Evaluation of the Performance Properties of Asphalt Mixes Produced with Re-refined Heavy Vacuum Distillate Bottoms

John A. D’Angelo, Ph.D., P.Eng.
Chief Operating Officer
D’Angelo Consulting, LLC
Annandale, Virginia

Ken Grzybowski
President
PRI Inc.
Tampa, Florida

Steve Lewis
Director Oil RFO Sales
Safety-Kleen Systems
Geneva, Illinois

Rodney Walker
Safety-Kleen Systems
Geneva, Illinois

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ABSTRACT

Asphalt mixtures used for paving are required to perform under extreme conditions. At high temperatures, the mix must withstand heavy traffic loading to prevent rutting. At low temperatures, it must remain flexible to resist cracking from traffic and thermal stresses. The aggregate structure is a primary performance characteristic for high temperature rutting, but it is the asphalt binder that has a much more critical role when it comes to cracking. Re-refined Heavy Vacuum Distillation Bottoms (RHVDB) - the residue from re-refining of used engine oil - has been used to improve the low temperature properties of asphalt binders and improve its cracking response. Previous papers have shown the improved binder properties with the addition of RHVDB, but the question still remains - will these materials perform well in a mixture?

An in-depth evaluation was performed to determine the performance characteristics of asphalt mixtures produced with binders modified with RHVDB at several different levels. The rutting, moisture damage, fatigue and low temperature properties of the mixtures were evaluated against control mixes produced with unmodified binders. Multiple tests were run to compare the mixtures with RHVDB against control mixes. The study provides an extensive evaluation of the effects of RHVDB modification on mix performance.

RÉSUMÉ

Les enrobés bitumineux utilisés pour les chaussées doivent performier dans des conditions extrêmes. À température élevée, le mélange doit supporter le trafic lourd sans orniéer. À basse température, il doit rester assez flexible pour résister à la fissuration causée par le trafic et les contraintes thermiques. La structure granulaire est une caractéristique primordiale pour la résistance à l’orniérag à haute température, mais c’est le bitume qui a le rôle principal pour la résistance à la fissuration à basse température. Les huiles usées re-rafinées (RHVDB) ont été utilisées pour modifier les caractéristiques à basse température des enrobés et améliorer leur réponse face à la fissuration. Des publications antérieures ont montré que les propriétés des bitumes sont améliorées avec l’addition de RHVDB, mais la question demeure, est-ce que ces matériaux vont bien performier dans les enrobés?

Une évaluation en profondeur pour déterminer les caractéristiques des enrobés modifiés avec différentes quantités de RHVDB a été effectuée. La résistance à l’orniérag, la tenue à l’eau, la fatigue et les propriétés à basse température ont été comparées avec l’enrobé témoin contenant du bitume non modifié. Plusieurs tests ont été effectués pour comparer les enrobés avec RHVDB avec l’enrobé de référence. Cette étude propose une évaluation en profondeur de l’effet d’ajout de RHVDB sur les performances des enrobés.
1.0 INTRODUCTION

Asphalt mixtures used for paving are required to perform under extreme conditions. At high temperatures the mix must withstand heavy traffic loading to prevent rutting. At low temperatures, it must remain flexible to resist cracking from traffic and thermal stresses. The aggregate structure is a primary performance characteristic for high temperature rutting, but it is the asphalt binder that has a much more critical role when it comes to cracking. Re-refined Heavy Vacuum Distillation Bottoms (RHVDB) is the residue from re-refining of used engine oil. Commercially available as EcoAddz, RHVDB has been used to improve the low temperature properties of asphalt binders and improve its cracking response. Previous papers have shown the improved binder properties with the addition of RHVDB, but the question still remains - will these materials perform well in a mixture [1]?

The intent of this study is to provide an in-depth evaluation to determine the performance characteristics of asphalt mixes produced with asphalt binders modified with RHVDB, at several different addition levels. The mixes were tested for high temperature properties related to rutting, intermediate fatigue properties, low temperature fracture properties and moisture damage.

2.0 MATERIALS

In this study, two course graded Superpave mix designs typically used by the Illinois Department of Transportation (DOT) were produced with asphalt binders blended with RHVDB at various add rates. In the various tables and graphs, the RHVDB is referred to by a brand name EcoAddz. The Illinois mixes and aggregates were selected because they were reported to have a higher potential for moisture damage.

Table 1 shows the various asphalt binder blends used in the study. RHVDBs were added at 2, 4, 6, and 10 percent levels to a BP PG 64-22. The PG 64-22 was used as the control for the 2 percent RHVDB addition. Separate control binders were developed for the four and six percent RHVDB additions. This was done to have the PG grading of the control binders match as closely as possible the RHVDB blends. This allowed the mix results to be compared based on equi-stiffness binder properties.

<table>
<thead>
<tr>
<th>Binder Blend</th>
<th>Designation</th>
<th>Performance Grade (PG)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BP PG64-22</td>
<td>Control</td>
<td>64-22</td>
</tr>
<tr>
<td>BP PG64-22 with 2% EcoAddz</td>
<td>2% EcoAddz</td>
<td>64-22</td>
</tr>
<tr>
<td>80% BP PG64-22 blended with 20% BP PG46-34</td>
<td>Control&lt;sub&gt;4&lt;/sub&gt;</td>
<td>58-22</td>
</tr>
<tr>
<td>BP PG64-22 with 4% EcoAddz</td>
<td>4% EcoAddz</td>
<td>58-22</td>
</tr>
<tr>
<td>75% BP PG64-22 blended with 25% BP PG46-34</td>
<td>Control&lt;sub&gt;6&lt;/sub&gt;</td>
<td>58-22</td>
</tr>
<tr>
<td>BP PG64-22 with 6% EcoAddz</td>
<td>6% EcoAddz</td>
<td>58-22</td>
</tr>
<tr>
<td>BP PG64-22 with 6% EcoAddz + 0.5% Anti-Strip (AS)</td>
<td>6% EcoAddz &amp; 0.5% AS</td>
<td>58-28</td>
</tr>
<tr>
<td>BP PG64-22 with 10% EcoAddz</td>
<td>10% EcoAddz</td>
<td>58-28</td>
</tr>
</tbody>
</table>

The control binders were produced by blending a soft flux produced by BP with the PG 64-22. The flux was graded as a PG 46-34. The exact percentages that were added to produce the control binders are shown in Table 1. Each of the blends both controls and RHVDBs were continuous graded to determine the exact temperatures where they met specification requirements.
The continuous grades are presented in Figure 1. The figure shows that control blends match the RHVDB blends within 0.5°C for both the high and low temperature grade. A liquid anti-strip was added to the RHVDB six percent blend. The addition of the liquid anti-strip (AS) significantly softened the binder which is typical. This actually changed the six percent blend from a PG 58-22 to PG58-28.

Figure 1. Continuous performance grading for the different asphalt binder blends used in the study.

The aggregates for the mixes were a Dolomitic Limestone from the Vulcan, Kankakee quarry just south of Chicago, Illinois. All aggregate was a 100 percent crushed material from the quarry. Two course graded Superpave mixes were produced from the aggregate source. An N70 (70 gyration) Superpave mix and an N90 (90 gyration) Superpave mix were produced using 19 mm nominal maximum aggregate size. The N70 mix was slightly finer than the N90 mix. The two gradations are plotted in Figure 2 on the Federal Highway Administration (FHWA) 0.45 power chart. The course graded designation is based on the gradations plotting below the maximum density line for over 50 percent of the mass.

3.0 SUPERPAVE MIX DESIGN

The N90 mix is slightly courser than the N70 to be able to maintain the four percent air voids (Va) and minimum 13 percent Voids in Mineral Aggregate (VMA). The mix design binder content was established for the PG 64-22 control in each mix and the optimum binder content from the control was maintained for each of the other mix variations for the specific design designation. The volumetric mix properties for each of the N70 and N90 mixes are shown in Tables 2 and 3, respectively. There were only minor variations in air voids and VMA, from the control for the various binder blends used with each mix.
Figure 2. Federal Highway Administration 0.45 power chart of the N70 and N90 gradations used in the study.

Table 2. Volumetric properties of the N70 mixes produced with the various binder blends.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>IL DOT N70 Mix Design Results</th>
<th>Control</th>
<th>2% Eco-Addz</th>
<th>4% Eco-Addz PG Equiv.</th>
<th>4% Eco-Addz</th>
<th>6% Eco-Addz PG Equiv.</th>
<th>6% Eco-Addz</th>
<th>6% Eco-Addz &amp; 0.5% AS</th>
<th>10% Eco-Addz</th>
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<tbody>
<tr>
<td>Design Gyrations</td>
<td>70</td>
<td>70</td>
<td>70</td>
<td>70</td>
<td>70</td>
<td>70</td>
<td>70</td>
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<tr>
<td>Percent Binder, Pb(%)</td>
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<td>4.8</td>
<td>4.8</td>
<td>4.8</td>
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<tr>
<td>Effective Asphalt Content, Pbe, %</td>
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<td>3.83</td>
<td>3.83</td>
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<td>3.76</td>
<td>3.76</td>
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<tr>
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<td>4.30</td>
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<td>4.30</td>
<td>4.30</td>
<td>4.30</td>
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<tr>
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<td>4.02</td>
<td>4.10</td>
<td>3.74</td>
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<td>Volume of Voids in Mineral Aggregate, VMA, %</td>
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<td>13.02</td>
<td>13.09</td>
<td>12.76</td>
<td>12.87</td>
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<td>12.69</td>
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<td>12.91</td>
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<tr>
<td>Dust Proportion, DP, %</td>
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<td>1.12</td>
<td>1.12</td>
<td>1.12</td>
<td>1.10</td>
<td>1.14</td>
<td>1.11</td>
<td>1.14</td>
<td>1.12</td>
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Table 3. Volumetric properties of the N90 mixes produced with the various binder blends.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>IL DOT N90 Mix Design Results</th>
<th>Control</th>
<th>2% EcoAddz</th>
<th>4% EcoAddz PG Equiv.</th>
<th>4% EcoAddz</th>
<th>6% EcoAddz PG Equiv.</th>
<th>6% EcoAddz &amp; 0.5% AS</th>
<th>10% EcoAddz</th>
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<tbody>
<tr>
<td>Design Gyrations</td>
<td>90</td>
<td>90</td>
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<td>90</td>
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<td>Performance Grade (PG)</td>
<td>--</td>
<td>64-22</td>
<td>64-22</td>
<td>58.22</td>
<td>58-22</td>
<td>58-22</td>
<td>58-22</td>
<td>58-28</td>
</tr>
<tr>
<td>Percent Binder, Pb(%)</td>
<td>5.4</td>
<td>5.4</td>
<td>5.4</td>
<td>5.4</td>
<td>5.4</td>
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<tr>
<td>Effective Asphalt Content, Pbe, %</td>
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<td>4.17</td>
<td>4.11</td>
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<td>4.18</td>
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<td>Aggregate Content Passing the 0.075 mm Sieve ,P0.075, %</td>
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<tr>
<td>Air Voids in Compacted Mixture, Va, %</td>
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<td>4.08</td>
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<td>4.05</td>
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<td>Volume of Voids in Mineral Aggregate, VMA, %</td>
<td>13</td>
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<td>13.86</td>
<td>13.75</td>
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<td>1.18</td>
<td>1.16</td>
<td>1.17</td>
<td>1.16</td>
<td>1.16</td>
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</tbody>
</table>

4.0 EXPERIMENTAL DESIGN

The experimental design included two aggregate gradations and eight different asphalt binders. This provided 16 different mixes to test for rutting, dynamic modulus, fatigue, cracking and moisture damage properties. The mixes included binder blends with 2, 4, 6, and 10 percent RHVDBs and PG 64-22 control along with the controls for the 4 percent and 6 percent RHVDBs. A full factorial experimental plan was used, which allows for direct comparison of the mixes made with RHVDB modified binders and mixes produced with standard binders of the same performance grading.

A full range of performance tests were run on each mix to allow for comparison of the RHVDB modified mixes to the control mixes. Rutting tests included the Hamburg Wheel Tracking test (HWT) and the Flow Number test. Moisture damage testing included AASHTO T 283 and the HWT. Fatigue was evaluated using the four point bending beam test and low temperature cracking was evaluated using the Disk-Shaped Compact Tension test (DCT).

Rutting was evaluated using both the HWT test and Flow Number test. The HWT test has been well-established as a good indicator of a mixes rut potential [2-4]. The HWT test is considered a severe test using a steel wheel with a 705 Newton load tracking back and forth over the mix sample maintained at 50°C in a water bath. The Flow Number Test was conducted on each mix as a comparison to the HWT test. The Flow Number Test was developed as a continuation of the Superpave system for performance testing [5]. In the Flow Number test a cylindrical specimen is subjected to cyclic loading with a 0.1 second axial load followed by a 0.9 second rest period for up to 10,000 repetitions or failure of the specimen [6].

Moisture damage potential was evaluated using AASHTO T 283 and the HWT test. AASHTO T283 has been used as a standard test for evaluating moisture damage potential for many years. The HWT test has also been used to evaluate moisture damage in addition to evaluating rut potential of a mix [7, 8]. While
the AASHTO T283 has been used for many years, its reliability has been questioned. Combining AASHTO T283 with the HWT test provides additional validation of the results.

Beam fatigue testing has been used to evaluate the fatigue properties of mixes since the early 1960s [9]. The current four point bending beam test was developed as part of the Strategic Highway Research Program (SHRP) and is the most widely use approach to evaluating mixture fatigue [10]. ASTM D7460 was used to test beams for each mix.

The Disk-Shaped Compact Tension test (DCT) was developed at the University of Illinois as part of the MnRoad pooled fund study on low temperature cracking [11, 12]. The DCT is a fundamental tension test for evaluating tensile fracture of the asphalt specimen. The test is done at low temperatures where the specimen is in the brittle state and little to no plastic flow will occur.

5.0 TEST RESULTS

5.1 Rutting

All HWT tests specimens were compacted to 7 percent air voids and tested under water at 50°C. Two gyratory specimens were combined for each sample. Rutting ranged from 4 to 8 mm for the various binders blends used in with the N70 mix. Rutting ranged from 5 to 10 mm for the binder blends in the N90 mix. Rutting basically followed the binder stiffness with the PG 64-22 control having the lowest rutting and the 10 percent RHVDB blend having the highest rutting. All the mixes were well below the Illinois DOT requirement that rutting be less than 12.5 mm at 7500 wheel passes for a PG 64-22 binder. This was the case even for the PG 58 binders. Figure 3 and 4 show the rutting for each blend of the N70 and N90 mixes.

![Figure 3. Rutting in the HWT test at 7500 wheel passes for the various N70 mixes.](image-url)
Comparison of the various RHVDB percentage blends with the specific control developed for the specific percent indicates that they are equivalent or better in rutting to the control. For the N70 blends, both the 4 and 6 percent RHVDB blend mixes had less rutting than the control mixes. For the N90 mixes, the 4 percent RHVDB blend had better rutting than the control while the 6 percent blend was basically equivalent to the 6 percent control.

The Flow Number test, run on the Asphalt Mix Performance Tests (AMPT), was used to validate the results from the HWT test. All testing was done at 47.5°C, which is the 50 percent reliability pavement temperature of the Chicago, Illinois area. A cyclic axial 600 kPa load is applied to the specimen for 10,000 repetitions or until two percent permanent strain is reached. The flow number is the number of repetitions to reach tertiary flow or when the rate of deformation increases. A higher flow number means a stiffer mix with less potential for rutting.

The Flow Number data mirrored the HWT test data. Figures 5 and 6 are bar charts of the flow number results for the N70 and N90 mixes. Again, for the Flow Number the results followed the binder stiffness with the PG 64-22 having the highest Flow Number and the 10 percent RHVDB PG 58-28 having the lowest Flow Number. In both mix types, N70 and N90, the RHVDB mixes provided equivalent results to the individual controls for each percentage.

Figure 7 shows a comparison of HWT results to the Flow Number results for the N70 mixes. These mixes provided an excellent correlation of Flow Number to HWT rutting. The $r^2$ for the results was 0.81 with the proper trend in relation between the different tests. The $r^2$ for the N90 mixes was not as good only being 0.5, but the trend was in the proper direction and very distinct between the test results.
Figure 5. Bar chart of the Flow Number results for the various N70 mixes.

Figure 6. Bar chart of the Flow Number results for the various N90 mixes.
Illinois modified AASHTO T 283 and the HWT test were both run as moisture damage tests on all mixes in the study. The Illinois modification to AASHTO T 283 is to not require a freeze thaw cycle. The HWT test as stated in the rutting evaluation section was run at 50°C under water with a 705 Newton loading. All the samples were tested to 20,000 wheel passes.

All mixes for both the N70 and N90 designs except the 10 percent RHVDB met the Illinois DOT requirement for Tensile Strength Ratio (TSR) of 85 percent. Even the 10 percent RHVDB mixes had TSR values greater than 80 percent, but were just under the 85 percent requirement. Figure 8 and 9 show bar graphs of the various mixes for the N70 and N90 designs. The PG 64-22 control mixes for both the N70 and N90 designs actually had the lowest passing TSRs of all the mixes. The addition of 0.5 percent liquid anti-strip in the 6 percent RHVDB mixes did improve the TSR for the N70 design, but had little effect on the N90 design. This is likely due to the higher binder content in the N90 mixes. Addition of a liquid anti-strip to the 10 percent RHVDB mixes may well improve them to passing the 85 percent TSR requirement.

The HWT tests verified what was seen in the AASHTO T283 testing. Figure 10 shows a plot of the HWT results for the N70 mixes. Only the 10 percent RHVDB mix shows any sign of the stripping inflection point, which is typically defined as indicating moisture damage in the test. The N90 mixes (though not shown) produced the same results. Again, based on this it is likely the addition of a liquid anti-strip or hydrated lime would eliminate any indication of moisture damage even in the 10 percent mixes.

5.2 Moisture Damage

![Figure 7. Comparison of the Flow Number and Hamburg Wheel Tracking (HWT) test results for the N70 mixes.](image-url)
Figure 8. AASHTO T283 Tensile Strength Ratio (TSR) results for the N70 mixes.

Figure 9. AASHTO T283 Tensile Strength Ratio (TSR) results for the N90 mixes.
5.3 Fatigue Properties

Fatigue properties of the mixes were evaluated using ASTM 7460 4 – Point Flexural Fatigue. Samples for the test were made by compacting slabs to 7 percent air voids and then cutting 380x50x68 mm beams from the slabs. Two strain levels were used to evaluate the mix properties; a 300 micro-strain level to simulate low strain levels in a pavement and 700 micro-strains to simulate high strain levels. All testing was done at 20°C, which represents a moderate intermediate temperature for fatigue evaluation. Cycles to failure for the testing were determined at the number of cycles to reach 50 percent loss of the initial beam modulus.

The PG 64-22 control for both the N70 and N90 mixes had the lowest number of cycles to failure at both the high and low strain levels, indicating the poorest fatigue response. The 6 percent RHVDB with 0.5 percent liquid anti-strip had the highest cycles to failure at both strain levels for both mix types, indicating the better fatigue response. The 2, 4, 6 percent RHVDB mixes and intermediate controls mixes all fell in between the PG 64-22 and 6 percent RHVDB mixes for both strain levels. All of the RHVDB mixes provided better fatigue response than the strait run PG 64-22. Figures 11 and 12 show the plots of the micro-strain verses cycles to failure for all the samples.

5.4 Low Temperature Cracking

Low temperature cracking was evaluated using the ASTM D7313 “Determining Fracture Energy of Asphalt-Aggregate Mixtures Using the Disk-Shaped Compact Tension Geometry.” Cylindrical shaped mix specimens 150 mm in diameter by 50 mm wide with a specified size notch are pulled in direct tension to determine the fracture energy of the mix. In the test a tensile load is applied to the specimen such that the Crack Mouth Opening Displacement (CMOD) is at a constant rate.
Figure 11. Cycles to failure verses strain level in the four point bending beam fatigue test for the N70 mixes.

Figure 12. Cycles to failure verses strain level in the four point bending beam fatigue test for the N70 mixes.
Figure 13 shows a schematic of the specimen geometry. The fracture energy is determined from the area under the load-CMOD plot divided by the initial ligament length.

Figure 14 shows a plot of the load-CMOD plot for two of the N70 mixes. The plot shows how the N70 4 percent RHVDB mix requires significantly more energy to cause failure than the N70 control mix. All testing for this study was done at -12°C.

Bar graphs showing the fracture energy for the N70 and N90 mixes are shown in Figures 15 and 16. The N70 mixes show a clear increase in fracture energy with the addition of the RHVDBs, indicating improved cracking properties. In each case, the RHVDB mix is equal or better than the corresponding control mix and better than the PG 64-22 control. The N90 mixes indicate that the 2, 4 and percent RHVDB mixes have similar fracture energy properties to the PG 62-22 control and the 4 and 6 percent EcoAddz equivalent. It is not until the 6 percent RHVDB with 0.5 percent AS and the 10 percent RHVDB mix that the improvement in fracture energy is seen.
Figure 14. Plot of the Load-Crack Mouth Opening Displacement (CMOD) curve showing the N70 control mix and 4% RHVDB mix.

Figure 15. Bar graph of the fracture energy for the N70 mixes.
None of the RHVDB mixes provide reduced fracture energy. The N90 mixes have higher binder content than the N70 mixes, which likely is masking some of the difference in the individual binder properties in the N90 mixes. Increases in binder content will improve fracture properties of mixes.

For the N90 mixes, the improvement in binder properties are not evident until the addition of liquid anti-strip and the high percentages of RHVDB. The N70 mixes show an improvement in fracture energy from about 450 J/m² for the PG 64-22 up to 700 J/m² for the 6 and 10 percent RHVDB mixes. The N90 mixes start at 650 J/m² and increase to 750 J/m² for the 6 percent RHVDB mixes, indicating that the increased binder content provides a 200 J/m² improvement and the softer binder provides about 200 J/m² improvement.

6.0 CONCLUSIONS

An in-depth evaluation was performed to determine the performance characteristics of asphalt mixtures produced with binders modified with RHVDB at several different levels. The rutting, moisture, fatigue and low temperature properties of the mixtures were evaluated against control mixes produced with unmodified binders. Multiple tests were run to compare the mixtures with RHVDB against the control mix. The study provides an extensive evaluation of the effects of RHVDB modification on mix performance.

The binders in the study included a PG 64-22 control, four and six percent EcoAddz equivalent controls, RHVDB blended at 2, 4, 6 and 10 percent, and six percent RHVDB with 0.5 percent liquid anti-strip. Each binder was used in two different mix designs; N70 (70 gyration) and N90 (90 gyration) mixes. The eight mixes for each design were tested using the HWT test, AASHTO TP 79 Flow Number test, AASHTO T283, ASTM D7460 Beam Fatigue, and ASTM 7313 DCT test.
The following conclusions were drawn from the investigation:

- Both of the high temperature rut performance tests, HWT and Flow Number, correlated well with each other. Both tests indicated that the rutting was related to the binder stiffness. Mixes produced with RHVDBs performed as well or better than the control mixes of similar binder stiffness.

- AASHTO T283 testing demonstrated that the RHVDB binder blends up to six percent provided equal results to the various control binders and did not indicate any stripping potential. The 10 percent RHVDB blend, while not meeting the stringent Illinois DOT TSR requirement of 85 percent, did provide a TSR of well over 80 even without an anti-stripping additive. HWT test graphs indicate that none of the mixes indicated a stripping inflection point except the 10 percent RHVDB blend. Testing of the six percent RHVDB blend with a liquid anti-strip indicated a significant improvement in rut resistance and reduction in rutting slope. This additional indicates that the addition of an anti-strip will likely eliminate the stripping inflection point for the 10 percent RHVDB mix.

- ASTM D7460 Beam Fatigue testing indicated that the RHVDB mixes provided equivalent or better fatigue response than the control mixes. This was true at both a 300 and 700 micro-strain level representing a high strain and low strain pavement environment.

- The ASTM D7313 Disk-Shaped Compact Tension test indicated that the RHVDB mixes provided equal or greater crack resistance than the control mixes.

Overall in rut resistance, moisture damage potential, fatigue response and cracking potential the Re-refined Heavy Vacuum Distillation Bottoms provided equal or better performance than the control neat binders. This study indicates that binders modified with RHVDB should provide good performance in the field.

REFERENCES


