PROPERTIES OF FOAMED WARM-MIX ASPHALT INCORPORATING RECYCLED ASPHALT PAVEMENT FROM TWO FIELD PROJECTS – CASE STUDIES

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ABSTRACT
This study evaluated the volumetric and mechanical properties of foamed WMA plant-produced mixtures obtained from two field projects in Reno, Nevada including 15% RAP. The Chism Street and Bravo Avenue mixtures were produced with an unmodified PG64-22 and a polymer-modified PG64-28 asphalt binders, respectively. This study addressed the impact of short-term oven aging on the Marshall properties and sample reheating on the mechanical properties of the foamed WMA. The mixtures were also evaluated for their resistance to moisture damage, permanent deformation and thermal cracking using dynamic modulus, repeated load triaxial (RLT) and thermal stress restrained specimen testing (TSRST), respectively. The results indicate that the Marshall air voids, flow and stability of the unmodified foamed WMA mixture are met when short-term aged in a sealed container at the measured lay-down temperature and compacted within four hours of manufacturing at the plant. However, the Marshall air voids for the polymer-modified foamed WMA mixture were difficult to meet when compacted at the WMA lay-down temperature regardless of the short-term oven aging period. Overall, the WMA mixture showed no significant additional reduction in moisture damage resistance although the reverse was true for permanent deformation resistance. The polymer-modified mixtures exhibited higher resistance to moisture damage in comparison to unmodified mixtures. The WMA generally showed better resistance to thermal cracking than the corresponding HMA mixture. Conducted condition surveys showed no distresses in the WMA pavements on Chism Street and Bravo Avenue despite their relatively lower rutting resistance observed in the laboratory.
INTRODUCTION

Conventionally, hot mix asphalt (HMA) has been used extensively in paving applications; however, in recent years, the interest in using warm mix asphalt (WMA) has been increasing due to rising energy costs and more stringent environmental regulations. WMA mixtures are produced, laid and compacted at temperatures that are 15 to 55°C lower than their conventional HMA counterpart. Several WMA technologies, such as foaming (water-based) processes, wax-based additives, emulsion-based products, and surfactants are currently being used to produce WMA mixtures. In spite of the technology used to produce a WMA mixture, the reduction in temperature is anticipated to have significant benefits such as reduced energy consumption, reduced plant emissions, better workability, better compaction during construction, and the capability for further hauling or seasonally later applications.

Regardless of all the promising benefits and advantages that WMA has to offer, the produced mixtures must still perform well in field applications as would be expected from HMA mixtures. The produced WMA mixtures should still have acceptable mechanical properties including high resistance to moisture damage, permanent deformation and thermal cracking as well as pliable to the increasingly popular use of recycled asphalt pavement (RAP) in the mixtures.

There have been concerns that the reduced production temperatures may impair the hardening of the asphalt binder, or hinder the evaporation of moisture from aggregates, leading to an increased occurrence of rutting and an increased incidence of moisture damage in asphalt concrete pavements, respectively. There may also be further asphalt mixture interactions that affect other performance properties of an asphalt concrete pavement depending on the warm-mix technology.

Several research studies have consistently reported that WMA shows greater potentials for moisture damage and rutting than conventional HMA when evaluated using conventional laboratory procedures (1, 2, 3, 4). However, reported field data showed generally good performance, particularly with respect to moisture damage and rutting with premature failures often being associated with construction issues or plant malfunctions (1, 2). At the time of construction, the WMA mixtures showed lower tensile strength than HMA; however, after two years in service, the tensile strength of the WMA were similar to the HMA mixtures (1, 5, 6).

Consequently, a successful implementation of a WMA technology should entail both laboratory and field evaluation, through demonstration or trial projects, to ensure proper performance.

Among the various WMA technologies available nowadays, an increase use of the water-based technologies is being observed in the United States, particularly with the Double Barrel® green and the Ultrafoam GX™ foaming systems. Both of the systems utilize proprietary foaming nozzles to inject a percentage of water (typically 1-2% by weight of binder) into the asphalt binder flow line. The introduction of water causes an immediate volume increase of the asphalt binder, or the foaming effect, as the liquid surface area increases. The water also temporarily lowers the asphalt binder viscosity while improving uniform aggregate coating and mixture workability at the lower WMA temperatures.

In an attempt to assess the use of foamed WMA mixtures with local materials in Northern Nevada, the City of Reno (COR) and the Regional Transportation Commission (RTC) each constructed a field project in 2009 and 2010, respectively. Both projects used the Ultrafoam GX™ technology to produce WMA which contained 15% RAP. Plant-produced mixtures were
sampled during production and were evaluated in the laboratory for volumetric and mechanical properties.

OBJECTIVES

The specific objectives of this study are summarized as follows:

- Evaluate the rheological properties of the recovered asphalt binders
- Evaluate the impact of short-term oven aging on the Marshall properties of WMA mixtures.
- Evaluate the resistance of WMA mixtures to moisture damage, permanent deformation and thermal cracking.
- Evaluate the impact of sample reheating on the mechanical properties of WMA mixtures in comparison to corresponding HMA mixtures.

DESCRIPTION OF PROJECTS

In June 2009, a foamed WMA road section with an unmodified PG64-22 asphalt binder was placed along Chism Street and another with a polymer-modified PG64-28 asphalt binder was placed along Bravo Avenue in August 2010; both in Reno, Nevada. The mixtures obtained from the two field projects were subjected to various tests in an extensive collaborative evaluation effort between the University of Nevada, Reno (UNR) and Granite Construction, Inc. Each of the field mixtures were produced at the Granite Construction plant in Lockwood, Nevada. The WMA mixtures were produced using the Ultrafoam® process at an average water injection rate of 1.25% by weight of binder. Each of the mixtures contained 15% RAP and 1.5% hydrated lime by the dry weight of virgin aggregate added dry on damp aggregate. At both locations the mixtures were placed into a total thickness of 6 inches with two 3 inch lifts. Only the Bravo Avenue project included a control plant-produced section of HMA with 15% RAP.

On both projects, the temperature of the WMA, when leaving the plant, ranged between 129 and 135°C. An average lay-down temperature of 121 and 124°C was determined at both locations and consequently used in all WMA laboratory evaluations. The HMA mixture on Bravo Avenue had a lay-down temperature of 152°C. Upon construction, no issues related to the use of foamed WMA with RAP were observed and the required in-place densities were met on both projects.

EXPERIMENTAL PROGRAM

Plant-produced mixtures were sampled at the plant at the discharge time into tightly-sealed buckets and brought back to the laboratory for evaluation. Additionally, in the case of Chism Street, cold feed aggregates, RAP and asphalt binder were sampled during production for laboratory reproduction of the HMA mixture to serve as a control, since no HMA field mixture was produced for this project.

HMA samples are often reheated for a variety of acceptance and performance tests. However since the Ultrafoam® WMA technology produces foamed asphalt, which is an irreversible component, reheated samples should not be used for volumetric acceptance. Nevertheless, reheated samples can be used to evaluate the mechanical properties of WMA mixtures provided the reheating effect on WMA is similar to that for HMA.
Each of the WMA mixtures were tested at the Granite Construction plant laboratory for Marshall mix design properties after 0 (i.e. right at delivery), 2, 4 and 15 hours of aging in a sealed container at the corresponding recorded lay-down temperatures. The WMA and HMA mixtures were compacted at the UNR laboratory for mechanical properties after a maximum of 4 hours short-term oven aging in a sealed container at the corresponding lay-down temperatures. The approximate haul time between the plant and the UNR laboratory was similarly 20 to 30 minutes as that between the plant and either project paving site. Additionally, the mechanical properties were evaluated for samples reheated from ambient temperature to 135°C in the oven, for 4 hours, followed by 2 hours at the corresponding lay-down temperature before compaction.

The following nomenclatures were used throughout this study for the various evaluated mixtures:

- **WMA_64-22 and HMA(LM)_64-22**: WMA plant mixture and laboratory-produced HMA mixture, respectively, from Chism Street manufactured with PG64-22 virgin binder and 15% RAP.
- **WMA_64-22(R)**: reheated WMA plant mixture from Chism Street manufactured with PG64-22 virgin binder and 15% RAP that was subjected to 4 hours of short-term oven aging at 135°C followed by 2 hours at 121°C.
- **WMA_64-28 and HMA_64-28**: WMA and HMA plant mixtures, respectively, from Bravo Avenue manufactured with PG64-28 virgin binder and 15% RAP.
- **WMA_64-28(R) and HMA_64-28(R)**: reheated WMA and HMA plant mixtures, respectively, from Bravo Avenue manufactured with PG64-28 virgin binder and 15% RAP that were subjected to 4 hours of short-term oven aging at 135°C followed by 2 hours at the corresponding lay-down temperature (i.e. 124°C for WMA and 152°C for HMA).

Figure 1 shows the experimental program for this effort. It included the following three major aspects.

- Rheological properties of virgin, RAP and extracted/recovered asphalt binders from plant-produced mixtures.
- Impact of short-term oven aging periods on the Marshall air voids, flow and stability. Four short-term oven aging periods (0, 2, 4 and 15 hours) at the corresponding lay-down temperatures were evaluated for the plant-produced mixtures. This evaluation may be used to determine a short-term aging time limit for which the mixtures begin to fail specifications, which may assist in the assessment of WMA quality control or quality assurance.
- Mechanical properties of plant mixtures according to the test matrix are shown in Table 1. The resistance of the mixtures to moisture damage, permanent deformation and thermal cracking were evaluated by means of dynamic modulus testing at multiple freeze-thaw cycles, repeated load triaxial (RLT) and by thermal stress restrained specimens testing (TSRST), respectively.
FIGURE 1 Study Experimental Program.

TABLE 1 Test Matrix for Mechanical Properties Evaluation

<table>
<thead>
<tr>
<th>Mechanical Property</th>
<th>Mixture ID</th>
<th>Chism Street</th>
<th>Bravo Avenue</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>WMA_64-22</td>
<td>WMA_64-22(R)</td>
<td>HMA(LM)_64-22</td>
</tr>
<tr>
<td>Resistance to Moisture Damage</td>
<td>x*</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>-</td>
<td>vs. Freeze-Thaw (F-T): 3 samples at 0, 1 &amp; 6 F-T</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Resistance to Permanent Deformation</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>- Unconditioned Flow Number (FN): 3 samples</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Resistance to Thermal Cracking</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>- Unconditioned TSRST: 3 samples</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Tests were conducted

MATERIALS AND MIX DESIGNS

The WMA mixtures of the two field projects were designed using the Marshall Mix Design method for HMA (8). Granite’s aggregate pit in Lockwood, Nevada, from which the aggregates were treated with 1.5% hydrated lime to mitigate moisture damage susceptibility, was used as the
aggregate source for both projects. Table 2 summarizes the primary mix designs data along with the corresponding specifications.

A sieve analysis performed on extracted aggregates (AASHTO T308 and T30 (9)) from the plant mixtures sampled during production revealed that all aggregate gradations were well controlled with respect to the corresponding job mix formulas (JMF). Additionally, the WMA and HMA from Bravo Avenue had very similar gradations. The asphalt binder contents of the plant mixtures were determined during production using the ignition oven method (AASHTO T308 (9)) and are shown in Table 3 along with the 95% confidence interval. Overlapping of the confidence intervals implies the similarity in the measured binder contents between the mixture types. All mixtures met the corresponding asphalt binder content JMF. Additionally, the WMA mixture from Bravo Avenue showed a significantly higher measured asphalt binder content than the corresponding HMA mixture.

**TABLE 2 Mix Design Summary and Specifications**

<table>
<thead>
<tr>
<th>Property</th>
<th>Chism St</th>
<th>Bravo Ave</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asphalt Binder Grade</td>
<td>PG64-22</td>
<td>PG64-28</td>
<td>--</td>
</tr>
<tr>
<td>Mixing Temperature Range, Viscosity Based (°C)</td>
<td>153-159</td>
<td>160-166</td>
<td>--</td>
</tr>
<tr>
<td>Compaction Temperature Range, Viscosity Based (°C)</td>
<td>142-147</td>
<td>150-155</td>
<td>--</td>
</tr>
<tr>
<td>Number of Compaction Blows</td>
<td>50</td>
<td>50</td>
<td>--</td>
</tr>
<tr>
<td>Hydrated Lime (%DWVA*)</td>
<td>1.5</td>
<td>1.5</td>
<td>--</td>
</tr>
<tr>
<td>RAP Content (%)</td>
<td>15.0</td>
<td>15.0</td>
<td>--</td>
</tr>
<tr>
<td>RAP Binder Content (%TWM*)</td>
<td>5.70</td>
<td>4.25</td>
<td>--</td>
</tr>
<tr>
<td>Total Design Binder Content (% TWM*)</td>
<td>4.9</td>
<td>5.1</td>
<td>--</td>
</tr>
<tr>
<td>RAP Binder Replacement (% TWM*)</td>
<td>0.9</td>
<td>0.6</td>
<td>--</td>
</tr>
<tr>
<td>Design Air Voids (%)</td>
<td>4.0</td>
<td>4.0</td>
<td>4.0</td>
</tr>
<tr>
<td>Voids in Mineral Aggregates (%)</td>
<td>13.9</td>
<td>13.2</td>
<td>13 Min.</td>
</tr>
<tr>
<td>Voids Filled with Asphalt (%)</td>
<td>71.6</td>
<td>70.1</td>
<td>65-75</td>
</tr>
<tr>
<td>Marshal Stability (lbs)</td>
<td>3,252</td>
<td>3,386</td>
<td>1,800 Min.</td>
</tr>
<tr>
<td>Marshal Flow (0.01 inches)</td>
<td>13</td>
<td>14</td>
<td>8-20</td>
</tr>
</tbody>
</table>

* DWVA and TWM denotes “Dry Weight of Virgin Aggregate” and “Total Weight of Mix,” respectively

**TABLE 3 Asphalt Binders Production Testing**

<table>
<thead>
<tr>
<th>Project</th>
<th>Mixture ID</th>
<th>Number of Samples</th>
<th>Asphalt Binder Content</th>
<th>JMF</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Average (%) Standard Deviation 95% Confidence Interval</td>
<td></td>
</tr>
<tr>
<td>Chism Street</td>
<td>WMA_64-22</td>
<td>8</td>
<td>5.1 0.20 5.0-5.3</td>
<td>4.4-5.4</td>
</tr>
<tr>
<td>Bravo Avenue</td>
<td>WMA_64-28</td>
<td>15</td>
<td>4.9 0.14 4.8-5.0</td>
<td>4.6-5.6</td>
</tr>
<tr>
<td></td>
<td>HMA_64-28</td>
<td>3</td>
<td>4.7 0.12 4.5-4.8</td>
<td></td>
</tr>
</tbody>
</table>
PROPERTIES OF ASPHALT BINDERS

The virgin, RAP and recovered blended binders from the various plant-produced loose mixtures were graded by the Superpave Performance Grading (PG) binder system (AASHTO M320 (9)). All recovered binders were extracted using a centrifuge (AASHTO T164 (9)) and recovered using a rotary evaporator (ASTM D5404 (10)) using a solution of 85% Toluene and 15% Ethanol by volume. Figure 2 and Table 4 summarize the critical temperatures and PG grades of the various binders, respectively. Critical temperatures are the temperatures at which a binder meets the appropriate specified Superpave criteria. All recovered asphalt binders from the plant mixtures containing 15% RAP met or exceeded the target grades for the projects. The recovered binders from the WMA and HMA mixtures from Bravo Avenue exhibited similar critical temperatures.

![Figure 2: Superpave PG True Temperatures of Various Asphalt Binders.](image-url)
TABLE 4 Superpave PG Grades of Various Asphalt Binders.

<table>
<thead>
<tr>
<th>Binder</th>
<th>PG Grade</th>
</tr>
</thead>
<tbody>
<tr>
<td>PG64-22 virgin</td>
<td>64-22</td>
</tr>
<tr>
<td>RAP binder (Chism)</td>
<td>76-16</td>
</tr>
<tr>
<td>Recovered from WMA 64-22 plant mixture</td>
<td>64-22</td>
</tr>
<tr>
<td>PG64-28 virgin</td>
<td>64-34</td>
</tr>
<tr>
<td>RAP binder (Bravo)</td>
<td>82-16</td>
</tr>
<tr>
<td>Recovered from WMA 64-28 plant mixture</td>
<td>70-28</td>
</tr>
<tr>
<td>Recovered from HMA 64-28 plant mixture</td>
<td>70-28</td>
</tr>
</tbody>
</table>

**IMPACT OF CURING TIME ON AIR VOIDS, FLOW AND STABILITY**

Figure 3 shows the impact of the short-term oven aging duration on the Marshall air voids, stability and flow of the WMA mixtures from both projects. The short-term oven aging was conducted in a forced-draft oven at 121 and 124°C for the WMA from Chism Street and Bravo Avenue, respectively.

The Chism Street WMA mixture had an increase in air voids as a function of short-term oven aging duration, indicating a reduction in the mixture compactability, with a significant increase observed after 15 hours of aging. On average all specimens met the JMF of 4±1% except when compacted after 15 hours of curing. The results suggest that the mixture fell short of the JMF sometime between 4 and 15 hours of curing time. The flow and stability data show that their criteria were met at all short-term aging periods and the specimens exhibited similar flow and stability within 4 hours of short-term aging. The measured flow and stability values were respectively slightly higher and lower than the values observed in the mix design (see Table 2); however, after 15 hours, the measured values were very similar to the mix design values. The test results show that both properties changed sometime between 4 and 15 hours of short-term aging at 121°C.

For the Bravo Avenue mixture, the air voids of the compacted specimens were consistently equal to or larger than 5% for all short-term aging periods. In general, the compacted specimens did not meet the JMF of 4±1%. The flow and stability data show that their criteria were met at all short-term aging periods; but a reduction in values was observed after 15 hours of aging at 124°C. The measured stability values for the compacted specimens at all short-term aging periods were lower than the reported stability at the mix design stage for the HMA mixture (see Table 2) by 716 to 1,149 lbs.

The Bravo WMA mixture was short-term aged immediately upon delivery at the HMA lay-down temperature (i.e. 152°C) for two hours and then compacted for Marshall properties. Air voids, flow and stability values of 4.3%, 19 and 3,126 lbs were respectively measured. When the WMA mixture was compacted at the HMA temperature, it clearly met the JMF for air voids and resulted in a stability value similar to that of the corresponding HMA mix design.
FIGURE 3 Impact of curing period on Marshall-compacted specimens: (a) Voids in total mix; (b) Marshall Flow; (c) Marshall Stability. (Whiskers represent mean ± 1 STD).
EVALUATION OF ASPHALT MIXTURES

Resistance to Moisture Damage

The resistance of the various mixtures to moisture damage was evaluated using the measurement of the dynamic modulus $|E^*|$ as a function of multiple freeze-thaw (F-T) cycling. The process of F-T cycling was conducted as defined by AASHTO T-283 but at multiple stages. A total of three samples from each mixture were evaluated at the unconditioned (i.e. 0 F-T) and moisture-conditioned stages after 1 and 6 F-T cycles.

Figure 4 shows the $|E^*|$ of the various mixtures for different F-T cycles at 10 Hz loading frequency and a temperature of 21°C. The reheated WMA and laboratory-produced HMA mixtures from Chism Street exhibited similar unconditioned $|E^*|$ values while the non-reheated WMA mixture was slightly lower. After 1 and 6 F-T cycles, all mixtures from Chism Street exhibited similar $|E^*|$ values. As can be seen in Figure 5, the $|E^*|$ ratios of the moisture-conditioned to the unconditioned $|E^*|$ after 1 and 6 F-T cycles were higher for the non-reheat WMA while similar $|E^*|$ ratios were observed for the reheat WMA and laboratory-produced HMA mixtures from Chism Street. Hence, the resistance of the WMA mixture did not decrease in comparison to the HMA laboratory-produced mixture even after reheating.

![Figure 4](image_url)

FIGURE 4 $|E^*|$ at 21°C as a function of F-T cycles.
FIGURE 5 |E*| ratio at 21°C after 1 and 6 F-T cycles.

In the case of Bravo Avenue, excluding the HMA reheat mixture, all mixtures exhibited similar unconditioned and moisture-conditioned |E*| values (Figure 4). The impact of reheating on |E*| was significantly less for the polymer-modified asphalt mixtures than the unmodified ones. Figure 5 shows that all mixtures exhibited good resistance to moisture damage with |E*| ratios greater than 80% even after 6 F-T cycles. The WMA mixture exhibited higher |E*| ratios even after reheating. In all cases, the |E*| values for the polymer-modified mixtures from Bravo Avenue were significantly lower than the unmodified mixtures from Chism Street.

Resistance to Permanent Deformation

The resistance of the asphalt mixtures to rutting was evaluated through the use of the repeated load triaxial (RLT) test to measure the flow number (FN). Cylindrical samples were subjected to a static confining pressure and a repeated haversine deviator stress that is applied for an appropriate pulse (loading) time and a rest (unloading) period. The axial deformation of each of the tested samples is measured and the cumulative permanent axial strain is calculated and plotted with respect to the number of loading cycles. The plot is defined by three stages: primary, secondary and tertiary, with the FN being the point at which the tertiary flow begins.

Through the use of the predictive equations developed by Hajj et al. (11), the appropriate RLT test parameters of confining and deviator stresses were determined for a 6-inch thick asphalt layer.

Provided that the operational speed for both projects is 20 mph, the determined RLT test parameters consisted of a respective 0.05 and 0.09 second pulse and rest period. The confining
and deviator stresses used, dependent upon operational speed, asphalt layer temperature and stiffness, were: 35 and 78 psi for Chism Street mixtures, and 30 and 80 psi for Bravo Avenue mixtures. The RLT tests for Chism Street and Bravo Avenue were conducted at 52 and 58°C, respectively. The temperatures were determined as the effective pavement temperature 2 inches below the pavement surface as indicated by the LTPPBind software for those given project locations.

The FN results for the mixtures from both projects are shown in Figure 6. The samples made with the laboratory-produced HMA mixture from Chism Street displayed significantly greater FN values than those for either of the WMA mixtures. A slight increase in the FN was observed for the WMA mixture from Chism Street after reheating. A similar trend can be seen with the resulting FNs for Bravo Avenue mixtures.

In both projects, the HMA mixtures had FNs greater than the WMA mixtures. Overall, the data show a reduction in the mixture rutting resistance with the use of WMA, even after reheating the loose samples. However, the WMA mixtures still exhibited FNs greater than 400 cycles which may be considered acceptable for low volume roads.

![FIGURE 6 Flow Numbers at 52°C for Chism Street Mixtures and 58°C for Bravo Avenue Mixtures. (Numbers represent mean values and whiskers represent mean ± 95% confidence interval).](image)

**Resistance to Thermal Cracking**

The low-temperature cracking resistance of the various mixtures was evaluated using the TSRST (AASHTO TP10-93). The test chills down a 2x2x10 inch beam specimen at a rate of 10°C/hour while restraining it from contracting. The fracture temperature represents the temperature at which the asphalt mixture will crack due to thermal stresses, while the fracture stress represents
the magnitude of stress caused by the thermal contraction of the mixture. However, the fracture stress controls the spacing of thermal cracks once they occur.

Given that low-temperature cracking is a long-term pavement distress, each of the compacted samples was long-term oven aged for 5 days at 85°C prior to testing. Figure 7 shows the TSRST test results for all evaluated mixtures.

The WMA mixture from Chism Street had the greatest fracture stress when compared to the reheated WMA or laboratory-produced HMA mixtures, which exhibited similar fracture stresses to each other. However, regardless of reheating, the WMA mixture exhibited similar fracture temperature that was lower than the HMA laboratory-produced mixture.

The WMA and HMA mixtures from Bravo Avenue had statistically similar fracture stresses. The WMA mixture exhibited lower fracture temperature than the companion HMA mixture. Reheated mixtures from Bravo Avenue were not evaluated as part of this study. Both, the polymer-modified HMA and WMA mixtures exhibited significantly better resistance to thermal cracking than the unmodified HMA and WMA mixtures.

In general, the measured fracture temperatures by the TSRST were consistent with the low performance grades of the recovered asphalt binders from the various plant mixtures (see Figure 2).

![FIGURE 7 Fracture stresses and temperatures of various mixtures. (Numbers represent mean values and whiskers represent mean ± 95% confidence interval).](image)

**FIELD PERFORMANCE**

In May 2011, a field visual inspection was performed for the Chism Street and Bravo Avenue projects. Figures 8 and 9 show pictures taken at the time of assessment. The inspection revealed no distresses in the WMA mixture on Chism Street after 2 years of service. Despite the extremely cold winter season evidenced by temperature drops to as low as -19°C on December 9th 2009, no thermal cracks were evident in the pavement.
Similarly, the inspection revealed no distresses in the HMA and WMA mixtures on Bravo Avenue after 9 months of service. Overall, the pavement condition was excellent and uniformly the same along the total length of the project.

In summary, the foamed WMA with 15% RAP has been performing well with both unmodified and polymer-modified asphalt binders. The field performance for both projects will continue to be monitored over the next few years.

**FIGURE 8 Photo for WMA Pavement on Chism Street (May 18, 2011)**

**FIGURE 9 Photo for HMA and WMA Pavements on Bravo Avenue (May 18, 2011)**

**SUMMARY OF FINDINGS**

This study evaluated the volumetric and mechanical properties of foamed WMA mixtures with 15% RAP from two field projects. The findings based on the evaluated mixtures from this study are summarized as follows:

- The foamed WMA mixtures with 15% RAP had recovered asphalt binders that met or exceeded the target PGs for the projects. No significant difference was observed in the
PG of the recovered asphalt binders from the polymer-modified WMA and HMA plant-produced mixtures.

- The Marshall air voids, flow and stability requirements of the unmodified foamed WMA mixture were met when compacted within four hours of manufacturing at the plant. The data indicate the foaming effect is lost sometime between 4 and 15 hours of short-term oven aging at 121°C. As for the polymer-modified foamed WMA mixture, the Marshall properties were difficult to meet when compacted at the WMA lay-down temperature (i.e. 124°C) regardless of the short-term oven aging period. The properties were only met when the foamed WMA mixture was compacted at the HMA lay-down temperature (152°C).

- The foamed WMA mixtures with 15% RAP exhibited good resistance to moisture damage. The reheating protocol evaluated in this study did not have a significant impact on the mixtures resistance to moisture damage. The polymer-modified WMA and HMA mixtures showed significantly better resistance to moisture damage in comparison to unmodified WMA mixture.

- A reduction in the mixture resistance to rutting was observed with the foamed WMA mixtures when evaluated using the FN test. However, acceptable FN values (greater than 400 cycles) for the test conditions were measured for the foamed WMA mixtures.

- A good resistance to thermal cracking was observed with the foamed WMA mixtures from both projects. The fracture temperatures measured using the TSRST met or exceeded the target PGs for the projects.

- The condition surveys conducted to date showed no distresses in the WMA pavements on both projects. Given that no rut depths were observed in the pavement should suggest that the relatively low flow number values measured in the laboratory for the foamed WMA mixtures are adequate for the applied traffic and environmental conditions.

Based on this study, the Ultrafoam GX™ technology seems to be a promising technology for producing foamed WMA mixtures with 15% RAP when using local materials from Northern Nevada without jeopardizing the mixture performance. However, care should be taken when selecting the right testing protocol (e.g. laboratory aging procedure and compaction temperature) for QC/QA, particularly when dealing with polymer-modified asphalt mixtures.

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