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Authors
Rahman, Mohammad Ashiqur
Harvey, John T
Elkashef, Mohamed
et al.

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Mohammad Ashiqur Rahman,[1] John T. Harvey,[2] Mohamed Elkashef,[3] Liya Jiao,[2] and David Jones[2]

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Mohammad Ashiqur Rahman,[1] John T. Harvey,[2] Mohamed Elkashef,[3] Liya Jiao,[2] and David Jones[2]

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[1] University of California Pavement Research Center, Department of Civil and Environmental Engineering, University of California, Davis, 1 Shields Ave., Davis, CA 95616, USA (Corresponding author), e-mail: mohrahman@ucdavis.edu, https://orcid.org/0000-0001-7855-5346

[2] University of California Pavement Research Center, Department of Civil and Environmental Engineering, University of California, Davis, 1 Shields Ave., Davis, CA 95616, USA

[3] Department of Civil and Environmental Engineering, Oklahoma State University, 601 N Willis St., Stillwater, OK 74078, USA, https://orcid.org/0000-0002-8028-1935

ABSTRACT

The aging of asphalt concrete is mainly governed by the aging of the asphalt binder, which is a naturally occurring organic hydrocarbon. Both chemical and rheological properties of asphalt binder are expected to change as aging continues. The pavement industry is increasing the use of different recycled materials in the construction and rehabilitation of flexible pavements to preserve natural resources, save costs, and reduce environmental emissions. The aged binder from recycled materials is expected to alter the binder properties and its aging characteristics in the new mix. In this study, 3 different virgin base binder types (PG 64-16, PG 58-22, and PG 70-10) and 7 different binder blends containing recycled binders (up to 100 % binder replacement) were subjected to different aging conditions. The rheological and chemical properties of these binders were characterized using a dynamic shear rheometer and Fourier transform infrared spectroscopy, respectively. It was found that the Glover-Rowe parameter distinctively captured the change in binder rheological properties with aging for the different binder blends. A good correlation (R^2 value of 0.83–1.00) was observed between binder chemical and rheological properties. The source and performance grade of the base binder were found to govern the correlation between the rheological and chemical properties of the blended binder. Hamburg wheel tracking (for rutting and moisture sensitivity) and indirect tensile asphalt cracking test (for fracture) tests were conducted on asphalt mixes maintaining the same blended binder ratios. The laboratory mix performance parameters were found to correlate well with the properties of the blended binders. Therefore, properties of the blended binders can be an important source of information for predicting the performance of asphalt mixes containing recycled materials.

Keywords

asphalt binder aging, modified carbonyl area parameter, recycled materials, Glover-Rowe parameter, asphalt mix performance

Introduction

Aging is an important phenomenon for the medium and long-term performance (5–30 years) of asphalt concrete because it can lead to a reduction in a flexible pavement's resistance to raveling, cracking, and moisture-induced damage.[1,2] On the other hand, asphalt aging is believed to significantly increase the short-term (<5 years) rutting resistance of pavements and can increase fatigue cracking resistance in thicker layers (generally asphalt layers when resistance to bending of the structure is considered).[3–6] Therefore, understanding the mechanism of aging for asphalt mixes is very important. However, the aging of asphalt mixes is a complex chemical phenomenon. Apart from the properties of the asphalt mixes, this chemical process also depends on pavement temperatures, access to oxygen, exposure to ultraviolet light, and moisture. Therefore, pavements in different regions and at different depths in the pavement are expected to age differently despite having the same asphalt mix properties.[7,8] The aging of asphalt binder has also been found to vary significantly with variations in crude oil origin and refinery processes.[2,3] Additionally, increasing use of reclaimed asphalt pavement (RAP), reclaimed asphalt shingles (RAS), and rejuvenating agents (used to promote blending of RAP/RAS and virgin binders and soften the blended binder) in pavement construction poses further challenges in predicting the effects of aging on asphalt concrete.[2,9]

As part of efforts toward improving the cost and environmental sustainability of asphalt pavements, various recycled materials have been used in the maintenance, rehabilitation, and construction of new pavements for more than 40 years.[4,9–11] A survey conducted by Williams, Willis, and Shacat[12] reported that about 94 % of RAP has been put back into new asphalt mixes in 2019. The amount of RAP used in 2019 in the United States was 89.2 million tons, about 8.5 % more than in 2018 and about 60 % more than in 2009.[12] Approximately 1.37 million tons of RAS was stockpiled during 2018. Of the RAS used in 2018, more than 96 % was utilized by the asphalt industry.[12]

The use of these highly aged materials is beneficial for asphalt mixes in terms of short-term rutting resistance and fatigue resistance in thicker asphalt layers because of an increase in stiffness.[4,6,13–16] However, an increase in RAP/RAS has been found to reduce low-temperature cracking resistance in the longer term.[5,9,17] For asphalt mixes with high recycled material contents (more than 30 % reclaimed binder), a suitable rejuvenator is typically used to reduce the effects of stiffer RAP/RAS binder and to increase low-temperature and block cracking resistance, both of which are top-down aging-related phenomena. However, the addition of all these materials causes more complexity in the asphalt aging behavior.

Both the chemical and the rheological properties of asphalt binder are found to change with asphalt aging. Several researchers have used chemical properties to track the aging of asphalt.[1,18–20] Rheological properties have also been used to characterize the aging of asphalt.[21–23] Therefore, it is useful to investigate the relationship between asphalt binder rheological and chemical properties together with the effect of the recycled materials on binder aging properties, and the relationship between mix performance parameters and different aging parameters. This will help generalize understanding of the complex interactions and help develop less expensive testing methods (binder chemical characterization) for mix design and potentially for quality control. Based on this discussion, the objectives of this study are as follows:

- Evaluate the effect of laboratory aging on asphalt binders containing RAP/RAS, with and without a rejuvenator
- Evaluate the correlation between binder rheological and chemical properties for asphalt binders containing recycled materials
- Correlate the binder properties with mix properties for asphalt mixes containing recycled materials

Materials and Methods

ASPHALT BINDER

In this study, 10 different binder blends were prepared in the laboratory to evaluate the binder rheological and chemical properties with aging as shown in Table 1. In the blend summary, "B," "RP," "RS," and "RJ" represent the base binder type, percentage of RAP, percentage of RAS, and percentage of rejuvenator, respectively. For example, B1 RP13+RS15+RJ6 presents the binder blend with Base Binder 1 (PG 64-16) containing 13 % RAP, 15 % RAS, and 6 % rejuvenator. It must be noted that these are binder percentages, not percentages by mass of RAS and RAP in the mix. In this paper, only one source of RAP and one type of aromatic extract rejuvenator are discussed. The rejuvenator dosages were selected to maintain the high performance grade (PG) of binder blends as close to Base Binder 1 (PG 64-16) as possible. Also, an upper limit of 10 % rejuvenator by the weight of total binder was maintained to ensure workability. The RAP/RAS binder was auto-extracted following ASTM D8159, *Standard Test Method for Automated Extraction of Asphalt Binder from Asphalt Mixtures*. The extracted RAP/RAS binder was then recovered using the rotary evaporation process following ASTM D5404, *Standard Practice for Recovery of Asphalt from Solution Using the Rotary Evaporator*.

Three different virgin binder grades (PG 64-16, PG 58-22, and PG 70-10) were considered, but binder blends were only produced with the PG 64-16 binder. These virgin binders were collected from three different refinery sources. The PG 58-22 and PG 70-10 virgin binders were considered to evaluate the effect of base binder type and source on chemical and rheological properties. The binder blends were prepared using a shear mixer at 163°C for 30 min to achieve complete binder blending. The rejuvenator was considered as part of the replaced binder. A rolling thin-film oven (RTFO) and pressure aging vessel (PAV) were used to simulate short- and long-term aging of asphalt binder blends according to AASHTO T 240, *Standard Method of Test for Effect of Heat and Air on a Moving Film of Asphalt Binder (Rolling Thin-Film Oven Test)*, and AASHTO R 28, *Standard Practice for Accelerated Aging of Asphalt Binder Using a Pressurized Aging Vessel (PAV)* respectively.

The chemical properties of the binder blends were evaluated using Fourier transform infrared spectroscopy (FTIR). The spectra measured by the FTIR were recorded in a reflective mode, from 4,000 to 400 cm^{-1}, at a resolution of 4 cm^{-1}. An average value of 24 scans was recorded for each measurement. Nine replicate measurements were taken to ensure that representative measurements were collected for each binder sample. The carbonyl area (CA) index determined from FTIR was used to track chemical properties with aging. The tangential integration of the component area index was calculated between the upper and lower wavenumbers (1,671 and 1,720 cm^{-1}).[1] The aliphatic band at 2,923 cm^{-1} was used to normalize the spectra and eliminate any variability

TABLE 1
Summary of binder blends

Blend Number	Blend Summary	Virgin Binder	Rejuvenator Dosage, % of Total Binder	RAP Amount, % of Total Binder	RAS Amount, % of Total Binder	Binder Replacement, %	Mix Testing
1	PG 64-16 (B1)	PG 64-16	…	…	…	0	Yes
2	B1 RP25+0RJ	PG 64-16	…	25	…	25	Yes
3	B1 RP19+ 6RJ	PG 64-16	6	19	…	25	Yes
4	B1 RP40+RJ10	PG 64-16	10	40	…	50	Yes
5	B1 RP50+RJ0	PG 64-16	…	50	…	50	No
6	B1 RP19+RS15	PG 64-16	…	19	15	34	Yes
7	B1 RP13+RS15+RJ6	PG 64-16	6	13	15	34	Yes
8	RP100	…	…	100	…	100	No
9	PG 58-22 (B2)	PG 58-22	…	…	…	0	No
10	PG 70-10 (B3)	PG 70-10	…	…	…	0	No

Note: RAP amount = RAP binder/(RAP binder + virgin binder + rejuvenator). Binder replacement = (RAP and/or RAS binder + rejuvenator)/(RAP and/or RAS binder + rejuvenator + virgin binder).

introduced by the operator and any background impacts between repeat measurements. Previous literature suggested that this aliphatic band structure is not affected by aging over time.[24,25] The following equation was used to integrate the chemical component area index:

$$I_i = \int_{w_{l,i}}^{w_{u,i}} a(w)\mathrm{d}w - \frac{a(w_{u,i}) + a(w_{l,i})}{2} \times (w_{u,i} - w_{l,i}) \quad (1)$$

where:

I_i = index of area i,

$w_{l,i}$ = lower wavelength integral limit of area i,

$w_{u,i}$ = upper wavelength integral limit of area i, and

$a(w)$ = absorbance as the function of wavelength.

Rheological properties were determined with a dynamic shear rheometer. PGs of the 10 binder blends were determined following AASHTO M 320, *Standard Specification for Performance-Graded Asphalt Binder*. Also, the complex shear modulus (G^*) and phase angle (δ) values at four different temperatures (5°C, 10°C, 25°C, and 40°C) and at 16 different testing frequencies (0.02–15.92 Hz) for all 10 binder blends were evaluated. Several other aging parameters were calculated using the G^* and δ values as shown in **Table 2**. A symmetric sigmoidal fit function was used to convert the frequency sweep data into a master curve at the reference temperature using the fit function in equation (2). The reference temperature considered in this study was 15°C. Equation (2) can be used to generate a binder master curve by substituting the complex modulus (E^*) with the shear complex modulus (G^*).

$$log|E^*| = \delta + \frac{\alpha}{1 + e^{\beta + \gamma log \omega f_r}} \quad (2)$$

where:

$|E^*|$ = magnitude of complex modulus, kPa,

α = fitting parameter (the high asymptote of the master curve),

δ = fitting parameter (the lower asymptote of the master curve),

β, γ = fitting parameters (the slope of the transition region of the master curve),

ω = frequency, Hz, and

f_r = reduced frequency, which is the shifted frequency at the reference temperature from the frequency at the test temperature, Hz.

The reduced frequency can be calculated using the Williams-Landel-Ferry shift function, which is based on the time-temperature superposition as shown in equation (3).[26]

$$log(\alpha_T) = \frac{-C_1(T - T_r)}{C_2 + (T - T_r)} \quad (3)$$

where:

α_T = shift factor as a function of temperature T,

T = test temperature in Kelvin, °K,

T_r = reference temperature in Kelvin, °K, and

C_1 and C_2 = fitting parameters.

TABLE 2
Summary of rheological aging parameters

Parameters	Definition/Source	Expected Effect of Aging
GR	$GR = \frac{G^* \cos^2\delta}{\sin\delta}$ at 15°C and 0.005 rad/s	Increase
Crossover frequency, ω_C	Reduced frequency at $\delta = 45°$	Decrease
Crossover modulus, Gc	Complex modulus value (G^*) at $\delta = 45°$	Decrease
R value	Difference between the log of the glassy modulus (10^9 Pa) and the log of Gc	Increase

Then, equation (4) obtained from the Kramers–Kronig relation was used to develop the phase angle master curve.[27] The time-temperature shift factor was calculated using equation (3).

$$\delta(fr) = \frac{\pi}{2}\frac{\alpha\gamma}{(1+e^{\beta-\gamma log(f_r)})^2}e^{(\beta-\gamma log f_r)} \quad (4)$$

where:

α = fitting parameter (the high asymptote of the master curve),

δ = fitting parameter (the lower asymptote of the master curve),

β, γ = fitting parameters (the slope of the transition region of the master curve),

ω = frequency, Hz, and

f_r = reduced frequency, which is the shifted frequency at the reference temperature from the frequency at the test temperature, Hz.

ASPHALT MIXES

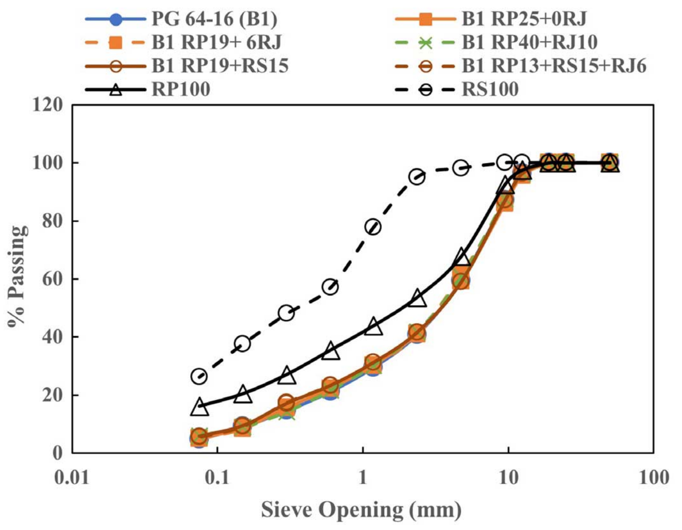
Hamburg wheel tracking (HWT) and indirect tensile asphalt cracking test (IDEAL-CT) tests were performed on asphalt mixes prepared using six of the PG 64-16 binder blend ratios. Binders containing 50 and 100 % RAP binder replacement with no rejuvenator (B1 RP50+RJ0 and RP100) were not considered to be feasible for field placement and were not tested in mixes. These two blends were prepared to assess aging trends in binders containing high recycled material contents with no rejuvenator. In this study, sieve analysis was performed on the aggregates extracted from RAP and RAS. The gradation curves of extracted RAP/RAS aggregates are shown in figure 1. The gradation of virgin aggregate was selected in a manner such that the combined aggregate gradation after the addition of RAP/RAS follows a similar pattern as the mix with no recycled material (mix with PG 64-16 (B1)). As shown in figure 1, the combined aggregate gradation follows a similar pattern for all six mixes.

Loose mixes were short-term oven aged at 135°C for 4 h prior to compaction per AASHTO R 30, *Standard Practice for Laboratory Conditioning of Asphalt Mixtures*, to simulate the conditioning of plant-produced mixes. Compacted specimens were prepared using a Superpave gyratory compactor. Target air-void contents were kept at 7 ± 0.5 % based on densities typically obtained in the field.

HWT tests were performed at 50°C according to AASHTO T 324, *Standard Method of Test for Hamburg Wheel-Track Testing of Compacted Asphalt Mixtures*. The test was automatically terminated after reaching a maximum rut depth of 20 mm or after 20,000 wheel passes had been applied, whichever was reached first.

FIG. 1

Combined aggregate gradation for different asphalt mixes, RAP (RP100) and RAS (RS100).



IDEAL-CT testing followed ASTM D8225, *Standard Test Method for Determination of Cracking Tolerance Index of Asphalt Mixture Using the Indirect Tensile Cracking Test at Intermediate Temperature*, with all specimens conditioned at 25°C for 2 h prior to testing. Strength and CT_{index} [equations (5)–(8)] were determined as the cracking resistance parameters. It should be noted that cracking is defined here to be low-temperature and block cracking phenomena, which are solely dependent on the mix properties and the environment, and not the bottom-up fatigue cracking phenomena that depends on the interaction of traffic loading, pavement structure, environment, mix stiffness, and fatigue cracking properties.

$$CT_{\text{index}} = \frac{t}{62} \times \frac{l_{75}}{D} \times \frac{G_f}{|m_{75}|} \times 10^6 \quad (5)$$

where:

t = thickness,
D = diameter, and
G_f = failure energy $(\frac{J}{m^2})$.

$$G_f = \frac{W_f}{D \times t} \times 10^6 \quad (6)$$

where:

W_f = total area under load – displacement curve till 0.1 kN load was reached after the peak, and
l_{75} = displacement at 75 % of peak load.

$$|m_{75}| = \left| \frac{P_{85} - P_{65}}{l_{85} - l_{65}} \right| \quad (7)$$

where:

P_{85} = 85 % of peak load,
P_{65} = 65 % of peak load,
l_{85} = displacement at P_{85}, and
l_{65} = displacement at P_{65}.

$$Strength, \sigma_0 = \frac{Peak\ load}{2rt} \quad (8)$$

where:

r = radius of the sample.

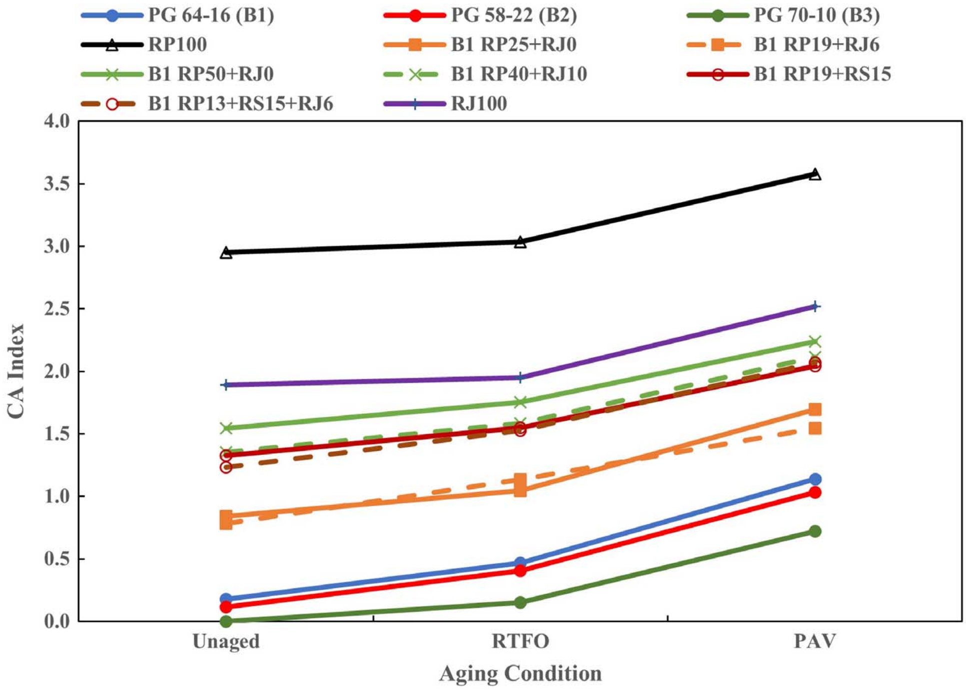
Results and Discussion

BINDER PROPERTIES WITH AGING

Chemical Properties

The CA index is a popular binder chemical parameter for tracking the aging of asphalt binders. The variation of CA with aging for the 10 different binder blends is shown in **figure 2**. Base Binder 1 (PG 64-16) had larger initial and final CA values compared with Base Binder 2 (PG 58-22) and Base Binder 3 (PG 70-10). The binder blend with 25 % RAP and no rejuvenator (B1 RP25+0RJ) had a CA index for all aging conditions, similar to the blend with 19 % RAP and 6 % rejuvenator (B1 RP19+RJ6). This was unexpected given that the addition of a rejuvenator is expected to reduce the degree of aging of asphalt binders but was attributed to the presence of CA in the rejuvenator. The CA indexes for the rejuvenator at unaged, RTFO-aged, and PAV-aged conditions were 1.89, 1.95, and 2.52, respectively (**fig. 2**). Based on these results, a modified CA parameter (CA_{mod}) was proposed to track the aging of binder blends containing rejuvenator as shown in equation (9). In this equation, the CA

FIG. 2 Variation of CA index with aging.



values of rejuvenator were selected based on the aging conditions (unaged, RTFO-aged, or PAV-aged) of the rejuvenated binder blends.

$$CA_{mod} = Measured\ CA - (\%\ Rejuvenator\ used) \times CA\ of\ Rejuvenator \tag{9}$$

Rheological Properties

The continuous high and intermediate binder grades for the 10 binder blends are shown in figure 3. As expected, an increase in RAP/RAS content increased the continuous grade for all cases. A reduction in binder grade was observed with an increase in rejuvenator content. For example, the continuous grade for unaged Blend 1 (PG 64-16) increased from 66.9°C to 74.9°C after adding 25 % RAP (Blend B1 to B1 RP25+RJ0). However, the addition of 6 % rejuvenator with 19 % RAP (B1 RP19+RJ6) decreased the continuous grade to 67.3°C. Therefore, the rejuvenator used in this study softened the binder blends. A similar trend was observed for the binder blends with 50 % RAP binder replacement (B1 RP50+RJ0 and B1 RP40+RJ10). Adding RAS had a greater effect on the continuous grade than adding RAP, as expected considering the types of asphalt binders used in shingles and the extended aging they typically experience on roofs. Adding 15 % RAS binder with 19 % RAP binder resulted in a similar high grade (84.0°C) to the 50 % RAP blend (84.5°C). This was mainly attributed to the higher degree of aging of the RAS materials.

The variation of complex shear modulus (G^*) with aging is shown in figure 4. For all 10 blended binders with three aging conditions (unaged, RTFO-aged, and PAV-aged), a total of 30 (3 × 10) numbers of G^* master curves were developed. However, in this figure, only four master curves are highlighted to clearly assess the aging effect on asphalt binders. G^* master curves for Base Binder 1 (B1) at 3 aging conditions and 100 % RAP binder (RP100) after PAV-aged condition are shown in figure 4. The increase in aging level moved the G^* master curve left and upward and changed the shape of the curve. For example, the G^* values at a reduced frequency of 10 Hz for the unaged, RTFO-aged, and PAV-aged Blend 1 binder (PG 64-16) were 5.6×10^4, 6.5×10^4, and

FIG. 3 High (unaged and RTFO-aged) and intermediate (PAV-aged) PG continuous grade temperatures for different binder blends.

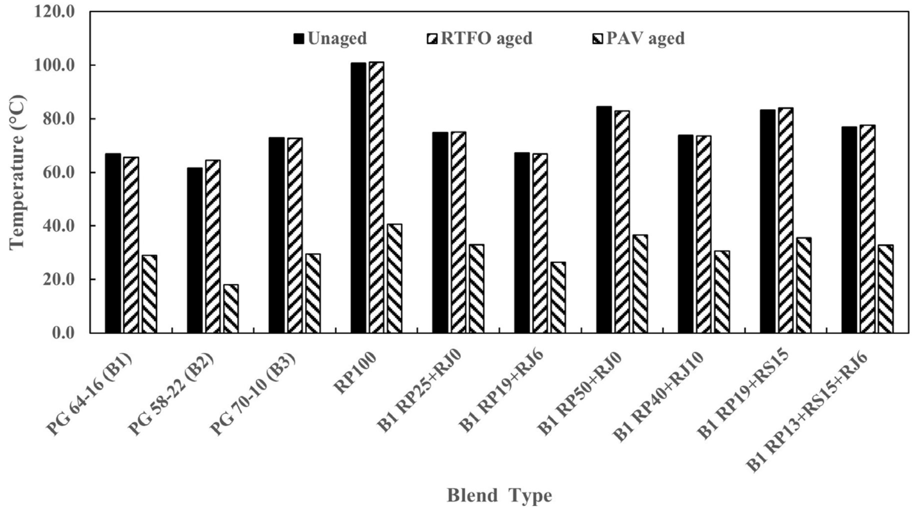
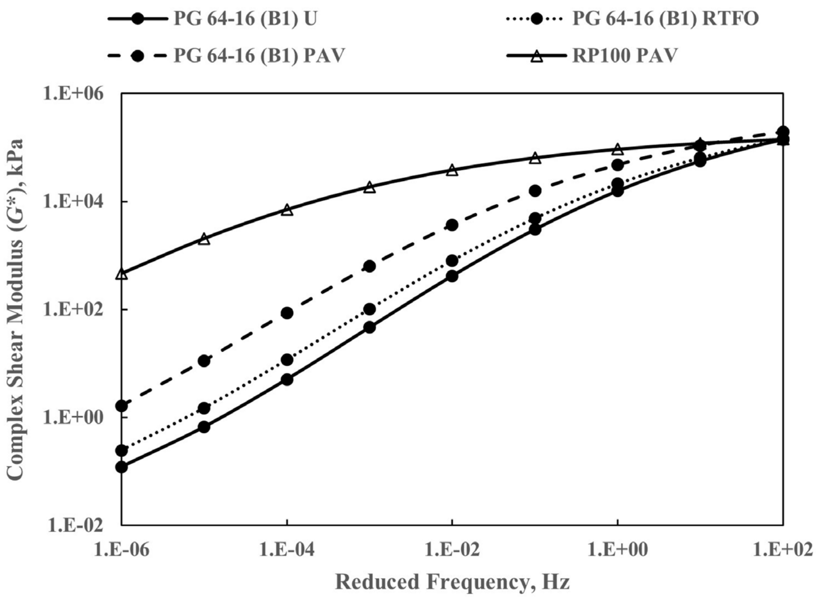


FIG. 4 Complex shear modulus master curves for different binders.

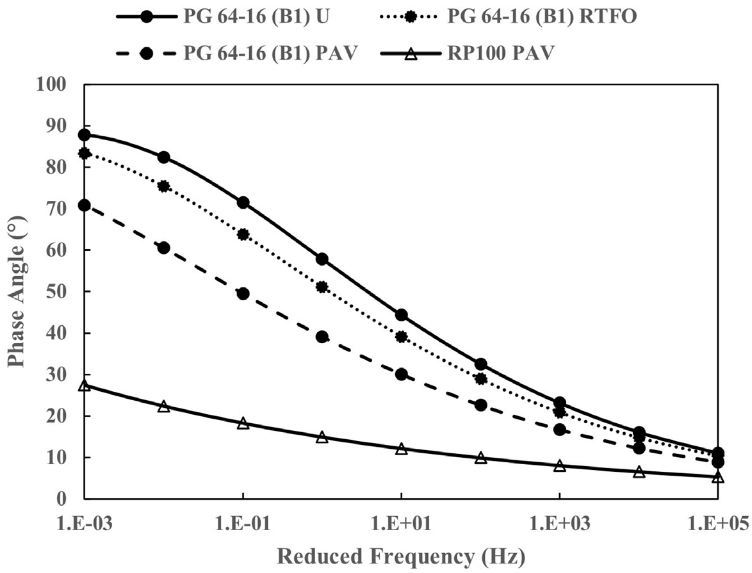


1.1×10^5 kPa, respectively. PAV-aged RAP binder had a G^* value of 1.2×10^5 kPa at 10 Hz. The increase in stiffness with aging was attributed to a loss of maltenes. The other binder blends also followed a similar trend with an increase in aging level. Similar findings were also reported by several other researchers.[4–6,9,28–30]

The phase angle (δ) master curves for the different blends are shown in figure 5. In the same way as figure 4, results for Base Binder 1 (B1) at 3 aging conditions and 100 % RAP binder (RP100) after PAV-aged condition are shown in this figure to evaluate the aging effect on phase angle master curves. At lower reduced frequencies, the δ values decreased with aging. At 10 Hz reduced frequency, the δ values obtained for the unaged, RTFO-aged, and PAV-aged Blend 1 binder were 44.4°, 39.1°, and 30.1°, respectively. RAP at the PAV-aged condition had the

FIG. 5

Phase angle master curves for different binder blends.



lowest phase angle value (12.2° at 10 Hz), indicating a nearly elastic material ($\delta = 0°$) that will not be able to relax stresses caused by low temperatures. The decrease in phase angle with aging has also been reported by other researchers.[21,31,32]

It is evident from figures 4 and 5 that the aging of asphalt binders leads to an increase in stiffness and decrease in phase angle. A similar trend was also observed for all other binder blends. To better understand the combination of these effects, Rowe[33] developed the Glover-Rowe (GR) parameter, which reports G^* and δ of the binder at 15°C and a frequency of 0.005 rad/s.

Figures 6 and 7 present the GR parameters in black space diagrams. GR values less than 180 kPa generally indicate a low risk of block cracking, 180–450 kPa indicates a transition zone, and greater than 450 kPa indicates that the binder is prone to block cracking.[21,32,34–36]

Figure 6 shows that different base binders follow different paths in the black space diagram. Base Binder 3 (PG 70-10) was the most prone to block cracking compared with the other two base binders (PG 64-16 and PG 58-22). This was attributed in part to a higher low-temperature PG (i.e., −10°C) for this binder. The 100 % RAP binder had the highest cracking potential compared with the other blends because of a higher degree of aging. An increase in RAP binder content in the B1 RP25+RJ0 blend increased the block cracking potential as shown in figure 6. The GR value for this blend after PAV aging was 638 kPa, which was higher than the 450 kPa limit value. However, the addition of 6 % rejuvenator with 19 % RAP (B1 RP19+RJ6) reduced the GR parameter to 65.2 kPa after PAV aging, which was close to the GR parameter of the base binder (53.9 kPa) at the same aging condition.

The rejuvenator used in this study increased the phase angle and reduced the G^* simultaneously. Mogawer et al.,[37] Shen, Huang, and Hachiya,[38] and Zaumanis, Mallick, and Frank[39] all reported improved cracking resistance with rejuvenated binders. Similar trends were observed in figure 7. However, the RAS blend with rejuvenator (B1 RP13+RS15+RJ6) after PAV aging had a GR value of 753 kPa (in the block cracking zone of fig. 7), indicating that higher doses of rejuvenator would be required for the B1 RP13+RS15+RJ6 binder blend to eliminate the block cracking potential. Hence, this GR diagram can be potentially used in combination with rutting parameters to optimize rejuvenator dosage rates in asphalt mixes. Care must be taken to ensure that optimal rejuvenator rates are not exceeded because this may lead to oversoftening of the binder, which can lead to rutting or to a tendency to replace virgin binder contents with rejuvenator beyond what is needed to prevent age-related cracking risk, to the potential detriment of fatigue performance (which needs further exploration).

FIG. 6

GR plots for base binders and binders with 25 % binder replacement.

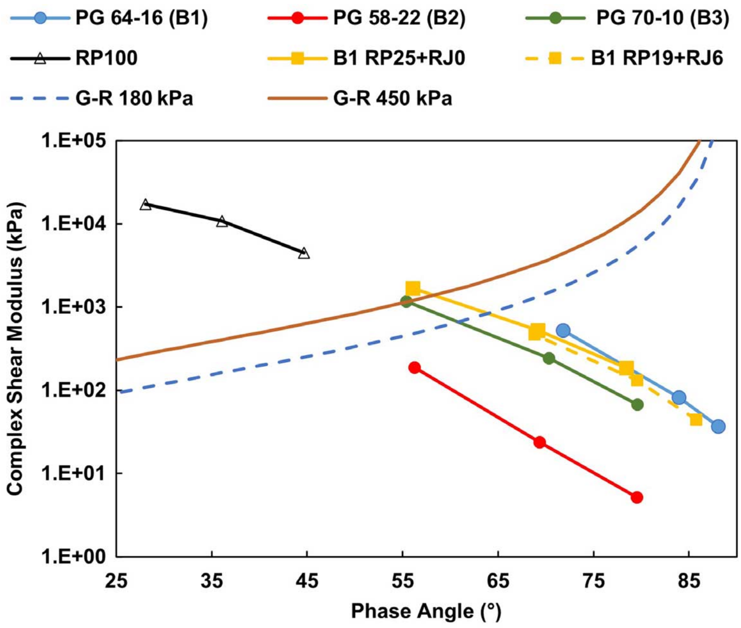
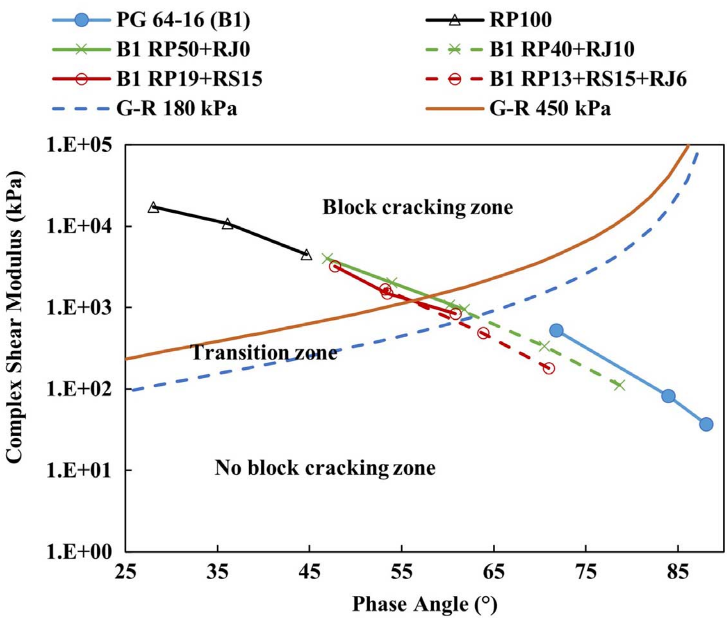


FIG. 7

GR plots for binders with 50 % binder replacement and RAS binder blends.



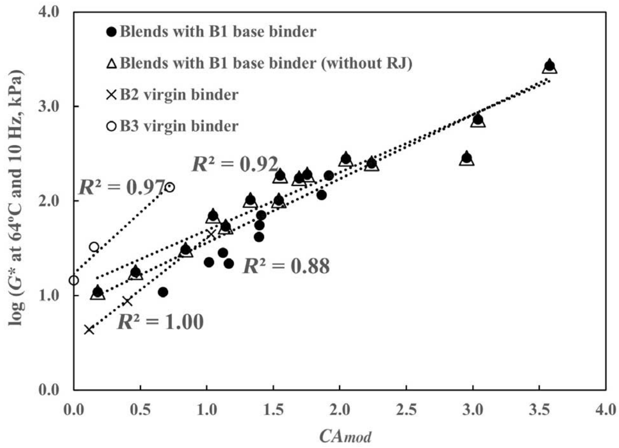
Chemical versus Rheological Properties

Relationship between Stiffness and GR

The literature suggests that the binder's G^* value at 64°C and 10 Hz is appropriate for evaluating the aging of asphalt.[22] The correlations between log G^* at 64°C and 10 Hz and the proposed chemical parameter (CA_{mod}) are shown for all 10 different binders in figure 8. The plot shows that CA_{mod} and stiffness (log G^*) have a strong

FIG. 8

Correlation between log G^* at 64°C and 10 Hz versus CA_{mod}. RJ = rejuvenator.



correlation (R^2 values of 0.88–1.00) and that the binder PG and other properties will influence the result. Also, the R^2 values obtained for binder blends containing B1 base binder with and without rejuvenator were 0.88 and 0.92, respectively. Therefore, the CA_{mod} value can be a useful aging indicator for rejuvenated binders as well. This correlation highly depends on the PG and source of the base binder. Different base binders were found to follow different trend lines, as shown in figure 8. However, once a correlation is established for a base binder, CA_{mod} can potentially be used for designing mixes with different combinations of RAP, RAS, and rejuvenator.

Figure 9 presents the variation of the log (GR) parameter with the CA_{mod} value. Good correlations (R^2 values of 0.83–0.96) were again observed between rheological and chemical properties. The R^2 value increased from 0.83 to 0.90 when considering only PAV-aged values for binder blends with B1 base binder, as shown in figure 9.

Relationship between Crossover Frequency (ω_c), Crossover Modulus (G_c), and R Value

The crossover frequency (ω_c), crossover modulus (G_c), and R values can also be used to characterize the aging of asphalt binders. Several researchers have reported that both ω_c and G_c values are expected to decrease with an increase in the level of aging.[2,32,40] The R value is defined as the logarithmic ratio of glassy modulus (10^6 kPa) and G_c and is expected to increase with aging.[2,32]

FIG. 9

Correlation between log (GR) versus CA_{mod}.

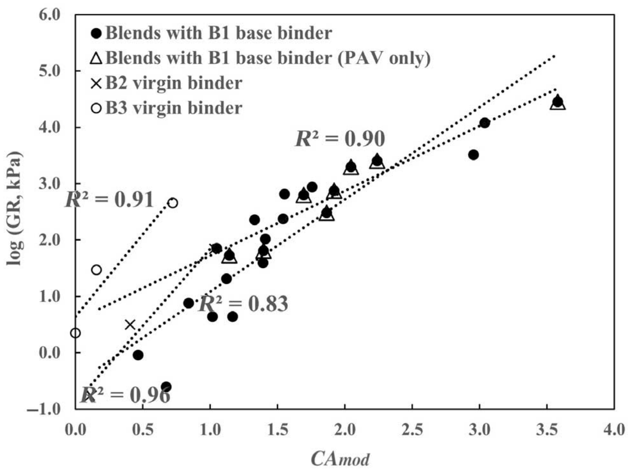


Figure 10 shows that the ω_c and G_c values decreased with an increase in the CA_{mod} value or increase in aging level. The R value increased with increasing CA_{mod} values, consistent with the literature (fig. 10C). Strong correlations (R^2 values of 0.91–0.98) were observed between different rheological and chemical properties while considering crossover values, with differences depending on the base binder PG and source.

RELATIONSHIP BETWEEN BINDER AND MIX PROPERTIES

Complete blending between the recycled and virgin binders was assumed for all binder blends containing recycled materials because it is forced to occur during the extraction process. However, complete binder blending might not always occur in asphalt mixes containing RAP/RAS in the field, with less blending from diffusion (or other processes of recycled and virgin binder blending) expected with a shorter time of exposure to air at high temperatures in mixing, silo storage, transportation, compaction, and shorter time in service.[41] HWT and IDEAL-CT tests were therefore done on mixes produced with the different binders to evaluate this. Results are summarized in figures 11 and 12, respectively.

FIG. 10 Correlation between chemical property (CA_{mod}) and (A) log (crossover frequency), (B) log (crossover modulus), and (C) R value.

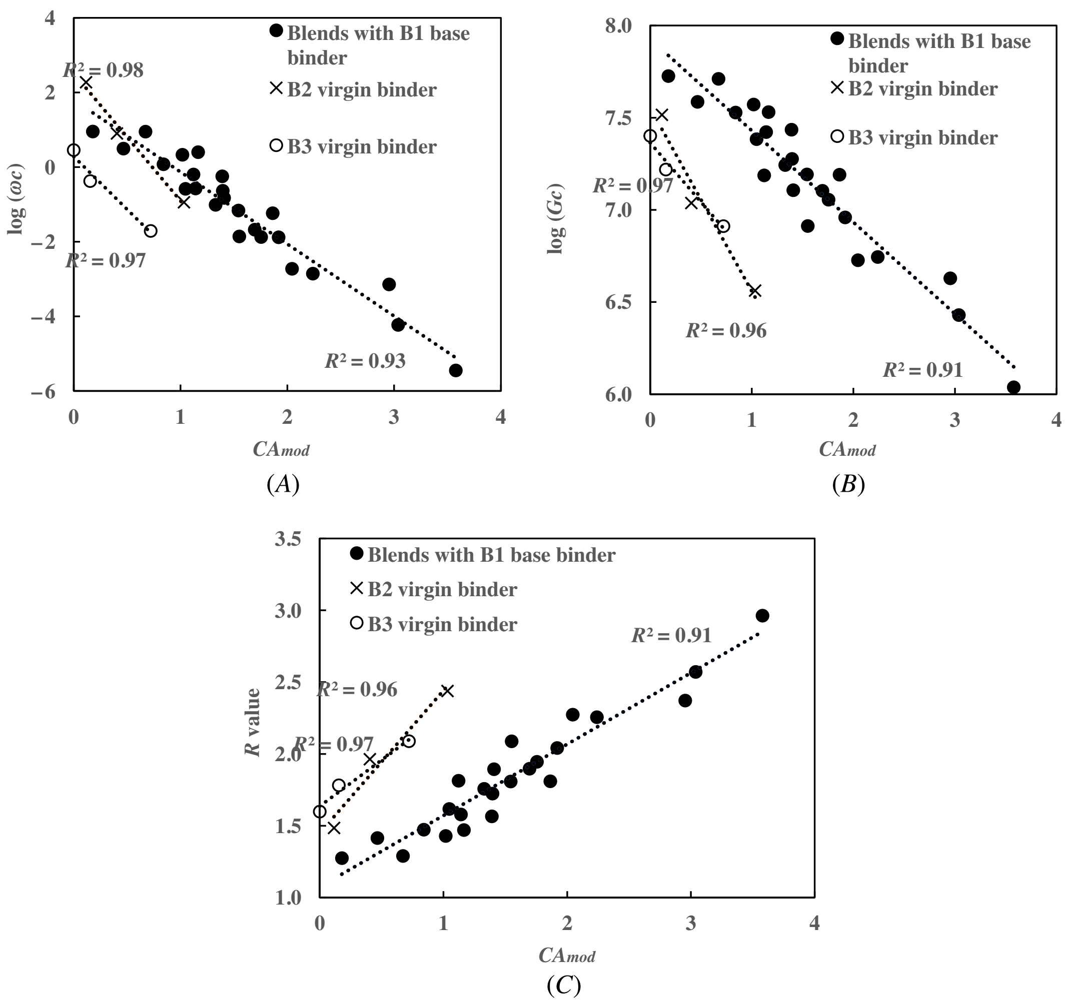


FIG. 11 Correlation between binder blend's parameters and HWT test (HWTT) passes to 12.5-mm rut depth: (*A*) rheological parameter and (*B*) chemical parameter.

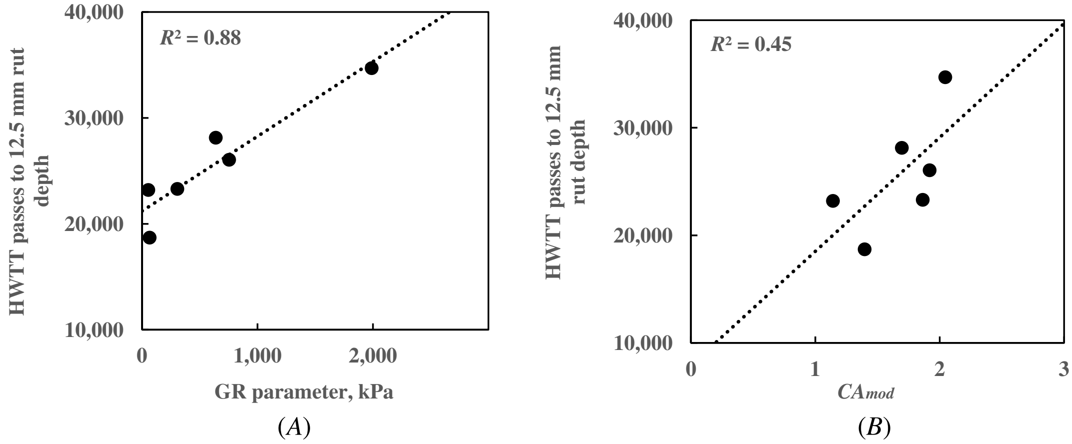


FIG. 12 Correlation between binder properties and IDEAL-CT test parameters: (*A*) CT_{index} and (*B*) strength.

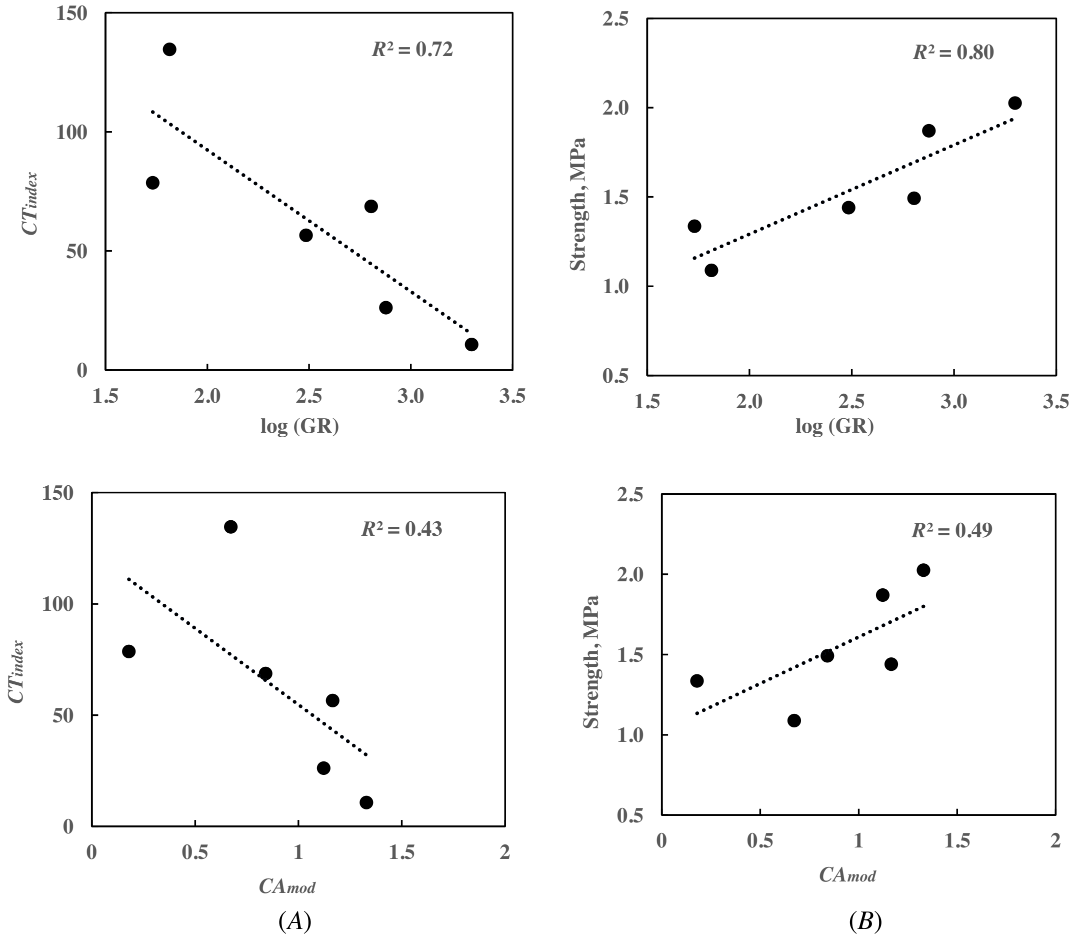


Figure 11*A* shows a reasonably strong correlation (R^2 value of 0.88) between the number of passes required to reach a 12.5-mm rut depth and the binder GR parameter. This was attributed to the known dependency of GR values on the complex shear modulus, with stiffer binders having better rutting performance.[4–6]

Figure 11*B* shows a poor correlation (R^2 of 0.45) between rutting and CA_{mod}. This result suggests that a better prediction for rutting performance of asphalt mixes containing RAP/RAS will be obtained from the binder's rheological properties than from the chemical properties only. Also, rutting performance has a strong dependence on aggregate properties because it occurs at higher temperatures when the contribution of the binder to the shear stiffness of the mix is less.

Figure 12 presents the correlation between binder properties (log [GR] and CA_{mod}) and parameters from the IDEAL-CT test results. An R^2 value of 0.72 was observed between CT_{index} and log (GR) values. A study conducted by Jiao et al.[42] suggested that the strength parameter measured during the IDEAL-CT test has a strong correlation with the flexural stiffness of asphalt mixes and a weak correlation with fatigue cracking resistance. The R^2 value increased from 0.72 to 0.80 when strength was considered instead of the IDEAL-CT parameter. Several other researchers have also reported a good correlation between the binder GR values and cracking resistance.[38,39,43] Also, **figure 12** shows poor correlations between the CA_{mod} and IDEAL-CT test parameters. A slight improvement in R^2 value was observed while considering IDEAL-CT strength instead of CT_{index}. The R^2 value increased from 0.43 to 0.49 after considering the strength parameter.

Although these correlations are not particularly strong, the results suggest that GR values can be used to obtain an indication of rutting, stiffness, and age-related cracking performance in mixes and could be useful to rank the performance of different binders and binder blends.

Conclusions

Evaluating the effect of aging is crucial to understanding the long-term performance of asphalt pavements. The aging of asphalt becomes more complex with the addition of RAP, RAS, and rejuvenators. In this study, 10 different binder blends with and without recycled materials were prepared and aged to track the changes in aging properties. Asphalt mixes prepared with 6 of the 10 binders were prepared to evaluate the correlation between aging parameters of binder blends and mix rutting and age-related cracking performance parameters. The main findings of this study are summarized as follows:

- Both chemical and rheological parameters can be used to evaluate the aging effect on asphalt binders containing recycled materials. However, a modification is required for the chemical parameter when considering binder blends prepared with a rejuvenator. Otherwise, the chemical parameter of the rejuvenator may rank the binder blends differently from their actual aging status. A new parameter (CA_{mod}) based on the CA of the rejuvenator was suggested in this study. This parameter can be used to characterize the aging effect more accurately for different binder blends compared with the traditional CA parameter.
- Strong correlations between the rheological parameters and CA_{mod} of the different binder blends were observed. The R^2 values varied between 0.83 and 1.00 for different combinations of rheological and chemical parameters. In addition, the relationship shows a dependency on the base binder grades and sources. Different base binders were found to follow different trend lines.
- Results from the limited testing reported in this study indicate that binder testing parameters could be used to provide an indication of the rutting and age-related cracking potential of asphalt mixes containing RAP/RAS and rejuvenator. Reasonable linear correlations were found between binder aging parameters and mix parameters obtained from HWT and IDEAL-CT tests.

In this study, the correlation between binder properties and asphalt mix performance parameters was developed considering only one base binder type (PG 64-16). The authors are currently working on mixes containing other base binder types.

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