Methodologies for Estimating Effective Performance Grade of Asphalt Binders in Mixtures with High Recycled Asphalt Pavement Content

Case Study

Elie Y. Hajj, Luis Guillermo Loría Salazar, and Peter E. Sebaaly

In 2009, hot-mix asphalt pavement sections containing 0%, 15%, and 50% recycled asphalt pavement (RAP) were built in a collaborative effort between Manitoba Infrastructure and Transportation and the Asphalt Research Consortium. Two types of 50% RAP mixtures were evaluated: one with no grade change in asphalt binder (PG 58-28) from mixtures with lower RAP content and one with a grade change in asphalt binder (PG 52-34). The following methodologies were used to determine the effective binder properties of the evaluated field-produced mixtures: grading of the recovered binders, blending chart process, mortar procedure, and backcalculation of binder properties from the measured dynamic modulus of mixtures with the Hirsch model and the modified Huet–Sayegh model. Overall, good correlations were observed between the estimated critical temperatures from the blending chart process and the measured ones from the recovered asphalt binders. Of the various evaluated methods, the mortar procedure provided promising results when used to estimate the mixture binder properties at critical pavement temperatures. The findings from the mortar procedure were consistent with the mixtures' resistance to thermal cracking and their current field performance. The procedure indicated that a partial blending was occurring between the virgin and RAP binders of the evaluated mixtures. Although some difficulties arose with the use of the Hirsch model, the backcalculated binder shear moduli were reasonable. The modified Huet–Sayegh model requires further evaluation to assess the true relationship between the characteristic times of the binders and mixtures.

In the United States alone, demand for asphalt products was expected to increase 1.2% annually to nearly 40 million tons, or 211 million barrels, in 2011. About 85% of the total asphalt demand was projected to go toward asphalt paving applications (*1*). Alongside demand, consistently rising construction, shipping, and manufacturing costs have generated a need for serious conservation movements within the asphalt industry. Beginning in the mid-1970s, recycling asphalt became a widely accepted practice, with more than 40 states practicing some form of pavement recycling between 1976 and 1982. Today, all 50 states accept the use of recycled pavements in some form, either as aggregate material or as binder replacement (*2*). Consequently, an effective mix design for hot-mix asphalt (HMA) containing recycled asphalt pavement (RAP) is deemed necessary. The mix design should account for the presence of the stiff, oxidized reclaimed binder from the RAP and its effect on the virgin binder properties at all critical pavement temperatures, particularly when dealing with mixtures with high RAP content (i.e., more than 25%).

Evaluating the RAP materials consists of measuring the properties of the binder and aggregates of the RAP mixture. Several research studies have been conducted to identify the best methods for separating and testing the binder and aggregates of the RAP materials, but there have been no standard procedures that agencies can use on a routine basis.

The two critical properties of aggregates in RAP are gradation and specific gravity. The gradation of the aggregates in the RAP materials can be easily evaluated through the extraction process. Determining the specific gravity of the RAP aggregates represents a challenge. Several techniques have been used in the past, but there is no established standard procedure for evaluating RAP aggregate properties.

The two critical properties of the binder in RAP are binder content and binder properties. The binder content of RAP can be easily identified through the extraction process. However, measuring the properties of the binder is still a challenging process.

Methods currently available for quantifying the effect of the reclaimed binder on the mixture binder properties include, but are not limited to, chemical extraction and recovery of the reclaimed binder, backcalculation from testing of gyratory-compacted mixture samples, and testing samples cut from gyratory-compacted samples in the bending beam rheometer (BBR). Additionally, research conducted within the Asphalt Research Consortium (ARC) has resulted in a testing procedure in which mortar and binder samples are tested in the BBR and dynamic shear rheometer (DSR) to quantify the effect of RAP binder on the continuous grade profile of fresh (i.e., virgin) binder, allowing for an estimation of mixture binder properties at critical pavement temperatures (*3–5*). This approach has been developed with the intent to minimize labor and eliminate the need for binder extraction. Although it is currently the most widely used

E. Y. Hajj and P. E. Sebaaly, Western Regional Superpave Center, Department of Civil and Environmental Engineering, University of Nevada, Reno, 1664 North Virginia Street, MS257, Reno, NV 89557. L. G. Loría Salazar, Transportation Infrastructure Program, National Laboratory of Materials and Testing Models, LanammeUCR, University of Costa Rica, CP-11501-2060 San Jose, Costa Rica. Corresponding author: E. Y. Hajj, elieh@unr.edu.

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method, extracting and recovering the asphalt binder from the RAP materials creates fundamental issues of the impact of the extraction and recovery process on the properties of the recovered binder and the health and environmental impact of the chemicals used in the process.

The backcalculation process was introduced in 2003 by Christensen et al. after they refined the Hirsch model to predict the dynamic modulus of HMA using the shear modulus of the binder used and volumetrics of the mix (*6*). Unlike the Witczak equation for dynamic modulus (*7*), which is based entirely on a regression approach, the Hirsch model is based on the theory of composite materials.

In 2010, Daniel and Mogawer assessed various methods to determine the binder grade in mixtures designed with RAP from the properties of the mixture itself (*8*). The study evaluated mixtures with 0%, 10%, 25%, and 40% RAP with a virgin PG 64-28 binder. Furthermore, virgin mixtures with PG 58-28, PG 70-22, and PG 76-22 binders were evaluated. Testing included dynamic modulus, creep compliance, and strength tests in the indirect tensile mode. Partial shear modulus master curves were measured on the recovered binder from each mixture. Several methods of estimating the effective performance grade of the binder in the RAP-containing mixture were examined: linear blending chart, empirical method using measured mixture properties, and backcalculation using the Hirsch model. The researchers found that the empirically based methods of interpolating values from measured mixture properties require an extensive amount of testing in the laboratory. Additionally, the relationship between material properties and performance grade must be established for each type of mixture (gradation, asphalt content). The most promising method for determining the effective performance grade of a mixture was using the Hirsch model to backcalculate the binder stiffness from the measured mixture modulus.

Zofka et al. investigated the use of the BBR test on thin beams of asphalt mixture to estimate the asphalt binder properties in RAP-containing mixtures (*9*). It was shown that the Hirsch model can be used to backcalculate the asphalt binder stiffness at low temperature from the creep compliance (and stiffness) of HMA mixtures (thin beams). Additional research was needed to further investigate the Hirsch model and refine it to obtain reasonable stiffness values and binder *m*-values.

In an attempt to encourage the construction of more sustainable asphalt pavements, Manitoba Infrastructure and Transportation (MIT), in collaboration with ARC, built pavement sections with high RAP contents on Provincial Trunk Highway 8 in Manitoba, Canada, in 2009. The pavement sections were intended to provide necessary information for assessing the feasibility of using HMA mixtures with high RAP content as surface layers in cold weather regions such as Manitoba. This paper focused on the effect of reclaimed binder on the field-produced mixture binder properties from Manitoba.

OBJECTIVE

The overall objective of this paper was to evaluate the binder properties of field-produced mixtures from Manitoba with the following methodologies:

- Grading of asphalt binders recovered from the field-produced HMA mixtures with RAP,
- Estimating the blended asphalt binder grade according to the blending chart process described in the AASHTO M323 testing procedure,
- Estimating mixture binder properties with the mortar testing procedure developed in the ARC research,
- Backcalculating the mixture binder properties from the measured mixture dynamic modulus, and
- Backcalculating the mixture binder properties with the modified Huet–Sayegh model.

Additionally, the low-performance temperatures of the field-produced mixture binders were compared with the fracture temperatures of the corresponding mixtures.

DESCRIPTION OF MANITOBA PROJECT

The project is located on Provincial Highway 8 between Gimli and Hnausa in Manitoba. The total project length is approximately 17 mi, with the comparative pavement site accounting for 6 mi of the project. The evaluated sections were constructed in September 2009, and each consisted of two 2-in. lifts with conventional HMA (i.e., 0% RAP), HMA with 15% RAP, or HMA with 50% RAP. Two sections containing 50% RAP were made: one with no grade change for the new asphalt and one with a grade change. The pavement sections were laid on top of 4-in. HMA with 50% RAP that was constructed the year before (i.e., 2008), which is on top of a base and a subgrade. All four evaluated mixtures in the top two lifts consisted of a dense-graded asphalt mixture manufactured with a Pen 150–200 asphalt binder (average penetration of 158 and graded as PG 58-28) except for the 50% RAP mixture with grade change that was manufactured with a Pen 200–300 asphalt binder (average penetration of 223 and graded as PG 52-34). The target binder grade for the project location was a Pen 150–200. The average in-place densities for the HMA with 0%, 15%, 50% (Pen 150–200), and 50% (Pen 200–300) RAP were, respectively, 98%, 97%, 96%, and 94%.

During the paving of the top lift, loose mixtures were sampled from the paving auger at the project site. Those mixtures were referred to as "field-produced mixtures" and labeled F-0%-150, F-15%-150, F-50%-150, and F-50%-200. For instance, the F-0%-150 mixture represented the field mixture with 0% RAP manufactured with the Pen 150–200 asphalt binder (i.e., PG 58-28), and the F-50%-200 mixture represented the field mixture with 50% RAP manufactured with the Pen 200–300 asphalt binder (i.e., PG 52-34). Additionally, virgin asphalt binders and RAP materials (i.e., 100% RAP mixture) were sampled during production at the plant location.

DYNAMIC MODULUS TESTING OF ASPHALT MIXTURES

The dynamic modulus ($|E^*|$) test was performed according to AASHTO TP62-07 for all mixtures, including the 100% RAP mixture. Figure 1*a* shows the $|E^*|$ master curves for the various mixtures that were determined with the data from three replicates. The $|E^*|$ values at 10 Hz loading frequency and 21°C are presented in Figure 1*b*. Examining the $|E^*|$ data leads to the observation that the $|E^*|$ property of field-produced mixtures increases with the increase in RAP content. A reduction in the $|E^*|$ property was observed for the mixture with 50% RAP and PG 52-34 as compared with the mixture with 50% RAP and PG 58-28. The highest $|E^*|$ was observed for the 100% RAP mixture, closely followed by the mixture with 50% RAP and PG 58-28. The measured $|E^*|$ master curves were used in estimating the effective performance grade of asphalt binders in the various RAP-containing mixtures; both the Hirsch model and the modified Huet–Sayegh model theories were used in the calculations.

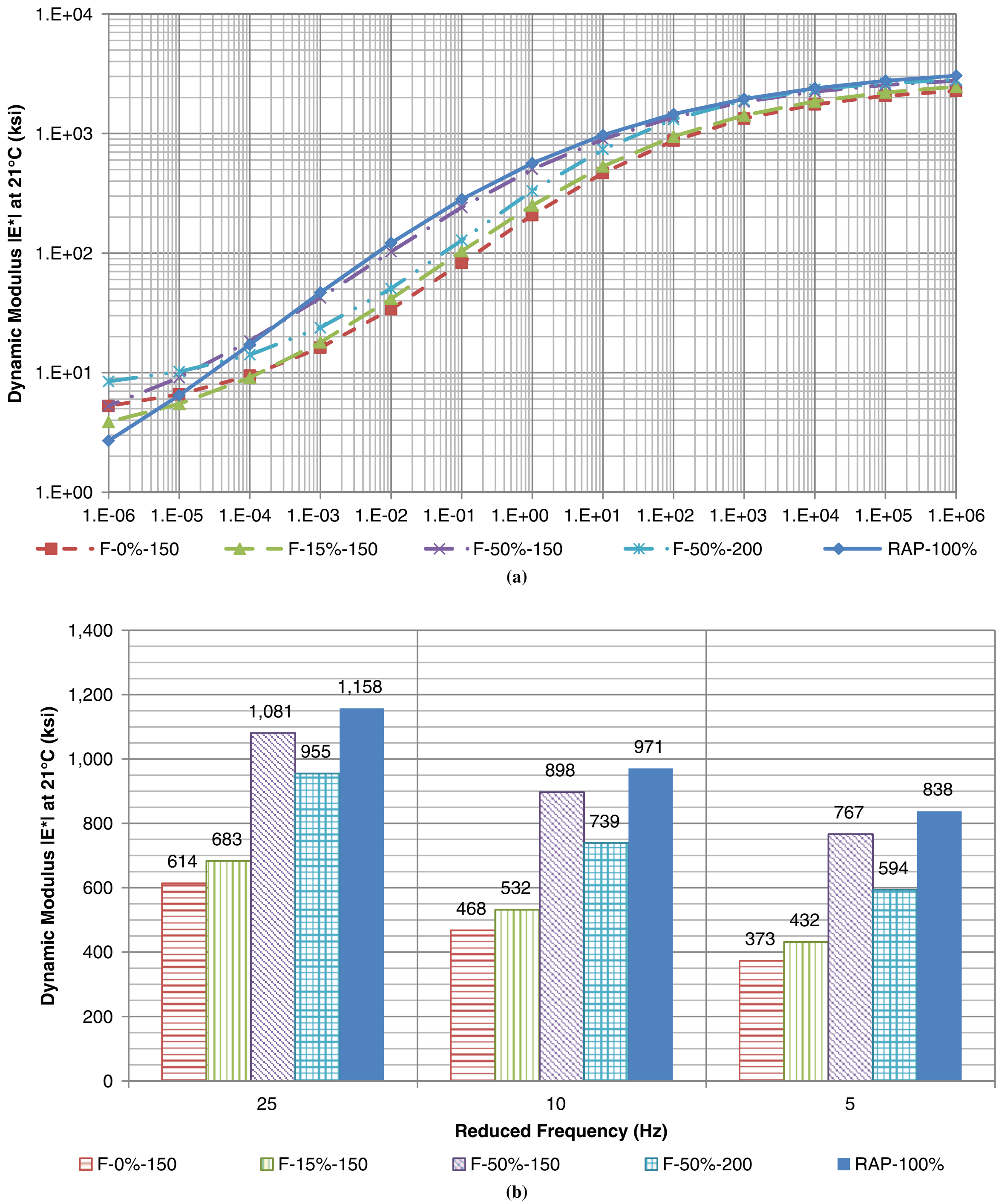

FIGURE 1 Dynamic modulus at 21°C for (*a*) field-produced mixtures and RAP mixture master curves and (*b*) at 5, 10, and 25 Hz.

SHEAR MODULUS MASTER CURVES OF ASPHALT BINDERS

All binders were extracted from the field-produced and RAP mixtures with a centrifuge (AASHTO T164) and recovered with a rotary evaporator (ASTM D5404) with a solution of 85% toluene and 15% ethanol by volume. Then, the shear modulus and phase angle master curves of the various recovered asphalt binders were determined with the Christensen–Anderson–Sharrock model shown in Equation 1. All binder testing was conducted at the Western Research Institute laboratory.

$$G_b^*(\omega) = G_o\left[1+(\omega_o/\omega)^{\beta}\right]^{-1/\beta} \quad (1a)$$

$$\delta = 90/\left[1+(\omega/\omega_o)^{\beta}\right] \quad (1b)$$

$$\beta = \frac{\ln\left(G_o/2^{\kappa}\right)}{\ln\left(G^*(\omega_o)\right)} \quad (1c)$$

where

G_b^* = complex shear modulus,
G_o = glassy shear modulus,
κ = fitted parameter,
ω = reduced frequency (rad/s),
ω_o = crossover frequency (rad/s),
β = width parameter, and
δ = phase angle constant.

The temperature dependency of the shift factors, a_T, is modeled with the Kaelble modification of the Williams–Landel–Ferry (WLF) model. The reduced time, ξ, is then determined by dividing the physical time by the shift factor:

$$\log a_T = -C_1\left(\frac{T - T_k}{C_2 + |T - T_k|} - \frac{T_r - T_k}{C_2 + |T_r - T_k|}\right) = \log t - \log\xi \quad (2)$$

where

a_T = shift factor,
t = physical time,
ξ = reduced time,
C_1, C_2 = model constants,
T_r = reference temperature (°C),
T_k = inflexion temperature (°C), and
T = analysis temperature (°C).

Figure 2*a* presents the shear modulus master curves of the various recovered binders at 20°C. Examining the master curve data leads to the observation that the $|G_b^*|$ property of field-produced mixtures increases with the increase in RAP content. A reduction in the $|G_b^*|$ property was observed for the mixture with 50% RAP and PG 52-34 as compared with the mixture with 50% RAP and PG 58-28. The highest $|G_b^*|$ was observed for the 100% RAP mixture. In summary, the same trends were observed for the moduli of the binders and mixtures.

GRADING OF VIRGIN AND RECOVERED ASPHALT BINDERS

The Superpave® performance grading binder system (AASHTO M320) was used to grade the virgin binders, RAP binder, and recovered blended binders from the various loose field-produced mixtures. As mentioned before, all recovered binders were extracted and recovered using toluene–ethanol solution. The recovered binders were graded by testing them as original, short-term aged through the rolling thin-film oven, and long-term aged through the pressure aging vessel. Figure 2*b* and Table 1 summarize the high, intermediate, and low critical temperatures of the various binders as well as the Superpave performance grades. Critical temperatures are temperatures at which a binder just meets the appropriate specified Superpave criteria. On the basis of the presented data, the following observations can be made:

- The low critical temperatures of both virgin binders (i.e., Pen 150–200 and Pen 200–300) were only within 2°C of each other. However, the high critical temperatures were within 5°C of each other.
- In field-produced mixtures manufactured with PG 58-28 asphalt binder, the increase in RAP content in a mixture resulted in warmer high and low critical temperatures for the recovered asphalt binders.
- The recovered blended asphalt binder from the F-50%-200 mixture was softer than the recovered blended asphalt binder from the F-50%-150 mixture by about 4°C.

The recovered binders from the mixtures containing 0% and 15% RAP met the target grade of PG 58-28 for the project location. The recovered binders from the mixtures with 50% RAP met or exceeded the target high performance grade of 58°C but failed to meet the target low performance grade of −28°C. This observation was true for both mixtures with and without grade change. The use of softer asphalt binder (i.e., PG 52-34) with the 50% RAP mixture did not improve the low performance temperature of the blended asphalt binder in the mixture enough to meet the target low performance grade. As mentioned before, the low critical temperatures of both virgin binders were only within 2°C of each other. Because of the limited availability of various asphalt binder types in the project vicinity, the only available commercial soft binder was used in this study (i.e., Pen 200–300). MIT has been using the Pen 200–300 asphalt binder in its asphalt base layers with mixtures containing up to 70% RAP.

ESTIMATION OF ASPHALT BINDER PROPERTIES

Blending Chart Process

The blending chart process, which is described in AASHTO M323, is used to determine the virgin binder grade or the maximum amount of RAP that can be used. The concept assumes that a 100% blend of the virgin binder and the binder from the RAP occurs. For a known RAP percentage, the critical temperatures of the virgin asphalt binder at high, intermediate, and low properties can be determined with Equation 3, which is based on the assumption that a linear relationship exists between the critical temperature and the RAP content:

$$T_{\text{virgin}} = \frac{T_{\text{blend}} - (\%\text{RAP binder} \times T_{\text{RAP}})}{(1 - \%\text{RAP binder})} \quad (3)$$

where

T_{blend} = critical temperature of blended asphalt binder,
T_{virgin} = critical temperature of virgin asphalt binder,
T_{RAP} = critical temperature of recovered RAP binder, and
%RAP binder = percentage of RAP binder in RAP expressed as a decimal.

The measured critical temperatures of the virgin and recovered RAP binders were used to estimate the grade of the blended asphalt binder in the mixtures with different RAP contents. Figure 2*b* and Table 1 show the blending chart results for the critical temperatures along with the performance grades of the blended binders. The estimated critical temperatures from the blending chart process were in the vicinity of the critical temperatures measured for the recovered blended asphalt binders from the various mixtures. When the performance grade from the blending chart analysis was compared with that of the recovered blended binders, the following observations were made:

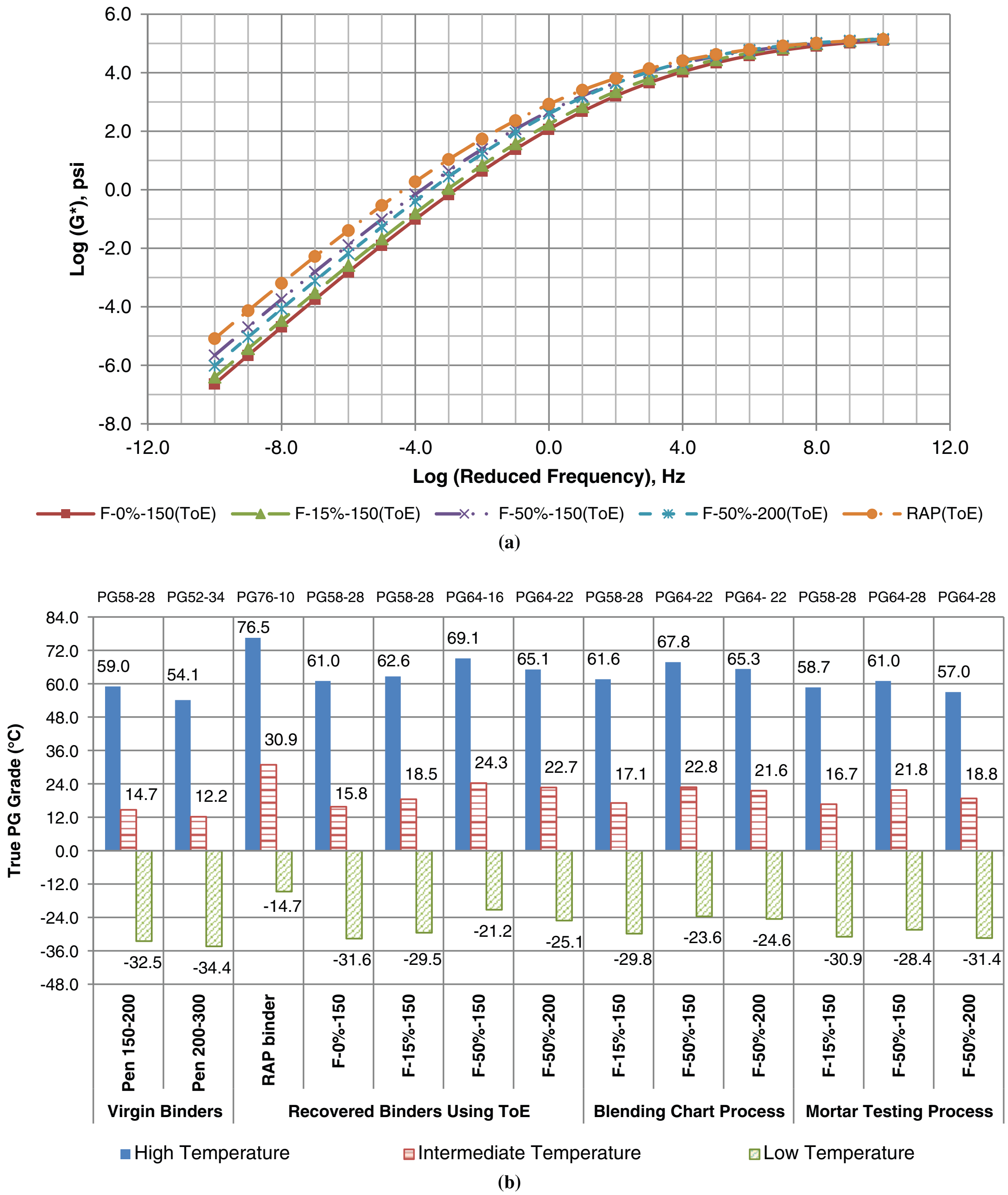

FIGURE 2 Dynamic shear rheometer test results: (*a*) recovered asphalt binder master curves at 20°C and (*b*) asphalt binder critical temperatures and performance grades.

- For mixtures with 15% RAP, the estimated grade for the blended asphalt binder was PG 58-28 and was consistent with the performance grade measured from the field-produced mixture (i.e., F-15%-150).
- For mixtures with 50% RAP, the estimated grade for the blended asphalt binder was PG 64-22 and was consistent with the performance grade measured from the field-produced mixture manufactured with PG 52-34.

The data show that the blending chart process can sometimes underestimate or overestimate the critical temperatures of the recovered binder by 2°C.

Mortar Testing Process

Research conducted within ARC has resulted in a testing procedure in which mortar and binder samples are tested in the BBR and DSR to quantify the effect of RAP binder on the continuous grade profile of the virgin binder (referred to as "fresh binder"), allowing for an estimation of mixture binder properties at critical pavement temperatures (*3–5*). The testing procedure allows users to estimate the performance grade of the mixture binder given any amount of RAP binder replacement within the mixture.

In the proposed analysis procedure, three samples were tested at low, intermediate, and high critical temperatures. These samples

TABLE 1 Summary of Critical Temperatures for Asphalt Binders

Mixture	RAP Content (%)	Virgin Binder True Grade	Recovered Binder True Grade	Blending Chart	Mortar	Hirsch Model[a]	Modified Huet–Sayegh[a]
High Critical Temperature (°C)							
F-0%-150	0	59.0	61.0	—	—	49.5	59.7
F-15%-150	15	59.0	62.6	61.6	58.7	50.6	62.0
F-50%-150	50	59.0	69.1	67.8	61.0	60.2	69.3
F-50%-200	50	54.1	65.1	65.3	57.0	57.9	68.5
RAP-100%	100	—	76.5	—	—	63.3	65.5
Intermediate Critical Temperature (°C)							
F-0%-150	0	14.7	15.8	—	—	na	na
F-15%-150	15	14.7	18.5	17.1	16.7	na	na
F-50%-150	50	14.7	24.3	22.8	21.8	na	na
F-50%-200	50	12.2	22.7	21.6	18.8	na	na
RAP-100%	100	na	30.9	—	—	na	na
Low Critical Temperature (°C)							
F-0%-150	0	−32.5	−31.6	—	—	na	na
F-15%-150	15	−32.5	−29.5	−29.8	−30.9	na	na
F-50%-150	50	−32.5	−21.2	−23.6	−28.4	na	na
F-50%-200	50	−34.4	−25.1	−24.6	−31.4	na	na
RAP-100%	100	—	−14.7	—	—	na	na

NOTE: na = analysis not applicable for intermediate and low temperatures; — = no prediction.
[a]Corresponds to $G^*/\sin\delta = 2.2$ kPa.

included one fresh binder and two mortar samples; the mortars consisted of the same fresh binder and a single gradation aggregate source. The procedure is founded on the idea that if the two mortar samples are prepared with identical gradation and identical total asphalt content (maintaining the same constituents), but one mortar sample contains a percentage of reclaimed binder (replacing an identical percentage of fresh binder), then any difference in properties between the mortar samples can be directly attributed to the percentage of reclaimed binder. If the properties of the fresh binder (also used for making the mortar samples) are also known, then the change in properties of the fresh binder resulting from blending with the reclaimed binder can be isolated. That is, if the continuous grade of the fresh binder is known, the mortar testing will allow for the estimation of the resulting continuous grade of the fresh binder–reclaimed binder blend. Figure 3 illustrates the mortar preparation process and the distinction between the above-mentioned mortars for low-temperature characterization (*5*). The R100 RAP material in Figure 3 consisted of the RAP material passing the Number (No). 50 sieve and retained on the No. 100 sieve. The burned R100 material consists of extracted RAP aggregate using an ignition oven.

In summary, this procedure allowed for the direct characterization of the reclaimed binder and eliminated the need for chemical extraction and recovery. In the analysis, backcalculation from mortar to binder was not adopted and all calculations were for binder or blended binder only.

Figure 2*b* and Table 1 summarize the critical temperatures determined using the mortar procedure for the 15% and 50% RAP-containing mixtures. In the case of field-produced mixtures manufactured with PG 58-28 asphalt binder, the increase in RAP content in the mixture resulted in warmer high and low critical temperatures for the asphalt binders. The critical temperatures for the asphalt binder from the F-50%-200 mixture were softer than those of the asphalt binder from the F-50%-150 mixture by 3°C to 4°C. For all mixtures, the mortar procedure resulted in critical temperatures that were lower than those measured in recovered binders or determined with the blending chart process. The low critical tem-

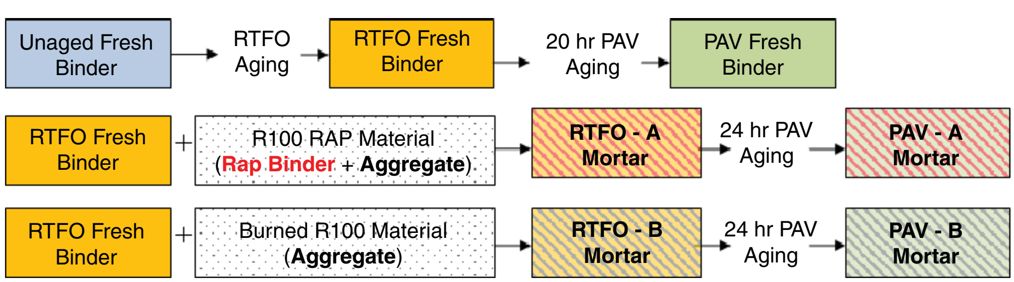

FIGURE 3 Sample preparation procedure for RAP binder characterization (RTFO = rolling thin-film oven; PAV = pressure-aging vessel).

peratures determined with the mortar procedure for the 50% RAP mixtures were significantly cooler (by 5°C to 7°C) than those measured in the recovered binders or estimated with the blending chart process. This observation was further examined through the resistance to thermal cracking of the mixtures as shown by the thermal stress restrained specimen test (TSRST). The results are presented later in the paper.

Hirsch Model Approach

The original model was developed by Hirsch in the late 1960s to calculate the modulus of elasticity of portland cement concrete on the basis of the theory of composite materials. In 2003, the model was refined by Christensen et al. to predict the $|E^*|$ of HMA by using the $|G^*|_{\text{binder}}$ of the applied binder and volumetrics of the mixture (*6*). The Hirsch model is as follows:

$$|E^*|_{\text{mixture}} = P_c\left[4{,}200{,}000\left(1-\frac{\text{VMA}}{100}\right)+3|G^*|_{\text{binder}}\left(\frac{\text{VFA}\times\text{VMA}}{10{,}000}\right)\right] + (1-P_c)\left[\frac{1-\text{VMA}/100}{4{,}200{,}000}+\frac{\text{VMA}}{3*\text{VFA}*|G^*|_{\text{binder}}}\right]^{-1} \quad (4)$$

$$P_c = \frac{\left(20+\dfrac{\text{VFA}\times 3|G^*|_{\text{binder}}}{\text{VMA}}\right)^{0.58}}{650+\left(\dfrac{\text{VFA}\times 3|G^*|_{\text{binder}}}{\text{VMA}}\right)^{0.58}} \quad (5)$$

where

$|E^*|_{\text{mixture}}$ = dynamic modulus for asphalt mixture (psi),
$|G^*|_{\text{binder}}$ = shear modulus for binder (psi),
P_c = contact volume,
VMA = voids in mineral aggregate (%), and
VFA = voids filled with asphalt (%).

The phase angle in shear can be estimated from the logarithm of P_c with the following equation:

$$\delta = -9.5\left[\log(P_c)\right]^2 - 39\log(P_c) + 9.6 \quad (6)$$

Table 1 summarizes the critical temperatures for the asphalt binders determined with the Hirsch model. The critical temperatures were determined at the frequency of 10 radians/s, which corresponds to the frequency used to grade binders. Overall, the Hirsch model resulted in high critical temperatures that were softer than those of the recovered binders.

Because it was not possible to test the mixtures at the high performance grade temperatures, the measured mixture properties were shifted to the higher temperatures according to the time–temperature superposition principle. Additionally, some difficulties were faced with the use of the Hirsch model to backcalculate the shear modulus of the binder at high temperatures, particularly with the relatively soft virgin binders used in this study. Because of the limitations inherent in the formulation of the Hirsch model itself, the $|G^*|_{\text{binder}}$ at high temperatures was estimated from the backcalculated binder properties at relatively lower temperatures (i.e., from the linear relationship between the logarithm of backcalculated $|G^*|_{\text{binder}}$ and temperature).

Modified Huet–Sayegh Model Approach

Olard and Di Benedetto (*10*) and Di Benedetto et al. (*11*) proposed the modified Huet–Sayegh model as an alternative to determining the HMA response at various test frequencies and temperatures. The advantage of the model is that it applies to both binders and mixtures and provides both the real and imaginary components of the dynamic modulus. The model is also called 2S2P1D (2 springs, 2 parabolics, 1 dashpot) and is based on a simple combination of physical elements (spring, dashpot, and parabolic elements). The Huet–Sayegh model (*12*) has been adapted by adding a linear dashpot in series with the two parabolic elements and the spring of rigidity $E_\infty - E_0$ (see Figure 4*a*). For binders, for which the minimum asymptotic stiffness (referred to as the "static modulus") E_0 is equal to 0, the model is equivalent to a linear dashpot at very low frequency.

The 2S2P1D model has a continuous spectrum (can be represented by an infinity of Kelvin–Voïgt elements in series or Maxell elements in parallel) and is presented in the following equation (*10*):

$$E^*(i\omega\tau) = E_0 + \frac{E_\infty - E_0}{1+\delta(i\omega\tau)^{-k}+(i\omega\tau)^{-h}+(i\omega\beta\tau)^{-1}} \quad (7)$$

where

i = complex number ($i^2 = -1$),
E_∞ = limit of complex modulus for $\omega\tau \to \infty$ (glassy modulus),
E_0 = limit of complex modulus for $\omega\tau \to 0$,
h, k = exponents such that $0 < k < h < 1$,
δ = dimensionless constant,
β = dimensionless parameter introduced to take into account Newtonian viscosity of linear dashpot,
τ = characteristic time varying with temperature accounting for time–temperature superposition principle, and
$\omega = 2\pi \times$ frequency.

To entirely determine the linear viscoelastic behavior of the considered material only seven constants (δ, k, h, E_∞, E_0, β, and τ_0) are needed at a given temperature. In binders, the experimental static modulus is close to zero; for this reason, E_0 can be taken equal to zero and the number of constants of the model can be reduced to six for binders. Assuming the material follows a linear viscoelastic thermorheologically simple behavior (meaning that the time–temperature superposition principle holds), then only the τ parameter depends on temperature.

Di Benedetto et al. (*11*) presented the relationship between the binder and the mixture complex moduli (Equation 8). If the mixture complex modulus is known at a given temperature, the binder complex modulus at the same temperature can be determined if $E_{0\text{binder}}$, $E_{\infty\text{binder}}$, and α are known. Di Benedetto and colleagues (*10, 11, 13*) and Falchetto et al. (*14*) reported good correlations between the characteristic times of the mixtures and binders with similar α values. In this study, the relationship between the characteristic times of the mixtures and binders was examined to backcalculate the binder properties from the mixture $|E^*|$:

$$E^*_{\text{mix}}(\omega, T) = E_{0\text{mix}} + \left[E^*_{\text{binder}}(10^\alpha\omega, T) - E_{0\text{binder}}\right]\frac{E_{\infty\text{mix}} - E_{0\text{mix}}}{E_{\infty\text{binder}} - E_{0\text{binder}}} \quad (8a)$$

$$\tau_{\text{mixture}}(T) = 10^\alpha \tau_{\text{binder}}(T) \quad (8b)$$

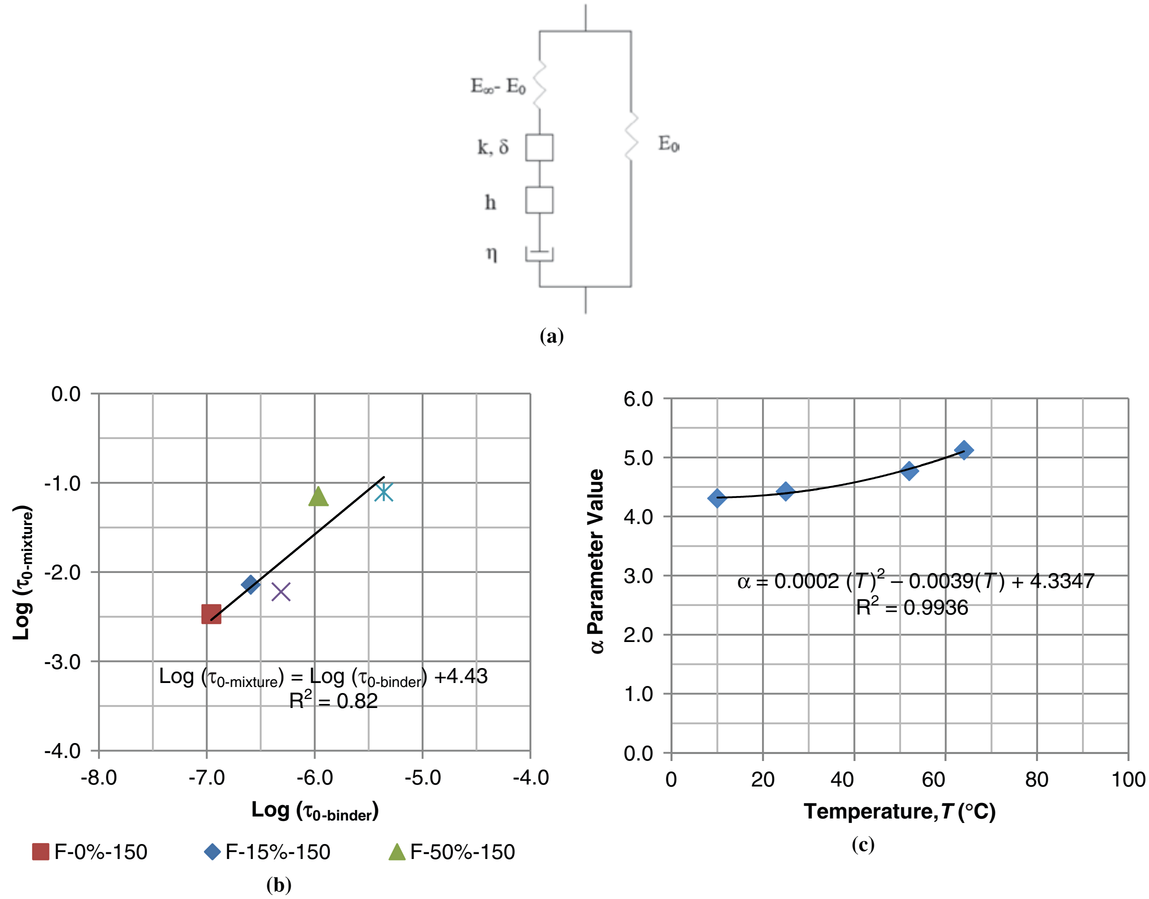

FIGURE 4 The Huet–Sayegh (2S2P1D) model: (*a*) representation of model (*h* and *k* = two parabolic creep elements and δ = dimensionless constant), (*b*) comparison between log($\tau_{0mixture}$) and log($\tau_{0binder}$) determined at 25°C, and (*c*) variation of α-parameter value with temperature.

where

E^*_{mix} = complex modulus of mixture,
E^*_{binder} = complex modulus of binder,
$E_{\infty mix}$ = glassy modulus of mixture,
E_{0mix} = static modulus of mixture,
$E_{\infty binder}$ = glassy modulus of binder,
$E_{0binder}$ = static modulus of binder,
T = temperature, and
α = regression coefficient depending on mixture and aging.

The constants required for all five mixtures and recovered binders at a reference temperature of 25°C were determined with a minimization process from the experimentally measured $|E^*|$ and shear modulus data, respectively. The results for both mixtures and binders are presented in Table 2. Each mixture showed the same parameters δ, *k*, *h*, and β of the associated binder, while only the static and glassy modulus (E_0 and E_∞) and τ_0 seemed to be specific to binders and mixtures. The findings are consistent with those reported elsewhere (*10, 11*).

Figure 4*b* shows the relationship between the characteristic times of the five binders and those of the corresponding field-produced mixtures for a reference temperature of 25°C. A good correlation was observed between the characteristic times at 25°C (R^2 of .82). An overall α-parameter value of 4.43 was observed for all evaluated mixtures. Although the α-value was expected to be constant with temperature, it increased as the temperature increased. The relationship between α and temperature is presented in Figure 4*c* and Equation 9.

$$\alpha = 0.0002(T)^2 - 0.0039(T) + 4.3347 \qquad (R^2 = .994) \qquad (9)$$

Equations 8 and 9 were used to estimate the characteristic times of binders from those of mixtures. Subsequently, the 2S2P1D model parameters in Table 2 were used to estimate the high critical temperatures of the binders at 10 radians/s. The predicted temperatures are shown in Table 1. Similar trends were observed for the critical temperatures except for the RAP mixture, which showed an unrealistic prediction for the high critical temperature. After careful revision of the data, it was found that the error was mainly attributable to significant deviations in the α-parameter values.

COMPARISON OF LOW-TEMPERATURE PROPERTIES OF BINDERS AND MIXTURES

The resistance of the various mixtures to thermal cracking was measured with TSRST (AASHTO TP10-93). The test cools down a 2- × 2- × 10-in. beam specimen at a rate of 10°C/h while restrain-

TABLE 2 Mixture and Binder Parameters of 2S2P1D Model

Parameter	Mixture				
	F-0%-150	F-15%-150	F-50%-150	F-50%-200	RAP
Mixtures					
δ	3.49	4.10	5.50	2.67	5.00
k	0.30	0.30	0.25	0.30	0.28
h	0.50	0.50	0.53	0.53	0.55
E_0 (ksi)	4.4	2.7	2.2	7.6	0.5
E_∞ (ksi)	2,704	2,704	3,177	3,177	3,481
β	5,000	5,000	5,000	5,000	5,000
log (τ_0 (25°C))	−2.469	−2.141	−1.149	−2.221	−1.105
Recovered Binders					
δ	3.49	4.10	5.50	2.67	5.00
k	0.30	0.30	0.25	0.30	0.28
h	0.50	0.50	0.53	0.53	0.55
E_0 (ksi)	0	0	0	0	0
E_∞ (ksi)	334	334	334	334	334
β	5,000	5,000	5,000	5,000	5,000
log (τ_0 (25°C))	−6.959	−6.593	−5.966	−6.311	−5.359
$\tau_{mixture}(T) = 10^{\alpha}\tau_{binder}(T)$					
α-parameter at 25°C	4.49	4.45	4.81	4.09	4.25

ing it from contracting. While the beam is being cooled down, tensile stresses are generated because the ends are being restrained. The HMA mixture would fracture as the internally generated stress exceeded its tensile strength. The temperature at which fracture occurs, referred to as "fracture temperature," represents the temperature at which the asphalt pavement will develop a transverse crack because of thermal stresses.

The resistance of the mixtures to thermal cracking was measured at the long-term aged stage because low-temperature cracking is a long-term pavement distress mode. The aging of the mixtures followed the Superpave recommendation for long-term aging of HMA mixtures, which consisted of subjecting the compacted samples to 85°C for 5 days in a forced draft laboratory oven. All samples were compacted with a kneading compactor to final air voids of 7% ± 0.5%.

Figure 5*a* shows the TSRST fracture temperatures of the evaluated mixtures. All mixtures met the target low-temperature performance grade of the asphalt binder (i.e., −28°C). The fracture temperatures of the mixtures manufactured with the PG 58-28 asphalt binder decreased with the increase of RAP content. The

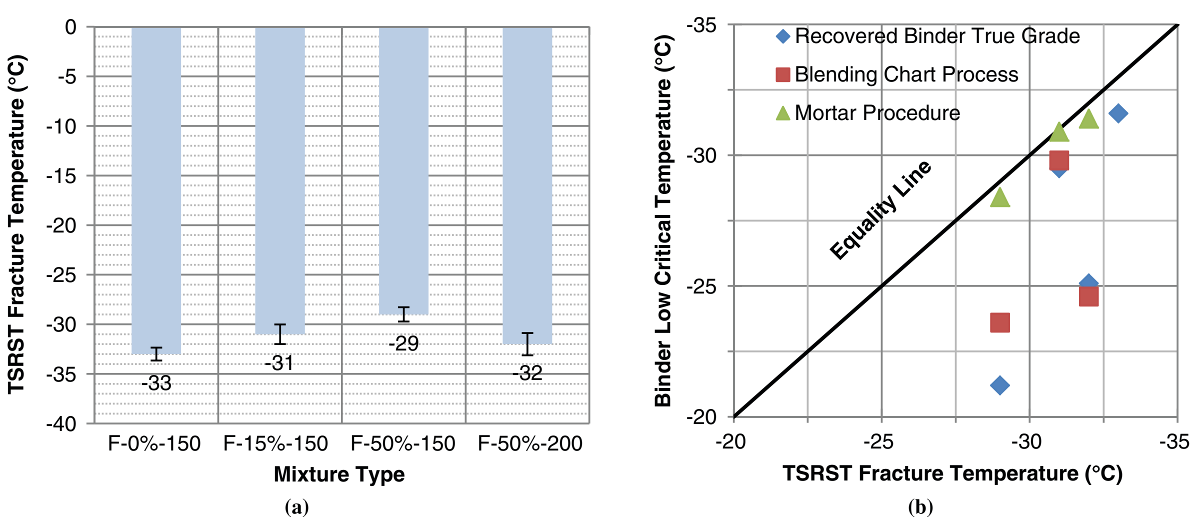

FIGURE 5 TSRST fracture temperatures (*a*) of various mixtures and (*b*) in relationship with binder low critical temperatures (numbers below bars represent mean values and error bars represent mean ±95% confidence interval).

mixtures manufactured with the PG 52-34 asphalt binder exhibited fracture temperatures that are similar to the virgin mixtures (i.e., 0% RAP). Figure 5*b* shows the relationship between the TSRST fracture temperatures and the low critical temperatures of the corresponding binder as determined using the various methodologies.

The TSRST fracture temperatures of the mixtures with 0% and 15% RAP were within 1°C of the critical low temperatures of the asphalt binders recovered from the same corresponding mixtures. Mixtures containing 50% RAP exhibited fracture temperatures that were colder than the critical low temperatures of the asphalt binders recovered from the same corresponding mixtures by 5°C to 8°C. However, consistent results were observed between the critical temperatures from the mortar procedure and the TSRST fracture temperatures. Therefore, full blending between the virgin and RAP binder did not seem to be evident for the evaluated mixtures.

INITIAL FIELD PERFORMANCE

In 2011, a condition survey of the test sections was performed by the Western Research Institute personnel. The inspection revealed no distresses in the 0%, 15%, and 50% RAP pavements after 2 years of service. Thermal cracking was not apparent in any of the sections. The lowest air temperature recorded at the project site during the first 2 years of service was −35.6°C. Overall, the pavement condition was excellent and uniformly the same along the total length of all test sections. Field performance will continue to be monitored over the next few years, and pavement distress survey and falling weight deflectometer data will be collected.

CONCLUSIONS

This study evaluated several methods of estimating the effective performance grade of the binder in field-produced mixtures designed with RAP. Good correlations were observed between the estimated critical temperatures from the blending chart process and the measured ones from the recovered asphalt binders. In some cases, the blending chart process underestimated or overestimated the critical temperatures of recovered binders by 2°C. Both methods showed significant increase in binder critical temperatures (i.e., warmer temperatures) with the increase in RAP content, particularly when 50% RAP was used. Specifically, the low critical temperatures of the binders recovered from the 50% RAP mixtures were 7°C to 8°C warmer than those recovered from the virgin mixture (i.e., 0% RAP). This observation is mainly related to the assumption that full blending is occurring between the virgin and the RAP binders.

The mortar approach showed promising results in determining the effective performance grade of the mixture. Although the method was sensitive to the percentage of RAP and the type of virgin binder used in the mixture, it did not result in drastically different mixture binder properties for the 0% and 50% RAP mixtures. Overall, the mortar procedure resulted in high, intermediate, and low critical temperatures that were lower (i.e., softer) than those determined for recovered asphalt binders. The mortar results for low critical temperatures were further confirmed with measured fracture temperatures in the various mixtures. The low critical temperatures from the mortar procedure were comparable and consistent with the performance of the mixtures regarding thermal cracking. Consequently, this procedure may well indicate that a certain level of blending is occurring between the virgin and RAP binders in a mixture. Therefore, further evaluation of the proposed mortar procedure is considered necessary; a larger set of mixtures that covers different binder types and sources at multiple levels of RAP content should be used.

The Hirsch model provided reasonable estimates to backcalculate binder shear modulus at high temperature from the measured mixture $|E^*|$. However, there are some difficulties in estimating the high-temperature performance grade, particularly when dealing with soft binders like the ones used in this study. The difficulties arise from (*a*) the difference in temperatures between the $|E^*|$ testing and performance grading temperatures, and (*b*) the limitation in the formulation of the Hirsch model at high temperatures and low frequencies. Subsequently, to get reasonable estimates, the binder modulus at high temperature was estimated from the backcalculated moduli (with the Hirsch model) at lower temperatures than the mixture $|E^*|$.

The modified Huet–Sayegh model was used to estimate the high performance grade of the asphalt binders from the measured $|E^*|$ of the corresponding mixtures. This approach resulted in high critical temperatures that were, respectively, similar and higher than those determined for the recovered binders and with the Hirsch model. The data showed good correlation between the characteristic times of the binders and mixtures, allowing for the determination of the binder properties from the measured $|E^*|$ of the mixture. However, this relationship was highly dependent on temperature and needs to be verified with other types of mixtures.

In summary, this study was specific to the use of RAP in typical mixtures in Manitoba, and further research is required on different types of RAP mixtures and different virgin performance grades to verify and validate the methods evaluated as part of this study. The mortar procedure provided promising results and needs to be further examined.

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