Performance Evaluation of Asphalt Mixtures with High Recycled Asphalt Pavement Content

Luis Loria, Elie Y. Hajj, Peter E. Sebaaly, Matt Barton, Said Kass, and Tara Liske

This study extensively evaluated the resistance to moisture damage and thermal cracking of hot-mix asphalt (HMA) mixtures with high recycled asphalt pavement (RAP) content (up to 50%) from field sections on provincial Highway 8 between Gimli and Hnausa in Manitoba, Canada. A comparison between the properties and performance of the field-produced and laboratory-produced mixtures was also conducted and was included in this study. HMA mixtures with 50% RAP resulted in acceptable resistance to moisture damage and thermal cracking. The use of multiple freeze–thaw cycles provided a better characterization of the mixtures' resistance to moisture damage. Acceptable correlations were observed between the estimated critical temperatures from the blending chart and the measured ones from the recovered asphalt binders. Overall, laboratory-produced mixtures could be used to evaluate the relative resistance of the field-produced mixtures to moisture damage and thermal cracking.

Reclaimed asphalt pavement (RAP) has been incorporated into hot-mix asphalt (HMA) pavements for a number of years, but its use is becoming even more popular with the limited space available in landfills, the decrease in the amount of high quality virgin aggregate, and the high price of oil. Although many highway agencies have realized the benefits of using RAP, the incorporation of high percentages of RAP (more than 25%) in HMA mixtures, especially in the asphalt surface layer, has been relatively low compared with the supply of RAP available. HMA mixtures with high RAP content have raised concerns about the adequacy of their resistance to fatigue and thermal cracking and their sensitivity to moisture.

There is a need therefore to develop design methods and analysis of the material properties of HMA mixtures with high RAP content. At low-RAP content, mixtures may not include a sufficient amount of old material to significantly affect the properties of the virgin asphalt binder. At higher RAP content, however, the hardened RAP binder may stiffen the mix, which is good for rutting, but may not be good for cracking.

L. Loria, E. Y. Hajj, P. E. Sebaaly, and M. Barton, Western Regional Superpave Center, Department of Civil and Environmental Engineering, University of Nevada, MS257, Reno, NV 89557. S. Kass and T. Liske, Materials Engineering Branch, Manitoba Infrastructure and Transportation, 920-215 Garry Street, Winnipeg, Manitoba R3C 3P3, Canada. Corresponding author: E. Y. Hajj, elieh@unr.edu.

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The overall goal of the mix design process of HMA is to recommend a mix that can withstand the combined actions of traffic and environment. It is critical therefore to assess the impact of the various mix components on the performance of the constructed pavement (i.e., resistance to rutting, fatigue, and thermal cracking). The existence of RAP in the mix presents a challenge to the design engineer because of the complex interaction among the new and recycled components of the mix. The inclusion of RAP materials in the HMA mix can improve its resistance to rutting, while it may jeopardize its resistance to fatigue and thermal cracking. The key to successfully include RAP in the HMA mix is the ability to assess its impact on pavement performance and recognize the uniqueness of each project with respect to both materials and loading conditions.

One of the concerns in producing HMA mixtures with high RAP content is the effect of the RAP material on the moisture susceptibility of the mix. The resistance of asphalt mixtures to moisture damage is critical to its long-term performance. Moisture damage manifests itself as a reduction in the overall strength or stiffness of the mixture. If an asphalt mixture is susceptible to moisture damage, it could eventually fail in any of the four failure modes (i.e., rutting, fatigue, thermal cracking, or raveling).

In 2010, Hassan presented, theoretically, the feasibility of producing plant-recycled HMA mixes with high RAP content (*1*). The consensus from the literature is that 40% RAP is the maximum, feasible content with the available, recycled, hot asphalt technologies. Higher RAP content would require the use of indirect heat techniques or warm asphalt technology and involve more processing and testing of RAP to reduce variability. The use of rejuvenating agents also allows for higher RAP content to be incorporated into HMA mixes. These options are associated with additional costs that not all authorities or suppliers are willing to incur, however.

Significant efforts have been made by FHWA, the National Center for Asphalt Technology, and various expert task groups to promote the use of mixtures with high RAP content by working with state departments of transportation on field projects to showcase the performance of high RAP mixtures (*2*).

In 2009, pavement sections with high RAP content were constructed on provincial Highway 8 between Gimli and Hnausa in Manitoba, Canada, to evaluate the feasibility of using HMA mixtures with high RAP content in surface layers in cold weather regions. The objective of the pavement sections were to (*a*) determine if current design techniques could be used to design high RAP content, (*b*) validate existing and new procedures for characterizing RAP materials, (*c*) construct field test sections so that the performance of HMA with high RAP, and HMA without RAP, could be compared side by side, and (*d*) determine if the properties of the laboratory-produced mixtures could be used to ensure quality field-produced mixtures.

The work described in this paper is only a part of the overall work plan for this effort and consists of an extensive evaluation of field-produced and laboratory-produced mixtures with 0%, 15%, and 50% RAP. All mixtures were evaluated for their resistance to moisture damage and thermal cracking. The applicability of the blending chart process to predict the performance grade (PG) of the blended asphalt binder was evaluated. A comparison between the properties and performance of the field- and laboratory-produced mixtures also was conducted and is described in this paper.

PROJECT DESCRIPTION

The project is located on provincial Highway 8 between Gimli and Hnausa in Manitoba, Canada. The total project length is about 17 mi, and the comparative pavement site accounts for 6.0 mi of the project. The evaluated sections were constructed in September 2009 and consisted of two 2-in. lifts with conventional HMA (i.e., 0% RAP), 15% RAP, and 50% RAP with no grade change for the new asphalt and 50% RAP with a grade change for the new asphalt. The pavement sections were laid on top of a 4-in. HMA with 50% RAP, which was constructed the year before (i.e., 2008) and is on top of a base and a subgrade. All four evaluated mixes in the top two lifts consisted of a dense-graded asphalt mixture manufactured with a Pen 150-200 asphalt binder, except for the 50% RAP mix with grade change, which was manufactured with a Pen 200-300 asphalt binder. The target binder grade for the project location was Pen 150-200.

EXPERIMENTAL PROGRAM

Loose mixtures were sampled during paving of the top lift from the paving auger at the project site. Those mixtures were referred to as field-produced mixtures and were labeled F-0%-150, F-15%-150, F-50%-150, and F-50%-200. For instance, the F-0%-150 mix represented the field mix with 0% RAP manufactured with the Pen 150-200 asphalt binder, while the F-50%-200 mix represented the field mix with 50% RAP manufactured with the Pen 200-300 asphalt binder. Cold feed aggregates, asphalt binders, and RAP materials for the various mixtures were sampled during production at the plant location. The raw materials were used to reproduce all four mixtures in the laboratory. Those mixtures were referred to as laboratory mixtures and were labeled L-0%-150, L-15%-150, L-50%-150, and L-50%-200.

Table 1 shows the experimental program for this study. The program builds on the basis of testing field-produced and laboratory-produced HMA mixtures as they are subjected to moisture conditioning. The moisture conditioning consisted of subjecting the samples to multiple freeze–thaw (F–T) cycling. The moisture sensitivity of the mixtures was evaluated by using the unconditioned and conditioned indirect tensile strengths (TS), along with the indirect tensile strength ratio (TSR) at multiple F–T cycles. The mechanical properties of the mixtures were evaluated by using the dynamic modulus test, and their resistance to thermal cracking was assessed by using the thermal stress restrained specimen test (TSRST) after multiple F–T cycles.

PAVEMENT SECTION CONSTRUCTION

During construction of the various sections the same hot plant (central feed plant), truck type, paver, crews, and compaction equipment were employed. During production, the Manitoba Infrastructure and Transportation (MIT) staff made significant efforts to ensure that the correct asphalt binder content and type were used for each test section and to ensure that the lifts were constructed on top of each other. The compaction effort applied to both the conventional HMA (i.e., 0% RAP) and RAP sections was identical. Target in-place densities were achieved in the various sections without any noticeable issues.

MIX DESIGNS

The Marshall mix design method, as outlined in the Asphalt Institute's *Mix Design Methods Manual MS-2*, was used to design the field-produced and laboratory-produced mixtures and followed MIT standard specifications. All evaluated mixtures were designed with 75 blows on each side. A sieve analysis performed on extracted aggregates from all four, field-produced mixtures revealed that all aggregate gradations met the job mix formula criteria. The asphalt binder contents of RAP material and field-produced mixtures were determined by using the ignition oven method (AASHTO T308). An asphalt binder content of 4.7% was measured for the RAP material. A binder content of 5.1% was measured for the 0% and 15% field-produced mixtures (i.e., F-0%-150 and F-15%-150) while a binder content of 4.9% was measured for the 50% field-produced mixtures (i.e., F-50%-150 and F-50%-200). All extracted asphalt binder contents were within 0.1% of the design binder contents.

TABLE 1 Experimental Program

Property	Specimen Size	Mixture ID							
		F-0%-150	F-15%-150	F-50%-150	F-50%-200	L-0%-150	L-15%-150	L-50%-150	L-50%-200
AASHTO T283 at multiple F–T									
TS versus F–T cycles: 0, 1, and 3 F–T	4.0 × 2.5 in.	X	X	X	X	X	X	X	X
TSR at 1 and 3 F–T	4.0 × 2.5 in.	X	X	X	X	X	X	X	X
Mechanical property: $\lvert E^* \rvert$ versus F–T cycles: 0, 1, and 3 F–T	4.0 × 6.0 in.	X	X	X	X	X	X	X	X
Resistance to thermal cracking TSRST: 0 and 3 F–T	2.0 × 2.0 × 10.0 in.	X	X	X	X	X	X	X	X

NOTE: $\lvert E^* \rvert$ refers to dynamic modulus.

ASPHALT BINDER PROPERTIES

The Superpave® PG binder system (AASHTO M320) was used to grade the virgin binders, RAP binder, and recovered blended binders from the various field-produced and laboratory-produced loose mixtures. All recovered binders were extracted by using a centrifuge (AASHTO T164) and were recovered by using a rotary evaporator (ASTM D5404) and a solution that consisted of 85% toluene and 15% ethanol by volume. The recovered binders were graded by testing them as original, short-term aged through a rolling thin film oven, and long-term aged through a pressure aging vessel. All laboratory-produced loose mixtures were subjected to short-term aging for 4 h at 275°F in a forced draft oven, while field-produced mixtures were not. Figure 1 summarizes the critical temperatures of the various binders. Critical temperatures are temperatures at which a binder just meets the appropriate, specified Superpave criteria. Table 2 summarizes the Superpave PGs. The following observations were made on the basis of the data:

TABLE 2 Superpave PGs of Various Asphalt Binders

Binder	PG
Pen 150-200	58-28
Pen 200-300	52-34
RAP binder	76-10
Recovered from F-0%-150	58-28
Recovered from F-15%-150	58-28
Recovered from F-50%-150	64-16
Recovered from F-50%-200	64-22
Recovered from L-0%-150	58-28
Recovered from L-15%-150	58-28
Recovered from L-50%-150	64-22
Recovered from L-50%-200	58-22

- The low critical temperatures of both virgin binders (i.e., Pen 150-200 and Pen 200-300) were within only 2°C of each other. The high critical temperatures were within 5°C of each other, however.
- In the case of both field-produced and laboratory-produced mixtures manufactured with PG58-28 asphalt binder, the increase in RAP content in a mix resulted in higher and warmer high and low critical temperatures for the recovered asphalt binders, respectively.
- On average, regardless of the RAP content, the recovered blended asphalt binders from field-produced mixtures had warmer critical temperatures than blended asphalt binders recovered from the laboratory-produced mixtures. On average, the high and low critical temperatures of the blended asphalt binders recovered from the field-produced mixtures were higher by about 2.4°C and 1.2°C, respectively. In other words, the asphalt binders recovered from field-produced mixtures were stiffer than those recovered from laboratory-produced mixtures. This indicated that 4 h of aging in a forced draft oven at 275°F did not simulate the aging of the field-produced mixtures.
- The recovered blended asphalt binders from the F-50%-200 and L-50%-200 mixtures were softer than the recovered blended asphalt binders from the F-50%-150 and L-50%-150 mixtures by about 4.0°C and 4.2°C, respectively.

Overall, the recovered binders from the mixtures that contained 0% and 15% RAP met the target grade for the project location of PG 58-28. The recovered binders from the mixtures with 50% RAP met or exceeded the target high PG of 58°C but failed to meet the target low PG of −28°C. This observation was true for both mixtures with and without grade change. The use of softer asphalt binder (i.e., PG

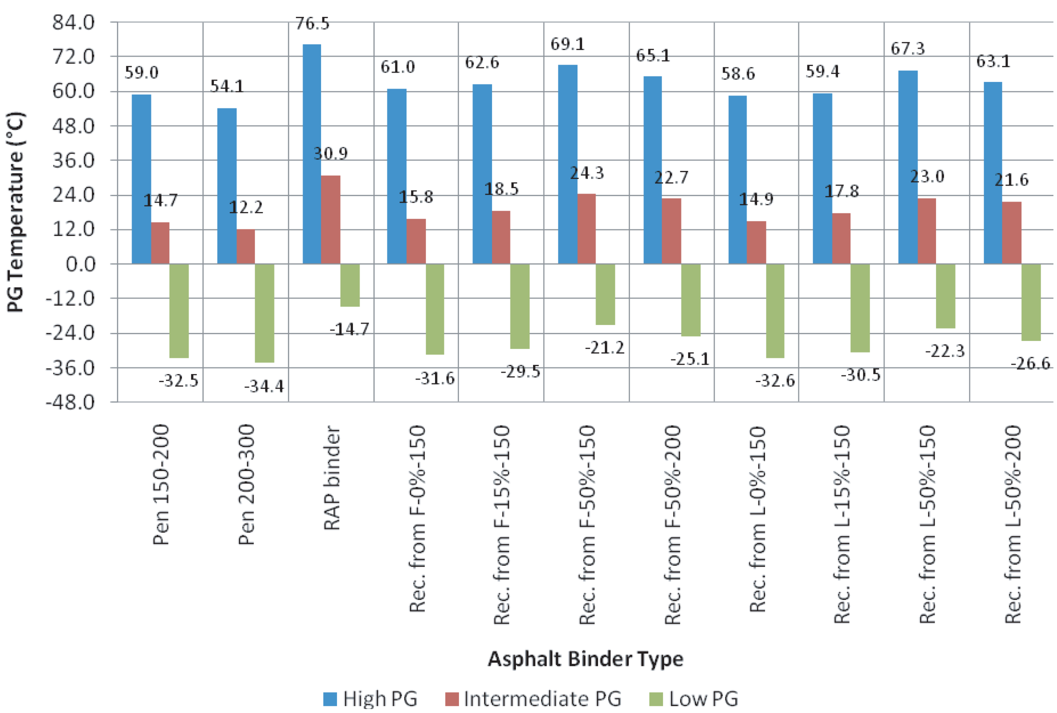


FIGURE 1 Superpave PG temperatures of various asphalt binders.

52-34) with the 50% RAP mix did not improve the low-performance temperature of the blended asphalt binder in the mix sufficiently to meet the target low PG. As mentioned earlier, the low critical temperatures of both virgin binders were only within 2°C of each other. As a reflection of the short supply of different types of asphalt binders in the vicinity of the project, 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 that contain up to 70% RAP.

VERIFICATION OF BLENDING CHART PROCESS

In an effort to assess the effectiveness of the blending chart technique with high RAP content mixtures, the blending chart process was used to estimate the PG of blended asphalt binders at different RAP contents and followed the recommendations of NCHRP Project 09-12 (*3*). The blending chart process has its basis in the following equation, which assumes a linear relationship between the critical temperature and RAP content:

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

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
$\%\text{RAP}_{\text{binder}}$ = percent RAP binder in the RAP expressed as a decimal.

The previously measured PG grades of the virgin and RAP binders were used to estimate the grade of the blended asphalt binder in the mix. The estimated blended binder grades from the blending chart process were compared with the measured PG of the recovered asphalt binders from the corresponding field- and laboratory-produced mixtures. The estimated critical temperatures from the blending chart process (Figure 2) were in the vicinity of the critical temperatures measured for the recovered blended asphalt binders from the various evaluated mixtures. A comparison of the PG from the blending

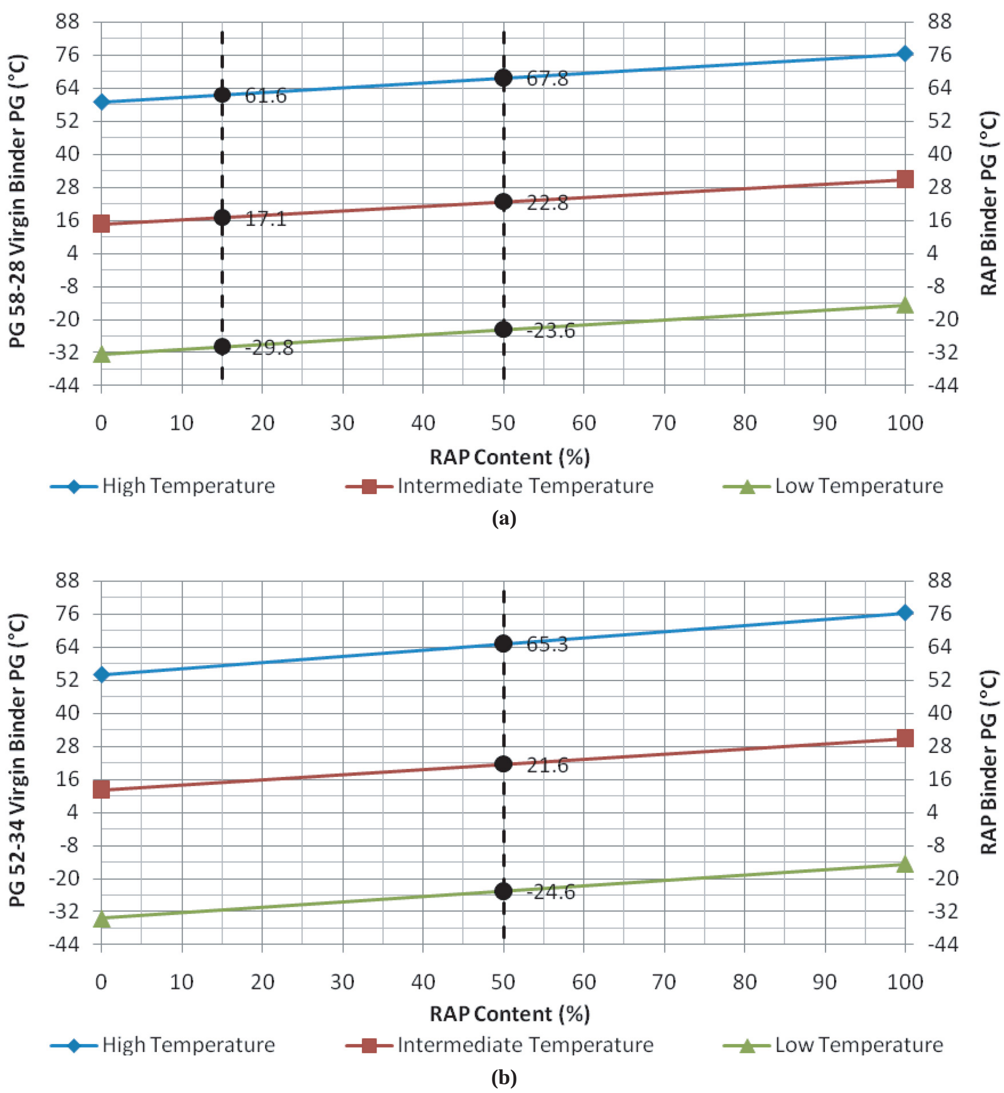


FIGURE 2 Blending chart process for (*a*) PG 58-28 and (*b*) PG 52-34.

chart analysis with the PG of the recovered blended binders in Figure 1 led to the following observations:

- For mixtures with 15% RAP, the estimated grade for the blended asphalt binder was PG 58-28 and consistent with the PG measured from the field- and laboratory-produced mixtures (i.e., F-15%-150 and L-15%-150).
- For mixtures with 50% RAP manufactured with PG 58-28, the estimated grade for the blended asphalt binder was PG 64-22 and was the same as the PG measured from the laboratory-produced mixture L-50%-150.
- For mixtures with 50% RAP manufactured with PG 52-34, the estimated grade for the blended asphalt binder was PG 64-22 and was the same as the PG measured from the field-produced mixture F-50%-200.

Figure 3 shows the comparison between the estimated critical temperatures from the blending chart and the measured ones from the recovered asphalt binders. Overall, a good correlation is observed between the two methods. If it is assumed that the grade for the recovered binder is the true value, the data show that the blending chart process sometimes underestimated or overestimated the critical temperatures by 2°C.

In general, the blended binder failed to meet the target low-temperature grade of −28°C at 50% RAP even when a softer binder (i.e., PG 52-34) was used. As mentioned previously, however, even though the Pen 200-300 is PG-graded as a softer binder than the Pen 150-200, the difference in their low critical temperatures was only 2°C and was not enough to reduce the low critical temperature of the blended asphalt binder in the 50% RAP mix to −28°C.

The findings of this analysis are validated later in this paper in the thermal cracking evaluation of the mixtures by using the TSRST. The resulting fracture temperatures are compared with the low critical temperatures of the associated asphalt binders.

LABORATORY EVALUATION

AASHTO T283 Test at Multiple F–T Cycles

The moisture sensitivity of the various mixtures was evaluated by using the unconditioned and moisture-conditioned, indirect TS along with the indirect TSR at multiple F–T cycles. The multiple F–T cycles followed the procedure outlined in AASHTO T283 at multiple stages. For each mixture a total of 15 samples, 4-in. in diameter, were compacted with the Marshall compactor to 7 ± 0.5% air voids. The samples were divided into three subsets of five samples each: unconditioned subset (i.e., zero F–T), moisture-conditioned subset to one F–T, and moisture-conditioned subset to three F–T cycles. The three F–T cycles represented the moisture-damaged stage, because some of the mixtures started to disintegrate after four F–T cycles. Each mixture was evaluated by using the following procedure:

- Measure the TS of the unconditioned subset (i.e., zero F–T cycles);
- Subject the five samples of each of the second and third subsets to 75% ± 5% saturation;
- Subject the saturated samples to the required number of F–T cycles in which one F–T cycle consists of freezing at 0°F for 16 h, 24 h of thawing at 140°F, and 2 h of conditioning at 77°F;

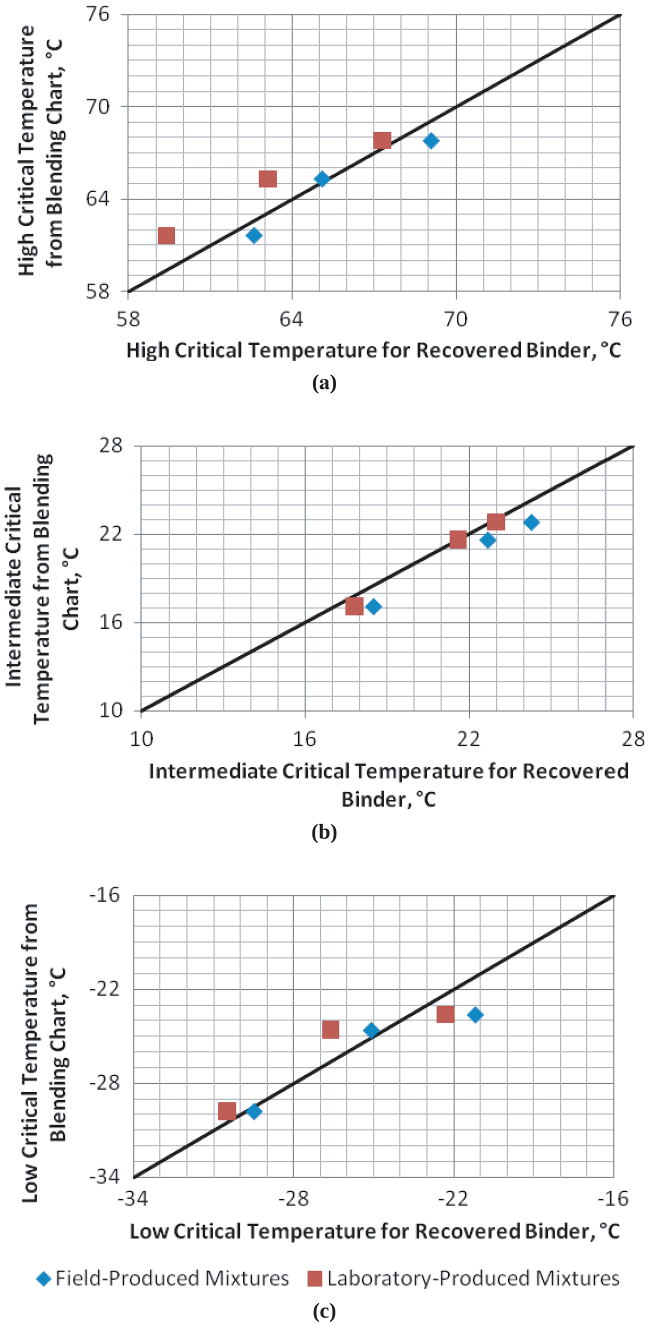
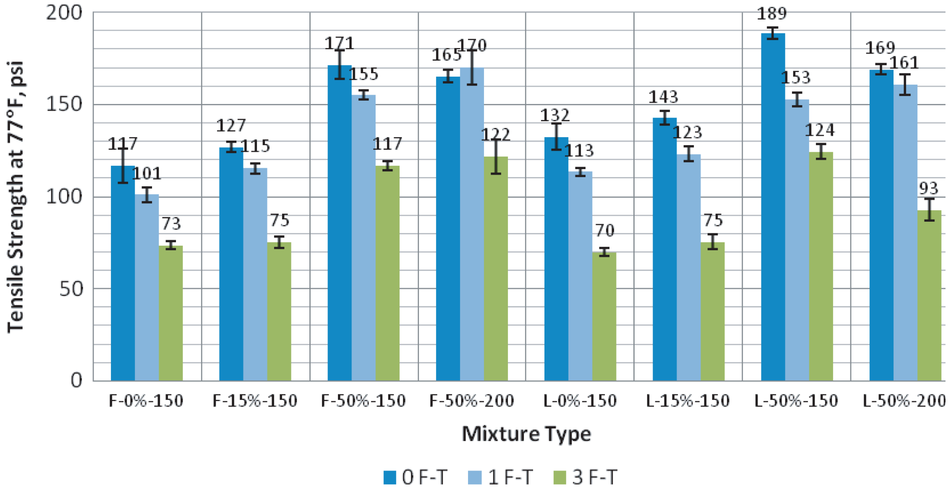


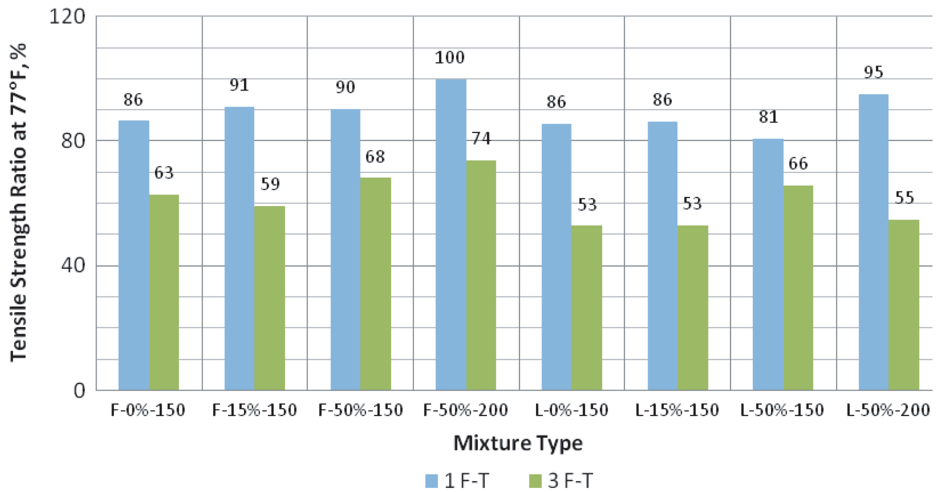
FIGURE 3 Comparison between estimated and measured temperatures: (*a*) high critical, (*b*) intermediate critical, and (*c*) low critical.

- Measure the TS after cycles one and three for the second and third subset, respectively; and
- Calculate the TSR ratio after cycles one and three.

A minimum value of 70 psi at 77°F for the unconditioned TS and 80% for the TSR after one F–T cycle were adopted. Figure 4 summarizes the test results for the TS and TSR for all the field-produced and laboratory-produced mixtures; the error bars represent the 95% confidence intervals. Overlap of the confidence intervals implies the similarity in the measured TS between the mixture types. In summary, the data showed that all mixtures met the minimum TS crite-



(a)



(b)

FIGURE 4 TS values at (*a*) 77°F and zero, one, and three F–T; and TSR values at (*b*) one and three F–T (numbers above bars represent mean values and whiskers represent mean ± 95% confidence interval).

rion of 70 psi at 77°F after one F–T cycle. None of the mixtures required antistrip additives to pass the Superpave moisture sensitivity criterion of 80% TSR after one F–T cycle. All mixtures, however, exhibited a TSR value lower than 80% after three F–T cycles.

The data in Figure 4 show that in the case of both field-produced and laboratory-produced mixtures the addition of RAP increased both the unconditioned and moisture-conditioned TS after one and three F–T cycles. A significant reduction in the TS was observed after three F–T cycles for all mixtures. Consequently, the HMA mixtures with RAP did not exhibit an increase in moisture damage because of the use of RAP when compared with virgin mixes.

A paired mean comparison analysis at a significance level of 0.05 was conducted to determine whether there was any statistically significant difference between the TS of field-produced and laboratory-produced mixtures. The conclusions were as follows:

- In general, the TS of the laboratory-produced mixtures were either similar or statistically significantly higher than the TS of the field-produced mixtures. In other words, the laboratory-produced mixtures were generally found to be stronger and more durable than the corresponding field-produced mixtures.
- Laboratory-produced mixtures with up to 15% RAP exhibited TS significantly higher than the field-produced mixtures at zero and one F–T cycles, while similar TS were observed at three F–T cycles.
- Laboratory-produced mixtures with 50% RAP exhibited TS similar to the field-produced mixtures, except for the laboratory mixture with PG 58-28 binder at zero F–T cycles and the laboratory-produced mixture with PG 52-34 at three F–T cycles, which exhibited significantly higher and lower TS than the field-produced mixtures, respectively.

Overall, the test results on the laboratory-produced mixtures can be used to evaluate the relative resistance of the field-produced mixtures to moisture damage. The ranking of the mixtures based on the data for laboratory-produced mixtures, was similar to the ranking of the field-produced mixtures.

Dynamic Modulus of HMA Mixtures

The AASHTO *Mechanistic–Empirical Pavement Design Guide* uses the dynamic modulus (|*E**|) master curve to evaluate the structural response of the HMA pavement under various combinations of traffic loads, speed, and environmental conditions (*4*). The dynamic modulus test was performed according to AASHTO TP62-07 to generate the dynamic modulus master curve of the various mixtures.

All mixtures were evaluated at the unconditioned (i.e., undamaged condition) and the moisture conditioned (i.e., moisture-damaged condition) stages. The moisture conditioning consisted of subjecting the samples to multiple F–T cycles. A total of three samples from each mix were evaluated by using the following procedure:

- Measure the unconditioned |*E**| master curve (i.e., zero F–T cycles);
- Subject the samples to 75% saturation;
- Subject the saturated samples to multiple F–T cycling in which one F–T cycle consists of freezing at 0°F for 16 h, 24 h thawing at 140°F, and 2 h conditioning at 77°F;
- Subject each sample to the required number of F–T cycles; and
- Conduct |*E**| testing after cycles one and three.

All laboratory-produced loose mixtures were subjected to short-term oven aging for 4 h at 275°F before compaction, while field-produced mixtures were compacted directly. The measured |*E**| properties were examined as a function of F–T cycles.

Figure 5*a* shows the |*E**| for the various field-produced and laboratory-produced mixtures for different F–T cycles at 10 Hz loading frequency, which represents average highway traffic and a temperature of 77°F. The error bars represent the 95% confidence intervals for the average |*E**|.

Examination of the |*E**| data in Figure 5*a* shows that the |*E**| property of both field- and laboratory-produced mixtures became lower as the mixtures were subjected to multiple F–T cycles. At a

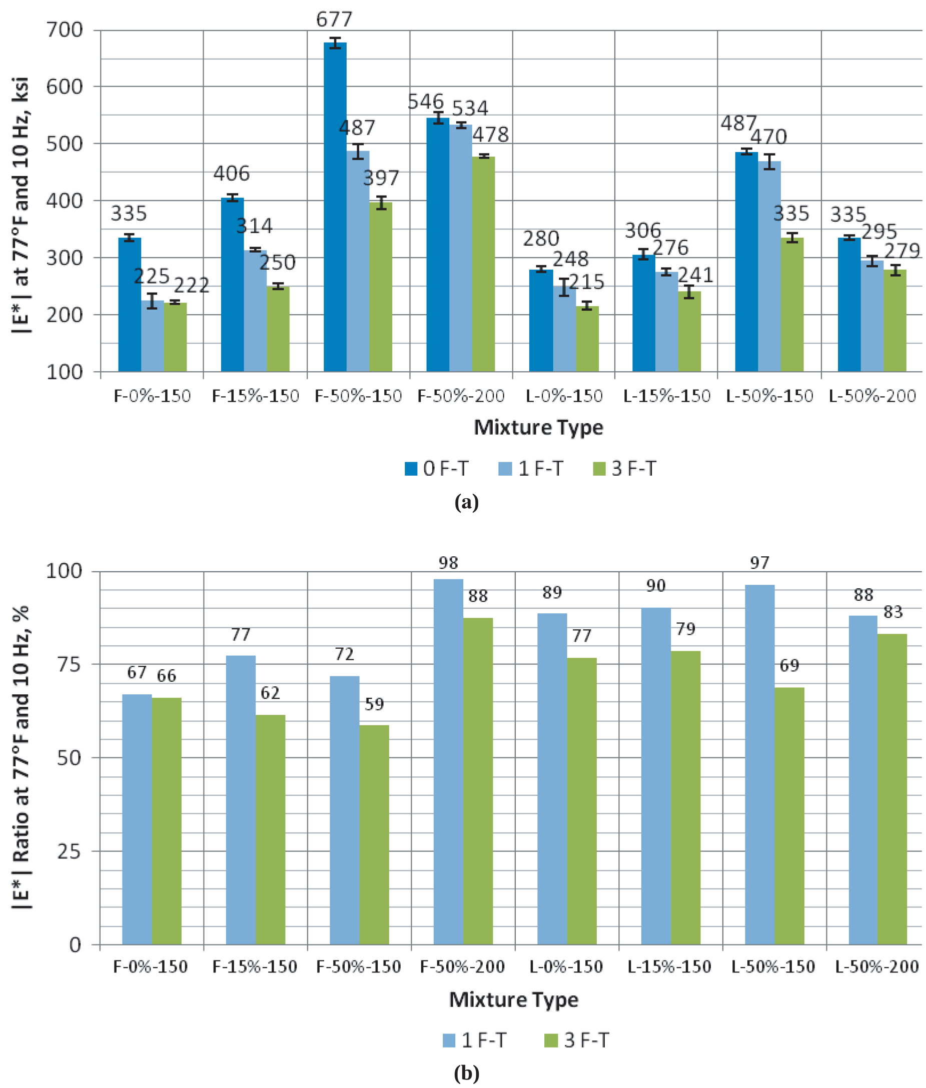


FIGURE 5 |*E**| values at (*a*) 77°F as a function of F–T cycles and (*b*) |*E**| ratio at one and three F–T cycles (numbers above bars represent mean values and whiskers represent mean ± 95% confidence interval).

given F–T cycle, the $|E^*|$ property increased with the increase in RAP content. A reduction in the $|E^*|$ property was observed for the mixtures with 50% RAP and PG 52-34 as compared with the mixtures with 50% RAP and PG 58-28.

A paired mean comparison analysis at a significance level of 0.05 was conducted to determine whether there was any statistically significant difference between the $|E^*|$ at multiple F–T cycles of field-produced and laboratory-produced mixtures. The field-produced mixtures exhibited a significantly higher $|E^*|$ property than the laboratory-produced mixtures, except for the field- and laboratory-produced mixtures with 0% and 50% RAP (without grade change, i.e., with PG 58-28) after one F–T cycle. The field and laboratory-produced mixtures with 0% and 15% RAP after three F–T cycles exhibited similar $|E^*|$ properties. Again, the stiffer $|E^*|$ may have been the result of the difference between the field and laboratory aging. This finding is consistent with the binder data presented earlier, which showed stiffer binders for the field-produced mixtures when compared with the laboratory-produced mixtures.

Figure 5*b* shows the ratios of the moisture-conditioned to the unconditioned $|E^*|$ after one and three F–T cycles. Overall, the data indicate that the retained $|E^*|$ ratio for each mix decreased with the number of F–T cycles. The data for the field-produced mixtures show that the use of RAP in the mix resulted in a higher $|E^*|$ ratio after one F–T cycle when compared with the virgin mix (i.e., 0% RAP), which indicated improvement in the resistance of the mixtures to moisture damage. Except for the F-50%-200 mix, however, the use of RAP in the mix resulted in a lower $|E^*|$ ratio after three F–T cycles when compared with the virgin mix. This indicated that RAP mixtures may be more prone to moisture damage than the virgin mix when multiple F–T cycles are used to assess moisture damage of asphalt mixtures. RAP mixtures nonetheless exhibited a relatively high $|E^*|$ value after three F–T cycles when compared with the virgin mix.

Overall, trends similar to those for the field-produced mixtures were observed for the $|E^*|$ ratios of the laboratory-produced mixtures. The $|E^*|$ ratios of the laboratory-produced mixtures at a given F–T cycle were higher, however, than the corresponding $|E^*|$ ratios of the field-produced mixtures, except for the mixtures with the 50% RAP manufactured with PG 52-34 for which the opposite was observed. The test results on the laboratory-produced mixtures therefore can be used to evaluate the relative resistance of the field-produced mixtures to moisture damage.

The use of the PG 52-34 asphalt binder with the mixtures that contained 50% RAP (i.e., F-50%-200) improved the resistance of the mixture to moisture damage as measured by the $|E^*|$ ratio after three F–T cycles. Even though the Pen 150-200 and Pen 200-300 were graded as PG 58-28 and PG 52-34, respectively, their true high and low PGs were only within 5°C and 2°C, respectively. The observed improvement in moisture damage had more to do with the compatibility of the PG 52-34 virgin asphalt binder with the RAP binder.

Resistance of the HMA Mixtures to Thermal Cracking

The resistances of the various mixtures to thermal cracking were measured by using the TSRST (AASHTO TP10-93). The test cools down a 2 in. × 2 in. × 10 in. beam specimen at a rate of 10°C/h and restrains it from contracting. While the beam is cooling down, tensile stresses are generated because the ends are restrained. An HMA mixture fractures because the internally generated stress exceeds its tensile strength. The temperature and stress at which fracture occurs is referred to as fracture temperature and fracture stress, respectively. The fracture temperature is the temperature at which the asphalt pavement develops a transverse crack as a result of thermal stresses. The fracture stress controls the spacing of the thermal cracks once they occur. It is believed that a higher fracture stress in the TSRST indicates a longer spacing of the transverse cracks in the field.

The resistance of the mixtures to thermal cracking was measured at the long-term-aged, unconditioned (i.e., zero F–T) and moisture-conditioned (i.e., three F–T) stages. The aging of the mixtures followed the Superpave recommendation for long-term aging of HMA mixtures, which consisted of subjecting the compacted samples to 185°F for 5 days in a forced draft laboratory oven. All compacted samples were long-term aged, because low-temperature cracking is a long-term pavement distress mode.

The data in Figure 6 indicate an increase in both unconditioned and moisture-conditioned fracture stresses of the field-produced mixtures when 50% RAP was used. In the case of laboratory-produced mixtures, statistically similar fracture stresses were observed at a significance level of 0.05. An average reduction of 53% was observed for the fracture stress after three F–T cycles. The fracture temperatures of the mixtures manufactured with PG 58-28 asphalt binders decreased with the increase of RAP content. An average reduction of 6°C was observed for the TSRST fracture temperatures at zero and three F–T cycles when 50% RAP was used. Mixtures manufactured with the PG 52-34 asphalt binder, however, exhibited fracture temperatures that were similar to the virgin mixtures (i.e., 0% RAP). Overall, similar fracture temperatures were observed in field-produced and laboratory-produced mixtures at zero and three F–T cycles. Consequently, laboratory-produced mixtures could be used to evaluate the anticipated relative resistance of field-produced mixtures to thermal cracking on the basis of fracture temperatures.

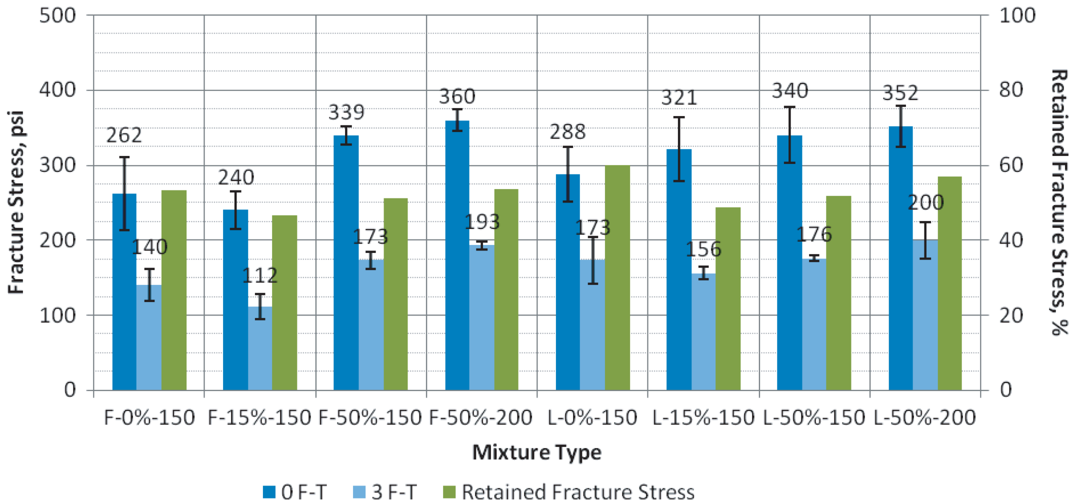
Most of the mixtures after the zero and three F–T cycles met the target low-temperature PG of the asphalt binder (i.e., −28°C). The TSRST fracture temperatures of the mixtures with 0% and 15% RAP were within 1°C of the critical low temperatures of the asphalt binders recovered from the same corresponding mixtures (Figure 1). Mixtures that contained 50% RAP, however, 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.

INITIAL FIELD PERFORMANCE

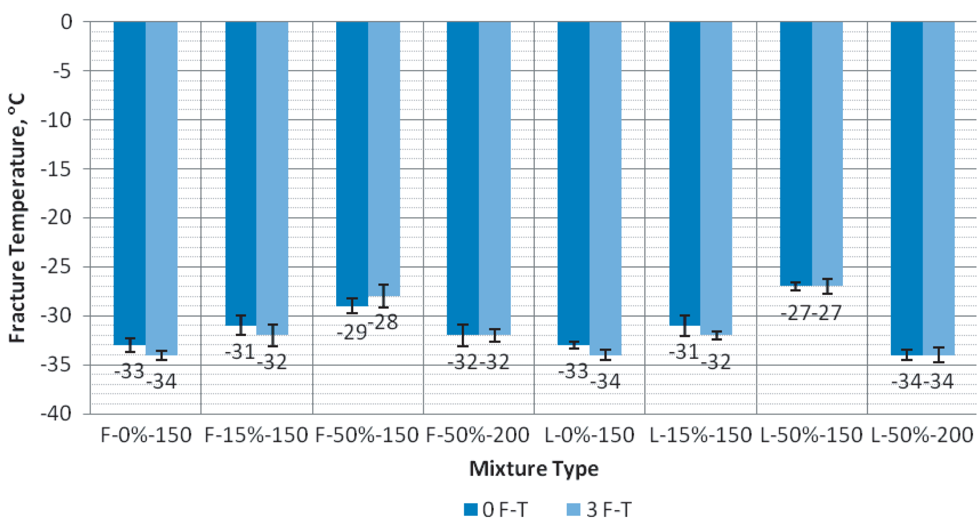
Initial performance of the various RAP sections was excellent at the time of this writing (after about 10 months of service). Neither measurable rutting nor thermal cracking had occurred at either section, and no moisture damage was apparent. Field performance will continue to be monitored over the next few years, and pavement distress survey data will be collected.

FINDINGS AND CONCLUSIONS

This research effort involved an extensive laboratory evaluation of field-produced and laboratory-produced mixtures with RAP content up to 50%. The impact of high RAP content on moisture damage and the thermal cracking resistance of HMA mixtures were



(a)



(b)

FIGURE 6 Thermal cracking characteristics of the various mixtures: (*a*) fracture stresses at zero and three F–T cycles, and (*b*) fracture temperatures at zero and three F–T cycles (numbers above bars represent mean values and whiskers represent mean ± 95% confidence interval).

evaluated by using advanced testing techniques. No change to the virgin binder grade was deemed necessary for mixtures with 15% RAP. The blended asphalt binder from 50% RAP mixtures, however, failed to meet the low target PG of −28°C even when a PG 52-34 was used. The study findings for the evaluated mixtures are as follows:

- Overall, good correlations were observed between the estimated critical temperatures from the blending chart 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.
- In general, the use of multiple F–T cycles provided a better characterization of the mixtures' resistance to moisture damage.
- The AASHTO T283 test at multiple F–T cycles did not show additional reduction in the resistance of the HMA mixtures to moisture damage because of the use of 50% RAP.
- In general, higher or similar TS were observed for the laboratory-produced mixtures when compared with the field-produced mixtures.
- The $|E^*|$ test after three F–T cycles showed additional reduction in the resistance of the HMA mixtures to moisture damage because of the use of 50% RAP. RAP mixtures nonetheless exhibited a relatively high $|E^*|$ after three F–T cycles when compared with the virgin mix.
- No additional reduction in the TSRST fracture stress after three F–T cycles was observed because of the use of RAP.
- The use of 50% RAP without a grade change for the virgin binder resulted in a reduction in the TSRST fracture temperature. Use of a softer virgin binder with the 50% RAP mixture, however, resulted in a similar fracture temperature to that of the virgin mix.
- The TSRST fracture temperatures of the evaluated mixtures with 0% and 15% RAP were within 1°C of the recovered asphalt binder critical low temperatures. The TSRST fracture temperatures

of mixtures with 50% RAP were colder than the recovered asphalt binder critical low temperatures by 5°C to 8°C, however.

- Overall, field-produced and laboratory-produced mixtures ranked similarly in the AASHTO T283, |*E**|, and TSRST tests.

In summary, the HMA mixtures with 50% RAP had an acceptable resistance to moisture damage and a better resistance with PG 52-34 (i.e., Pen 200-300) asphalt binder. The observed difference in the mixtures' resistance to moisture damage had more to do with the compatibility of the PG 52-34 virgin asphalt binder with the RAP binder. The mixtures with 50% RAP exhibited an acceptable resistance to thermal cracking as measured with the TSRST. Again, the mixtures had a better resistance with PG 52-34 asphalt binder. Continued monitoring of the field performance will help validate the findings of this study. It is hoped that the difference between the TSRST fracture temperatures and the recovered asphalt binders' critical low temperatures of the 50% RAP mixes will be explained.

Regardless of the RAP content, the Superpave procedure of 4 h at 275°F in a forced draft oven did not simulate the aging of the evaluated field-produced mixtures.

Overall, all test results showed that laboratory-produced mixtures can be used to evaluate the relative resistance of the field-produced mixtures to moisture damage and thermal cracking. Some differences in the measured values were observed, however, between the field-produced and laboratory-produced mixtures, which may require adjustment to any criteria used.

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