Title: An Investigation of the Effects of Three Warm Mix Asphalt Additives on Asphalt Binder and Mixture Properties

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Abstract

Warm mix asphalt (WMA) is one of the newest and fastest growing technologies in the construction materials industry. WMA requires significantly lower mixing and compaction temperatures as compared to conventional HMA (typically 35 to 100 °F lower). Several potential advantages arise from the use of WMA including: reductions in energy consumption, lower plant emissions, decreased amounts of compaction effort, and reduced cracking potential. WMA additives are added to the asphalt binder immediately prior to mixing with the heated aggregate in the majority of cases. As a result, the properties of the asphalt binder change considerably from those determined using conventional Superpave tests. However, these property modifications do not occur in the same fashion for all WMA technologies. Therefore, this paper studies three distinct WMA additives, including their effects on asphalt binder and mixture properties at three mixing temperatures.

Each of the additives was mixed into the unmodified asphalt binder at recommended rates according to the WMA producer. The study included one additive from each major WMA category (organic, chemical, and water bearing). The Brookfield rotational viscometer was used to characterize the viscosity of the unaged asphalt binders at temperatures ranging from 60 to 180°C. Unaged, short-term aged, and long-term aged binders were tested in the dynamic shear rheometer (DSR) to determine the binders’ complex moduli and phase angles at the Superpave-specified test temperatures. Virgin and WMA mixtures containing Illinois aggregates were compacted at three different temperatures. These temperatures include: the HMA compaction temperature (HMA-CT), HMA-CT minus 25°C, and HMA-CT minus 50°C. The reduced temperatures correspond to likely WMA production temperatures. The design number of gyrations, $N_{des}$, for each mixture irrespective of compaction temperature or WMA additive was chosen to equal the number of gyrations required to reach 7% air voids in the HMA compacted at HMA-CT. The resulting air void contents of each mixture compacted to $N_{des}$ were calculated and compared to one another to examine the effects of WMA additives and compaction temperature. Finally, AASHTO T-283 testing was completed using the compacted samples to determine the effects of air void content and WMA additives on mixture moisture sensitivity.

Testing results revealed that viscosity reductions at production temperatures were not in fact realized for all WMA technologies investigated. WMA additives had significant effects on DSR results at all three binder age-conditioning levels investigated, which suggests that the WMA modifiers may have a significant effect on rutting and fatigue cracking resistance. In particular, the results suggest that fatigue cracking resistance may be adversely affected by the use of organic and water bearing additives. Finally, WMA technologies and production temperatures significantly impacted asphalt concrete moisture sensitivity according to the AASHTO T-283 procedure. Reduced production temperatures led to increasingly moisture damaged mixtures while the chemically-based WMA technology studied herein led to improved moisture resistance. The combined results obtained support two key findings: (1) preconceived effects of WMA additives on asphalt binder and mixture properties may or may not be realized, depending upon a number of variables including additive system used, binder source, and mixture properties, and; (2) until extensive field performance data is available, mixture performance testing can be used to evaluate new WMA designs so that potential performance issues can be addressed prior to material placement.
INTRODUCTION

Warm mix asphalt (WMA) is gaining popularity very rapidly and becoming a mainstream technique for producing asphalt concrete mixtures in European nations and the United States. WMA differs from hot mix asphalt (HMA) in terms of the production temperatures required to appropriately meet production standards. Generally, WMA is produced 35-55°F (20-30°C) less than HMA \((1)\). The production temperature changes lead to sustainability improvements via reduced fuel consumption and emissions production. In an era of rising fuel prices, the use of WMA has the ability to reduce plant fuel consumption by 10-35% \((2)\). In addition, as dangerous gaseous emissions such as sulfur dioxide, nitrogen oxide, and carbon dioxide have been significantly regulated in developed nations, WMA may be a solution because research has found that 15-70% reduction in emissions can be achieved with its use \((1)\).

Early WMA literature reported that reduced production temperatures of WMA were caused by an altered binder viscosity-temperature relationship \((1)\). In particular, WMA binder viscosities at mixing and compaction temperatures were thought to be reduced such that production at lower temperatures met the Superpave viscosity criteria. Prowell and Hurley \((3)\) determined that Sasobit additives reduced asphalt binder viscosity in comparison with unmodified binder at temperatures above the wax additive’s melting point. However, recent literature has found that viscosities may not be altered significantly in all WMA technologies \((4)\). Therefore, WMA binder viscosity-temperature characterization from intermediate to high temperatures should be studied in order to evaluate the rheological properties of these modified asphalt binders.

A significant number of WMA technologies have been introduced throughout the United States and Europe over the past decade. In general, WMA consists of three distinct groups which include: organic additives, chemical additives, and foaming processes and additives. Each group and technology affects the properties of the asphalt binder in a unique fashion as compared to Superpave-regulated binders. Therefore, Superpave-specified tests such as the Dynamic Shear Rheometer in addition to viscosity-temperature characterization should be considered to examine the effects of WMA technologies on complex shear modulus \((G^*)\) and phase angle \((\delta)\) and their correlation to field distresses such as rutting and fatigue cracking.

Finally, numerous early WMA demonstration projects displayed increased mat densities and reduced permeability. This has also hastened the implementation of WMA, as end-result and performance-related construction specifications often include pay incentives and disincentives, where in-place mat density carries significant weight in the pay factor formula. Moisture related distresses such as stripping were thought to be partially alleviated by the improved densities. However, laboratory research of WMA mixtures compacted to the same approximate densities and tested using the AASHTO T-283 procedure resulted in an opposing conclusion in which some WMA additives and processes displayed increased moisture sensitivity. Therefore, moisture sensitivity testing of laboratory specimens with varying densities should be evaluated to determine if potentially improved density reduces stripping in WMA mixtures.

OBJECTIVES

The goal of this study was to evaluate the effects of three WMA additives and production temperatures on asphalt binder and mixture properties with the following objectives:

1. Examine the effects of WMA additives on intermediate and high temperature asphalt binder properties via the Brookfield Rotational Viscometer (RV) and Dynamic Shear Rheometer (DSR).
2. Determine and evaluate the air void contents of HMA and WMA mixtures produced at three different temperatures.
3. Evaluate the tensile strength ratios of WMA and HMA mixtures with varying air voids and WMA additives using AASHTO T-283.
APPROACH, MATERIALS, AND TESTS

The scope of this research consists of obtaining virgin aggregate and three WMA additives, characterizing unmodified and WMA-modified binders at intermediate and high temperatures using the RV and DSR, preparing and compacting asphalt concrete mixture at three temperatures using unmodified and WMA binders, and testing the laboratory mixed and compacted samples via the AASHTO T-283 procedure. The WMA technologies were chosen such that an additive from the organic, chemical, and foaming groups were included in the study. Sasobit, Advera, and Evotherm M1 were selected as the three candidate WMA technologies. Sasobit is a synthetic paraffin wax material produced through via the Fischer-Tropsch method. Advera is a synthetic zeolite material which released water to foam the asphalt binder. Furthermore, Evotherm M1 is an Evotherm 3G liquid chemical additive produced by Meadwestvaco which does not contain water. Each of the WMA technologies was added at rates within the specified manufacturer tolerances. Two rates were selected for both Sasobit (1.5 and 3.0% by weight of the binder) and Advera (0.2 and 0.5% by weight of the mixture) while one rate was chosen for Evotherm M1 (0.5% by weight of the binder) for the RV testing. One rate was chosen for each of the additives for tests involving the DSR and mixtures. Sasobit, Advera, and Evotherm were added at rates of 3.0, 0.25, and 0.5%, respectively for these tests.

The unmodified asphalt binder was supplied by Emulsicoat, LLC in Urbana, IL. The following characteristics in Table 1 were provided for the asphalt binder. PG 64-22 asphalt binder was chosen in this study to comply with central Illinois environmental conditions.

<table>
<thead>
<tr>
<th>Test</th>
<th>PG 64-22</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific Gravity (15.6°C)</td>
<td>1.036</td>
</tr>
<tr>
<td>Viscosity, (135°C, Pa-s)</td>
<td>0.412</td>
</tr>
<tr>
<td>Creep Stiffness (-12°C, MPa)</td>
<td>192.0</td>
</tr>
<tr>
<td>m-Value (-12°C)</td>
<td>0.314</td>
</tr>
</tbody>
</table>

The aggregate used in this study included CM16, FM20, FM02, and mineral filler. The CM16 and FM20 materials were dolomitic limestone coarse and manufactured fine aggregates from Kankakee, IL. The FM02 aggregate was a natural fine aggregate from Heyworth, IL and the mineral filler was sampled from Thornton, IL. This aggregate combination was chosen in order to produce a 9.5mm NMAS surface mixture adhering to Superpave guidelines with a gradation as shown in Figure 1.
The Superpave requirements of a 9.5mm NMAS 70 gyration mixture are shown below in Table 2. The design gyration total of 70 gyrations was chosen when considering a medium-to-low volume road with a 20 year traffic level between 3 and 10 million ESALs. The optimized asphalt binder content was experimentally determined to be 6.7% with volumetric properties as shown in Table 3. Finally, the mixing and compaction temperatures were chosen based upon the RV testing results to be shown in the results section. According to the Asphalt Institute Superpave mix design procedure, the mixing temperature range lies with viscosities between 0.15 and 0.19 Pa-s and the compaction temperature range lies with viscosities between 0.25 and 0.31 Pa-s (8). As a result, mixing and compacting temperatures of 160°C and 150°C, respectively, were selected for the unmodified PG64-22 binder. The production temperature reductions chosen for the WMA technologies were 25 and 50°C. (Each of these reductions was applied to the mixing and compacting temperatures.) The 25°C temperature reduction was selected because it was within the acceptable range for each of the WMA additives. The more aggressive production temperature reduction of 50°C was chosen to be twice as large as the acceptable temperature reduction and still remain a viable production temperature for WMA technologies.

Table 2 - Superpave Requirements

<table>
<thead>
<tr>
<th>20 yr Traffic</th>
<th>Number of Gyrations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( N_{des} )</td>
</tr>
<tr>
<td>3 to &lt; 10</td>
<td>70</td>
</tr>
<tr>
<td>Required Density (%)</td>
<td>96.0</td>
</tr>
<tr>
<td>VMA (min %)</td>
<td>15.0</td>
</tr>
<tr>
<td>VFA Range (%)</td>
<td>65-75</td>
</tr>
<tr>
<td>Dust to Binder Ratio</td>
<td>0.6-1.2</td>
</tr>
</tbody>
</table>

FIGURE 1 9.5mm NMAS Gradation.
The Brookfield Rotational Viscometer (RV) was used to quantify the viscosity of asphalt binders at a variety of temperatures. Testing was carried out in accordance with ASTM D4402. Six total control and WMA binder specimens were prepared for RV testing during this study. As stated previously, an unmodified PG 64-22, 2 percentages of Sasobit and Advera, and 1 percentage of Evotherm M1 were tested. Samples were tested at approximately 10°C increments between 60 and 180°C to fully capture the viscosity-temperature relationship of each asphalt binder. Furthermore, a Dynamic Shear Rheometer (DSR) examined the complex shear modulus and phase angle of each asphalt binder at each aging level. The DSR testing was completed with respect to AASHTO T-315. The rolling thin film oven (RTFO) and pressure aging vessel (PAV) were used as well in order to condition the asphalt binders. One percentage of each WMA additive was tested in addition to the unmodified asphalt binder. Once testing was complete, the results were compared with Superpave specifications to determine if the presence of the additive affected the high temperature performance grade of the asphalt binder.

The asphalt concrete mixtures were produced at the three compaction temperatures, namely, 150°C, 125°C, and 100°C. The design number of gyrations, \( N_{des} \), for each mixture irrespective of compaction temperature or WMA additive was chosen to equal the number of gyrations required to reach 7% air voids in the HMA compacted at 150°C. The resulting air void contents of each mixture compacted to \( N_{des} \) were calculated and compared with one another to examine the effects of both WMA additives and compaction temperature. Two specimens were compacted per mixture to determine the average densities present within each mixture. Finally, AASHTO T-283 testing was completed using the compacted samples to determine the effects of air void content and WMA additives on mixture moisture sensitivity. This study deviated slightly from the AASHTO T-283 specification in terms of production aging periods and total testing set size. Samples were produced according to the Illinois-modified AASHTO T-283 in which a 2 hour aging period at the compaction temperature was conducted prior to compaction without a 16 hour curing period at 60°C. Furthermore, one specimen was tested per mixture per conditioning set. This deviates from AASHTO T-283, but was employed to evaluate the effects of both air content and WMA additives on the tensile strength ratio (TSR).

**TEST RESULTS AND DISCUSSION**

Rotary viscometer viscosity-temperature profiles are plotted in Figures 2 to 4 on log-log scales. As shown in Figure 2, Advera additives did not significantly change the viscosity-temperature profile of asphalt binder in comparison with the unmodified PG 64-22 binder at temperatures below 140°C. However, between 140 and 160°C, the 0.2% Advera-modified asphalt binder produced viscosities 25% less than the unmodified asphalt binder. These results agreed with those found in the Estakhri et al. (2010) paper which tested PG 64-22 asphalt binder viscosity at five temperatures between approximately 80°C and 140°C (4). In addition, increasing the rate of Advera additive added to the asphalt binder slightly increased the viscosity of the asphalt binder throughout the suite of test temperatures.
Consequently, Advera tended to stiffen the asphalt binder as the percentage of Advera increased from 0.2 to 0.5%.

The Sasobit viscosity-temperature profile displayed the most deviation from the unmodified PG 64-22 asphalt binder profile. The viscosity of the modified asphalt binder did not show a dependency on additive percentage because the viscosities of 1.5 and 3.0% Sasobit modified asphalt binders were approximately equal at all temperatures. At temperatures above 90°C, the results were approximately similar to those found by Prowell and Hurley (2005) (3). Sasobit is considered a flow enhancing or viscosity reducing material at production temperatures so this behavior was captured and verified during this experiment. At temperatures below 90°C, Sasobit no longer acted as a flow enhancer in this study and significantly increased the viscosity. Therefore, the wax additive tended to transform into a semi-solid material that stiffened the asphalt binder below this temperature.
Figure 4 displays the viscosity-temperature plot of Evotherm M1 modified asphalt binder. As shown in this plot, the Evotherm-modified asphalt binder did not deviate significantly from the unmodified binder below 140°C and above 160°C. However, between 140 and 160°C, the Evotherm-modified asphalt binder displayed a 19% reduction in viscosity as compared to the unmodified asphalt binder. The reduction in viscosity in this region agreed with the results found by Buss et al. (2011) (9). Similar to the Advera RV results between 80 and 140°C, the Evotherm findings agree with those found by Estakhri et al. (2010) (4). All in all, these results indicate that viscosity reductions may not be the primary cause for production temperature reductions of Evotherm WMA mixtures produced below 140°C.

Several observations can be taken from the RV testing results. First, the assumption that WMA technologies reduce production temperatures by reducing the asphalt binder viscosity may not be valid in all cases. Some technologies, such as Advera and Evotherm, did not significantly alter the viscosity-temperature relationship of the asphalt binder. Therefore, other aspects of binder modification (i.e. chemical changes or emulsification) may be more important contributors to improved workability at reduced production temperatures.

The DSR results for tank, RTFO, and PAV unmodified and WMA-modified binders are shown in Figures 5 to 7. Superpave specifications specify that a PG 64-22 asphalt binder must have a G*/sinδ (‘rutting parameter’) value greater 1.0 kPa for tank binders and 2.2 kPa for RTFO-conditioned samples to avoid rutting due to the performance grade of the binder. As shown in Figure 3, all asphalt binders passed the requirement with Sasobit and Evotherm exhibiting the highest and lowest respective potential rutting resistances among the WMA-modified binders. The wax within the Sasobit led to increased viscosity at intermediate temperatures. Consequently, Sasobit-modified asphalt binder was expected to produce one of the highest G*/sinδ results. On the other hand, the Evotherm additive exhibited the lowest potential rutting resistance which was expected because this type of WMA technology has the propensity to act as an emulsifying agent. All in all, mixture laboratory testing and field evaluations must be considered in order to determine the rutting resistance of WMA-modified mixtures because production temperatures and moisture within the aggregate structure have significant effects on rutting resistance.
According to Superpave specifications, a PAV conditioned PG 64-22 asphalt binder tested at 25°C must have a $G*/\sin\delta$ value (‘fatigue parameter’) less than 5000 kPa to be considered a performance grade which does not potentially lead to significant fatigue cracking. Originally, researchers
hypothesized that the reduced production temperatures of WMA mixtures would lead to improved fatigue cracking resistance over the mixture’s life span. In this study, only one of the WMA-modified asphalt binders (Evotherm) passed the Superpave specified maximum. Advera and Sasobit-modified asphalt binder exhibited the most potential for fatigue cracking according to this test. Advera-modified binder displayed a higher fatigue parameter as compared to the Sasobit-modified binder. The Sasobit PAV result in this study differed from the result found by Buss et al. (2011) (9). However, due to the variability among binder sources and chemical reactions between asphalt binder and WMA additives, differences in rheological performance results from material to material are not unexpected. Overall, laboratory testing of mixture samples and field evaluations should be conducted in the future to more rigorously investigate how WMA technologies affect fatigue cracking resistance, since laboratory age-conditioning and Superpave-specified binder requirements (intended as a binder purchase specification) may not necessarily correlate strongly with field performance.

The air void contents produced during this study for each mixture at each compaction temperature are shown in Figure 8. The HMA compacted at 150°C had a compactive effort of 28 total gyrations applied to it to reach 7.0% air voids. All remaining mixtures received the same level of compaction and the resulting air contents were evaluated. As shown in Figure 8, void contents decreased with decreasing production temperatures. This occurred because the maximum theoretical specific gravity, $G_{mm}$, decreased with decreasing production temperatures as the bulk specific gravity, $G_{mb}$, remained approximately constant for each mixture. In particular, the control HMA $G_{mm}$ decreased from 2.466 at 150°C to 2.456 at 125°C to 2.444 at 100°C. Originally, it was anticipated that air voids would increase with reduced production temperatures and equal compactive effort (Bennert et al. (2010) (10) and Akisetty et al. (11)). However, in Bennert’s study, specimens were compacted to approximately 4.0% air voids using 100 total gyrations, while this study used a total of 25 gyrations to reach 7.0% air voids. In this study, it is hypothesized that asphalt absorption played a major role in the unexpected trend observed. As the production temperatures decreased, more asphalt binder was available to fill voids instead of being absorbed into the aggregate pores. Therefore, the voids in the asphalt mixture were more readily filled with the unabsorbed asphalt binder and more particle lubrication was available during compaction.
Advera WMA mixtures displayed the highest air void contents at each of the three temperatures. This likely occurred because the Advera-modified asphalt binder absorbed into the aggregate. On the other hand, Sasobit had the lowest air contents at all compaction temperatures. In this case, it is hypothesized that the wax additive may not have absorbed into the aggregate as well as the other modified or unmodified asphalt binders. Finally, WMA additives did not display improved densification as compared to the control HMA in all cases in this study. In general, WMA technologies do in fact improve field densification, so further research involving field evaluations should be carried out to study densification characteristics of WMA mixtures as compared to HMA. The importance of conducting a separate mix design for WMA mixtures (rather than assuming that an HMA mix design can be utilized when a WMA additive will be introduced) is also suggested by these findings.

As stated in the objectives, the effects of air voids and WMA additives on moisture sensitivity were evaluated using the AASHTO T-283 procedure. Table 4 and Figures 9 to 11 display the tensile strengths, tensile strength ratios (TSR’s), and visual rating results for the mixtures tested in this study. In general, tensile strengths and TSR’s dropped considerably with reductions in production temperature. Therefore, improved densification with reduced production temperature did not lead to reduced moisture sensitivity in this study. The effects of reduced absorption likely played a key role because it would tend to reduce the ability of the asphalt binder to retain its adhesion to the aggregate in the presence of moisture and hence resist stripping. At 150°C, all WMA mixtures passed the 80% minimum requirement as specified by the AASHTO T-283 guideline, while the control HMA marginally failed. As this aggregate-asphalt combination is common in central Illinois and generally requires a liquid antistrip, the result for the control mixture was not unexpected. Upon reaching the compaction temperatures of 100 and 125°C, only the Evotherm mixtures passed the TSR minimum requirement. However, Evotherm mixtures still displayed visual stripping as shown in Figure 10 at the reduced production temperatures. This stripping may not have been quantitatively defined in the TSR result because softer mixtures such as Evotherm tend to fail at the points of load application and not in an indirect tensile manner at the center of...
the specimen. Finally, the Advera mixtures displayed the greatest change in TSR and conditioned tensile
strength over the compaction temperature range. This result was likely caused by the residual moisture
present in Advera mixtures at lower production temperatures. All in all, according to the TSR results and
visual assessments, each of the mixtures including those modified using Evotherm will likely need to
include liquid anti-strip or hydrated lime to pass the TSR test and to better control stripping in the field.

<table>
<thead>
<tr>
<th>TABLE 4 WMA and HMA Tensile Strength, TSR, and Visual Rating</th>
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</thead>
<tbody>
<tr>
<td><strong>150°C Mixtures</strong></td>
</tr>
<tr>
<td><strong>Mix Type</strong></td>
</tr>
<tr>
<td>Control</td>
</tr>
<tr>
<td>Advera</td>
</tr>
<tr>
<td>Sasobit</td>
</tr>
<tr>
<td>Evotherm</td>
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</table>

| **125°C Mixtures**                                         |
| **Mix Type** | Conditioned Str. psi (kPa) | Unconditioned Str. psi (kPa) | TSR | Visual Rating |
| Control      | 59.3 (408.9)               | 105.0 (723.9)                | 56% | 5            |
| Advera       | 61.4 (423.3)               | 116.5 (803.2)                | 53% | 5            |
| Sasobit      | 69.8 (481.3)               | 106.0 (730.8)                | 66% | 4            |
| Evotherm     | 92.9 (640.5)               | 107.6 (741.9)                | 86% | 2            |

| **100°C Mixtures**                                         |
| **Mix Type** | Conditioned Str. psi (kPa) | Unconditioned Str. psi (kPa) | TSR | Visual Rating |
| Control      | 56.9 (392.3)               | 101.5 (699.8)                | 56% | 5            |
| Advera       | 46.4 (319.9)               | 102.5 (706.7)                | 45% | 5            |
| Sasobit      | 70.6 (486.8)               | 112.3 (774.3)                | 63% | 5            |
| Evotherm     | 82.2 (566.7)               | 93.6 (645.3)                 | 88% | 3            |
FIGURE 9 HMA and WMA Tensile Strength Ratios.

FIGURE 10 Evotherm TSR Specimens Produced at 100°C (Left-Unconditioned and Right-Conditioned).
FIGURE 11 Advera Conditioned Samples Produced at 150°C (Left) and 100°C (Right).

SUMMARY

The findings of this study can be summarized as follows:

1. Reduced viscosities at production temperatures may not be the primary mechanism behind the ability to utilize lower production temperatures with the WMA technologies investigated herein. In this study, Evotherm and Advera did not display significantly different viscosities in the production temperature range as compared to unmodified asphalt binder.

2. WMA technologies may not produce rutting susceptible mixtures according to DSR testing in this study. All asphalt binders passed the Superpave-specified minimum values of $G^*/\sin\delta$ for both tank and RTFO-conditioned samples. However, further research is required to determine how reduced production temperatures and residual moisture affect rutting resistance using these technologies.

3. Fatigue cracking may be a concern for mixtures containing Sasobit or Advera additives. In this study, these two WMA technologies did not pass the Superpave specification for PAV-conditioned asphalt binders. However, future research is needed in order to examine the true correlation of PAV-conditioned WMA binder DSR results with field fatigue cracking.

4. WMA technologies may not improve densification to 7.0% air voids as compared to HMA mixtures at lower production temperatures. HMA mixtures displayed lower void levels than mixtures containing Advera in this study. Furthermore, all mixtures in this study which were compacted at lower temperatures displayed reduced air void levels. Reduced asphalt binder absorption may be the primary cause for the observed reduction in air voids.

5. Improved densification of laboratory compacted specimens did not lead to improved moisture resistance according to the AASHTO T-283 procedure in this study. TSR values decreased considerably with specimens produced at lower compaction temperatures. This result was likely caused by the inability of the asphalt binder to absorb into the aggregate structure and resist stripping.

6. WMA technologies likely have significant effects on the moisture sensitivity of asphalt concrete mixtures. In this study, Evotherm improved the moisture resistance of asphalt mixtures produced at each of the compaction temperatures according to AASHTO T-283. On the other hand, Advera displayed increased moisture sensitivity when produced at reduced production temperatures, possibly due to the presence of residual moisture in the mixture.
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