Influence of Hydrogreen Bioasphalt on Viscoelastic Properties of Reclaimed Asphalt Mixtures

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The incorporation of reclaimed asphalt pavement (RAP) into asphalt mixtures exposes some challenges from the design perspective because of the aged asphalt binder in RAP. Steps are being taken to offset the addition of stiff materials, often with the use of rejuvenating additives. This paper summarizes the laboratory evaluation of one of the available bio-rejuvenating agents called BituTech RAP. High RAP content mixtures used in Manitoba, Canada, were evaluated to study the impact of BituTech RAP on the viscoelastic properties of asphalt mixtures to overcome any possible moisture damage or thermal cracking problems that might arise in such a wet–freeze environment. The laboratory experiment consisted of the production and test of mixtures that contained 15% and 50% RAP, with and without BituTech RAP. The 2S2P1D analogical model was used to generate the complex modulus (*E) of the various evaluated mixtures and to assess the influence of BituTech RAP on the storage and loss moduli. The addition of BituTech RAP improved the moisture resistance of the mixtures that contained RAP, as observed after three freeze–thaw cycles. The addition of BituTech RAP restored the thermal cracking properties of the mixtures revealed by the thermal stress restrained specimen test. The use of BituTech RAP could result in cost savings without the need to use a softer binder, as long as the high-temperature properties of the mixtures were not jeopardized.**

Reclaimed asphalt pavement (RAP) is the mixture of asphalt and aggregates that is created from a hot-mix plant reject or when an existing asphalt surface has been milled or completely removed. Although RAP has been implemented by several highway agencies, issues with respect to binder and mixture stiffening have prevented various states from the use of higher percentages of RAP (greater than 30%) in hot-mix asphalt (HMA). This stiffening behavior is a function of the age of the RAP material and the compatibility between the virgin and reclaimed asphalt binders. Consequently, the mixture durability and resistance to fatigue and thermal cracking may be reduced, which results in a poor pavement performance.

Solaimanian and Tahmoressi observed that projects with higher variability in the stiffness of the RAP binder also exhibited higher variability in the stiffness of the binder in the plant-produced mix (*1*). Moreover, several studies have indicated that the addition of RAP to an asphalt mixture may change the physical behavior of the mixture (*2, 3*). The increased stiffness of the RAP binder is believed to be the cause of increased modulus of the asphalt mixture. Likewise, the use of high RAP content was found to possibly affect fatigue behavior and low-temperature cracking properties of asphalt mixtures (*3–5*).

Rejuvenating agents have been used traditionally to offset the high stiffness of the aged RAP binder. The use of rejuvenating agents could possibly increase the durability and the low-temperature performance of mixtures that contained RAP without jeopardy to the overall performance of the mixture. This paper focuses on one such bioasphalt additive called BituTech RAP, which is also sold under the brand name Hydrogreen, and developed by Green Asphalt Technologies, LLC, Diamondhead, Mississippi, as an alternative to carcinogenic aromatic oil rejuvenants. BituTech RAP is a unique combination of selected natural plant extracts reacted in a distinct process to create a powerful asphaltene dispersant. It is intended to offer maltenes without an aromatic content to eliminate environmental concerns associated with the use of oil-based products (*6*). Compositionally, BituTech RAP is derived from selected rosins, esters, and fatty acids, which are 100% "green," safe, and renewable resources in abundance worldwide (*7*). The product is a liquid that is easy to handle, and it can form homogenous and stable asphalt bonds. The performance grade (PG) may be reduced by one grade for both the high and the low grade of the binder through the addition of BituTech RAP directly to a base binder (*8*). Because this additive effectively reduces the low temperature at which a pavement cracks, it offsets one of the main concerns about the use of mixtures with a high RAP content.

LITERATURE REVIEW AND OVERALL OBJECTIVE

The Florida Department of Transportation (DOT) constructed in 2009 two trial sections on I-95 with 40% RAP and 0.75% BituTech RAP on weight of RAP used (*8*). The mixtures for the two sections were identical except that the HMA was, respectively, mixed and compacted at 132°C and 124°C for Trial Sections 1 and 2. The BituTech RAP was added to the virgin binder and injected into a double-barrel mix drum. These two mixes were compared with two earlier mixes constructed with Hydrolene. Hydrolene was previously

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used in cold recycling and with high RAP percentages because of its high aromatic content (*9*). There was no distinct difference in compaction between the BituTech RAP and Hydrolene, but other observations set the two apart. The BituTech RAP mixtures emitted no blue smoke or odor, which added to the comfort of the paving crew. The product has been in use by the Florida DOT for more than 3 years with perfect performance, and several million tons of RAP mixtures have been paved to date with no reported complaints (*8*).

In 2009, trials were completed in Connecticut to study the mixing and compaction process with the use of two rejuvenating agents: Hydrolene and BituTech RAP (*8*). The prepared mixtures consisted of about 98% RAP, 0.2% rejuvenating agent, and 2% recycled asphalt shingles (RAS). Both mixes were heated to 154°C in the mixer and discharged at temperatures that ranged from 143°C to 152°C. Although both mixtures had good compaction, the Hydrolene emitted noticeable amounts of blue smoke and an oily smell. No detectable smoke or odor was observed for the BituTech RAP. In 2010, the New York City DOT also used BituTech RAP additive with 20% RAP on two trial roads. A reduction in compaction temperature between 14°C and 28°C was observed, and did not raise issues with respect to in-place pavement densities.

In 2011, a laboratory study was conducted for the Texas DOT with the use of 35% RAP and 5% RAS with BituTech RAP additive (*8*). Compacted HMA specimens failed at 42,626 passes in the Hamburg wheel track test to reach 12.5 mm of rutting, which exceeded the minimum number of passes to meet the specifications (10,000 passes). In addition, the specimens exhibited an indirect tensile strength of 1,045 kPa, which fulfilled the specification range (585 to 1,380 kPa).

Elseifi et al. evaluated the use of Green Asphalt Binder (developed by Asphalt & Wax Innovations, LLC, Diamond Head, Mississippi) and BituTech RAP products in HMA (*7*). Use of green asphalt technology showed an improved performance of the high-temperature properties as a result of increased stiffness in the binders. However, the fracture properties were reduced. BituTech RAP also was used as a rejuvenating agent with asphalt mixtures that contained 40% RAP, and it softened the oxidized RAP binder enough to extend the target useful PG grade.

The National Center for Asphalt Technology studied the effect of BituTech RAP on RAP mixtures in Florida (*8*). Two mixtures were tested: the control mixture, with a RA1000 flux grade binder, and another mixture that used the same binder with 35% RAP and 5% RAS, plus 0.75% BituTech RAP on the weight of the combined RAP and RAS. The mixtures were mixed and compacted at 141°C and 121°C, respectively. Similar rutting resistance and tensile strength ratio results were observed for both mixtures. The RAP mixture with BituTech RAP had compaction properties superior to those of the control mixture. The study recommended the use of 0.75% of BituTech RAP with RAP mixtures to meet Florida DOT requirements.

In summary, although limited in number, studies in the literature show potential benefits from the use of BituTech RAP with RAP mixtures. However, none of the studies illustrated the impact of BituTech RAP on the viscoelastic properties of asphalt mixtures and how those properties are influenced by moisture damage. The study reported here evaluated the effectiveness of BituTech RAP biorejuvenating agent with mixtures that contained RAP in Manitoba, Canada, as a means to overcome any possible moisture damage or thermal cracking problems that might arise in a wet–freeze environment. In particular, the study looked at the effect of BituTech RAP on the storage and loss moduli of a 15% and 50% RAP that contained HMA mixtures as a function of moisture-induced damage. The effect was evaluated of BituTech RAP on the thermal properties (e.g., relaxation modulus, viscous–glassy transition point, microcracking initiation point) of the asphalt mixtures. A cost analysis associated with the use of BituTech RAP and RAP material is presented in this paper.

EXPERIMENTAL DESIGN

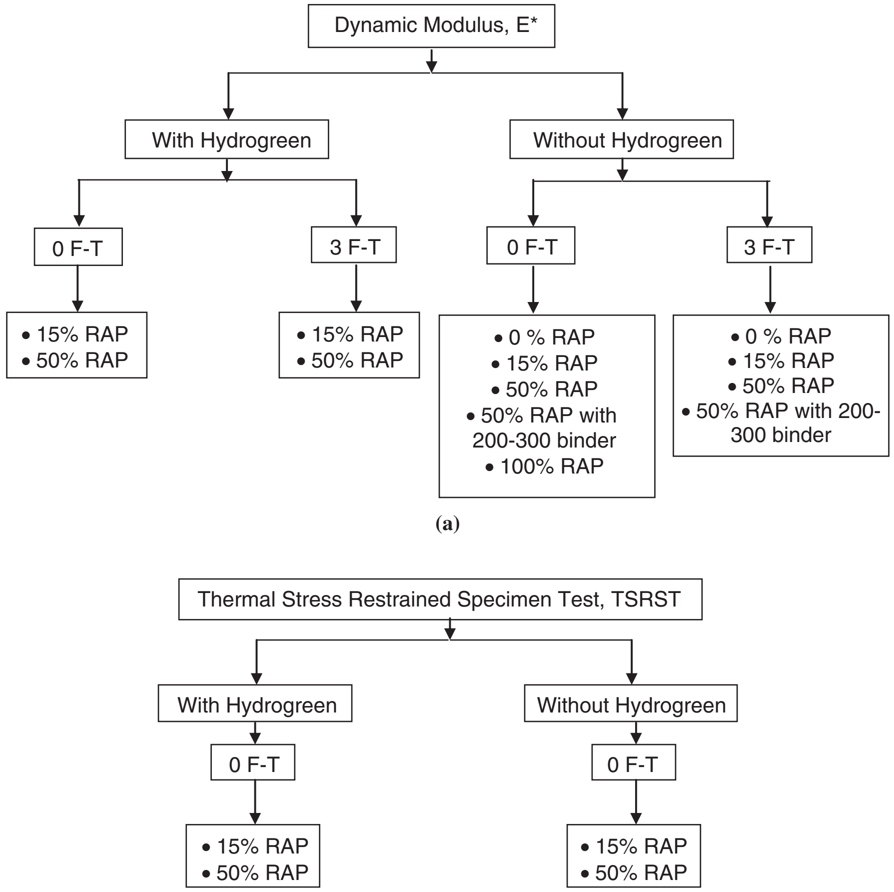
Figure 1 illustrates the experimental matrix implemented in this study. All mixtures were designed with the Marshall Mix Design method, as outlined in the Asphalt Institute's Mix Design Methods Manual MS-2 in accordance with the standard specifications of the Government of Manitoba's Infrastructure and Transportation department. The mixtures with BituTech RAP had the same binder contents as the corresponding control mixtures. All four mixtures without BituTech RAP were used on pavement sections built in 2009 on Provincial Trunk Highway 8, Manitoba, to assess the feasibility of HMA mixtures with high RAP content in cold weather regions. The laboratory and plant-produced mixtures from the various field sections have been evaluated extensively for performance and mechanistic properties, and the findings have been published elsewhere (*10, 11*). The field sections also are monitored by Western Research Institute, Laramie, Wyoming, for pavement performance.

The RAP binder was extracted with a centrifuge (AASHTO T 164) and recovered with a rotary evaporator (ASTM D5404) with a solution of 85% toluene and 15% ethanol by volume. The RAP material had an asphalt content of 4.7%. The RAP binder was graded as PG 76-10 in accordance with AASHTO M 320.

All mixtures were prepared with the use of Pen150-200 (PG 58-28), except for one case in which Pen200-300 (PG 52-34) was used with 50% RAP to study the effect of a softer binder on the mixture resistance to moisture damage and thermal cracking. The BituTech RAP was added at a rate of 1.5% by weight of RAP material. Two RAP percentages, 15% and 50%, were used for the BituTech RAP mixture. Control specimens that contained 0%, 15%, 50%, and 100% RAP without BituTech RAP were prepared for performance comparison purposes. Two tests were used in this study: (*a*) dynamic complex modulus and (*b*) thermal stress restrained specimen test (TSRST). The moisture damage was evaluated through the test and comparison of the dynamic modulus at the moisture-conditioned and unconditioned stages. The moisture-conditioned samples were subjected to three freeze–thaw (F-T) cycles. The TSRST was performed at the unconditioned stage only (i.e., 0 F-T). The notation used throughout the rest of the paper denotes whether the sample was with or without BituTech RAP, the percentage of RAP used, the binder grade, and the number of applied F-T cycles. For example, a BituTech RAP sample mixed with 15% RAP with Pen150-200 (PG 58-28) and subjected to three F-T cycles is denoted as HG-15-150-3FT. Laboratory samples that were prepared without BituTech RAP, mixed with 50% RAP and Pen200-300 (PG 52-34), and subjected to 0 F-T cycles are referred to as L-50-200-0FT.

STORAGE AND LOSS MODULI IN F-T CYCLES

The purpose of this study was to determine the impact of the additive BituTech RAP on the viscous and elastic properties of high RAP content mixtures. To study the viscoelastic behavior of an asphalt mixture in terms of the absolute value of the complex dynamic modulus ($|E^*|$) will not demonstrate the true rejuvenating effect of the additive on the viscous component. One of the few available



(a)

(b)

FIGURE 1 Experimental design: (*a*) dynamic modulus and (*b*) TSRST experiment.

physical models that can provide the elastic and viscous properties separately is the 2S2P1D (i.e., two springs, two parabolic, one dashpot) model (*12*). This model has its basis in simple combinations of physical elements (i.e., spring, parabolic, dashpot element) as shown in Figure 2*a*.

At a given reference temperature, the 2S2P1D model represents the complex modulus by seven constants through Equation 1 as follows (*12*):

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

where

i = complex number defined by $i^2 = -1$;
ω = 2π * frequency, the pulsation;
E_0 = static modulus when $\omega \to 0$;
E_∞ = limit of complex modulus when $\omega \to \infty$;
h, k = exponents such as $1 > h > k > 0$;
δ = dimensionless constant;
β = dimensionless constant = $\eta \cdot \tau^{-1}/(E_\infty - E_0)$; when $\omega \to 0$, then $E^*(i\omega\,\eta) \sim E_0 + i\omega\,\eta$; and
τ = characteristic time, which varies only with temperature and accounts for the time-temperature superposition principle, as follows:

- $\tau(T) = a_T(T) \cdot \tau_0$,
- $a_T(T)$ = shift factor at temperature T, and
- $\tau_0 = \tau(T_r)$ determined at reference temperature T_r.

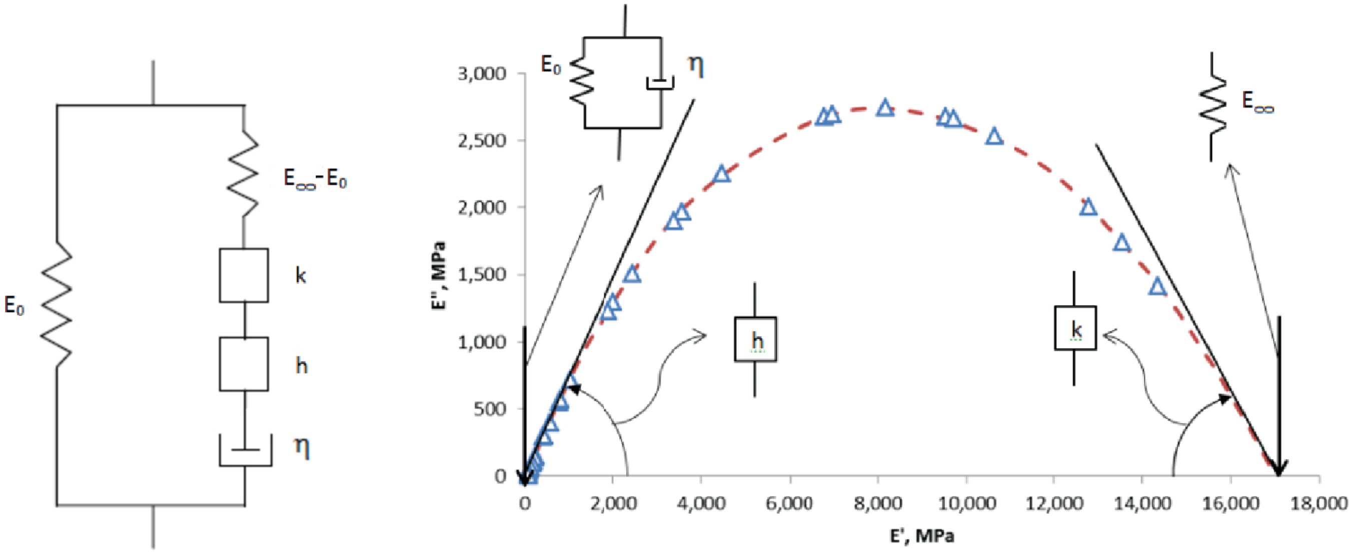
The shift factor at temperature T can be determined by means of the Williams–Landel–Ferry (WLF) equation for asphalt materials (Equation 2). A T_r of 25°C was selected in this study.

$$\log(a_T) = \frac{-C_1(T-T_r)}{C_2+(T-T_r)} \tag{2}$$

where C_1 and C_2 are empirical positive constants dependent on the material and reference temperature T_r.

Seven constants (δ, k, h, E_∞, E_0, β, and τ_0) are required to determine the linear viscoelastic behavior of the considered material at a given temperature. If the hypothesis of a linear, viscoelastic, thermorheological simple behavior can be applied to the material, the time–temperature superposition principle holds, and only the τ parameter depends on temperature.

If the time–temperature superposition principle holds, two additional constants of Equation 2 are needed: C_1 and C_2 (calculated at the reference temperature T_r chosen equal to 25°C). The number of constants of the model amount to nine. These nine constants can be obtained by an optimization process from the complex modulus



(a) (b)

FIGURE 2 2S2P1D model and Cole–Cole plot representation.

tests results. This optimization process is made at a reference temperature T_r with the use of the solver feature of Microsoft Excel software. The sum is minimized of the square error between the log of the magnitude of measured complex modulus, log ($|E^*|_{\text{measured}}$) and the log of the one estimated by the 2S2P1D model, log ($|E^*|_{\text{model}}$), at N points of frequencies. After the nine constants are determined for each mixture, Cole–Cole graphs are generated. They represent the relationship between the loss (viscous) modulus (E'') and the storage (elastic) modulus (E').

Figure 2*b* illustrates in the Cole–Cole plot the role of each element of the 2S2P1D model that describes the linear viscoelastic behavior of an asphalt mixture (*12*). The slope of the left and right ends of the Cole–Cole curve shows the *h* and *k* constants of parabolic elements, respectively. The value of E_∞ defines the maximum storage modulus at which the loss modulus is zero at high frequency ($\omega \rightarrow \infty$). The minimum value of the storage modulus represents the rigidity of the parallel configuration of the spring E_0 and the dashpot η, at which the loss modulus is zero at low frequency ($\omega \rightarrow 0$).

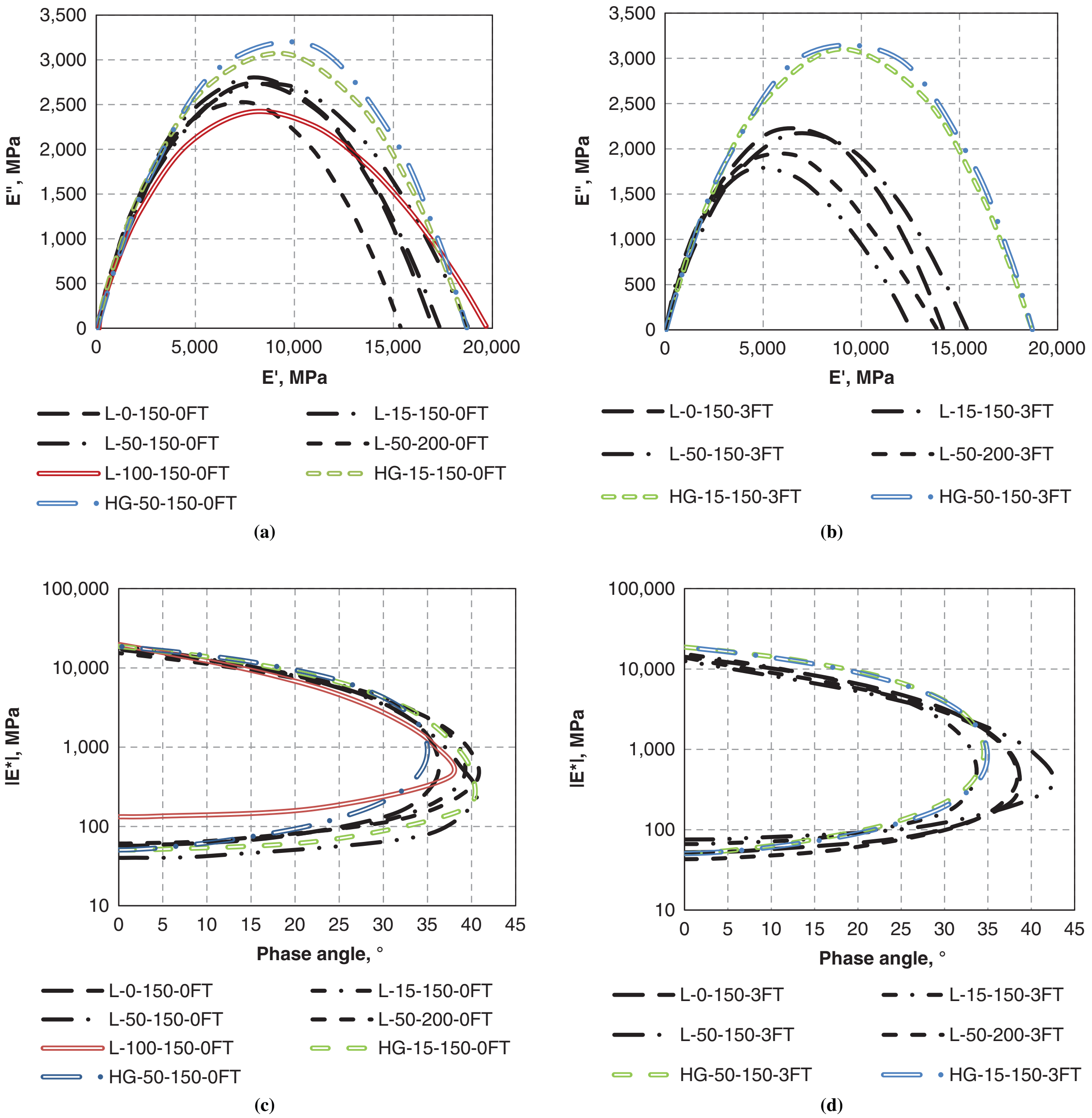
Dynamic modulus testing was conducted on all mixtures in accordance with AASHTO TP 62-07. The specimens were compacted with use of the Superpave® gyratory compactor to 7 ± 0.5% air voids. The mixtures were tested in both the unconditioned (i.e., 0 F-T) and moisture-conditioned state. The moisture-conditioned specimens were subjected to three F-T cycles after 75% saturation was achieved. The multiple F-T cycling followed the procedure outlined in AASHTO T 283 at multiple stages. Table 1 presents the 2S2P1D and the WLF constants determined through the optimization process for the various mixtures evaluated in this study.

Figure 3*a* shows the Cole–Cole plot analysis for all mixtures at 0 F-T. The following observations can be made:

- The 15% and 50% RAP mixtures without BituTech RAP exhibited lower loss modulus (E'') values. The loss modulus decreased

TABLE 1 Parameters of 2S2P1D and WLF Shift Factors

Mixture Type	E_0 (MPa)	E_∞ (MPa)	δ	*k*	*h*	β	log(τ_0)	C_1	C_2
L-0-150-0FT	56.9	17,015	0.67	0.48	0.29	2,000	−3.6	42.8	427.3
L-15-150-0FT	57.4	17,354	0.49	0.52	0.26	2,000	−3.7	17.6	167.1
L-50-150-0FT	40.1	18,794	0.45	0.48	0.24	2,000	−3.4	34.7	300.7
L-50-200-0FT	60.8	15,381	0.27	0.55	0.27	2,000	−3.8	17.8	168.5
L-100-150-0FT	132.4	19,737	0.29	0.47	0.19	2,000	−3.4	7.1	63.2
HG-15-150-0FT	50.5	18,715	0.28	0.51	0.30	2,000	−4.7	5.7	60.3
HG-50-150-0FT	50.5	18,715	20.00	0.44	0.30	2,000	−1.4	53.4	631.5
L-0-150-3FT	52.4	14,189	0.38	0.51	0.26	2,000	−4.2	7.6	85.9
L-15-150-3FT	66.3	15,398	0.81	0.45	0.23	2,000	−3.6	15.0	148.3
L-50-150-3FT	75.6	12,539	0.24	0.54	0.19	2,000	−3.8	7.7	71.3
L-50-200-3FT	42.9	13,877	0.78	0.50	0.17	2,000	−3.4	8.5	91.9
HG-15-150-3FT	50.5	18,716	3.05	0.45	0.29	2,000	−3.5	4.1	55.5
HG-50-150-3FT	50.5	18,716	4.09	0.41	0.50	2,000	−3.6	1.4	34.1



(a) (b)

(c) (d)

FIGURE 3 Cole–Cole plots and black diagram of asphalt mixtures at 0 and three F-T cycles: (*a*) Cole–Cole plot at 0 F-T cycles, (*b*) Cole–Cole plot at three F-T cycles, (*c*) black diagram at 0 F-T cycles, and (*d*) black diagram at three F-T cycles.

with an increase in RAP content because of the stiffening effect of the RAP materials. Mixtures with BituTech RAP showed a significant enhancement in their loss modulus because of the RAP binder rejuvenation introduced through the addition of BituTech RAP.

- Both mixtures with 15% and 50% RAP with the use of BituTech RAP additive produced similar viscoelastic properties as a result of the similar storage and loss moduli. The mixture with 50% RAP with BituTech RAP had slightly lower loss modulus than the 15% RAP with BituTech RAP on account of the higher amount of stiff RAP binder in the mixture.
- The viscoelastic properties of the mixtures with virgin materials and 15% RAP had a similar response. Moreover, the mixture with 50% RAP and PG 52-34 exhibited lower storage and loss moduli than the one that contained 50% RAP with PG 58-28. Use of a softer binder decreased the stiffness of the mixture, which reduced its storage and loss moduli. This result also confirmed that the addition of RAP to a mixture increased its storage modulus and decreased its loss modulus. This behavior was apparent when 100% RAP was used.
- In general, the maximum loss modulus was identical for all mixtures without BituTech RAP and with the use of PG 58-28. The difference in storage modulus of these mixtures was observed as a result of the addition of RAP.
- Mixtures with 15% and 50% RAP showed the highest loss modulus and similar storage modulus compared with mixtures with 50% RAP and PG 58-28.

These findings clearly indicate that use of BituTech RAP increases the loss modulus, because the RAP binder is rejuvenated without jeopardy to the storage modulus of the mixture. A higher loss modulus is anticipated to positively affect the mixture resistance to fatigue and low-temperature cracking.

Figure 3*b* shows the Cole–Cole plot analysis for all mixtures after three F-T cycles. The following observations were made:

- The viscoelastic properties represented by the storage and loss moduli of the mixtures with 15% and 50% RAP with the use of BituTech RAP after three F-T cycles were almost the same as the ones without F-T cycles (Figure 3*a*).
- All mixtures after three F-T cycles followed a trend similar to that of the 0 F-T cycles, except for the mixture with 50% RAP. Both storage and loss moduli of the mixture with 50% RAP with use of PG 52-34 were higher than the mixture with 50% RAP and use of PG 58-28.
- The difference between the storage modulus of the virgin and 15% RAP mixtures increased after three F-T cycles. Figure 3*b* also illustrates that the storage and loss moduli of the RAP mixtures that used BituTech RAP were significantly higher than those without BituTech RAP.

These findings from the three F-T cycles indicated that RAP mixtures without BituTech RAP had a significant reduction in the loss modulus after F-T cycling. Use of BituTech RAP helped, however, to maintain a similar loss modulus before and after F-T cycles because of the rejuvenation of the RAP binder.

Figure 3, *c* and *d,* shows the relationship between the phase angle and the dynamic modulus of asphalt mixtures before and after three F-T cycles (black diagram). The behavior shown in the black diagram supported the findings obtained from the Cole–Cole plots. The 15% and 50% RAP mixtures without BituTech RAP and with PG 58-28 exhibited the highest phase angle values. This result was due to the stiffening effect introduced by the RAP binder. Phase angle readings decreased slightly when the PG 52-34 was used. The addition of BituTech RAP reduced the maximum phase angle values and significantly softened the RAP binder as a consequence.

The effect of BituTech RAP on the mixture resistance to moisture damage was evaluated with the use of two distinct moduli ratios: storage modulus ratio (SMR) and loss modulus ratio (LMR). SMR represents the ratio of the maximum storage modulus (E') at three F-T cycles over the maximum storage modulus at 0 F-T obtained from a Cole–Cole plot. LMR represents the ratio between the maximum loss (E'') modulus at three F-T cycles and the maximum loss modulus at 0 F-T obtained from the Cole–Cole plot. These two ratios indicate in a precise way the effect of moisture damage on the elastic and viscous properties of an asphalt mixture.

Figure 4 displays the SMR and LMR for the various evaluated mixtures. In general, without BituTech RAP, the SMR and LMR of the 15% RAP mixture were similar to those of the 0% RAP mixture. However, the mixture with 50% RAP and PG 58-28 exhibited a significant drop in its SMR and LMR values. When a softer binder (i.e., PG 52-34) was used with the 50% RAP mixture, SMR and LMR values were restored to reach improved or similar values as the virgin (i.e., 0% RAP) mixture.

The addition of BituTech RAP to the 15% and 50% RAP mixtures significantly increased the SMR and LMR values to reach almost 100%. No significant difference was found in the SMR and LMR values between the 15% and 50% RAP when BituTech RAP was used. In general, the data indicated that Hydrogreen could improve the resistance of RAP mixtures to moisture damage without the need to use a softer binder.

THERMAL VISCOELASTIC PROPERTIES WITH TSRST

Low-temperature properties of asphalt mixtures were assessed with the use of TSRST. An asphalt mixture specimen is subjected to cooling below freezing from an initial temperature at a constant rate. Because the specimen is restrained from contraction, increased tensile stress is induced through a decrease at a constant rate in the temperature until the specimen fractures. The behavior of the asphalt mixture in the TSRST is assumed to follow the uniaxial linear viscoelastic Boltzmann constitutive equation (Equation 3).

$$\sigma(t) = \int_0^t E_r(t-t')\frac{\partial \varepsilon(t')}{\partial t'}dt' = \int_0^t E_r(t')\frac{\partial \varepsilon(t-t')}{\partial t'}dt' \qquad (3)$$

where

t' = variable of integration,
$E_r(t)$ = relaxation modulus,
$\sigma(t)$ = thermal stress, and
$\varepsilon(t)$ = thermal strain.

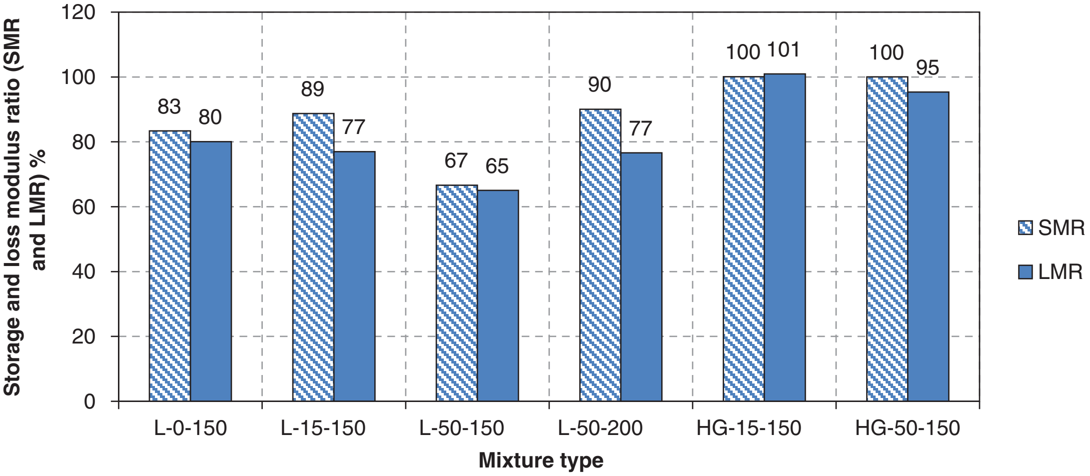


FIGURE 4 SMR and LMR of asphalt mixtures at 25°C.

The thermal stress values were available as a result of TSRST. Typically, thermal strain is not measured during testing and can be estimated through the assumption of a constant coefficient of thermal contraction, α, along with the measured temperatures during the TSRST. The thermal strain is then calculated with Equation 4.

$$\varepsilon(t) = \alpha \times (T(0) - T(t)) \tag{4}$$

where

$T(t)$ = temperature at time t,
$T(0)$ = initial temperature of the test at which the strain and stress values are set arbitrarily to zero, and
α = coefficient of thermal contraction.

For a constant cooling rate, C, and a constant thermal confident of contraction, the Boltzmann equation (Equation 3) can be simplified as follows:

$$\sigma(t) = \alpha \times C \int_0^t E_r(t')\,dt' \tag{5}$$

Thus the relaxation modulus of the asphalt mixture as a function of temperature can be determined numerically by obtaining the first derivative from both sides of Equation 5.

$$E_r(T(t_i)) = \frac{\dfrac{d\sigma(t)}{dt}}{\alpha \times C} = \frac{\dfrac{\sigma(t_i) - \sigma(t_{i-1})}{t_i - t_{i-1}}}{\alpha \times C} \tag{6}$$

After the determined relaxation modulus is observed as a function of temperature, three stages in the material behavior can be distinguished. The following low-temperature stages can be defined and are illustrated as an example in Figure 5:

- Viscous–glassy transition stage. This stage can be defined by the viscous–glassy transition temperature and modulus. These parameters can be captured when the second derivative of the relaxation modulus reaches its maximum (i.e., third derivative of the relaxation modulus is zero) (Figure 5, *c* and *d*).
- Microcracking initiation stage. In this stage, microcracks occur in the specimen from induced thermal stress. The stage can be defined by three parameters: microcracking initiation temperature,

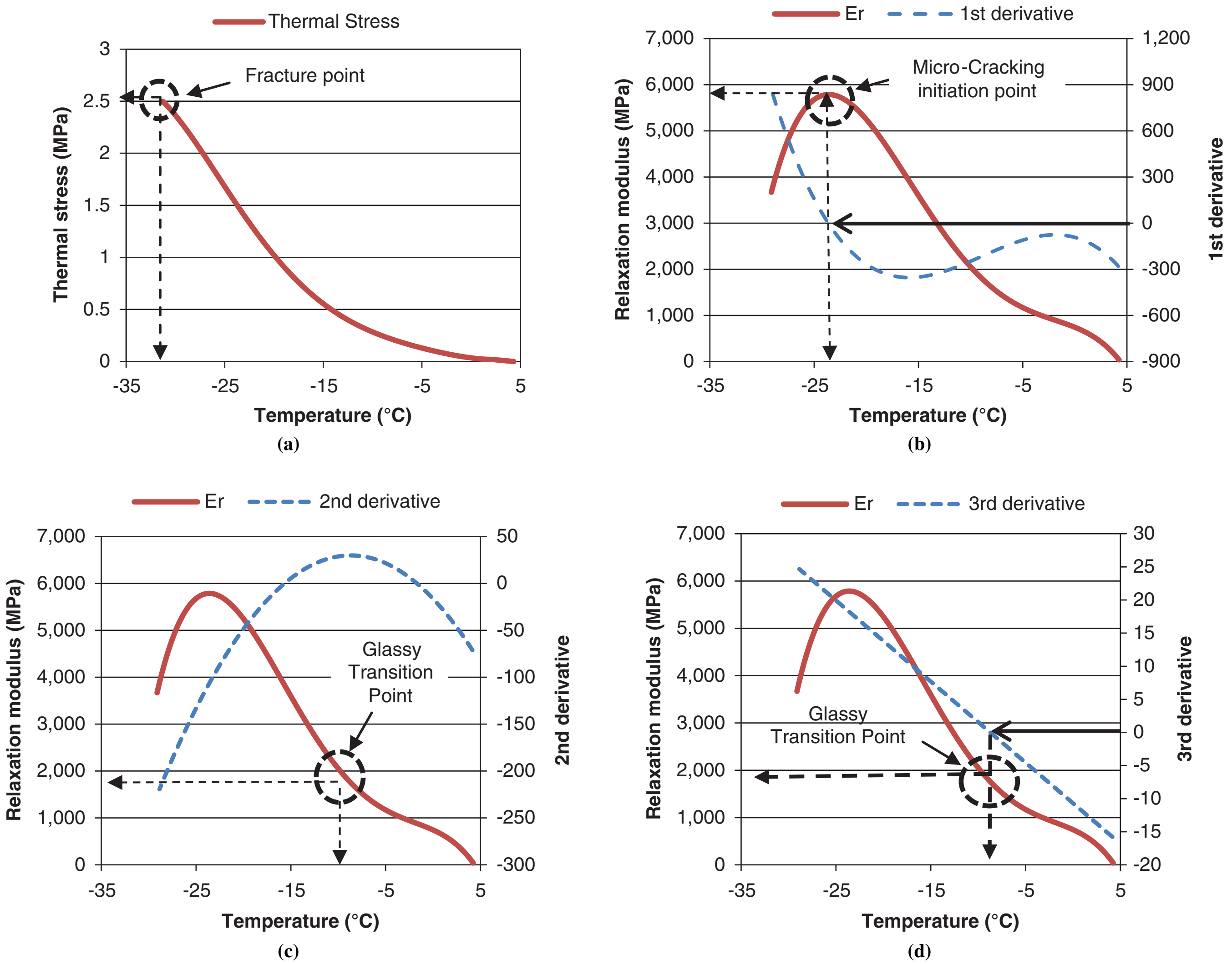


FIGURE 5 Determination of low-temperature crack properties of asphalt mixtures: (*a*) fracture point, (*b*) microcracking initiation point, and (*c*) and (*d*) glassy transition point.

microcracking initiation modulus, and microcracking initiation stress. The microcracking initiation modulus is identified as the maximum value of the relaxation modulus and the corresponding temperature. The stresses are then defined as microcracking initiation temperature and microcracking initiation stress, respectively (Figure 5*b*).

- Fracture stage. In this stage, the specimen breaks as a result of the propagation of microcracks in the specimen. The maximum stress value is defined as the fracture stress while the fracture temperature is captured when the fracture stress occurs (Figure 5*a*).

In this study, the TSRST was conducted on long-term, aged, unconditioned (i.e., 0 F-T) beam specimens (50.8 × 50.8 × 254 mm). The specimens were compacted with a kneading compactor to 7 ± 0.5% air voids after cutting was done to test dimensions. The TSRST was conducted for each asphalt mixture on three replicates. A beam specimen was subjected to cooling from an initial temperature of 5°C at a constant rate of 10°C/h, while the height of the specimen was maintained constant during the test. The aging of the mixtures followed AASHTO R 30 for long-term aging of HMA mixtures, which meant the compacted samples were subjected to 85°C for 5 days in a forced draft laboratory oven. The thermal cracking properties of the asphalt mixtures were measured at the long-term, aged stage, because low-temperature cracking was a long-term pavement distress mode.

Thermal stress buildup is illustrated in Figure 6*a,* and the calculated relaxation modulus of the various asphalt mixtures is shown in Figure 6*b*. Data points for E_{ThR} were reported up to the microcracking initiation stage. A constant value of 2.5E-5 1/°C was considered for the coefficient of thermal contraction to estimate thermal strain. Figure 6 shows that the thermal buildup stress increased, and the material became stiffer as the amount of RAP increased in the mixtures (Figure 6, *a* and *b*). The use of BituTech RAP decreased the thermal stress and the relaxation modulus compared with the corresponding control mixtures. The mixtures with 15% and 50% RAP with the use of BituTech RAP had thermal buildup stress and a relaxation modulus similar to those of the 0% and 15% RAP mixtures without BituTech RAP.

Table 2 presents the determined low-temperature properties of the asphalt mixtures. The data show that the addition of RAP to the mixture increased the fracture stress, microcracking initiation modulus, and the viscous–glassy transition modulus. It also decreased the fracture temperature, microcracking initiation temperature, and the viscous–glassy transition temperature. Thus the effect of stiff binder in the mixture became more significant with the increase of RAP content, which led to a decrease in the relaxation behavior of the asphalt mixture. The addition of BituTech RAP restored the low-temperature properties of asphalt mixtures significantly. It was observed that the addition of BituTech RAP softened the mixtures and decreased the fracture stress, microcracking stress, microcracking modulus, and the viscous–glassy transition modulus. BituTech RAP also shifted to the colder side the fracture temperature, microcracking initiation

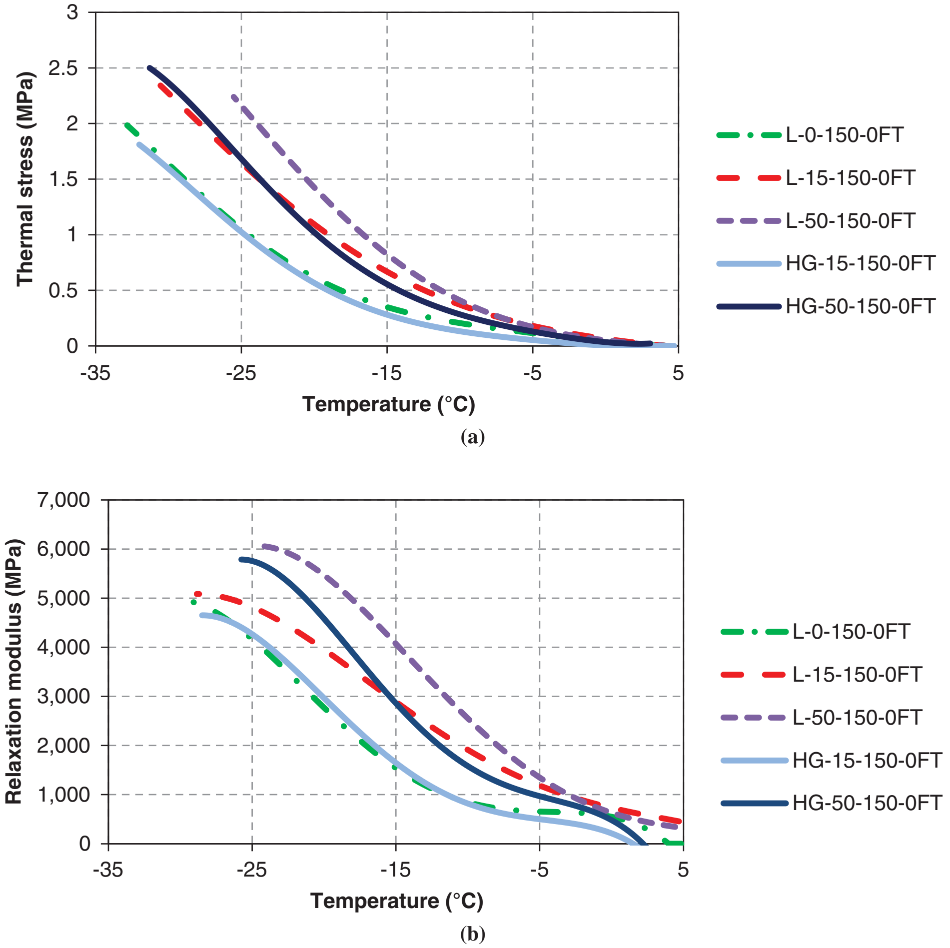


FIGURE 6 Obtained from TSRST results: (*a*) thermal stress and (*b*) relaxation modulus.

TABLE 2 Low-Temperature Properties of Asphalt Mixtures

	Mixture Type				
Low-Temperature Property	L-0-150-0FT	L-15-150-0FT	L-50-150-0FT	HG-15-150-0FT	HG-50-150-0FT
Viscous–glassy transition temperature (°C)	–13.0	–6.9	–4.2	–12.5	–11.2
Viscous–glassy transition modulus (MPa)	1,189.9	1,416.5	1,204.9	1,161.7	1,826.5
Microcracking initiation temperature (°C)	–30.5	–28.9	–24.7	–28.5	–25.7
Microcracking initiation stress (MPa)	1.7	2.1	2.1	1.4	1.8
Modulus at microcracking initiation (MPa)	4,983.5	5,084.9	6,065.3	4,650.9	5,787.2
Fracture temperature (°C)	–32.9	–30.7	–27.0	–33.0	–31.3
Fracture stress (MPa)	2.0	2.4	2.4	1.9	2.5

temperature, and the viscous–glassy transition temperature. These improvements in the low-temperature properties of the mixtures were the results of the rejuvenating effects of BituTech RAP, which restored the properties of asphalt binder in RAP materials.

COST ANALYSIS EXAMPLE

A preliminary cost saving analysis was performed to assess the effectiveness of different RAP percentages with the BituTech RAP additive. On the basis of the discussion presented in the National Asphalt Pavement Association information series publication on the cost associated with RAP (*13*), the value of RAP can be calculated as the value of the equivalent amount of virgin asphalt and aggregate materials as follows:

- RAP asphalt content = 4.7%,
- Cost of virgin asphalt: (*a*) PG 58-28 = $685/ton and (*b*) PG 52-34 = $755/ton (these 2010 cost figures were provided by the Manitoba Infrastructure and Transportation department), and
- Cost of virgin aggregate = $15/ton.

Thus the value of RAP is as follows:

- Asphalt binder in RAP = $685 × 0.047 = $32.20/ton,
- Aggregate in RAP = $15/ton × 0.953 = $14.30/ton, and
- Total value of RAP = $32.20/ton + $14.30 = $465/ton.

Table 3 shows two examples of the costs associated with obtaining and processing RAP at two percentages: 15% and 50% with and without BituTech RAP. The first example in the table is RAP obtained from millings on a project for which the cost of milling is included in the contract. The second example is RAP that was purchased and requires processing.

The cost analysis results presented in Table 3 show that cost savings through the use of 15% RAP may range from $5.36/ton to $5.14/ton. Savings could rise through an increase in the RAP percentage to 50% ($17.87/ton to $17.12/ton), but this increase also could lead to lower mixture performance in terms of thermal and moisture resistance (Figure 4). One potential solution in this study was to use a softer binder grade (i.e., PG 52-34), which introduced an additional cost (savings dropped from $14.57/ton to $13.82/ton). An enhanced solution was to continue the use of PG 58-28 with BituTech RAP

TABLE 3 Typical Savings Through Use of RAP

Cost	RAP Obtained from Millings[a]	RAP Purchased
Value of RAP	$46.5/ton	$46.5/ton
RAP cost	na	–$5.00/ton
Plant cost for extra equipment	–$0.85/ton	–$0.85/ton
Trucking cost	–$3.50/ton	na
Processing and handling cost	–$5.80/ton	–$5.80/ton
Extra quality control cost	–$0.60/ton	–$0.60/ton
BituTech RAP cost[b]	–$21.49/ton	–$21.49/ton
Total savings	$35.74/ton	$34.24/ton
Saving per 15% RAP in mix (without BituTech RAP)[c]	$5.36/ton	$5.14/ton
Saving per 50% RAP in mix (without BituTech RAP)[c]	$17.87/ton	$17.12/ton
Saving per 50% RAP in mix (without BituTech RAP) with softer binder (PG 52-34)	$14.57/ton	$13.82/ton
Saving per 15% RAP in mix (with BituTech RAP)[c]	$2.14/ton	$1.91/ton
Saving per 50% RAP in mix (with BituTech RAP)[c]	$7.12/ton	$6.37/ton

NOTE: na = not applicable.
[a] Cost of millings included in contract.
[b] A kilogram of BituTech RAP costs $1.43. BituTech RAP was added at 1.5% of the weight of RAP.
[c] With the use of PG 58-28.

and 50% RAP. Thermal and moisture resistance properties for this mixture were the greatest, and cost savings were achieved ($7.12/ton to $6.37/ton) despite the added cost of BituTech RAP.

CONCLUSIONS

An extensive laboratory evaluation was conducted to study the effect of BituTech RAP on asphalt mixtures that contained up to 50% RAP. The impact of RAP content and BituTech RAP on complex moduli, moisture damage, and thermal cracking resistance of HMA mixtures was evaluated with the use of advanced testing techniques. On the basis of the analysis of the data generated in this study, the following findings were made:

- Cole–Cole analysis showed that the loss modulus (E'') values for mixtures with BituTech RAP were significantly higher than the ones without. In addition, the performance of mixtures with 50% RAP with BituTech RAP was similar to that of the mixture with 15% RAP (with BituTech RAP).
- The addition of BituTech RAP to the RAP mixtures improved their resistance to moisture damage after three F-T cycles. Mixtures with BituTech RAP exhibited storage modulus and loss modulus values significantly higher than those of the mixtures without BituTech RAP.
- In the TSRST, the addition of BituTech RAP restored the low-temperature properties of the RAP mixtures. A reduction in the relaxation modulus was observed with a shift to the colder side in the fracture temperature, microcracking initiation temperature, and viscous–glassy transition temperature.
- Cost analysis showed potential savings associated with BituTech RAP with 50% RAP in addition to its effect as a rejuvenating agent. Use of BituTech RAP could promote the use of higher percentages of RAP as long as the high-temperature properties of the mixtures were preserved.

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