# Combining Warm Mix Asphalt Technologies with Mixtures Containing Reclaimed Asphalt Pavement

Word Count: 3714 (Abstract: 461; Manuscript: 3253)

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May 20, 2011

**ABSTRACT**
As energy costs continue to rise and the general public becomes more aware of environmental stewardship, state agencies and contractors are looking for innovative and effective methods of constructing a sustainable transportation infrastructure. Warm mix asphalt is one process which has the potential to both reduce costs of paving operations due to an increased energy savings while reducing the overall carbon footprint of the paving project. While there are several advantages to incorporating WMA technologies in an asphalt mixture, concerns have been raised about the mixture's resistance to rutting and moisture damage.

The use of warm mix asphalt (WMA) technologies with asphalt mixtures containing reclaimed asphalt pavement (RAP) may provide several synergistic advantages. An obvious synergy of WMA technologies and RAP mixtures is the combined environmental benefits. While the environmental benefits of WMA-RAP mixtures is evident, additional data are needed to suggest the combination of these two green products will produce mixtures which will perform in terms of rutting, moisture susceptibility, and cracking.

This paper examines eleven unique asphalt mixtures using seven WMA technologies sampled from field projects across the Southeast and Midwest United States. Each project contained at least one HMA control mixture for comparisons between lab tested properties of the WMA and HMA mixtures. Each mixture in this study contained between 10 and 45 percent RAP by weight of aggregate.

Each mixture was characterized to assess binder properties and mixture properties related to rutting, cracking, and moisture damage susceptibility. Asphalt binders were extracted and recovered from the RAP mixtures with and without WMA to determine the true grades of the binders. While using WMA did not typically reduce the high and low critical temperatures by a full performance grade, small reductions were sometimes noticed in the true binder grade. Dynamic modulus test results also indicate that using WMA technologies yields slightly lower mixture stiffness at high and intermediate temperatures. Moisture susceptibility of the mixtures was determined using AASHTO T 283 and AASHTO T 324. Although, the WMA mixtures typically had lower tensile strength ratios (TSR) and stripping inflection points (SIP) compared to corresponding HMA mixtures, the results for the WMA mixtures was statistically similar to HMA mixtures. Rutting susceptibility was assessed using the asphalt pavement analyzer (APA) and Hamburg Wheel Tracking Device (HWTD) tests. In each case, the WMA mixtures had greater rut depths in the HWTD and APA. However, the majority of the WMA mixtures were considered resistant to rutting by typical criteria for the APA. Cracking potential of each mixture was characterized using AASHTO T 321 flexural fatigue of asphalt beams. The bending beam fatigue analyses suggest that using WMA will enhance the performance of RAP mixtures in terms of cracking resistance at larger strain magnitudes. Therefore, this research suggests that combining WMA technology with mixtures containing RAP is a win-win.

## INTRODUCTION

As energy costs continue to rise and the general public becomes more aware of environmental stewardship, state agencies and contractors are looking for innovative and effective methods of constructing a sustainable transportation infrastructure. Warm mix asphalt (WMA) is one process which has the potential to both reduce costs of paving operations due to an increased energy savings while reducing the overall carbon footprint of the paving project (*1, 2, 3, 4, 5*).

While WMA has many benefits, many engineers have concerns about the long-term performance of the mixtures. This is especially true in terms of rutting and moisture susceptibility (*6*). Since WMA asphalt binders are exposed to cooler temperatures during mixture production, the asphalt mixtures produced are softer and more susceptible to these specific distresses (7). While laboratory tests have suggested WMA is more susceptible to moisture damage and rutting, field studies have shown WMA can be resistant to rutting in the field (8). Though these concerns still exist, WMA mixtures have proven to be more fatigue resistant than comparable HMA mixtures in laboratory and field settings (*9, 10*).

The use of WMA technologies with asphalt mixtures containing reclaimed asphalt pavement (RAP) may provide several synergistic advantages to a hot mix asphalt (HMA) RAP mixture or a virgin WMA. An obvious synergy of WMA technologies and RAP mixtures is the combined environmental benefits (*3*). Perhaps less obvious is the cancelling affect of negative aspects of WMA and recycling asphalt materials. Two concerns that have been cited for lower mixing temperatures with WMA production is the potential incomplete drying of the aggregate in the drum and dropping the gas temperature through the baghouse below the vapor point of water leading to muddling of the bags. Using WMA with RAP mixtures should alleviate this problem since the aggregate going through the drier are superheated to compensate for the addition of RAP at ambient temperatures.

Additionally, current procedures (AASHTO M320) for designing moderate and high RAP content mixtures (>25%) recommended the use of a softer grade of virgin asphalt binder. Since WMA binders are aged less during plan production due to lower mixing temperatures, the resulting softer new binder could interact with the RAP binder to result in an effective binder with has sufficient stiffness to resist rutting but also having adequate viscoelastic behavior to resist cracking. A final synergy between RAP and WMA can be found ultimately in cost savings. If using WMA allows states to progress towards allowing 50% RAP in asphalt mixtures, the state and contractor could see a 25% savings in costs per ton (*6*).

While the advantages of combining WMA and RAP are evident, little research has been published documenting the performance of these mixtures in either the field or the laboratory.

## OBJECTIVES AND SCOPE

The objective of this research was to characterize how incorporating WMA technologies in a RAP mixture affected the binder grade and mixture performance. To accomplish this objective, mix from four projects across the Southeast and Midwest encompassing six RAP-WMA mixtures and four RAP-HMA mixtures was collected. The mixtures were also characterized to assess binder and mixture properties related to rutting, cracking, and moisture damage.

## MATERIAL CHARACTERIZATION

Eleven mixtures (Table 1) from four different field projects were included in this research study. Each projects placed a control HMA-RAP mixture in addition to at least one WMA-RAP test section. Of the six WMA-RAP mixtures, six different WMA technologies were used. The

WMA –RAP mixture was also mixed and compacted at cooler temperatures than the HMA counterpart.

Each mixture was sampled during production at the plant, and if possible, performance testing specimens were prepared hot or warm in the National Center for Asphalt Technology (NCAT) mobile laboratory. When additional comparisons or sample fabrication proved too cumbersome for the mobile lab (e.g. beam fatigue specimens), mix was taken back to the NCAT laboratory in Auburn, Alabama for sample fabrication. The performance testing specimens for the HMA-RAP mixture paved in Royal, NE were also compacted at NCAT. This occurred because the mixture was paved before the research team arrived at the project. The paving crew sampled the mixture and saved it for the research team.

Upon the completion of sample fabrication, the testing plan described in Table 2 was performed to characterize each mixture and binder. Extracted and recovered binders were tested to determine the performance grade of the asphalt binders, and the mixtures were evaluated using the following tests: dynamic modulus (E*), tensile strength ratio (TSR), Hamburg Wheel Tracking Device (HWTD), asphalt pavement analyzer (APA), and bending beam fatigue (BBFT).

**TABLE 1 Mixture Production and Quality Control Data**

| Location | WMA | Mix Temp, °F | Compaction Temp, °F | RAP, % | NMAS, mm | AC, % | $V_a$, % |
|---|---|---|---|---|---|---|---|
| Daytona, FL | None | NA | NA | 45 | 12.5 | 5.4 | 4.3 |
| | Double Barrel Green (DBG) | 270 | 260 | 45 | 12.5 | 6.1 | 1.8 |
| Orlando, FL | None | 310 | NA | 30 | 12.5 | 5.1 | 4.0 |
| | Gencor | 265 | NA | 30 | 12.5 | 5.1 | 4.0 |
| Macon, GA | None | 325 | 300 | 15 | 9.5 | 5.7 | 1.4 |
| | Evotherm 3G | 260 | 235 | 15 | 9.5 | 5.6 | 1.9 |
| | Rediset | 285 | 255 | 15 | 9.5 | 6.0 | NA |
| | Cecabase | 260 | 235 | 15 | 9.5 | 5.8 | 1.6 |
| Royal, NE | None | 320 | 290 | 10 | 9.5 | 4.5 | 2.6 |
| | Evotherm DAT | 260 | 235 | 10 | 9.5 | 4.6 | 4.2 |
| | Advera | 260 | 235 | 10 | 9.5 | 4.8 | 3.8 |

**TABLE 2 Binder and Mixture Testing Plan**

| Location | WMA | PG Grade | E* | TSR | HWTD | APA | BBFT |
|---|---|---|---|---|---|---|---|
| Daytona, FL | None | X | X | X | | X | X |
| | DBG | X | X | X | | X | X |
| Orlando, FL | None | | X | X | X | X | X |
| | Gencor | | X | X | X | X | X |
| Macon, GA | None | X | X | X | X | X | X |
| | Evotherm 3G | X | X | X | X | X | X |
| | Rediset | X | X | X | X | X | X |
| | Cecabase | X | X | X | X | X | X |
| Royal, NE | None | | X | X | X | X | |
| | Evotherm DAT | | X | X | X | X | |
| | Advera | | X | X | X | X | |

**BINDER CHARACTERIZATION**

The asphalt binder from six of the eleven mixtures was extracted using the solvent trichloroethylene (TCE) (ASTM D2172-05) and recovered using the Rotovap methodology (ASTM D5404-03). Upon recovery, the binders underwent performance grading according to AASHTO R 29. The results of this testing can be found in Table 3.

**TABLE 3 Binder Characterization**

| Location | WMA | True Performance Grade | Performance Grade |
|---|---|---|---|
| Daytona, FL | None | 75.5 – 22.6 | 70-22 |
| | DBG | 71.8 – 24.0 | 70-22 |
| Macon, GA | None | 75.3 – 24.5 | 70-22 |
| | Evotherm 3G | 74.9 – 23.9 | 70-22 |
| | Rediset | 75.4 – 24.5 | 70-22 |
| | Cecabase | 77.9 – 27.8 | 76-22 |

As can be seen, the WMA technologies used on the project in Macon, with the exception of Cecabase, had little effect on the true grade at the critical high temperature. The Evotherm 3G reduced the critical temperature by less than a degree, and the Rediset binder was practically identical to the HMA. However, Cecabase increased the high temperature grade by 2.8°C producing a stiffer binder at higher temperatures. The reversal was also true for the low temperature grade on the Macon project. While the low temperature true grade of the Rediset was identical to the HMA binder, Cecabase produced a mix with a lower critical temperature by 3.3°C while the Evotherm 3G mixture increased the low temperature true grade by 0.6°C.

Though only one foaming technology was a part of this analysis in Daytona, this technology reduced both the high and low temperature true grades of the asphalt binder. While this reduction was not a full performance grade, a reduction of nearly 4°C was measured for the critical high temperature while the change in critical low temperatures was not as significant, 1.4. °C

**MIXTURE STIFFNESS**

Dynamic modulus testing was conducted under guidance of AASHTO TP62. This testing was performed using an IPC Global Asphalt Mixture Performance Tester (AMPT). Dynamic modulus testing was performed for each mixture described in Table 1. The air voids for these cut specimens were 7 ± 0.5 percent.

To provide the necessary information for M-E pavement analyses, the three samples of each mixture were tested using four temperatures (4.4, 21.1, 37.8 and 54.4$^{o}$C) and six frequencies (25, 10, 5, 1, 0.5, and 0.1 Hz). This testing produced a data set for generating master curves for each mixture using the sigmoidal function. This methodology is outlined in AASHTO PP62-09. The regression coefficients and shift factors, which are used to shift the modulus data at various test temperatures to the reference temperature of 21.1$^{o}$C, are determined simultaneously during the optimization process using the Solver function in an Excel® spreadsheet. The mixtures from two projects (Orlando and Royal) were run in the unconfined condition while the mixtures from the other two projects were run confined at 20 psi of pressure. The E* results for the unconfined and confined testing are shown graphically in Figures 1 and 2.

At the cooler temperatures and higher frequencies, the WMA and HMA behaved similarly in an unconfined condition; however, using 20 psi of confinement, differences between the HMA-RAP and WMA-RAP mixture stiffnesses were noticed. The Daytona DBG mixture was 5% stiffer than the Daytona HMA at the colder temperatures. On the other hand, the Macon Cecabase mixture was softer than the Macon HMA-RAP mix by almost 25%.

The most obvious differences between the E* of the WMA and HMA occur and the intermediate and high temperatures in both confinement states. While the Daytona mixtures average nearly 5% difference in stiffness between the HMA-RAP and DBG mixture, other mixtures such as the Macon Cecabase mixture had stiffness reductions near 40%. As seen in the figures, the WMA additives consistently, with the exception of the Daytona project, reduced the dynamic modulus of the RAP mixture.

While these reductions were noticed, it is difficult to quantify how a reduced modulus will impact the mixture performance without the use of predictive equations or pavement evaluation software such as the Mechanistic-Empirical Pavement Design Guide. Therefore, performance testing was necessary to determine how having a slightly softer mix influences the performance of these RAP mixtures.

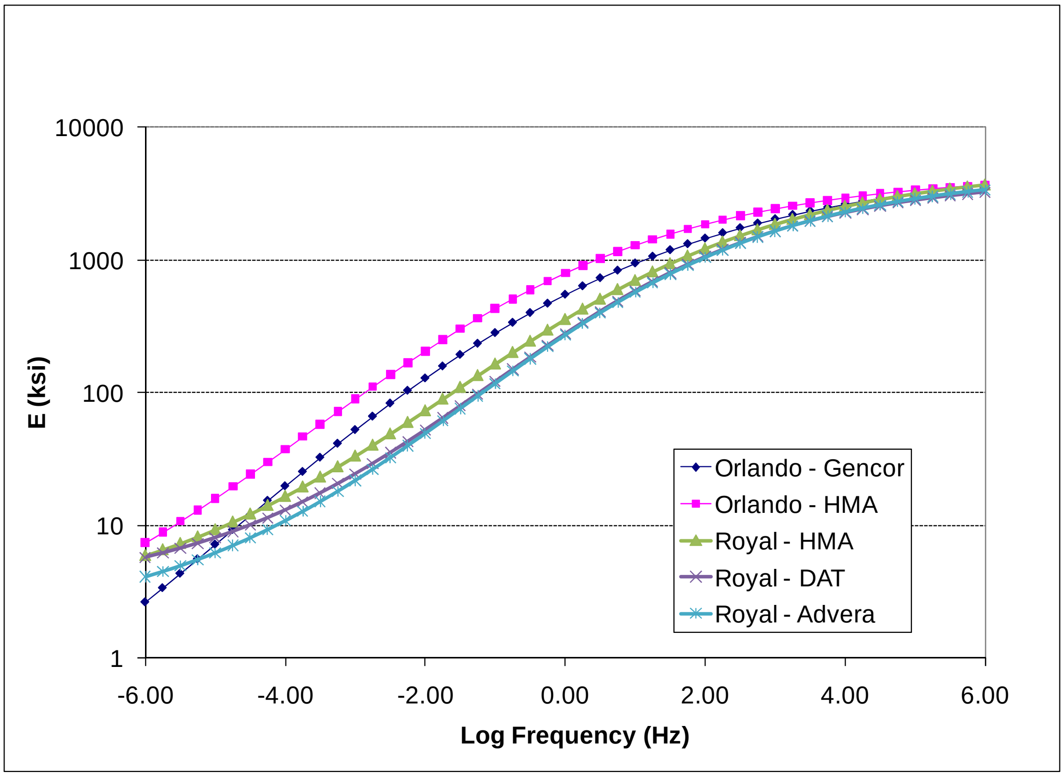


**FIGURE 1 Unconfined Dynamic Modulus Results.**

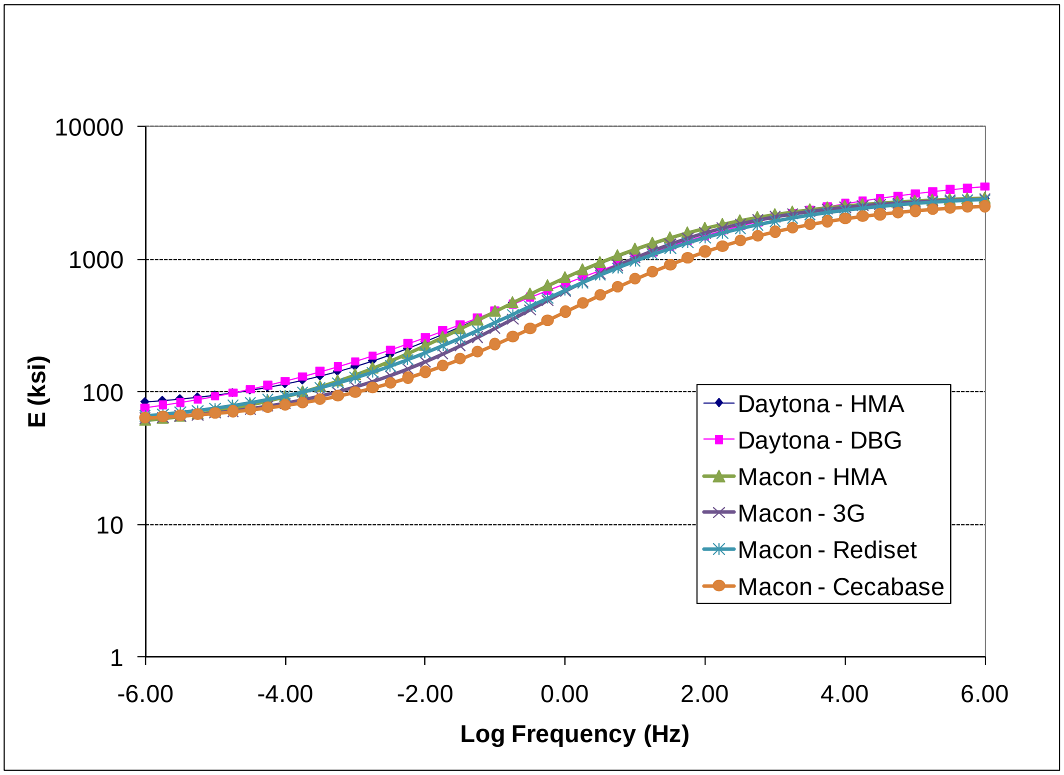


**FIGURE 2 Confined Dynamic Modulus Results.**

## MOISTURE SUSCEPTIBILITY

Since moisture damage is a primary concern for WMA mixtures, the moisture susceptibility of the mixtures was evaluated using AASHTO T283 and AASHTO T324. With the exception of the control mix from Royal, NE, the HWTD and TSR samples were fabricated hot or warm in the field.

### Tensile Strength Ratio

According to AASHTO T 283, two sets of three specimens were used to determine the tensile strength ratio (TSR). All of the specimens were compacted to a height of 95 mm and an air void level of 7 ± 0.5 percent. AASHTO M 320 recommends a TSR value of 0.8 and above for moisture resistant mixes.

All eleven mixtures were subjected to this testing protocol, and the results are displayed in Figure 3. One observes from this bar graph that the WMA mixtures typically had lower tensile strengths than the HMA mixtures. While this is true, only two of the eleven mixtures failed to meet the minimum TSR threshold of 0.80. In both cases (Daytona DBG and Orlando Gencor), foaming devices were used as the WMA technology. Despite two WMA-RAP mixtures failing to pass the TSR specification, a *t*-test ($\alpha = 0.05$) showed that overall differences between the HMA and WMA TSR values were not statistically significant ($p = 0.50$).

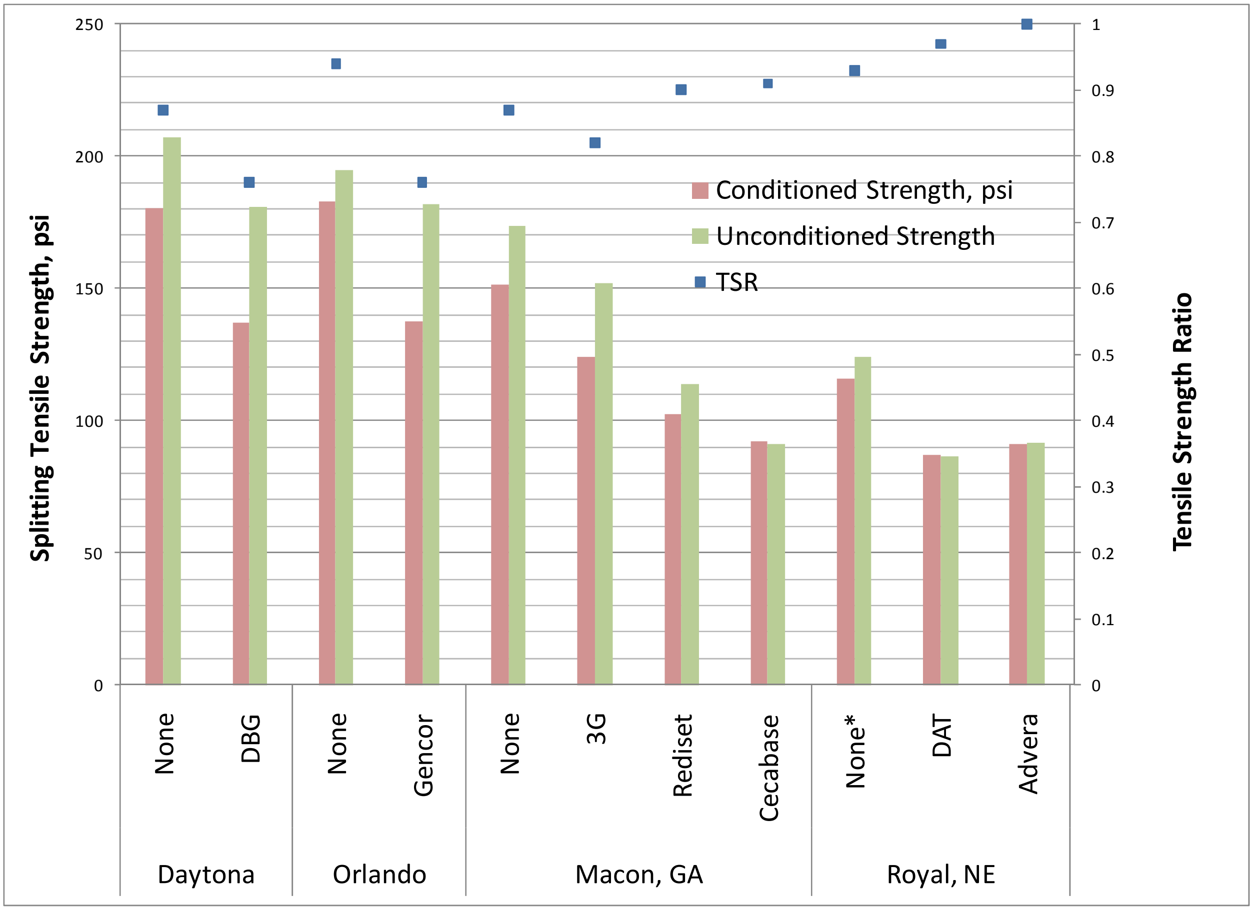


**FIGURE 3 Tensile Strength Ratio Results**
*Mixture reheated in laboratory

**Hamburg Wheel Tracking Device**
AASHTO T 324 prescribes the methodology for evaluating stripping susceptibility via the HWTD. For each mix, a minimum of two replicates with air voids between 5 and 9% were tested under a 158 ± 1 lbs wheel load for 10,000 cycles (20,000 passes) while submerged in a water bath which was maintained at a temperature of 50$^{o}$C. While being tested, rut depths were measured by an LVDT which recorded the relative vertical position of the load wheel after each load cycle. After testing, these data were used to determine the point at which stripping occurred in the mixture under loading. Mixtures with stripping inflection points less than 5000 are typically considered susceptible to stripping.

Nine mixtures were evaluated for stripping susceptibility using AASHTO T324 (Figure 4). Four of the mixtures fail to meet the meet the stripping inflection point criterion including all of the mixtures from the Royal, NE project. Only the Macon Cecabase mixture fails in stripping when its control HMA passes.

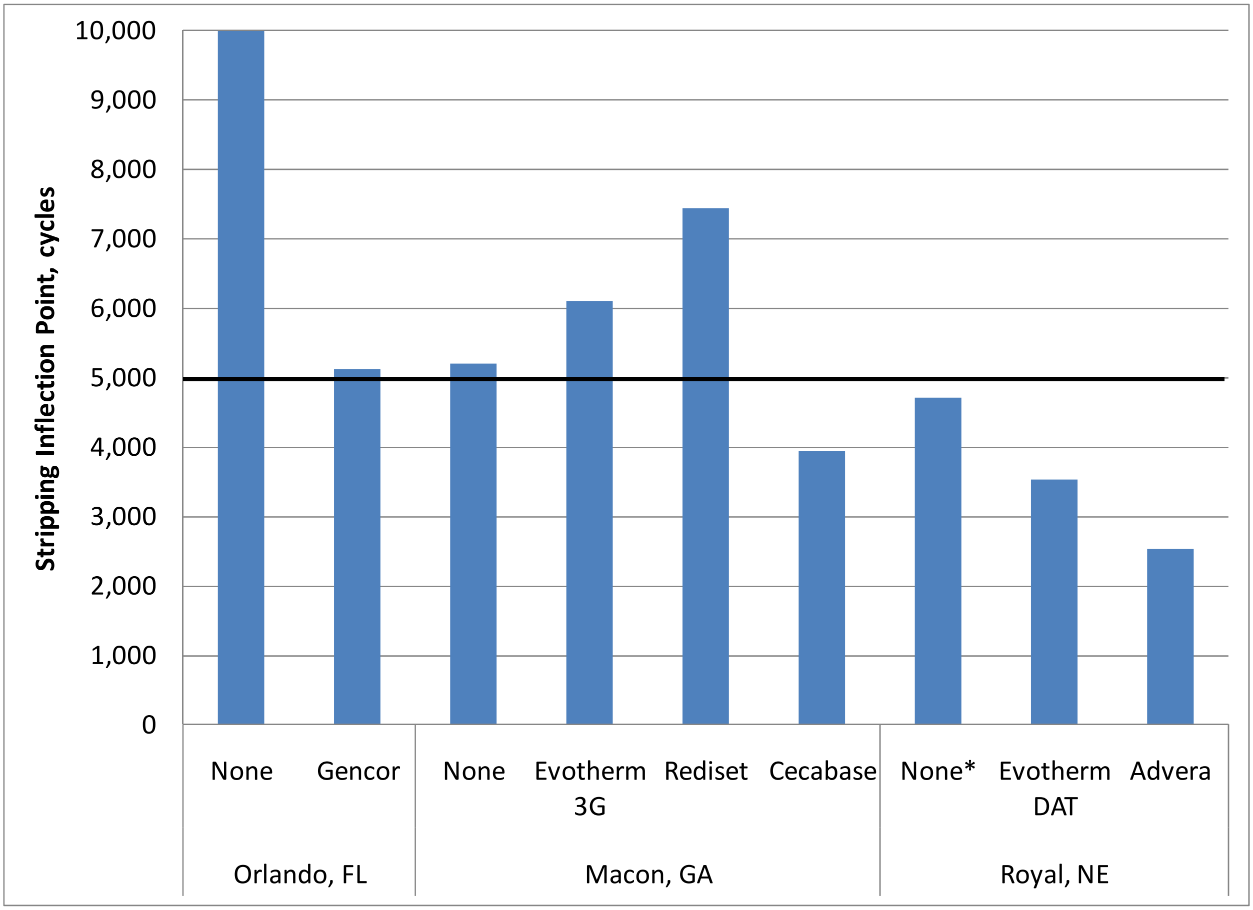


**Figure 2 Hamburg Stripping Inflection Point Results**

**Summary**

WMA mixtures tend to have lower moisture resistance than companion HMA mixtures in both the TSR and HWTD; however, the results between the two tests were significantly different. The Orlando Gencor mixture failed the TSR but passed the SIP criterion. The three other WMA-RAP mixtures failing the SIP criterion of the HWTD all passed the TSR. Additional research should be conducted to determine the most appropriate method for determining the moisture susceptibility of WMA.

**RUTTING SUSCEPTIBILITY**

One concern of reduced mixture stiffness in WMA mixtures is that the mix will become more susceptible to rutting. The APA and HWTD tests were used to evaluate if the combination of RAP and WMA produced softer mixtures which still could withstand rutting in the laboratory.

**Asphalt Pavement Analyzer**

The rutting susceptibility of all eleven mixtures was evaluated using the APA in accordance with AASHTO TP 63. The samples used for this testing were prepared to a height of 75 mm and an air void level of 7 ± 0.5 percent. Six replicates were tested for each mix at 64°C. The samples were loaded by a steel wheel (loaded to 100 lbs) riding atop a pneumatic hose pressurized to 100 psi for 8,000 cycles. Manual depth readings (Figure 5) were taken at two locations on each sample before and after the loading was applied to determine the rut depths.

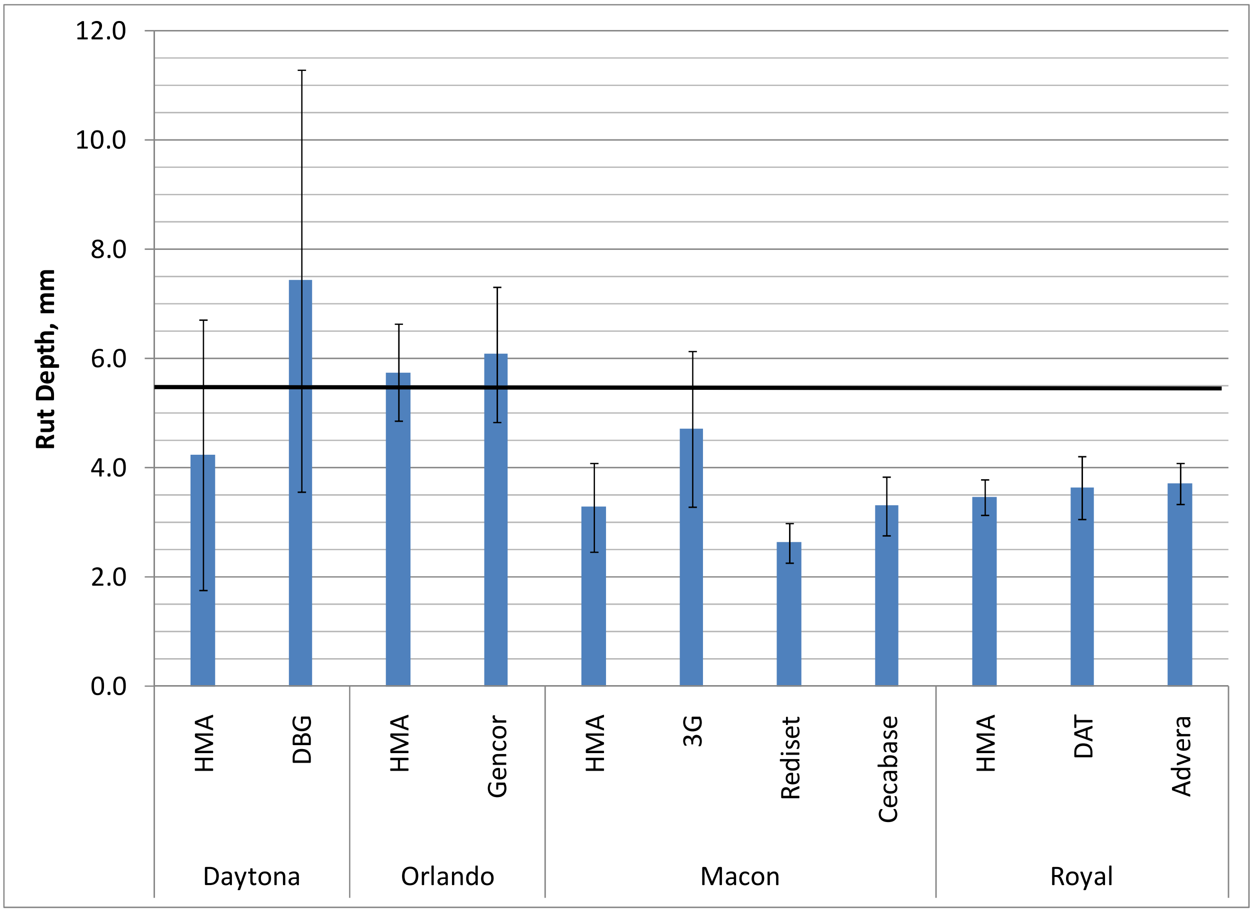


**FIGURE 5 APA Test Results.**

One observes that with only one exception (Macon Rediset) the WMA mixtures rutted more in the APA than the HMA mixtures. However, a *t*-test ($\alpha = 0.05$) showed the differences between the rut depths of the HMA and WMA mixtures were not statistically different (*p*-value = 0.75). A recent study conducted at the NCAT Pavement Test Track suggested that 5.5 mm of rutting should be set as a maximum rutting threshold value for the APA for heavy traffic surface mixtures (*11*). Using this recommendation, only the Daytona DBG mixture failed to meet the APA criterion when the HMA control mixture passed. Both the WMA-RAP and HMA-RAP mixture in Orlando failed to pass this criterion. These APA results suggest that while WMA might produce slightly larger rut depths in the APA, the mixtures are still resistant to rutting.

**Hamburg Wheel Tracking Device**

In addition to APA testing, the HWTD was used to capture the total rut depth for nine of the eleven mixtures using the previously described methodology. These test results are shown in Figure 6. While 5.5 mm of rutting is acceptable in the APA, 10 mm of rutting after 20,000 passes is the commonly accepted rutting threshold for mixtures in undergoing HWTD testing due to the increased load used in testing.

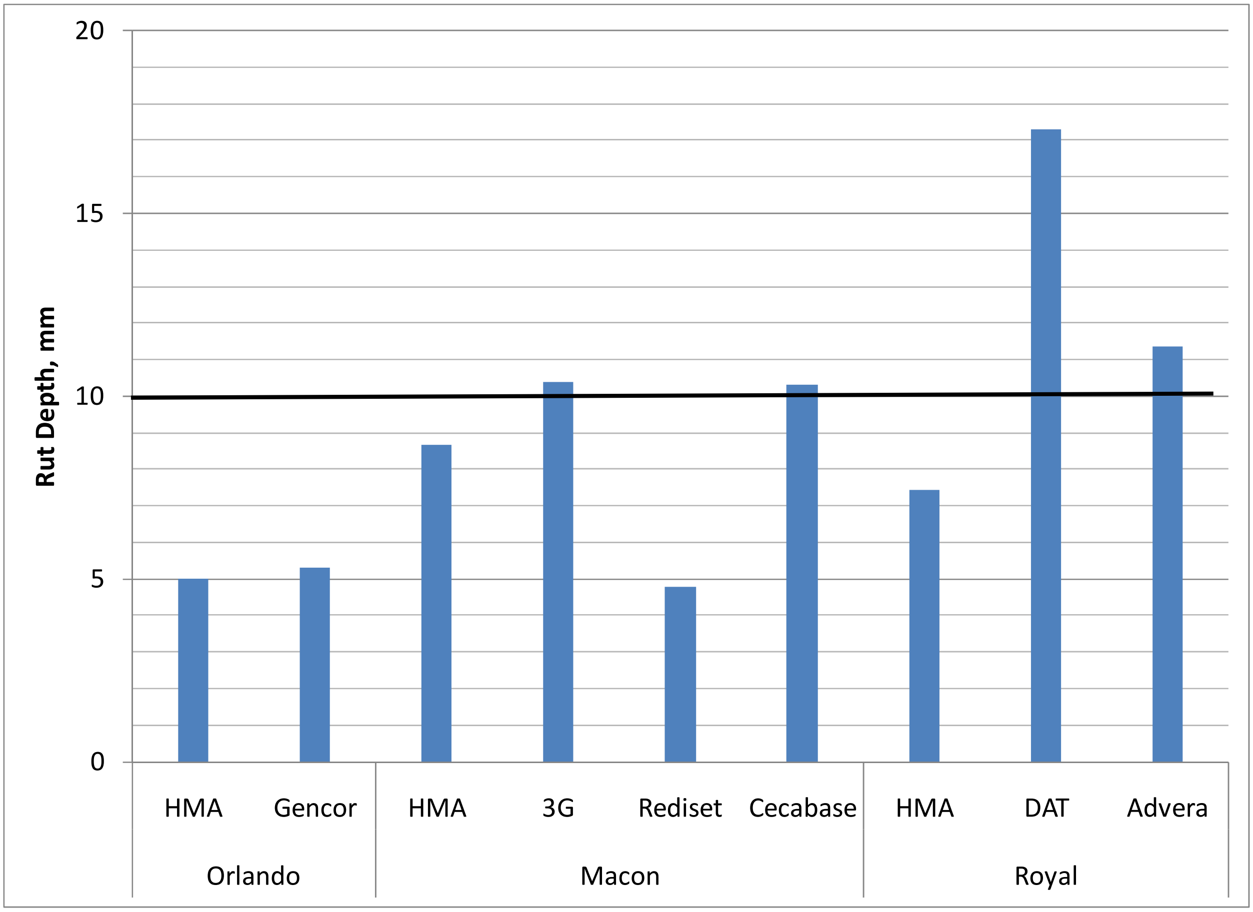


**FIGURE 6 Hamburg Rutting Results.**

As can be seen, the two-thirds of the WMA mixtures did not pass the HWTD rut depth requirement while the three HMA mixtures tested did. The only WMA mixtures that passed were the Orlando Gencor and Macon Rediset. However, a *t*-test ($\alpha = 0.05$) still showed no statistical differences between the rut depths of the HMA and WMA mixtures (*p*-value = 0.34).

**Summary**

It is interesting to see the results of the APA and HWTD also contradict each other. The two mixtures that failed the APA (Orlando HMA and Orlando Gencor) passed the HWTD. Three of the WMA mixtures which passed the APA failed the HWTD. Additional work should be conducted to determine which test best represents field rutting for WMA. Results from the HWTD suggest WMA mixtures are susceptible to rutting while the APA results suggest the opposite.

## CRACKING PERFORMANCE

Bending beam fatigue testing was performed in accordance with AASHTO T 321 to determine the cycles until failure of seven of mixtures in this research study. The specimens were originally compacted in a kneading beam compactor then were trimmed to the dimensions of 380 ± 6 mm in length, 63 ± 2 mm in width, and 50 ± 2 mm in height. Additionally, the orientation in which the beams were compacted (top and bottom) was marked and maintained for the fatigue testing as well.

The beam fatigue apparatus applies haversine loading at a frequency of 10 Hz. During each cycle, a constant level of strain is applied to the bottom of the specimen. The loading device consists of 4-point loading and reaction positions which allow for the application of the target strain to the bottom of the test specimen. Testing was performed at 20 ± 0.5°C. The data acquisition software was used to record load cycles, applied loads, beam deflections. The software also computed and recorded the maximum tensile stress, maximum tensile strain, phase angle, beam stiffness, dissipated energy, and cumulative dissipated energy at user specified load cycle intervals.  According to AASHTO T 321, failure occurs when the beam's initial stiffness has been reduced by 50%.  Table 4 provides the test results for each project's testing plan.

**TABLE 4 BBFT Cycles until Failure**

| **Location** | **Mix** | **600 με** | | | | | |
|---|---|---|---|---|---|---|---|
| | | **Beam 1** | **Beam 2** | **Beam 3** | **Beam 4** | **Beam 5** | **Beam 6** |
| Daytona | HMA | 71,470 | 73,340 | 74,440 | 14,650 | 51,980 | 38,100 |
| | DAT | 1,230 | 148,840 | 59,490 | 122,270 | 66,130 | 346,280 |
| | | **200 με** | | | **400 με** | | |
| | | Beam 1 | Beam 2 | Beam 3 | Beam 1 | Beam 2 | Beam 3 |
| Orlando | HMA | 9,308,690 | 8,360,300 | 5,089,400 | 41,580 | 102,230 | 137,500 |
| | Gencor | 2,811,180 | 8,844,360 | 4,042,650 | 55,510 | 95,010 | 106,740 |
| | | **800 με** | | | | | |
| | | Beam 1 | Beam 2 | Beam 3 | | | |
| Macon | HMA | 8,740 | 9,850 | 10,150 | | | |
| | 3G | 7,700 | 7,120 | 7,370 | | | |
| | Redi-set | 17,020 | 12,490 | 12,020 | | | |
| | Cecabase | 27,400 | 17,110 | 12,650 | | | |

While each project had a different testing plan, basic trends were noticed when evaluating the data.  When low strain levels were combined with a 30% RAP mixture, the WMA mixtures failed before the HMA mixtures.  At 200 microstrain, the WMA mixture endured 30% fewer cycles than the HMA mixture.  However, at 400 microstrain, the discrepancy between the two mixtures had been reduced to 8.5%.

The benefits of adding the WMA to the RAP mixtures were truly seen at the higher strain levels.  The Daytona mixtures (45% RAP) were tested at 600 microstrain.  This combination of mixture and testing parameters allowed the WMA-RAP mixture to endure more than double the load repetitions of the HMA-RAP and the prescribed strain magnitude.

Though the results were not as drastic, at 800 microstrain, two of the three Macon WMA mixtures proved more resistant to fatigue than the HMA.  Only the 3G mixture lasted fewer cycles until failure than the HMA mix.  The Redi-set mixture endured 45% more cycles and the Cecabase mixture endured 99% more cycles before failure occurred.  While these mixtures only had 15% RAP, the capacity to handle additional repetitions at higher strain levels should be considered a great benefit for using WMA in combination with RAP.

## CONCLUSIONS AND RECOMMENDATIONS

Based on the results of this research, the following conclusions were made:

- The addition of Rediset and Evotherm 3G technologies to HMA-RAP mixtures had little effect on the high and low temperature asphalt binder true grades.  Cecabase increased

the high temperature critical temperature while the DBG foaming system reduced the critical temperature. Neither the additive nor the foaming technology increased or decreased the critical temperature by a full binder grade.
- With the exception of the DBG foaming system, the addition of WMA to HMA-RAP mixtures decreased the stiffness of the asphalt mixture. This reduction typically ranged from 5 to 40% for the WMA technologies used on the projects.
- The TSR and HWTD test results proved contradictory; thus, a true consensus conclusion about the moisture susceptibility of WMA-RAP mixtures cannot be made.
- The APA and HWTD test results were not in agreement with each other in terms of rutting resistance. The APA results suggest WMA-RAP mixtures are typically resistant to rutting while the HWTD results suggest the converse.
- While using WMA technologies did not improve the fatigue resistance of HMA-RAP mixtures at low strain magnitudes (200 and 400 microstrain), the addition of WMA significantly increased the number of cycles until failure RAP mixture could withstand a higher strain magnitudes (600 and 800 microstrain) where a typical HMA-RAP mixture might prove brittle.

After examining the binder and mixture performance testing results of these eleven mixtures, the following recommendations are made.

- Additional research needs to be conducted to determine the most appropriate moisture susceptibility and rutting test for WMA-RAP mixtures. In both cases, the two tests returned directly opposing results. These tests should be correlated to WMA-RAP mixture field performance to determine which test best correlates to field rutting.
- WMA should be incorporated in RAP mixtures which will be subjected to strain magnitudes appropriate for the layer and loading conditions for the intended use of the mixture

## ACKNOWLEDGEMENTS

The authors of this paper would like to acknowledge and thank the Federal Highway Administration for their support on this project.

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