photons at the sample. These photons can be absorbed by the sample, exciting parts of the molecule to vibrate or rotate. Different molecules absorb different wavelengths of photons depending on their structure and the types of bonds and functional groups in the molecule. Thus, the infrared peak intensities measured from FTIR analysis have been widely used for identifying and characterizing key functional groups in asphalt (Lima et al., 2004; Pasandín et al 2015).

The peak-area intensity of the oxygenated groups (C=O and S=O) can be used to reflect the degree of aging and rejuvenation of the asphalt blends, thus are calculated for evaluation of the study binder blends. The functional groups indices including carbonyl index and sulfoxide index can be determined from the following equations (Marsac et al., 2014; Hofko et al., 2017).

$$I_{C=O} = \frac{Carbonyl\ Peak\ Area\ (around\ 1700\ cm^{-1})}{Asphaltic\ Peak\ Area(\ 1350\text{–}1500\ \ cm^{-1})} \tag{6}$$

$$I_{S=O} = \frac{Sulfoxide\ Peak\ Area\ (around\ 1030\ cm^{-1})}{Asphaltic\ \ Peak\ Area\ (\ 1350\text{–}1500\ \ cm^{-1})} \tag{7}$$

$$Peak\ Area = \int_L^U A(w)dw - \frac{A(U)+L(L)}{2} * (U - L) \tag{8}$$

Where the Peak Area represents the integral between the absorbance curve and baseline. U, L represent upper and lower wavenumber limit of the functional group respectively. A(w) represents the absorbance value at wavenumber of w.

The asphaltic peak area always shows good stability within the same bitumen; it can be used as the stable reference for both carbonyl index and sulfoxide index. However, wavenumbers that define the carbonyl range are not always fixed, and they might vary with the different material compositions (Hofko et al., 2018). Based on the research team's experience, the traditional quantification function should be adjusted with a carbonyl peak area defined by an extended range and baseline. The reason behind this adjustment is related to the addition of bio-based RA, where esters show high concentrations in the FTIR result for the study RA oil. As shown in **Figure 3-1**, both absorbance peaks of easter (1740 cm^{-1}) and carboxylic acids (1700 cm^{-1}) should be included to in the carbonyl group amount. **Equation 9** shows the adjusted equation for carbonyl group characterization that will be used in this study; the quantification area is expanded to 1676 cm^{-1} ~ 1763 cm^{-1} and the baseline is expanded to 1525 cm^{-1} ~ 1800 cm^{-1}.

$$I'_{C=O} = \frac{Carbonyl\ Peak\ Area\ (1676\text{–}\ 1763\ cm^{-1}}{Stable\ Region\ Peak\ Area\ (1350\text{–}1500\ \ cm^{-1})} \tag{9}$$

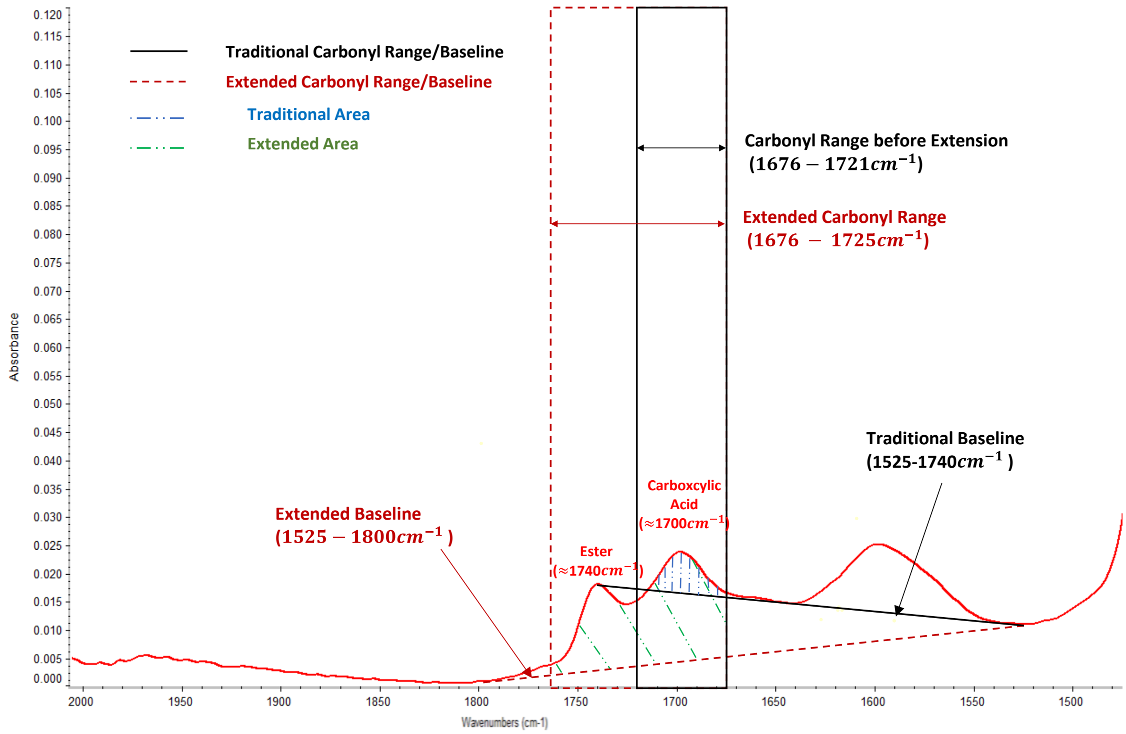


Figure 3-1 FTIR Scan Showing Extended Area for Carbonyl Quantification

3.4 AGING CONDITIONING LEVELS

For the virgin and binder blends sampled during production, the tests are conducted on binder samples with the original (unaged), RTFO (Rolling Thin-Film Oven) and standard 20 hrs. PAV (Pressure Aging Vessel) conditions. For the binders extracted and recovered from the ten mixtures/sections, the tests are performed on binder samples with the as-extracted and 20 hrs. PAV condition.

CHAPTER 4: In-Line Sampled Binder Results

4.1 RHEOLOGICAL PROPERTIES

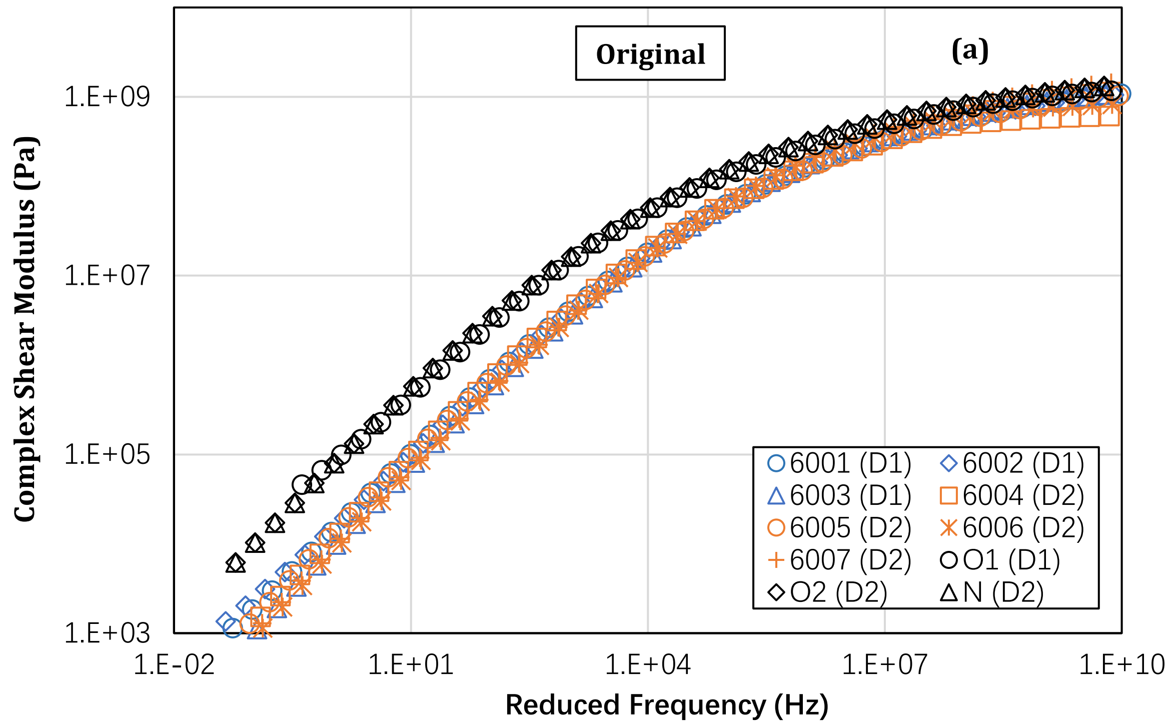
Table 4-1 below summarizes the continuous performance temperatures and performance grades for the study binders sampled in-line during production. The three base/virgin binders have similar grade with binder N having slightly lower temperatures than other two. All RA binders (6001-6007) meet the project requirement of decreasing the PGLT of the base binder (-28°C) to -34°C. The PGHT for all of the RA sections dropped 8-12°C (the equivalent of two grades) due to the addition of the RAs.

Table 4-1 Continuous PG Temperatures Grade of In-line Sampled Binders

Binder ID (production day)	Continuous PG Temperatures (°C)		Performance Grade (°C)
	PGHT	PGLT	
6001 (D1)	51.1	-36.1	46-34
6002 (D1)	51.5	-35.8	46-34
6003 (D1)	48.8	-37.1	46-34
6004 (D2)	50.6	-34.3	46-34
6005 (D2)	49.8	-37.3	46-34
6006 (D2)	46.3	-36.7	46-34
6007 (D2)	47.7	-38.5	46-34
O1 (D1)	59.9	-28.5	58-28
O2 (D2)	59.9	-28.3	58-28
N (D2)	59.4	-29.6	58-28

D1: Produced on day 1; D2: Produced on day 2.

Figure 4-1 to 4-3 below show the complex shear modulus and phase angle master curves for the study binders with different aging conditions at the reference temperature of 25°C. The three base binders have very similar stiffness (as indicated by norm of complex modulus) and relaxation capability (as indicated by phase angle). All RA binders have lower complex modulus and higher phase angle as compared to the base binders, indicating lower cracking susceptibility.



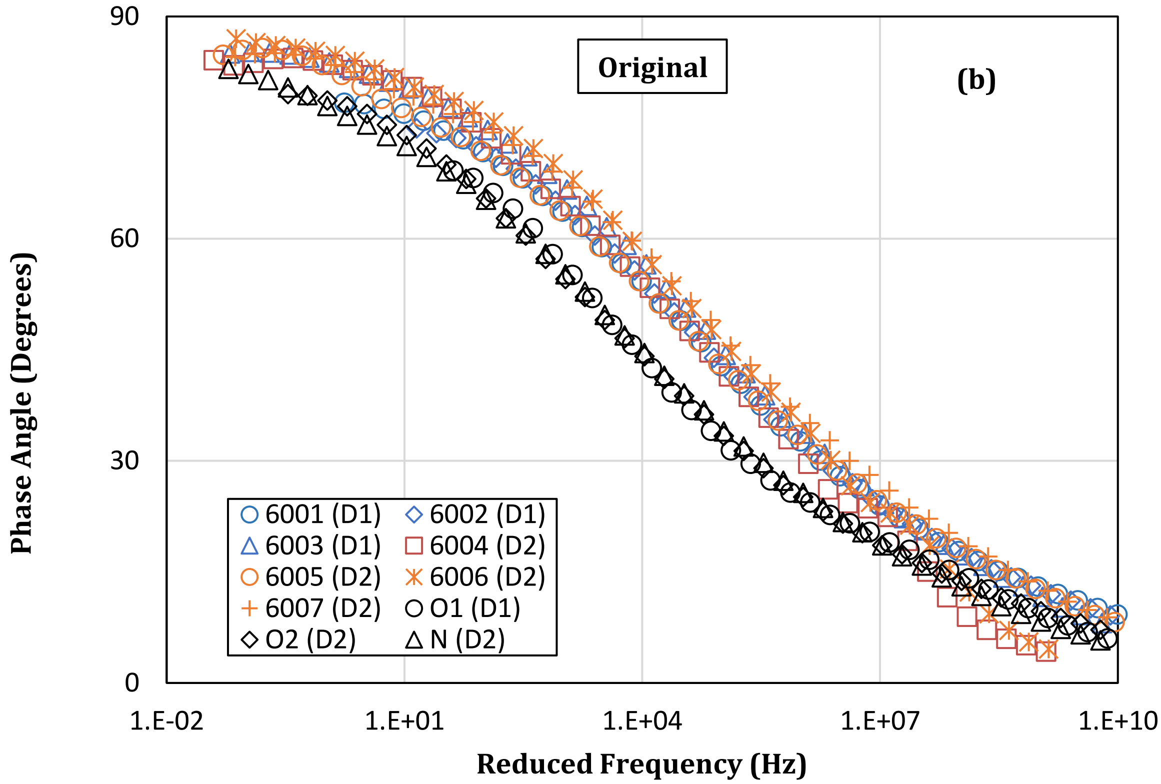


Figure 4-1 Master Curves of (a) Complex Modulus and (b) Phase Angle for Original Binders (Ref. 25°C)

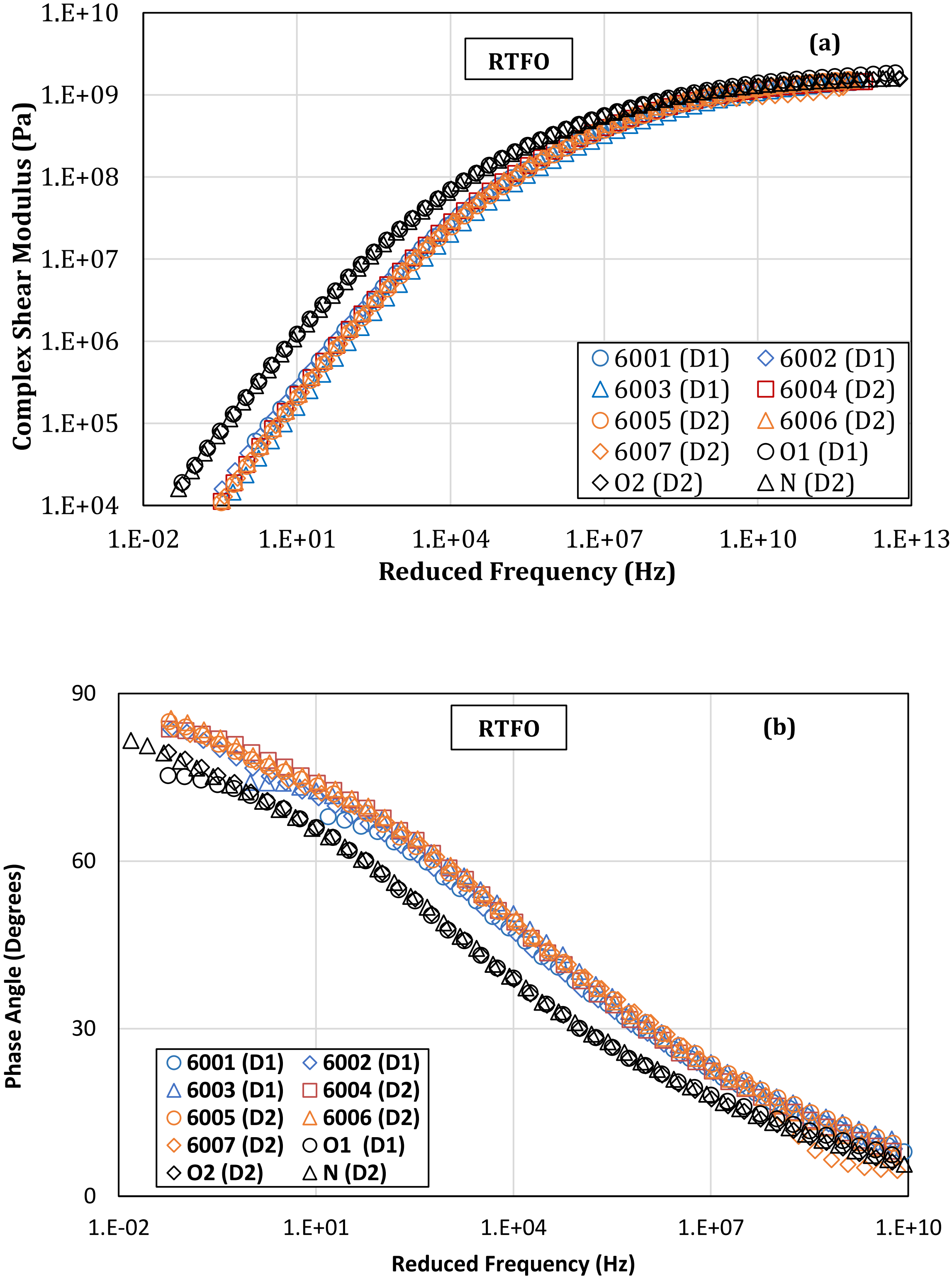


Figure 4-2 Master Curves of (a) Complex Modulus and (b) Phase Angle for RTFO Aged Binders (Ref. 25°C)

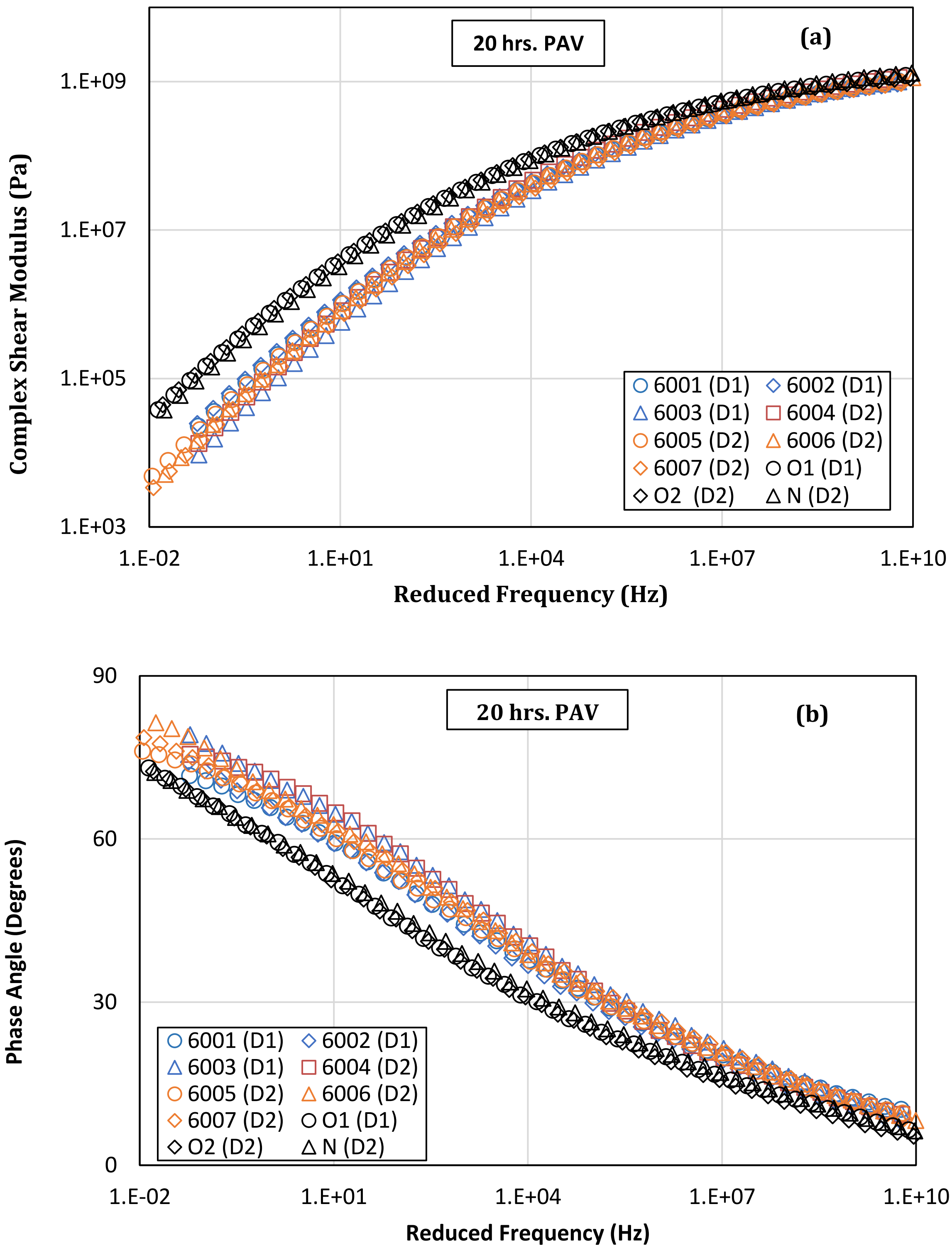


Figure 4-3 Master Curves of (a) Complex Modulus and (b) Phase Angle for 20 hrs. PAV Aged Binders (Ref. 25°C)

Figure 4-4 below shows how the R value for the different study binders changes with aging. The three base binders have a similar R value after each aging condition. All RA binders generally have lower R value than their corresponding base binder after each aging condition.

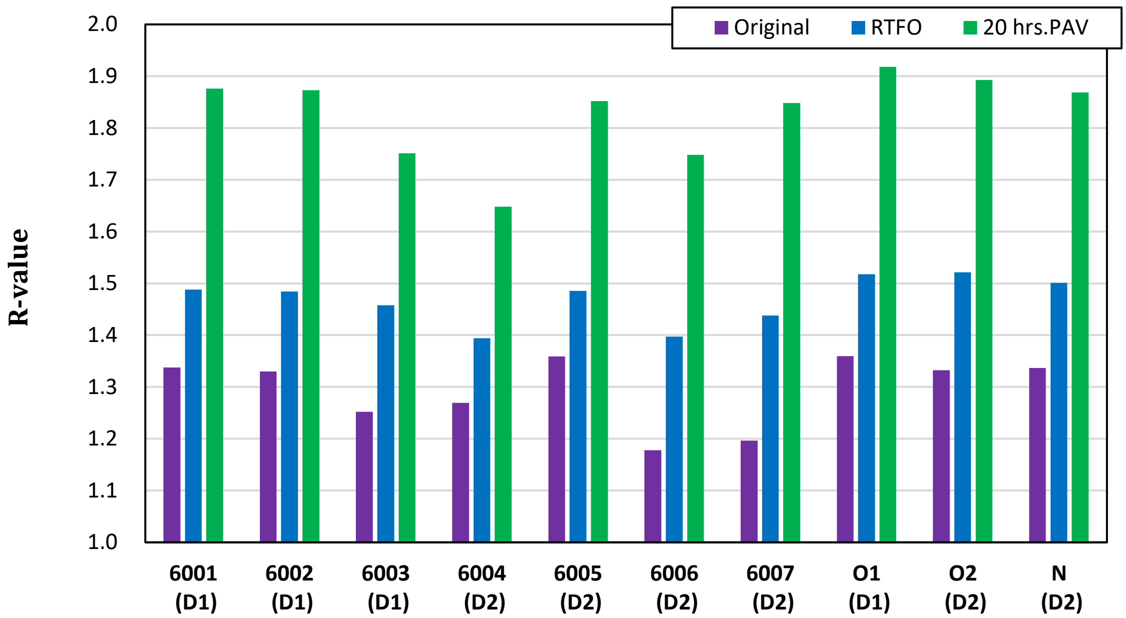


Figure 4-4 R-values for In-line Sampled Binders

Figure 4-5 below shows the ΔTc values for the study binders with different aging conditions. The ΔTc value for most of the binders with different aging conditions is positive, indicating these binders are primarily S-controlled. After aging, all binders still meet the cracking threshold value of -2.5°C. Base binders are similar in original and RTFO condition, while binder N retains a positive ΔTc value after PAV aging. Comparing the RA binders with their base binder, binder 6001 and 6003 consistently show higher ΔTc value than the base binder O1 after each aging condition. Binder 6002 originally has a higher ΔTc value than base binder O1 but lower value after the RTFO and 20 hrs. PAV conditions. RA binders 6004, 6005 and 6006 generally have higher ΔTc values than the O2 base binder. Binder 6007 has significantly higher ΔTc value than the base binder N with unaged and RTFO condition, but their ΔTc value becomes similar after 20 hrs. PAV aging.

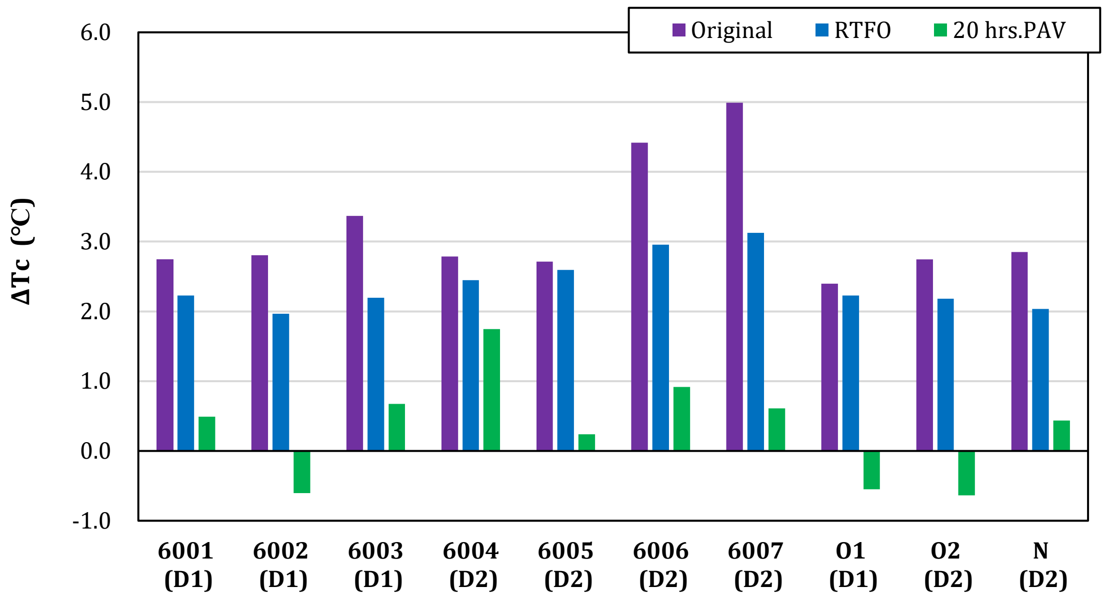


Figure 4-5 ΔTc Values for In-line Sampled Binders

Figure 4-6 below shows that all binders still meet the G-R cracking warning threshold value of 160kPa after aging. The three base binders have similar G-R values with unaged and RTFO conditions, while binder N has a lower G-R value after 20 hrs. PAV condition. All RA binders have a lower G-R value than their corresponding base binder after each aging condition.

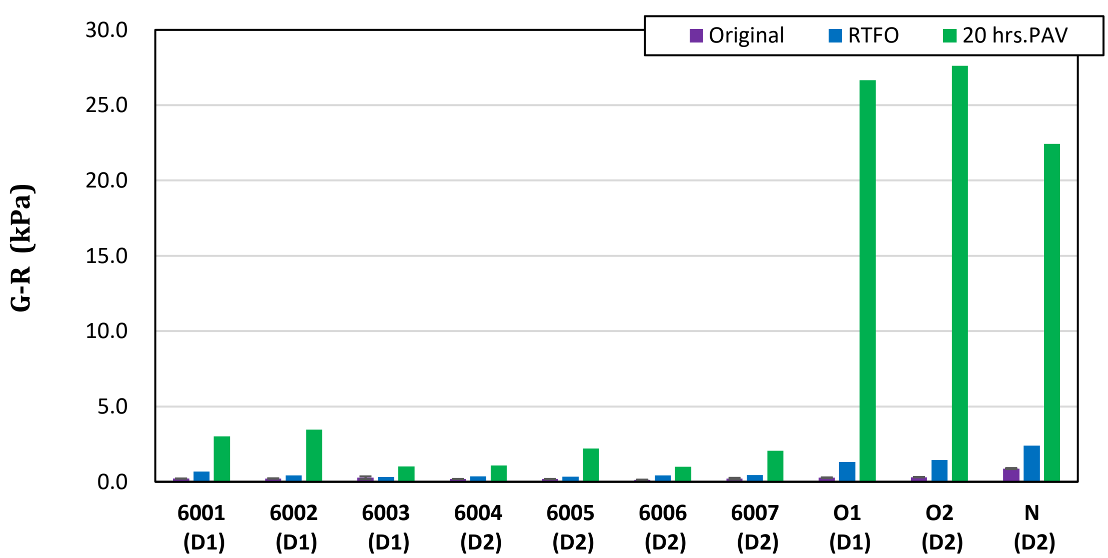


Figure 4-6 G-R Values at 15°C and 0.05 rad/s for In-line Sampled Binders

4.2 COLLOIDAL INDEX

Aging causes a decrease in CI value for all binders due to the increase of the asphaltene content and decrease of the light fractions, as shown in **Figure 4-7**. The base binders O1 and O2 have similar CI values after each aging condition, while binder N has a lower CI value. All RA binders have higher CI value as compared to their corresponding base binder after each aging condition, indicating improvement of the colloidal structure through addition of the study RAs.

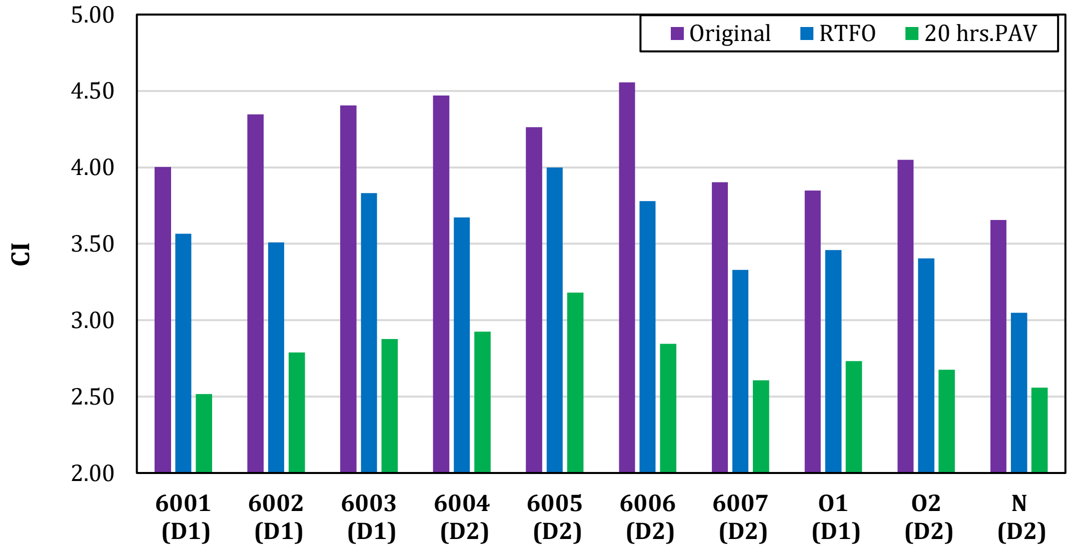


Figure 4-7 CI Values for In-line Sampled Binders

4.3 FTIR RESULTS

Aging causes an increase in carbonyl ratio ($I_{C=O}$) and sulfoxide ratio ($I_{S=O}$) for all binders as shown in **Figure 4-8**. The base binders O1 and O2 generally have similar $I_{C=O}$ and $I_{S=O}$ values after each aging condition (O1 has a higher $I_{S=O}$ value after PAV aging), while binder N has a slightly higher $I_{C=O}$ but lower $I_{S=O}$ value. All RA binders have higher $I_{C=O}$ value as compared to the base binders after each aging condition. In terms of the $I_{S=O}$ parameter, RA binders 6001, 6002 and 6003 have a lower value than the base binder O1 after each aging condition. RA binders 6004 and 6005 typically have a higher $I_{S=O}$ value than the base binder O2 after each aging condition, while binder 6006 has a lower value with original and RTFO condition but higher value after PAV aging. Binder 6007 originally has a higher $I_{S=O}$ value as compared to the base binder N, but the value is comparable after RTFO and PAV aging.

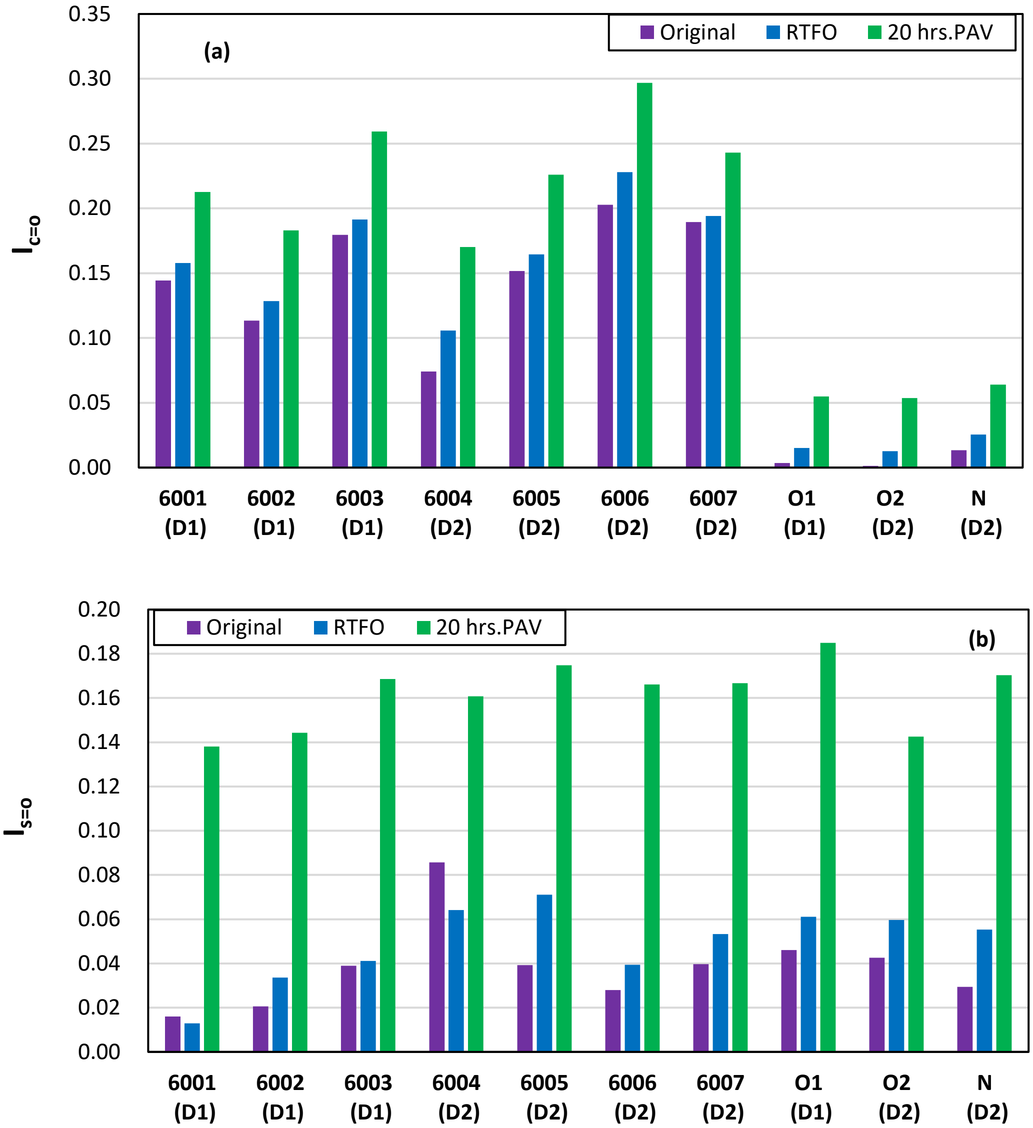


Figure 4-8 (a) $I_{C=O}$; and (b) $I_{S=O}$ Values for In-line Sampled Binders

CHAPTER 5: Results of Extracted and Recovered Binders from Production Mixes

5.1 RHEOLOGICAL PROPERTIES

Table 5-1 below summarizes the performance grades for the binder samples extracted and recovered from the sampled plant produced mixtures with as-extracted and 20 hrs. aging conditions. For the binders with as-extracted condition, 30% D0 and 40% D1 control binders have similar grade while both the PGHT and PGLT continuous grades for the 40% D2 are several degrees lower. Both PGHT and PGLT for RA binders 6001 and 6002 are lower (by over a full grade) than their control mix and the 30% mix, while binder 6003 PGHT drops over 10°C, resulting in a drop of two grades. RA binders 6004 and 6005 have slightly higher continuous PGHT, but same PG as the corresponding control mix; binder 6005 PGLT decreases just enough to change grade. RA binders 6006 and 6007 have PGHT increases over 6°C.

After PAV aging, 30% D0 and 40% D2 control binders have similar grade while both the PGHT and PGLT continuous grades for the 40% D1 are higher. RA binders 6001, 6002 and 6003 generally have lower continuous PGHT and PGLT than the control binder 40% D1 as well as the 30% D0 binder. RA binders 6004 and 6005 have a lower continuous PG than the control binder 40% D2 as well as binder 30% D0, while binder 6006 has a higher grade. Binder 6007 has a similar continuous grade to both control binder 40% D2 and 30% D0.

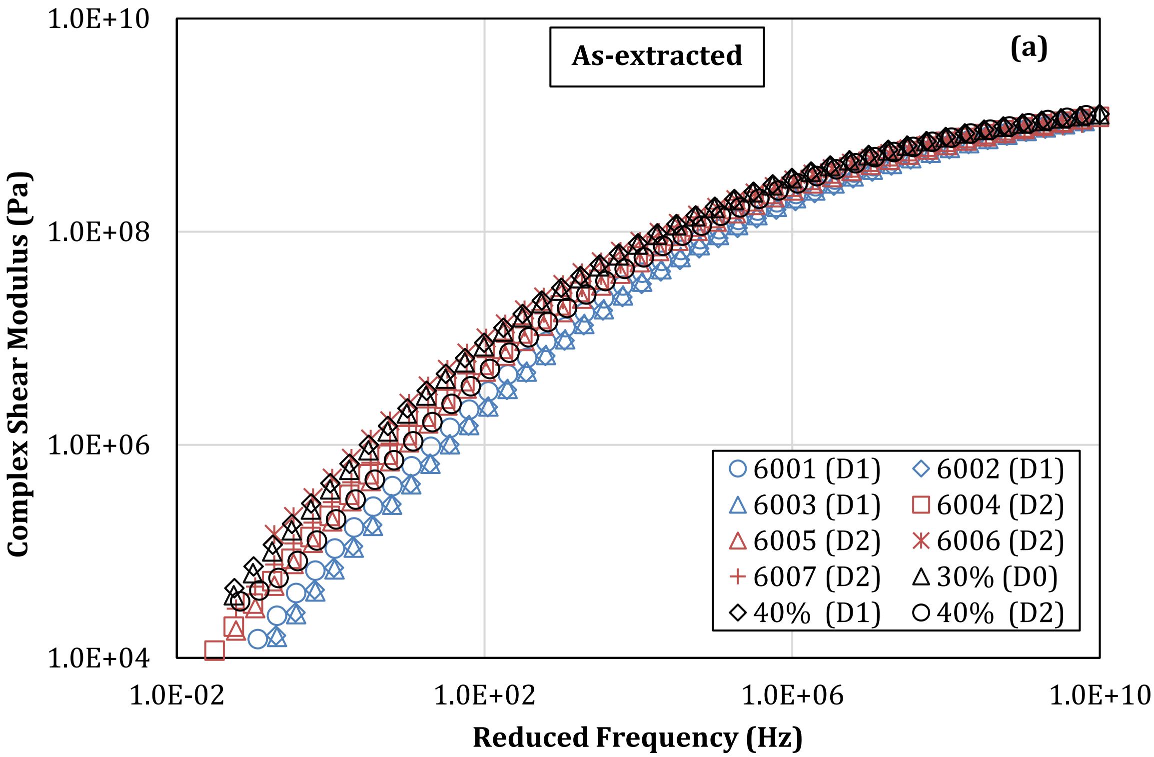
Table 5-1 Performance Grades of Binders Extracted and Recovered from Sampled Mixtures

Binder ID (production day)	Continuous PG (°C)				PG (°C)	
	PGHT		PGLT			
	As-extracted	20 hrs. PAV	As-extracted	20 hrs. PAV	As-extracted	20 hrs. PAV
6001 (D1)	58.1	70.2	-37.6	-31.8	58-34	70-28
6002 (D1)	61.4	67.7	-38.8	-33.8	58-34	64-28
6003 (D1)	54.9	65.9	-38.4	-33.8	52-34	64-28
6004 (D2)	62.6	72.2	-33.7	-28.3	58-28	70-28
6005 (D2)	61.7	72.7	-34.7	-30.2	58-34	70-28
6006 (D2)	66.8	76.9	-30.5	-25.8	64-28	76-22
6007 (D2)	70.5	74.8	-33.2	-28.4	70-28	70-28
30% (D0)	64.1	74.3	-31.5	-28.1	64-28	70-28
40% (D1)	65.5	76.5	-31.6	-26.6	64-28	76-22
40% (D2)	60.8	74.0	-33.7	-28.5	58-28	70-28

D0: Produced on the day before day 1; D1: Produced on day 1; D2: Produced on day 2.

Figure 5-1 to **5-3** below show the complex shear modulus and phase angle master curves for the study binders with different aging conditions at the reference temperature of 25°C. For the as-extracted binders, there is a large difference in the complex modulus and phase angle values between the two 40% control mixtures (6011 and 6012), indicating potential variability during the production of mixtures over the two days. RA binders 6001, 6002, 6003 and 6005 have lower modulus and higher phase angle values than corresponding control binder 40% RAP D1 and 40% RAP D2. RA binder 6006 and 6007 has higher modulus and lower phase angle values than the 40% D2 control binder. RA binders 6001, 6002, 6003, 6004 and 6005 have lower modulus and higher phase angle values than the 30% control binder.

After PAV aging, the complex modulus and phase angle values for the two 40% control binders (6011 and 6012) become similar. RA binders 6001, 6002, 6003 and 6005 still have lower modulus and higher phase angle values than all three control binders. RA binder 6006 and 6007 has slightly higher modulus and lower phase angle values than the 40% D2 control binder. RA binders 6001, 6002, 6003, 6004 and 6005 have lower modulus and higher phase angle values than the 30% control binder.



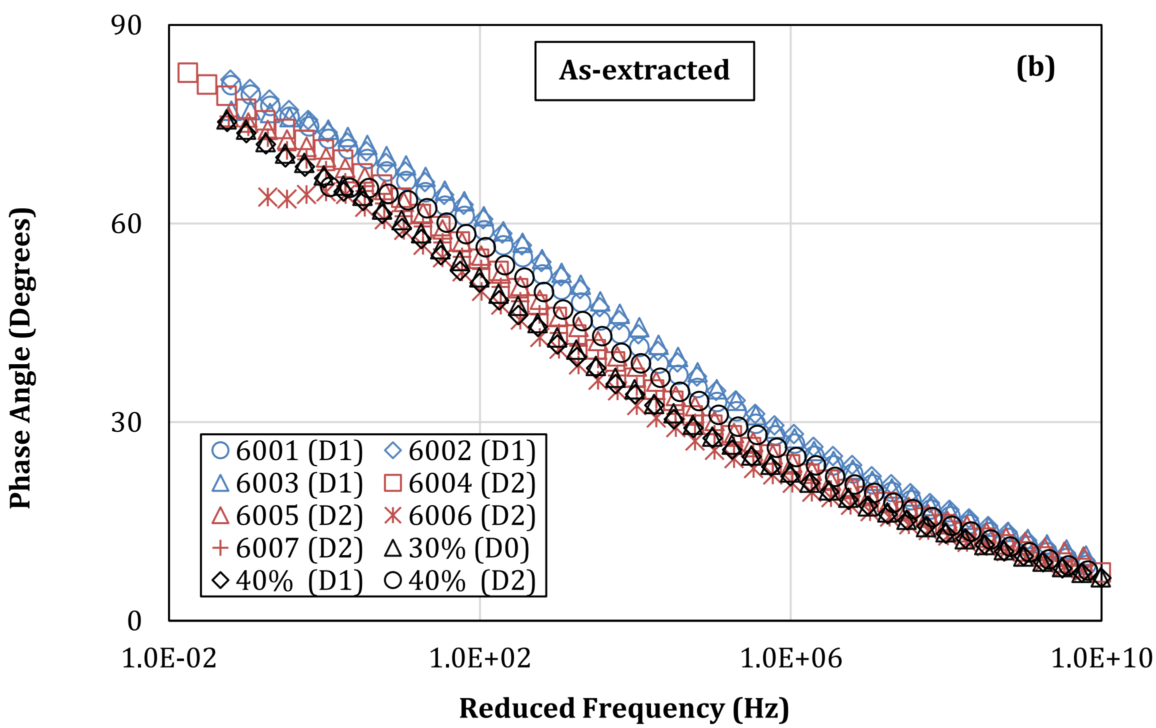
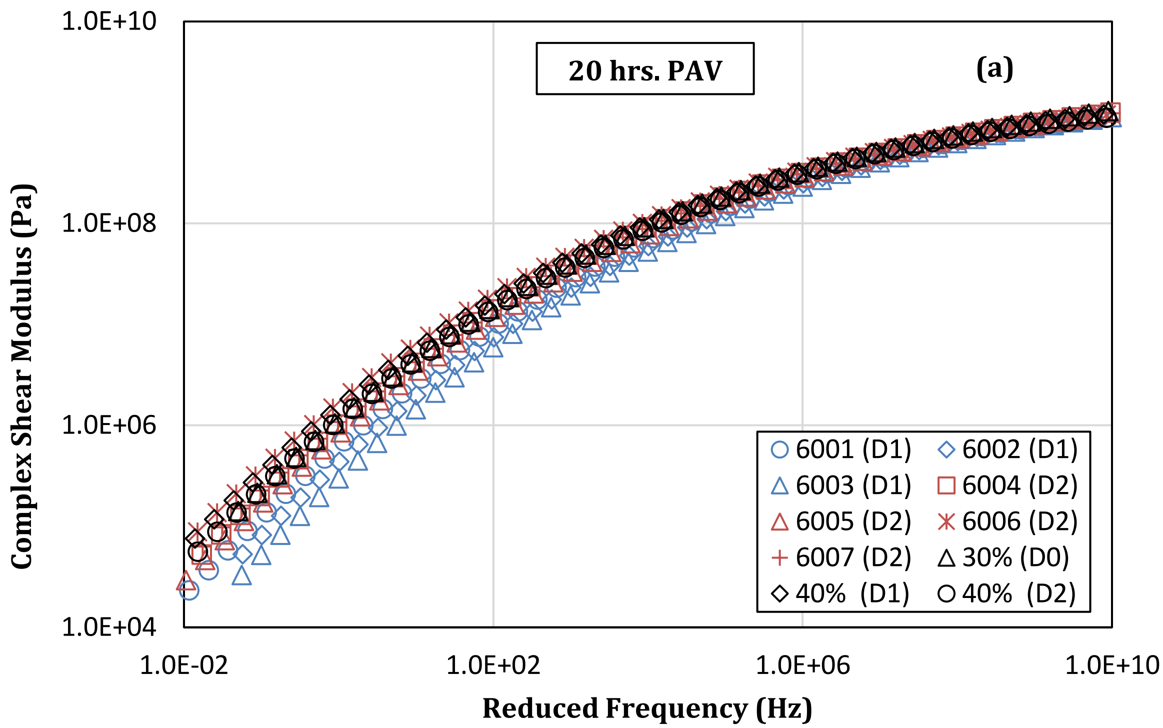


Figure 5-1 Master Curves of (a) Complex Modulus and (b) Phase Angle for As-extracted Binders (Ref. 25°C)



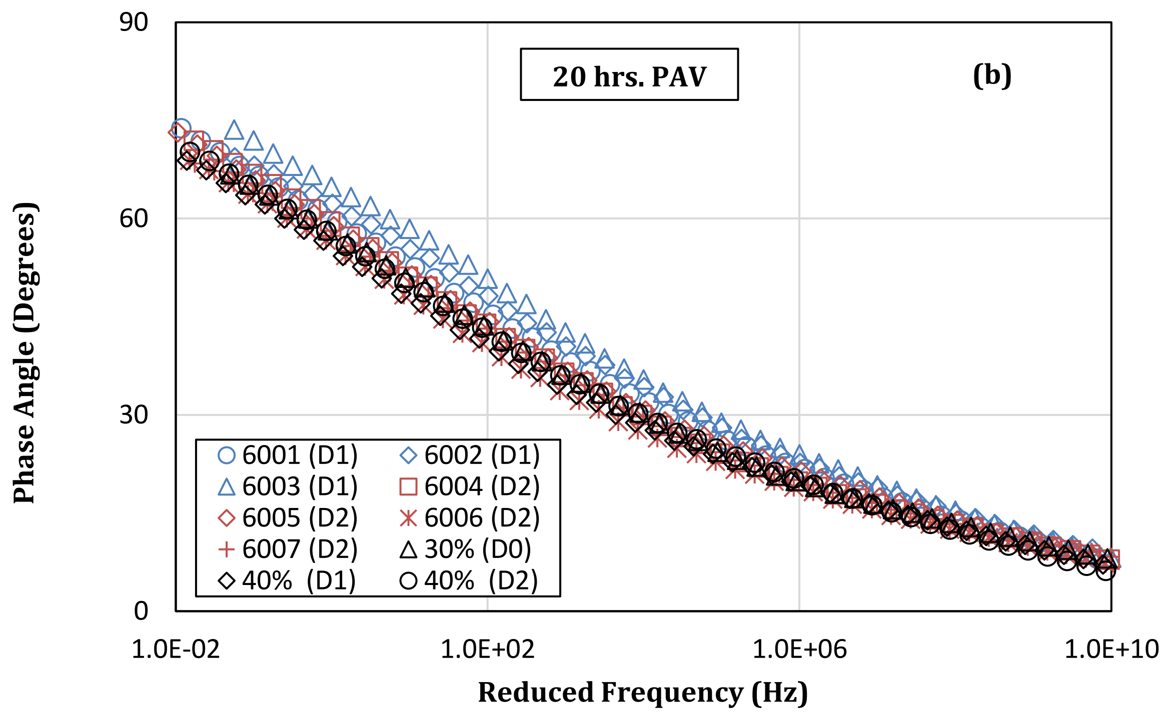


Figure 5-2 Master Curves of (a) Complex Modulus and (b) Phase Angle for20 hrs. PAV Aged Binders (Ref. 25°C)

Figure 5-3 below shows the R values for the different study binders. Binder 40% D2 has lower R values than binder 40% D1 after each aging condition. RA binders 6001, 6002 and 6003 have lower R values than their control binder and the 30% RAP binder. RA binders 6004 and 6005 have higher values than their control as-extracted, but lower values after aging. RA binders 6006 and 6007 have higher R values as-extracted, but similar values to their control after PAV aging.

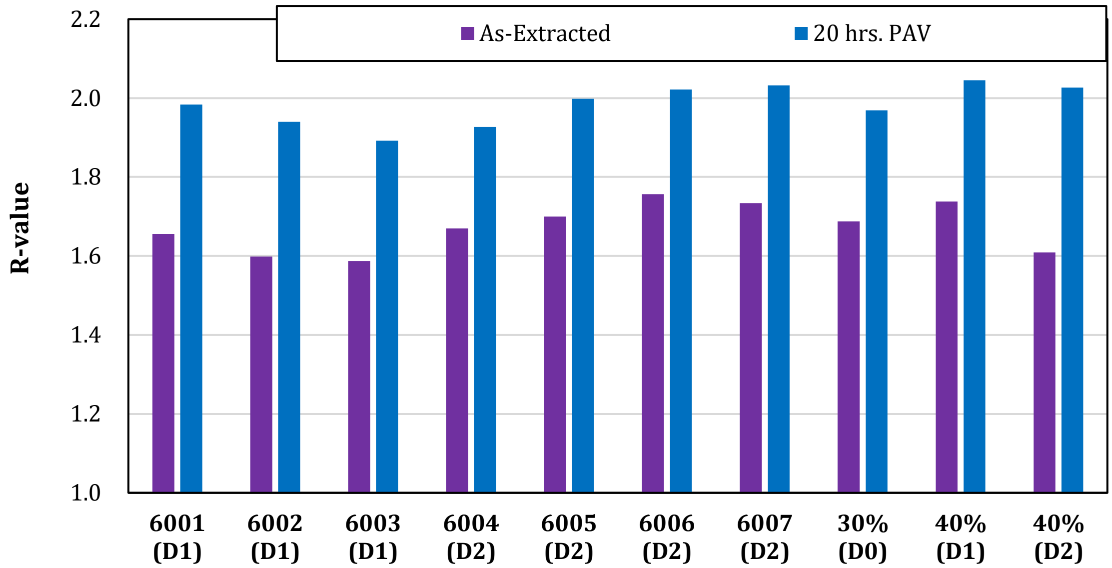


Figure 5-3 R Values for Extracted and Recovered Binders

Figure 5-4 below shows the ΔTc values for the different study binders with different aging conditions; all binders still meet the cracking warning threshold value of -2.5°C after 20 hrs. PAV condition. The 40% D2 binder has the warmest ΔTc value with as-extracted condition while the 30% D0 has the warmest value after PAV aging condition. There is a large difference in the ΔTc values between the two 40% control mixtures (6011 and 6012) in the as-extracted condition. RA binders 6001, 6002, 6003, and 6005 have warmer ΔTc values than their control binders. RA binders 6006 and 6007 have a lower ΔTc value than the 40% D2 control after each aging condition. RA binders 6001, 6002 and 6003 have warmer ΔTc values than the 30% control mixture as well.

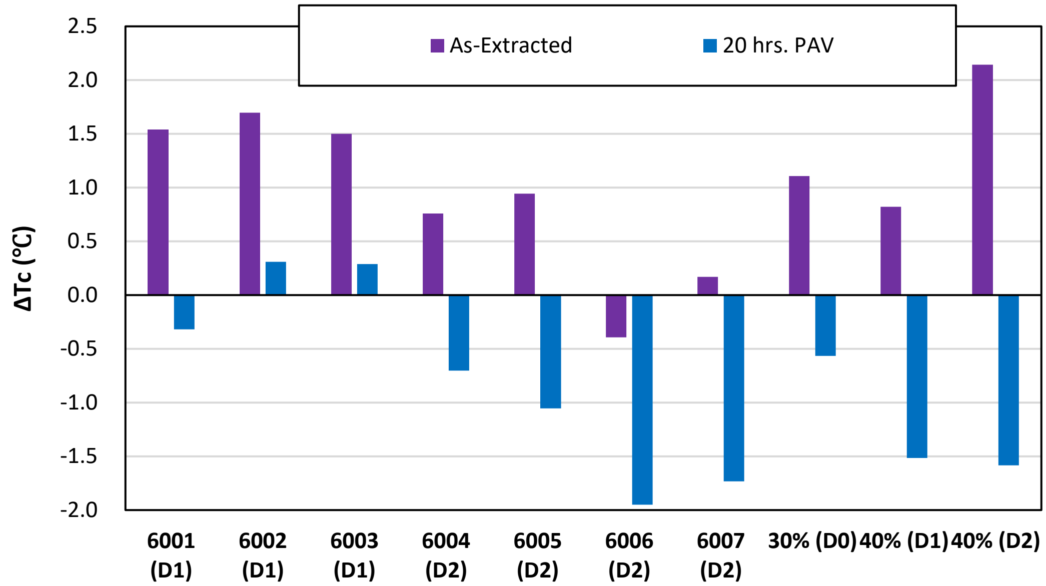


Figure 5-4 ΔTc Values for Extracted and Recovered Binders

Figure 5-5 below shows that all the recovered binders meet the G-R cracking warning threshold value of 180kPa after 20 hrs. PAV condition. There is a difference in G-R values for the two 40% binders at both aging conditions. RA binders 6001, 6002, 6003, 6004, and 6005 have lower G-R values than their control binder and the 30% RAP binder. RA binders 6006 and 6007 have similar extracted G-R values as compared to their control binder; however, they have higher values after PAV aging.

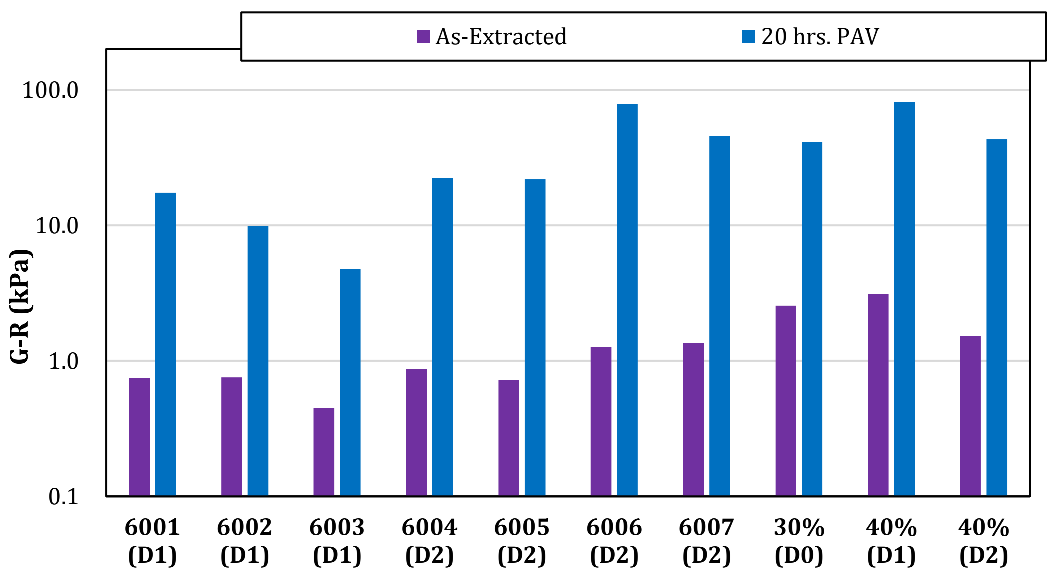


Figure 5-5 G-R Values at 15°C and 0.05 rad/s for Extracted and Recovered Binders

5.2 COLLOIDAL INDEX

Figure 5-6 below shows the CI values for the different study binders. There is a large difference in CI value between binder 40% D1 and 40% D2 with as-extracted condition, indicating potential variability during the production. RA binders 6001, 6002 and 6003 typically have higher CI values than their control binder after each aging condition, indicating improvement of the colloidal structure by adding the RA products. RA binders 6004, 6005, 6006 and 6007 all have lower CI values than their control binder after each aging condition, with larger differences for 6006 and 6007. Compared to the 30% control binder, RA binders 6005, 6006 and 6007 have lower CI values.

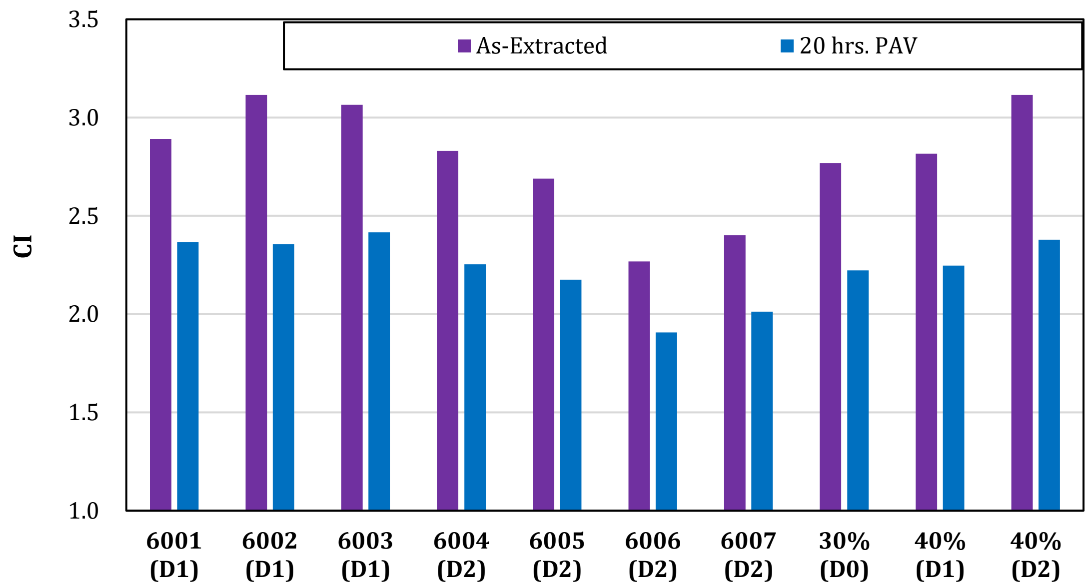


Figure 5-6 CI Values for Extracted and Recovered Binders

5.3 FTIR RESULTS

Figure 5-7 shows the carbonyl ratio ($I_{C=O}$) and sulfoxide ratio ($I_{S=O}$) for all binders. The $I_{C=O}$ parameter increases with aging, while there isn't a consistent trend for change of $I_{S=O}$ parameter with aging. Generally, there is a large difference in both $I_{C=O}$ and $I_{s=O}$ values between binder 40% D1 and 40% D2 (40% D1 and 40% D2 have similar $I_{C=O}$ values with as-extracted condition). All RA binders have higher $I_{C=O}$ value as compared to the control binders after each aging condition. In terms of the $I_{S=O}$ parameter, RA binders 6001, 6002 and 6003 have a lower value than the control binder 40% D1 with as-extracted condition but higher value after PAV aging. RA binders 6004, 6005, 6006 and 6007 all have higher $I_{S=O}$ parameter than the control binder 40% D2 as well as binder 30% D0.

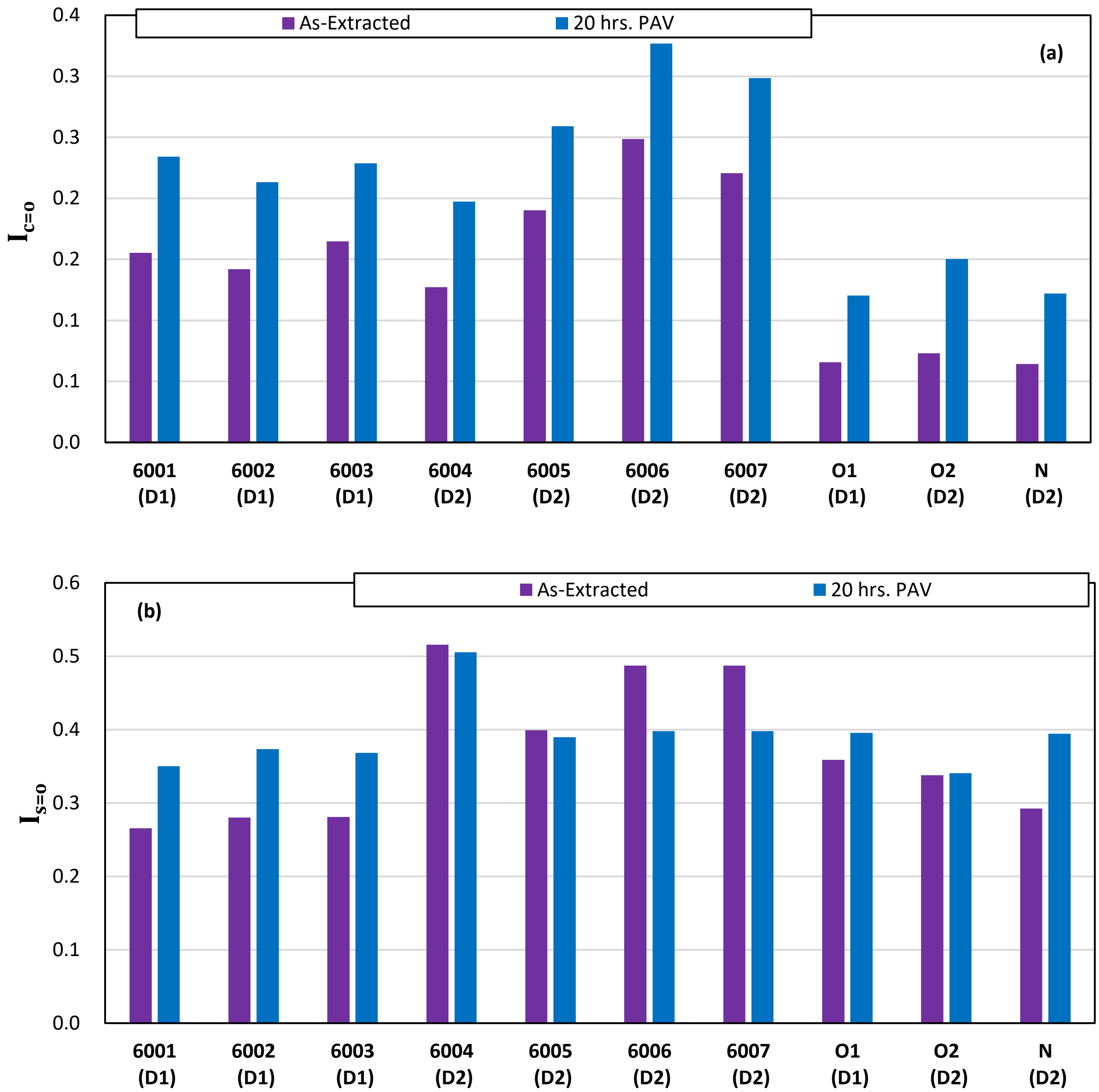


Figure 5-7 (a) $I_{C=O}$; and (b) $I_{S=O}$ Values for Extracted and Recovered Binders

CHAPTER 6: Summary

In this report, the available construction information is summarized and the results of the testing on in-line sampled binders and binders extracted recovered from the project mixtures are presented. The rheological properties, chemical composition and functional groups as well as the change of these properties with laboratory aging conditions are presented and discussed. This section provides a summary of binder testing and analysis conducted under Task-2.

In-line sampled binder:

- All RA binders (6001-6007) meet the project requirement of decreasing the PGLT of the base binder (-28°C) to -34°C. However, the PGHT for all of the RA modified binders drops 8-12°C (almost equivalent of two high-temperature performance grades) as compared to the base binder.
- The two base binders sampled on the two production days (O1 and O2) generally have very similar properties. The base binder N has slightly different measured rheological parameters than the other two base binders.
- All RA binders (6001-6007) generally show improved rheological parameters as compared to the respective base binders after each aging condition (unaged, RTFO and 20 hrs. PAV).
- All RA binders (6001-6007) generally have a higher colloidal index and carbonyl ratio than the base binders. RA binders 6004 and 6005 have a higher sulfoxide ratio than the base binder.

Table 6.1 below provides an overall summary of the effects of various RAs on the measured properties as compared to the base binders.

Table 6-1 Summary of the Effect of RAs on In-line Sampled Binder Properties

Properties/Parameters Compared to Corresponding Base Binder		Increased Original Value	Increased RTFO Value	Increased 20 hrs. PAV Value
Rheological Indices (DSR)	PG	None	--	--
	Modulus	None	None	None
	Phase Angle	All	All	All
	R-value	None	None	None
	ΔTc	All	All except for 6002	All except for 6002
	$G\text{-}R_m$	None	None	None
Colloidal Index (SARA)	CI	All	All	All except for 6001
Functional Group Indices (FTIR)	Carbonyl ratio	All	All	All
	Sulfoxide ratio	6004,6005,6007	6004,6005,6007	6004,6005,6006

Binders extracted and recovered from mixtures:

- Binder testing shows that there is a large difference between control section 6011 and 6012, indicating potential variability during the production of mixtures over the two days.

- For both as-extracted and 20 hrs. PAV aging condition, binders extracted from sections 6001, 6002 and 6003 have a lower PG than the control section 6011, while binder from 6006 has a higher grade than the control section 6012.
- Overall, the RA mixtures produced on day 1 (6001-6003) have improved rheological parameters as compared to the control section 6011. However, the RA mixtures produced on day 2 (6004-6007) do not show significant improvement in properties as compared to control section 6012.
- The RA mixtures produced on day 1 (6001-6003) have a higher colloidal index as compared to the control section 6011.
- All RA sections have higher $I_{C=O}$ value as compared to the control sections after each aging condition, while RA sections 6004, 6005, 6006 and 6007 have higher $I_{S=O}$ parameter than control section 6012.

Table 6.2 below provides an overall summary of the effects of various RAs on the measured properties as compared to the control mixtures.

Table 6-2 Summary of the Effect of RAs on Binder Properties (extracted and recovered binders)

Properties/Parameters Compared to Corresponding Control Mixture		Increased Original Value	Increased 20 hrs. PAV Value
Rheological Indices (DSR)	PG	6006,6007	6006
	Modulus	6006,6007	6006,6007
	Phase Angle	6001,6002,6003,6004,6005	6001,6002,6003,6004,6005
	R-value	6004,6005,6006,6007	None
	ΔTc	6001,6002,6003	6001,6002,6003,6004,6005
	$G\text{-}R_m$	None	6006
Colloidal Index (SARA)	CI	6001,6002,6003	6001,6002,6003
Functional Group Indices (FTIR)	Carbonyl ratio	All	All
	Sulfoxide ratio	6004,6005,6006,6007	All

Currently, work is underway under Task-3 and Task-4. Mixture tests on the sampled plant produced mixtures with unaged and 6 hrs. at 135°C aging condition as well as the testing on field cores is underway. The data analysis from mixture tests conducted by NRRA agencies has been completed. Tests on the binders extracted and recovered from the top 0.5 inch of field cores as well as the mixtures with 6 hrs. at 135°C aging condition are currently underway. The research team will evaluate and determine the additional long-term aging condition once the testing and analysis of the 6 hrs. aged mixtures and field cores is complete. In addition, research team is working with MnDOT staff to obtain other pavement construction information (e.g. plant records) and field performance for the different field sections.

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Appendix

Mix Design for 30% RAP Mixture

DEPARTMENT OF TRANSPORTATION

BITUMINOUS PLANT MIX DESIGN REPORT

District 3A Materials Lab
7694 Industrial Park Rd.
Baxter, MN 56425
Phone: 218-828-5755
Fax: 218-828-5816

 # 3A-2019-169
Date: 8/16/2019

THIS MIX DESIGN REPORT IS NOT VALID UNTIL PLANT NO. INDICATED BELOW IS CERTIFIED.

ENGINEER	FOR
PROJECT NUMBER	
CONTRACTOR SIGN.	

SPEC	2360 AFT
SPEC YEAR	2019
MIX TYPE	SPWEB340
AC GRADE	PER PROPOSAL

THIS MIXTURE HAS BEEN REVIEWED FOR VOLUMETRIC PROPERTIES ONLY, IT DOES NOT ASSURE THAT FIELD PLACEMENT AND COMPACTION REQUIREMENTS HAVE BEEN MET.

PLANT NO. AB BASE 4 - 2019 JOB MIX FORMULA

Begin With Test Number

SP	WE	301
- -	- -	- - -

AFT Properties

Pbe	4.6
SA	26.4
Adj. AFT	8.8

Sieve Size (mm)	(in.)	Composite Formula	Broad Band		For Information Only Virgin Formula PERCENT PASSING
25.0	(1)				
19.0	(3/4)	100	100	100	
12.5	(1/2)	99	85	100	
9.5	(3/8)	86	35	90	
4.75	(#4)	67	30	80	
2.36	(#8)	57	25	65	
1.18	(#16)	45			
0.600	(#30)	30			
0.300	(#50)	13			
0.150	(#100)	6			
0.075	(#200)	3.4	2.0	7.0	
Spec. Voids		4.0	3.0	5.0	
% AC		4.9 (TOTAL)	4.5		%AC (NEW) 3.5

TM # 3A-TM19-0058 Indicates a Gyratory Density of 150.0 (lbs/ft3) at 60 Design Gyrations
Use of anti-strip required: No

%	Pit	Source of Material	Total Sp. G	Minus #4 % Passing	Minus #4 Sp. G
34 %	18145	Andrews Ba Sand 3A-BA19-0198	2.658	95 %	2.658
6 %	18145	Andrews 1/2" Rock old pile 3A-BA19-0196	2.752	8 %	2.752
14 %	18145	Andrews Class "D" 3A-BA19-0206	2.709	86 %	2.709
16 %	18145	Andrews 1/2" Rock new pile 3A-BA19-0205	2.752	1 %	2.752
%				%	
%				%	
%				%	
30 %	18145	TH 6 Millings 3A-BR19-0028	2.667	74 %	2.667
		Mix Aggregate Specific Gravity at the Listed Percentages =	**2.688**		**2.671**

Remarks

Mix Design Reviewed by:

Thomas J. Boser

Mix Design Specialist
3A-2019-169 Ver. 2

cc: Dist Mat'ls Eng. - Sara Johnson
Contractor - ANDERSON BROS.

Mix Design for 40% RAP Mixture

DEPARTMENT OF TRANSPORTATION

BITUMINOUS PLANT MIX DESIGN REPORT

District 3A Materials Lab
7694 Industrial Park Rd.
Baxter, MN 56425
Phone: 218-828-5755
Fax: 218-828-5816

 # 3A-2019-184

Date: 8/26/2019

THIS MIX DESIGN REPORT IS NOT VALID UNTIL PLANT NO. INDICATED BELOW IS CERTIFIED.

ENGINEER	FOR
PROJECT NUMBER	
CONTRACTOR SIGN.	

SPEC	2360 AFT
SPEC YEAR	2019
MIX TYPE	SPWEA340
AC GRADE	PER PROPOSAL

THIS MIXTURE HAS BEEN REVIEWED FOR VOLUMETRIC PROPERTIES ONLY, IT DOES NOT ASSURE THAT FIELD PLACEMENT AND COMPACTION REQUIREMENTS HAVE BEEN MET.

PLANT NO. **AB BASE 4** - **2019** JOB MIX FORMULA

Begin With Test Number

SP	WE	301
- -	- -	- - -

AFT Properties

Pbe	4.6
SA	26.3
Adj. AFT	8.9

Sieve Size (mm) (in.)	Composite Formula	Broad Band (min)		Broad Band (max)	For Information Only Virgin Formula PERCENT PASSING
25.0 (1)			–		
19.0 (3/4)			–		
12.5 (1/2)	100	100	–	100	
9.5 (3/8)	85	85	–	100	
4.75 (#4)	65	60	–	90	
2.36 (#8)	55	45	–	70	
1.18 (#16)	44		–		
0.600 (#30)	29		–		
0.300 (#50)	13		–		
0.150 (#100)	6		–		
0.075 (#200)	3.6	2.0	–	7.0	
Spec. Voids	4.0	3.0	–	5.0	
% AC	4.9 (TOTAL)	4.5			%AC (NEW) 3.0

TM # 3A-TM19-0068 Indicates a Gyratory Density of 150.0 (lbs/ft3) at 60 Design Gyrations
Use of anti-strip required: No

%	Pit	Source of Material	Total Sp. G	Minus #4 % Passing	Minus #4 Sp. G
26 %	18145	Andrews Ba Sand 3A-BA19-0198	2.658	95 %	2.658
4 %	18144	Taylor 1/2" Rock 3A-BA19-0176	2.721	3 %	2.721
12 %	18145	Andrews Class "D" 3A-BA19-0206	2.709	86 %	2.709
18 %	18145	Andrews 1/2" Rock new pile 3A-BA19-0205	2.752	1 %	2.752
%				%	
%				%	
%				%	
40 %	18145	TH 6 Millings 3A-BR19-0028	2.667	74 %	2.667
		Mix Aggregate Specific Gravity at the Listed Percentages =	**2.687**		**2.670**

Remarks

Mix Design Reviewed by:

Thomas J. Boser

Mix Design Specialist

3A-2019-184 Ver. 1

cc: **Dist Mat'ls Eng.** - Sara Johnson
Contractor - ANDERSON BROS.