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Moisture Damage Characterization of Warm-Mix Asphalt Mixtures Based on Laboratory-Field Evaluation

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Abstract

This study presents laboratory evaluation integrated with field performance to examine two widely used warm-mix asphalt (WMA) approaches—foaming and emulsion technology. For a more realistic evaluation of the WMA approaches, trial pavement sections of the WMA mixtures and their counterpart hot-mix asphalt (HMA) mixtures were implemented in Antelope County, Nebraska. Field-mixed loose mixtures collected at the time of paving were transported to the laboratories to conduct various experimental evaluations of the individual mixtures. Among the laboratory tests, three (two conventional and one newly attempted) were performed to characterize moisture damage potential which is the primary focus of this study. From the laboratory test results, WMA mixtures showed greater susceptibility to moisture conditioning than the HMA mixtures, and this trend was identical from multiple moisture damage parameters including the strength ratio and the critical fracture energy ratio. Early-stage field performance data collected for three years after placement presented satisfactory rutting-cracking performance from both the WMA and HMA sections, which generally agrees with laboratory evaluations. Although the field performance data indicated that both the WMA and HMA show similar good performance, careful observation of field performance over a

period of years is necessary since moisture damage can be accelerated after rutting or cracking as a later-stage pavement distress.

Keywords: warm-mix asphalt, moisture damage, field performance, laboratory evaluation

1. Introduction

Conventional hot-mix asphalt (HMA) has been the primary material used in asphaltic paving in past decades. Recently, compared to conventional HMA mixtures, warm-mix asphalt (WMA) mixtures have shown great potential and offer benefits not given by HMA mixtures, since the WMA mixtures can produce asphaltic layers at lower temperatures. WMA additives can reduce the viscosity of the binder or mixture; thus, the production and compaction temperatures can be lower, compared to those needed for conventional HMA. One of the primary benefits of WMA is the opportunity to reduce carbon dioxide emissions during the production and compaction of asphalt mixtures. In addition, WMA technology presents other obvious advantages, such as less fuel usage, greater distances that asphalt mixtures can be hauled to paving sites, better working conditions, an extended paving season, and the potential use of more reclaimed asphalt pavement (RAP) materials.

Since the WMA technology has been brought into the United States from Europe in 2002, over the last decade, there has been intense interest among HMA producers, contractors, researchers, and government agencies because of various environmental-financial-engineering benefits. A number of WMA trial projects have been implemented in many states, and researchers have evaluated various types of WMA approaches. Research outcomes and field data monitored from different demonstration sites around the country have generally shown fine performance of WMA mixtures compared to their reference HMA mixtures.

Although the experience to-date with WMA is very promising, potential problems and unknowns still exist. Among those, moisture susceptibility has been a primary concern for some WMA approaches. In general, there are three primary approaches in the production of WMA by introducing WMA additives: foaming techniques, organic (or wax) mixture additives, and chemical binder additives (emulsions). Contrary to the approach based on wax additives, which reduces binder viscosity to decrease mixing-compaction temperatures by melting the additive, the other two approaches (i.e., foaming and chemical additives) have shown concerns with moisture damage [1–3]. This is because they are involved with water in the process. Lower temperatures in the process of mixing and compaction could result in incomplete drying of the aggregate. The resulting water trapped in the coated aggregate may cause moisture damage by compromising the bond between asphalt and aggregate.

Therefore, many studies [1–8] have been conducted to evaluate the moisture susceptibility of WMA mixtures when they are produced through foaming techniques or by adding water-based asphalt emulsions. Some studies [1–3,8] have demonstrated compromising effects of those WMA additives, while others [4–7] presented insignificant effects of the additives compared to HMA mixtures. This contradictory observation seems, at least to a certain extent, due to the lack of science in the conventional laboratory tests conducted,

which are empirical and mostly do not represent fundamental material characteristics. Recently, to overcome the shortcomings of empirical test methods, approaches based on fundamental material properties and mechanisms to assess the moisture susceptibility of asphalt mixtures have been actively pursued. Many studies [9–15] have proposed new concepts associated with key material properties such as fracture parameters, surface energy, diffusion coefficients, and adhesion characteristics to better understand the moisture damage characteristics of asphalt mixtures.

Currently, Superpave system recommends the standard test method, AASHTO T283, to estimate the moisture sensitivity of asphalt mixtures. Moisture damage associated with rutting performance has usually been examined by conducting wheel-tracking-type test methods such as the Hamburg test and asphalt pavement analyzer (APA) test under water. However, these tests present limitations for predicting moisture damage of mixtures under different boundary conditions and to validate the mechanisms of moisture damage in asphalt mixtures because the tests are not based on fundamental material characteristics such as fracture properties. Test methods that are more fundamentally sound need to be incorporated into the study of moisture damage to better estimate material-specific characteristics and damage mechanisms.

In addition to the use of reliable test methods to better estimate the fundamental characteristics related to moisture damage, better evaluation of WMA additives compared to their reference HMA mixtures can be achieved by incorporating the laboratory estimation with actual field performance data. Due to this clear fact, many WMA studies [16–20] have been conducted in an integrated manner by employing both laboratory tests and field evaluation.

2. Objectives and scope of this study

The primary objective of this study is to evaluate the moisture damage potential of different types of WMA mixtures. To that end, two WMA approaches (i.e., a powder additive based on foaming technology and a water-based liquid asphalt emulsion), which are known to be moisture damage susceptible, were implemented in actual pavement sections to monitor field performance. In addition, several laboratory tests to characterize moisture damage potential and mechanisms were conducted to compare the WMA mixtures and their control HMA mixtures. One of the laboratory tests has been newly attempted for this study to better identify material-specific moisture damage characteristics than the other two conventional test methods: the AASHTO T283 and APA test under water. Laboratory test results were then compared to field performance observations from the trial sections.

3. Materials and mixture design

The three most widely used local aggregates (limestone, 2A gravel, and CR gravel) were blended with millings from old pavements and an asphalt binder of PG 64-28. Table 1 illustrates gradation, bulk specific gravity (G_{sb}), and consensus properties (i.e., fine aggregate angularity [FAA], coarse aggregate angularity [CAA], sand equivalent [SE], and flat and elongated [F&E] particles) of the aggregates used in this study. To produce WMA

mixtures, two different WMA additives (0.25% by total weight of mixture for a powder type and 5.0% by weight of asphalt binder for a liquid type additive) were used.

Table 1. Gradation (% passing) and properties of aggregates used

Aggregate sources	%	19 mm	12.7 mm	9.5 mm	#4	#8	#16	#30	#50	#200
Gradation and properties of aggregates used in WMA-P and HMA-P										
Limestone	10	100	74	44	4.9	1.7	1.3	1.2	1.1	0.9
2A Gravel	5	100	99	94	78	25	10	6.4	4.3	1.5
CR Gravel	75	100	100	95	92	66	43	28	17	7
Millings	10	100	99	97	88	67	50	38	23	6.4
Combined gradation	100	100	97.3	90.1	82.2	57.6	37.9	25.2	15.4	6.1
Combined properties	G_{sb} = 2.576, FAA (%) = 45.2, CAA (%) = 85/82, SE (%) = 80, F&E (%) = 0.0									
Gradation and Properties of Aggregates Used in WMA-L and HMA-L										
Limestone	11	100	74	44	4.9	1.7	1.3	1.2	1.1	0.9
2A Gravel	9	100	99	94	78	25	10	6.4	4.3	1.5
CR Gravel	65	100	100	95	92	66	43	28	17	7
Millings	15	100	98	97	92	76	59	44	31	13
Combined gradation	100	100	96.8	89.6	81.2	56.7	37.8	25.5	16.2	6.7
Combined properties	G_{sb} = 2.571, FAA(%) = 45.1, CAA (%) = 91/90, SE (%) = 75, F&E (%) = 0.0									

The powder-type additive is one of the manufactured synthetic zeolites based on a foaming technique for producing WMA mixtures. It holds about 20% water within its crystalline form, which can be released at temperatures above 100°C. The water released creates foam to reduce the viscosity of the binder. The gradual release of water can provide improved workability and lead to mixing temperatures 30–40°C lower than those of conventional HMA. Comparing to the synthetic zeolite WMA additive, a liquid additive is a chemical emulsion to enhance aggregate coating, mixture workability, and compactability. The majority of water in the emulsion flashes off when mixing with hot aggregate. Although the two WMA additives are different in their mechanisms to improve workability by reducing binder/mixture viscosity, the lower mixing-compaction temperatures used when producing warm asphalt may increase the potential of moisture damage, since lower mixing and compaction temperatures can result in incomplete drying of the aggregate. The resulting water trapped in the coated aggregate may cause moisture damage.

The conventional Superpave method of mixture design was used in this study. All the mixtures were designed and compacted targeting intermediate-volume traffic pavements, since the trial sections have been subject to a traffic volume around 3.0–10.0 million equivalent single axle loads (ESALs). All WMA mixtures were produced at around 135°C, while their corresponding HMA control mixtures were mixed at around 165°C. Then, the WMA mixtures were compacted at around 124°C while HMA mixtures were compacted at around 135°C. For the following discussion, the WMA mixtures with the addition of the powder and liquid additive are denoted as WMA-P and WMA-L, respectively. The control HMA mixtures to each WMA mixture are denoted as HMA-P and HMA-L, respectively.

4. Field implementation and evaluation

In 2008, four trial sections, installing the two WMA mixtures (WMA-P and WMA-L) and their control HMA mixtures (HMA-P and HMA-L), were paved in Antelope County, Nebraska. The trial sections are a total of 17.7 km long, connecting Elgin to US Highway 20. Figure 1 illustrates the layout of the trial sections and their schematic representation of pavement thicknesses. As shown, all four different mixtures were intentionally placed at the same project site by neighboring each other with an identical pavement structure where only 76-mm asphalt surface layer varies with each different mixture. This allows one to better compare mixture-specific pavement performance without variability due to environmental conditions, traffic, and structural capacity of pavements. At the time of paving construction, field-mixed loose mixtures were collected and immediately transported to laboratories to conduct various tests including moisture damage susceptibility.
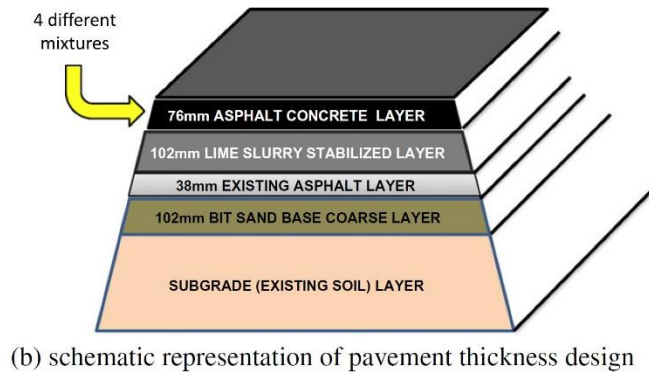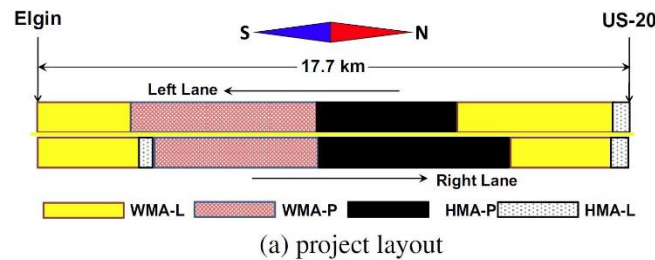

(a) project layout

(b) schematic representation of pavement thickness design

Figure 1. Field implementation of the WMA and HMA trial sections.

After construction, field pavement performance data were annually collected by a performance-monitoring vehicle, which is equipped with a video camera, measuring sensors, and a computer to collect data and video images of the roadway surface. Moving at normal highway driving speeds, it measures transverse and longitudinal profiles of the roadway surfaces. These measurements are then converted into pavement condition indicators such as roughness, rutting, and surface texture. There are two bars in the front and back of the vehicle. The front bar estimates the international roughness index (IRI) in the wheel path with a laser constantly taking readings and averaging them out at 1.5-meter increments.

The rutting is calculated from measurements made by the back bar. This bar shots multiple lasers, takes photographs of the pavement, and reads 1200 points transversely along each lane. In this study, performance data including IRI, rutting, and texture were collected every 9 m along the lane for 3 years (2009–2011) after placement of the four mixtures (i.e., two WMA mixtures and their control HMA mixtures).

5. Laboratory tests and evaluation

Various laboratory tests (i.e., two binder tests and six mixture tests) were conducted to estimate the effects of warm-mix additives on mixture characteristics and pavement performance related to stiffness, rutting, thermal cracking, and moisture damage. Among the eight laboratory tests, three tests were performed to specifically estimate the effects of warm-mix additives on moisture damage characteristics, which is the primary focus of this paper. The three tests include two conventional tests (i.e., the asphalt pavement analyzer (APA) test under water and the AASHTO T283 test) and a newly attempted test based on the nonlinear elastic fracture mechanics with moisture conditioning.

The APA test was performed to estimate the moisture resistance of individual mixtures incorporated with rutting susceptibility. Even though it has been reported that APA testing has presented several limitations [21–23], it is attractive because testing and data analyses are very simple, rapid, and easy to perform. Furthermore, it provides relatively repeatable test results when the testing is well designed and conducted. In this study, the APA testing was conducted on pairs each time, using gyratory-compacted specimens 75 mm high with 4.0 ± 0.5% air voids. To evaluate moisture damage and susceptibility, each specimen of different mixtures was maintained under water at the desired temperature (64°C), and then cyclic loads (hose pressure of 690 kPa and wheel load of 445 N) were applied. Final rut depths at the completion of 8000 cycles were recorded.

Along with the APA test, a standard test, AASHTO T283, was performed as another conventional laboratory test to evaluate the moisture susceptibility of WMA-HMA mixtures. Numerous studies have employed this test method for assessing the moisture sensitivity of various mixtures due to its simplicity, even if this laboratory evaluation has a relatively low correlation with actual field performance [24,25]. A Superpave gyratory compactor was used to produce test specimens with a diameter of 150 mm and a height of 95 ± 5 mm, and with 7 ± 0.5% air voids. Two subsets of specimens were fabricated and tested. One subset was tested under dry conditions for indirect-tensile strength. The other subset was subjected to partial vacuum saturation (with a degree of saturation of 70–80%) and a freeze cycle, followed by a warm-water soaking cycle, before being tested for indirect-tensile strength at a constant strain rate of 50 mm/min. The average tensile strength values of each subset were used to calculate the tensile strength ratio (TSR), which is the numerical index of the resistance of asphalt mixtures to moisture damage.

The two conventional tests are somewhat limited to address fundamental characteristics of mixtures. To further evaluate the effects of WMA additives on material-specific fracture characteristics incorporated with moisture damage, a classical fracture mechanics-based test was attempted in this study as a parallel laboratory evaluation. Contrary to the APA and AASHTO T283, the fracture mechanics-based test can provide better insights to the

damage mechanisms, since it can obtain fundamental damage-associated material characteristics such as fracture toughness, cohesive strength, and stress-separation curves.

Among various available fracture test methods, a semi-circular bend (SCB) fracture test was chosen for this study due to several practical benefits. The SCB testing is very simple to perform, and multiple testing specimens can be easily prepared via a routine process of mixing and Superpave gyratory compacting of mixtures. Furthermore, the SCB geometry is even more preferred when one considers fracture testing of field cores which are mostly in circular shape. The SCB test was originally proposed by Chong and Kuruppu [26,27] and has been used by many researchers [28–31] to identify the fracture characteristics of various types of engineering materials. The SCB test has shown sensitive test results depending on the testing conditions (temperatures and moisture), materials used in the mixtures, and loading conditions (e.g., rates).

In the preparation of SCB testing specimens, a Superpave gyratory compactor was used to produce tall compacted samples (150 mm in diameter and 125 mm high). Then, one slice with a diameter of 150 mm and a height of 50 mm was obtained by removing the top and bottom parts of the tall sample. The slice was cut into halves to yield one SCB specimen with a notch length of 25 mm and another specimen with a notch length of 20 mm. By using the two different initial notch lengths, one could identify fracture parameters as discussed later.

SCB fracture tests of each mixture were performed with two subsets: moisture conditioned with one freeze-thaw (F–T) cycle and unconditioned (dry). By doing so, test data and resulting fracture parameters can be used to estimate fracture process behavior and resistance to the fracture of each mixture with and without moisture damage. Comparing analysis results at dry condition simply enables one to investigate the fracture resistance of each mixture without moisture damage, and moisture damage susceptibility of each mixture can then be assessed by comparing ratios of the fracture parameters of the conditioned subset to the parameters of the unconditioned subsets. The moisture conditioning was performed by applying the same F–T cycling process designated in the AASHTO T283.

Individual SCB specimens were placed inside the environmental chamber of the testing station to reach temperature equilibrium targeting 21°C. Following the temperature equilibrium step, specimens were subjected to a simple three-point bending configuration with a monotonic displacement rate of 200 mm/min. applied to the top centerline of the SCB specimens. The relatively fast loading rate (200 mm/min.) was applied in this study to induce brittle fracture, since test results are analyzed based on the elastic fracture mechanics theory. Metallic rollers separated by a distance of 122 mm (14 mm from the edges of the specimen) were used to support the specimen. The reaction force at the loading point was monitored by the data acquisition system. Opening displacements at the mouth and at the tip of the initial notch were also monitored with high-speed video cameras and a digital image correlation (DIC) system. Figure 2 shows the SCB testing set-up, two pairs of gauge points attached on the specimen surface for the DIC analysis, and a SCB specimen fractured after the testing was completed.
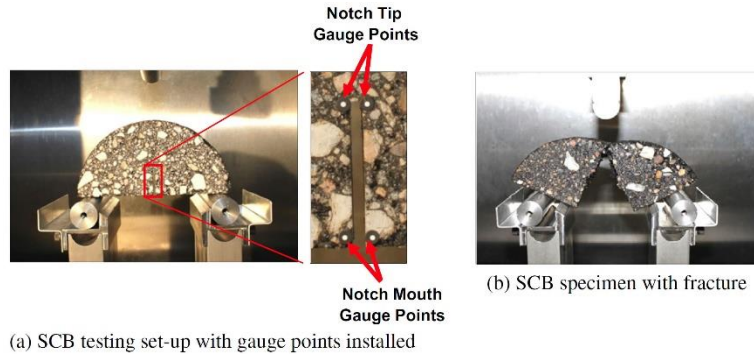
(a) SCB testing set-up with gauge points installed

(b) SCB specimen with fracture

Figure 2. SCB fracture test: initial testing setup and a specimen fractured after testing.

6. Analysis of SCB test results

For the analysis of data after SCB testing, the loads and load point displacements (LPD) were recorded as the loading time varied. Notch tip opening displacements (NTOD) were also captured by the DIC process. Typical load-LPD curves and the NTOD-LPD curves resulting from two different initial notch depths (20 and 25 mm in this study) are schematically shown in figure 3a and b.

The critical value of the *J*-integral (J_c) obtained from the two different load-LPD curves can be calculated by the following equation:

$$J_c(u) = \left(\frac{A_1}{t_1} - \frac{A_2}{t_2}\right) \cdot \frac{1}{a_2 - a_1} \tag{1}$$

where *u* is the load point displacements (LPD), A_1, A_2 the areas under the load-LPD curves (as shown in fig. 3a) for specimens with notch depth of 20 mm and 25 mm, respectively, t_1, t_2 the SCB specimen thicknesses, which are identical (i.e., 50 mm) in this study, and a_1, a_2 is the initial notch lengths ($a_1 = 25$ mm, $a_2 = 20$ mm).

(a) Load (*P*) – LPD (*u*) curves   (b) NTOD (*w*) - LPD (*u*) curves   (c) resulting σ – NTOD (*w*)
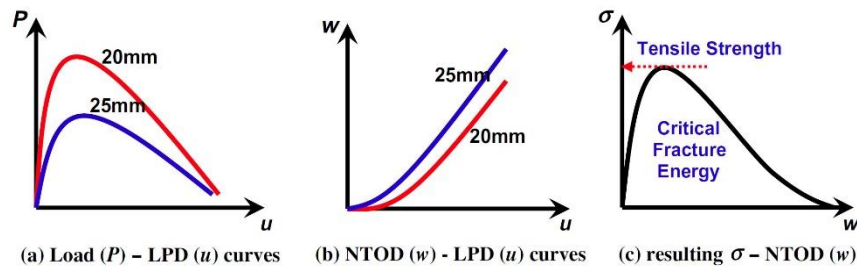
Figure 3. Schematic representation of typical SCB fracture test results.

The value of J_c can also be evaluated in terms of crack tip separation (*w*) as follows [32]:

$$J_c(w) = \int_0^{w_c} \alpha(w)\, dw \tag{2}$$

where w_c is the critical crack tip separation, and σ is the tensile stress at a crack tip.

If $w < w_c$ (i.e., noncritical case), Eq. (2) becomes [32]:

$$J(w) = \int_0^w \alpha(w)dw \tag{3}$$

By taking the derivative with respect to w (NTOD), equation (3) can be written as below to obtain the tensile stress at a crack tip $\sigma(w)$:

$$\alpha(w) = \frac{\delta J(w)}{\delta w} = \frac{\delta J(u)}{\delta u} \cdot \frac{\delta u}{\delta w} \tag{4}$$

Based on equation (4), the tensile stress at a crack tip $\sigma(w)$ can be determined by substituting the integral form of A_1 and A_2 (areas under the load-LPD curves for specimens 1 and 2, respectively) into equation (1) and differentiating them with respect to load point displacements (u). This modification results in [32]:

$$\alpha_i(w_i) = \frac{\delta J_i(u_i)}{\delta u_i}\frac{\delta u_i}{\delta w_i} = \frac{1}{a_2-a_1}\left(\frac{P_1(u_i)}{t_1} - \frac{P_2(u_i)}{t_2}\right)\frac{\delta u_i}{\delta w_i} \tag{5}$$

where $P_1(u_i)$ and $P_2(u_i)$ are the loads corresponding to the values of u_i for specimens 1 and 2, and u_i ($i = 1, 2, \ldots, n$) is the values of the LPD at different intervals.

It can be noted that, by using equation (5), which is the modified expression of equation (4), the tensile stress at a crack tip $\sigma(w)$ can be easily computed because $\delta J(u)/\delta u$ and $\delta u/\delta w$ can be obtained from the curves of load-LPD (P–u) and NTOD-LPD (w–u), as exemplified in figure 3a and b, respectively. As mentioned earlier, the loads (P), load point displacements (LPD), and notch tip opening displacements (NTOD) were all recorded by the testing equipment and the DIC system as the loading time varied. With the data presented in figure 3a and b, the resulting σ–w curve can be obtained as shown in figure 3c. This modification enables one to avoid directly defining $J(u)$ curve and then differentiating the function of $J(u)$ which is usually a polynomial regression function [32].

From the figure (i.e., fig. 3c), two key fracture parameters—tensile strength σ^f, which is a peak value of the $\sigma(w)$ curve and the critical fracture energy J_c, which is the area under the $\sigma(w)$ curve—can then be identified. Moreover, the shape of the $\sigma(w)$ curve presents entire fracture processes and cracking mechanisms of the material because the curve represents how the material resists to the increasing physical separation until failure. Analysis results and fracture characteristics at dry condition can be used to examine the fracture resistance of each mixture without moisture damage. The resistance of each mixture to moisture damage can then be assessed by comparing the ratio of the tensile strength (or critical fracture energy) of the conditioned subset (with one F–T cycle) to the tensile strength (or critical fracture energy) of the unconditioned subsets.

7. Results and discussion

Table 2 summarizes volumetric parameters of each mixture and the necessary specification requirements. As can be seen in the table, the mixture volumetric parameters between each

WMA mixture and its control HMA mixture were similar, and generally satisfied the required mixture specifications.

Table 2. Volumetric mixture design parameters

	% Binder	% Air voids	% VMA[1]	% VFA[2]
Required specification	N/A	3–5	≥ 14	65–75
WMA-P	5.2	4.0	13.9	71.0
HMA-P	5.4	4.1	13.8	69.9
WMA-L	5.2	3.3	13.2	75.1
HMA-L	5.1	3.9	13.2	70.8

Note: VMA[1]: voids in mineral aggregates, VFA[2]: voids filled with asphalt

Figure 4 presents the APA performance testing results for all four mixtures. As shown, the rut depth values after 8000 cycles did not differ from mixture to mixture. All mixtures provided satisfactory performance in terms of the typical failure criteria: 12-mm rut depth. APA testing did not show any sensitivity to the effect of WMA additives related to moisture damage.
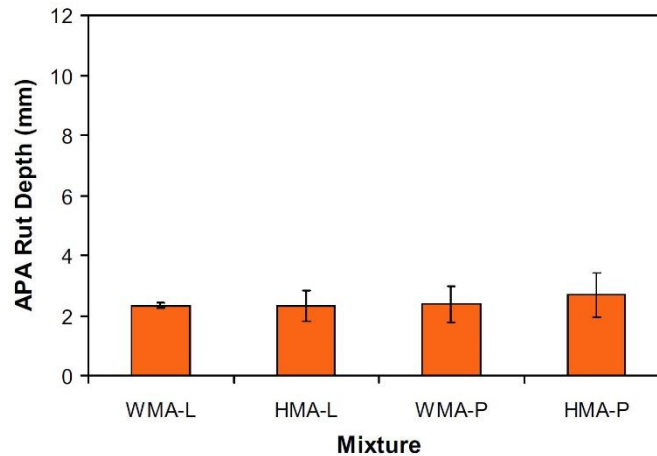

Figure 4. APA test results with moisture (rut depths at 8000 cycles).

Figure 5a shows the average tensile strengths with their error bars (representing standard deviations) of each mixture at dry and at moisture conditioned with one F–T cycle. It can be observed from the figure that, for both types of WMA mixtures at dry condition, fracture resistance of WMA mixtures was not quite different from the fracture resistance of HMA mixtures, while both WMA mixtures presented greater susceptibility to moisture conditioning than their counterpart HMA mixtures.
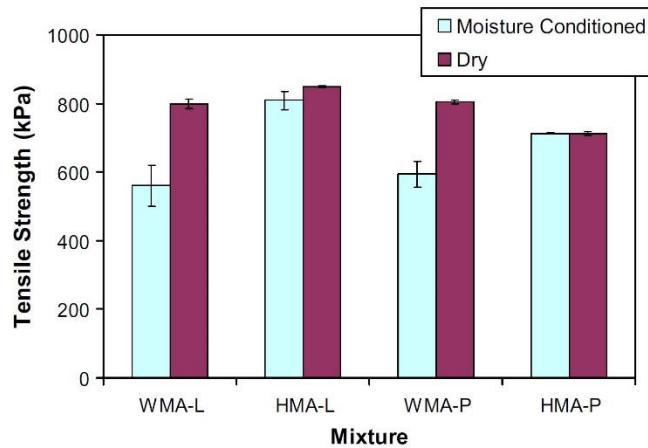
(a) tensile strength values of each mixture
at two different conditions
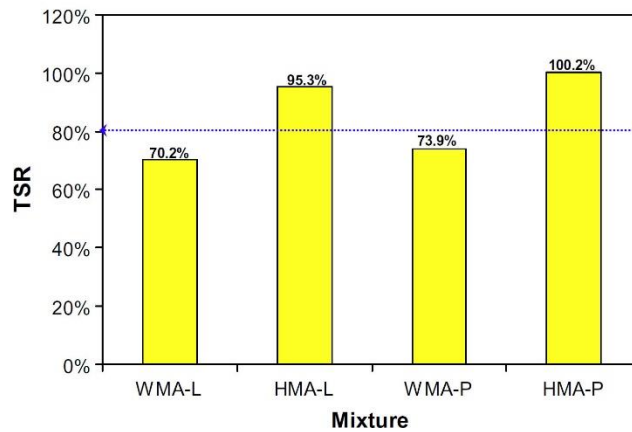
(b) tensile strength ratios of mixtures

Figure 5. AASHTO T283 test results.

Average tensile strength values of each mixture were then used to calculate tensile strength ratios (TSRs), which are plotted in figure 5b. The TSR represents a reduction in the mixture integrity due to moisture damage. A minimum of 80% TSR has been typically used as a failure criterion. As seen in the figure, TSR values of all WMA mixtures are below the failure criterion. This indicates that the addition of WMA additives increased the potential of moisture damage, as was also found by other similar studies [1–3,8]. The higher moisture damage potential of WMA mixtures might be due to lower mixing and compaction temperatures, which can cause incomplete drying of the aggregate. The resulting water trapped in the coated aggregate may act as a detrimental factor causing higher moisture susceptibility.

The SCB fracture tests were analyzed based on the procedure presented in the previous section to ultimately produce the $\sigma(w)$ curves of individual mixtures with and without

moisture conditioning. Then, the fracture resistance of mixtures can be examined by comparing the $\sigma(w)$ curves from dry subsets, and moisture damage susceptibility of mixtures can then be assessed by comparing the ratios (i.e., fracture parameters from the conditioned subset divided by fracture parameters from the unconditioned subset).

Fracture test results in the form of $\sigma(w)$ curves are presented in figure 6a for the WMA-L and HMA-L and in figure 6b for the WMA-P and HMA-P, respectively. In the figures, $\sigma(w)$ curves with and without moisture conditioning by the one cycle of F–T are compared, so that the strength ratio or critical fracture energy ratio of conditioned subsets to unconditioned subsets can be obtained. Resulting ratios are plotted in figure 7.
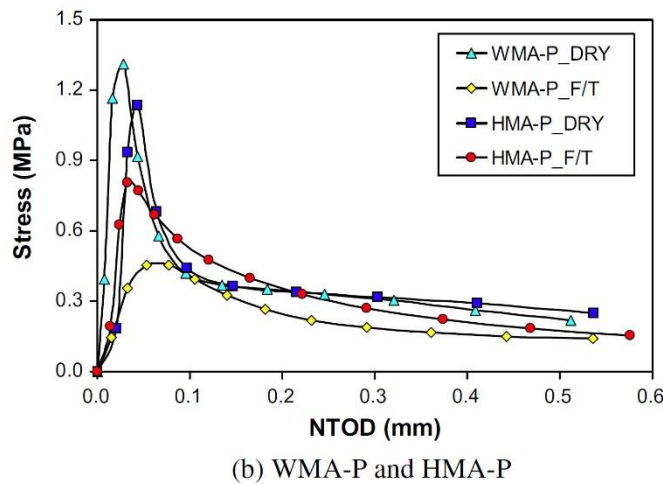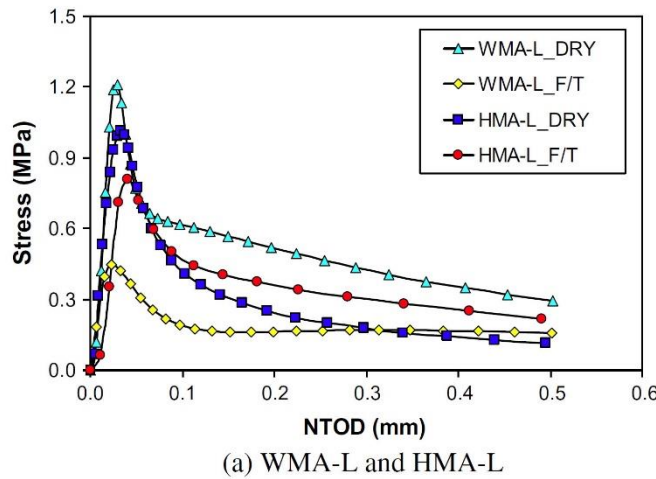

(a) WMA-L and HMA-L

(b) WMA-P and HMA-P

Figure 6. $\sigma(w)$ curves resulting from the SCB fracture tests.

Comparing analysis results from only dry subsets, figure 6 indicates that, for both types of WMA mixtures herein, fracture resistance of WMA mixtures are similar to or even better

than their counterpart HMA mixtures. However, WMA mixtures presented greater susceptibility to moisture conditioning than the HMA mixtures, and this trend was identical for the two different moisture damage parameters: strength ratio and critical fracture energy ratio, as demonstrated in figure 7. The similar fracture resistance between WMA and HMA mixtures at dry condition and the more detrimental effects of moisture conditioning on the WMA mixtures have also been observed from the AASHTO T283 TSR tests. The SCB fracture tests herein verified the observations from the AASHTO T283 tests at both dry state and moisture-conditioned. With the limited data and analysis results from this SCB fracture and the AASHTO T283, it can be implied that WMA mixtures can resist to fracture at least similar to HMA mixtures without moisture, however the fracture resistance of the WMA mixtures can be degraded more sensitively when moisture damage is involved.
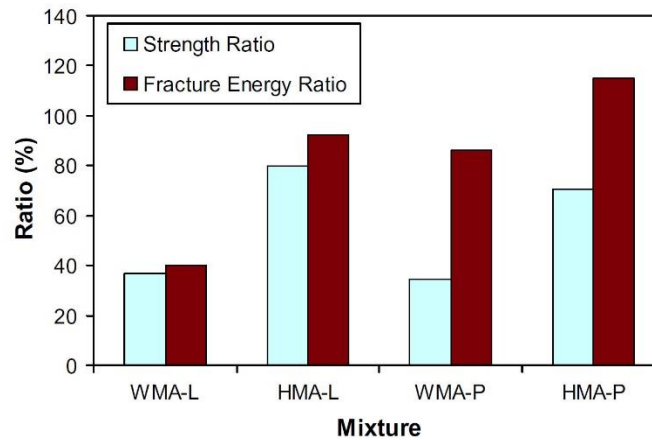

Figure 7. Fracture parameter ratios of each mixture.

The field performance data collected from 2009 to 2011 are summarized in figure 8. Each figure shows the average values and their standard deviations (indicated by error bars) obtained from multiple measurements made at different locations—L (left) and R (right). The typical failure criteria for rut depth and international roughness index (IRI) are 12 mm and 4 m/km, respectively. As apparent in the figures, the rut depth and IRI of both the WMA and HMA sections were similar and small compared to the typical failure criteria. Any major cracking or other failure modes have not been observed yet in the trial sections. Similar field performance between WMA and HMA mixtures to rutting and cracking is generally in good agreement with laboratory test results presented in this paper such as the APA results and fracture test results from dry subsets and other test results that are not included in this paper but are presented elsewhere [33]. In the report [33], the two WMA mixtures (WMA-L and WMA-P) did not show any significant differences from their HMA counterparts in the viscoelastic mixture stiffness and rutting potential that was evaluated by performing the dynamic modulus test and uniaxial static creep test, respectively.
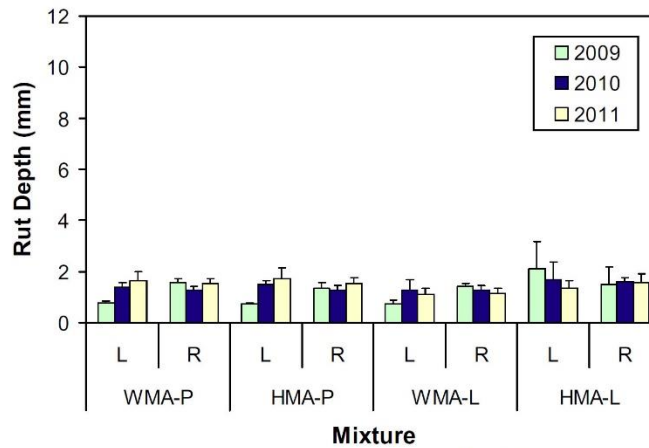
(a) average rut depths and standard deviations
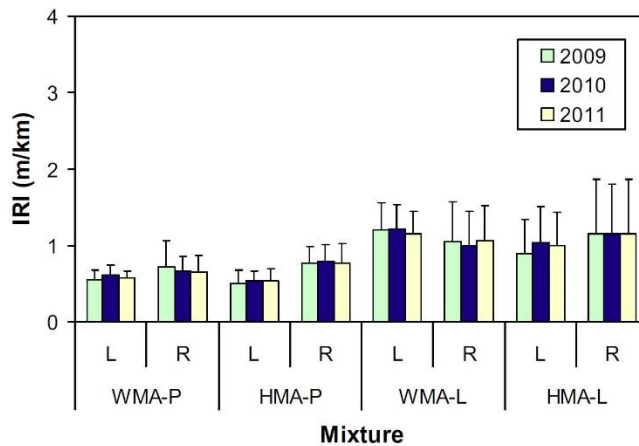
(b) average IRI values and standard deviations

Figure 8. Field performance monitoring results for 3 years.

The field performance data indicate that, for the three-year public service after placement, both WMA and HMA trial sections showed similar good performance without raising any major concerns. However, since moisture damage is usually accelerated after rutting and/or cracking in pavements as a later-stage distress, and the two laboratory tests (i.e., AASHTO T283 and SCB fracture test) in this study present potential concern, it seems somewhat premature to make any definite conclusions about the effects of WMA additives on moisture damage at this stage. Continued evaluation of field performance over the years is necessary.

8. Summary and conclusions

Two widely used WMA approaches were evaluated. For a more realistic evaluation of the WMA approaches, trial pavement sections of the WMA mixtures and their counterpart

HMA mixtures were implemented in Antelope County, Nebraska. Field-mixed loose mixtures were collected at the time of paving and were transported to the laboratories to conduct various evaluations of the individual mixtures. Among the laboratory tests, three (two conventional and one new) were conducted to characterize moisture-damage potential which is the primary focus of this study. These laboratory test results were then incorporated into three-year field performance of the WMA and HMA trial sections. Based on the test results and field evaluation, the following conclusions can be drawn:

- Among the three laboratory tests to evaluate moisture susceptibility, APA tests under water did not show any clear moisture damage sensitivity between the mixtures. All four mixtures presented satisfactory performance, according to the typical 12-mm failure criterion. On the other hand, two other moisture damage tests—the AASHTO T283 test and the SCB fracture tests with moisture conditioning—demonstrated an identical trend between WMA and HMA. WMA mixtures showed greater susceptibility to moisture conditioning than did the HMA mixtures, and this trend was confirmed by multiple moisture damage parameters, such as the strength ratio and the critical fracture energy ratio.

- In the fabrication process of SCB testing specimens, cutting and notching of the specimens was conducted before moisture conditioning, which may make the crack tip more sensitive to moisture damage as compared to the moisture conditioning of bulk specimens. Further investigation to the effects of surface characteristics and geometry of specimens on moisture damage sensitivity is recommended.

- The field performance data collected from 2009 to 2011 showed that both the WMA and HMA performed well. No cracking or other failure modes were observed in the trial sections, and the rut depth and pavement roughness of WMA and HMA sections were similar. The field performance data and observations are in good agreement with laboratory test results presented in this paper and other test results to estimate mixture stiffness and rutting potential.

- Although the field performance data indicate that both WMA and HMA mixtures showed similar good performance, considering the potential concern from the laboratory evaluations, it is premature to make any definite conclusions to the effects of WMA additives examined in this study on moisture susceptibility at this stage. This is because moisture damage can be severely activated after rutting and/or cracking occurs. Careful observation of field performance over the years is therefore necessary. It is in progress by the authors, and any new outcomes will be presented.

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