ARKANSAS’ EXPERIENCE WITH CRUMB RUBBER MODIFIED MIXES USING MARSHALL AND SHRP LEVEL 1 DESIGN METHODS

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ABSTRACT

Unmodified and crumb rubber modified mixes conforming to the Arkansas State Highway and Transportation Department (AHTD) Type II Surface Course specifications were designed for heavy traffic conditions and environmental conditions typical to the State of Arkansas using the Marshall and Superpave Level I methods. Specimens prepared at appropriate design asphalt contents were evaluated from both volumetric and performance considerations.

Three mix types, including an unmodified hot-mix asphalt concrete, a "dry process" rubber modified asphalt concrete (in which the crumb rubber is added to the aggregate prior to mixing with asphalt cement), and a "wet process" asphalt-rubber mix (in which the crumb rubber is blended with the asphalt cement prior to mixing with aggregate) were included in the investigation. For the asphalt cement, crumb rubber, aggregate type and aggregate gradation used in this study, the design asphalt content was reduced for the SHRP level I method relative to the Marshall method. Incorporation of crumb rubber into hot-mix asphalt concrete provided increased rutting resistance; however, the rubber modified mixes did not show enhanced resilient and tensile properties when tested at 25 C. Also, the performance related properties of the SHRP Level I asphalt-rubber mixes (5, 10 and 15% A-R blends) evaluated did not differ significantly at 5% level of significance.

KEY WORDS: Crumb Rubber Modifier, Asphalt-rubber, Rubber Modified Asphalt Concrete, Marshall mix design, and SHRP Level I Mix Design
INTRODUCTION

The Strategic Highway Research Program (SHRP) has revolutionized binder testing and mix design procedures through the development of performance related and performance based specifications currently bundled as a mixture design/analysis system called "Superpave". These specifications have resulted in the availability of advanced instrumentation for binder and mix testing. The instrumentation, currently at various stages of evaluation by different agencies, was basically developed for design and evaluation of unmodified binders and mixes; however, the Superpave Mix design system is reportedly applicable for both virgin/recycled mixes with/without modifiers[1].

The Superpave Level I mix design procedure is a clear departure from conventional mix design methods such as the Marshall mix design method. Not only are the binders evaluated with regard to performance related parameters, the mixes are prepared in the lab to simulate field production and compaction. Two important stages in the sample preparation process of Superpave mix design are: aging of the mixes to simulate the field aging, and gyratory compaction to simulate field compaction and to evaluate mix compactability for a given set of traffic and environmental conditions.

The above factors play a significant role in the design of mixes by Superpave. Any attempt to compare traditional mix design procedures with Superpave must clearly isolate the effect of aging and mix compaction while duly considering a wide range of variables like the aggregate, binder and modifier types. Previous studies [2] have indicated no general trends in the Optimum Asphalt Content (OAC) of mixes designed using the two different methods
and have stressed the need to compare the mix designs from performance related tests. The research reported in this paper reflects the Arkansas’ experience in designing crumb rubber modified mixes by the Marshall and Superpave Level I methods and evaluating the mixes using performance related properties.

OBJECTIVES AND SCOPE

The main objectives of this study were to:

1. Compare the mix design parameters of unmodified and crumb rubber modified hot mix asphalt concrete (HMAC) using Marshall and SHRP Level I procedures
2. Evaluate the performance related properties of the Marshall and Superpave Level I mixes prepared at their respective design asphalt contents for aged and gyratory compaction conditions.

This study adds to the data base of the similar work performed by other researchers [2;3]. Extensive studies using a wide range of aggregates, asphalt and crumb rubber types are essential to compare conventional and the SHRP mix design specifications. It must also be noted that the Superpave mix design system is a "three level" approach depending upon the magnitude of the traffic for which the mix is designed. This paper addresses only the Level I Volumetric Mix Design.

THE EXPERIMENTAL PROGRAM

General

In this study seven mixes conforming to the Arkansas State Highway and Transportation Department’s specifications[4] for Type II mixes were tested. The aggregate and asphalt used in the mixes were identical. The aggregate was a crushed limestone and the asphalt cement was an AC-30. The principal difference between the mixes were in the amount of rubber used and the method used in adding it to the mix.
One mix used only the unmodified AC-30 asphalt cement (no rubber). The other six mixes used various percentages of rubber with three mixes having rubber added by the "wet" process (added to and blended with the asphalt cement prior to mixing with aggregate), and the other three mixes having rubber added by the "dry" process (added to the aggregates prior to mixing with asphalt cement). The "wet" process mixes, referred to here as "A-R" mixes, had rubber blended with asphalt in amounts of 5, 10 and 15 percent by weight of asphalt. The "dry" process mixes, referred to here as "RUMAC" mixes, had rubber mixed with the aggregates in amounts of 1, 2 and 3 percent by weight of aggregate. The rubber used in the mixes (crumb rubber modifier, CRM) had a mean particle size of 74 microns and was supplied by Rouse Rubber Industries Inc. [5]

**Blending Asphalt-Rubber in the Lab**

The asphalt and rubber were blended in accordance with the procedures outlined by the Rouse Rubber Industries[5]. Using a mechanical mixing unit (used for preparing Marshall mixes) and a temperature controlled non-stick mixing bowl, it was possible to prepare about 4000 grams of asphalt-rubber blend in each setup. The preparation of A-R blends did not pose any major problems; however, caution had to be exercised to prevent segregation of the CRM particles when the blends had to be transferred into the sample cans.

**SHRP PG Classification of Binders**

About 500 grams of the unmodified and modified binder was split to conduct tests essential for PG classification. The tests to classify the binder were conducted in accordance with the specifications outlined in the SUPERPAVE Mix Design System Manual [6].

**Effect of Sample Confinement and Paraffin Coated Molds**

Previous studies[7] recommended the use of paraffin coated molds and confining the rubber modified mixes for 24 hours in the molds prior to extrusion. The product information on
CRM[5] indicated that the fineness of the material would ensure quick and adequate reaction (in terms of asphalt absorption) between the CRM and the asphalt binder at the normal mixing time and reduce swelling. It was decided to design mixes for confined and unconfined conditions with and without paraffin coating of the molds. From Table 1 and 2, it can be seen that the use of confinement and paraffin coated molds does not have a significant effect on the volumetric or strength (stability) of the mixes. Subsequent mix designs were performed without using confinement and without paraffin-coated molds.

In preparing the "dry" process mixes, the aggregate gradation was adjusted by substituting the CRM (1, 2 and 3% by total weight of the aggregates) for aggregate mineral fines. In other words, the job mix formula for the RUMAC (1, 2 and 3% CRM) mixes were determined by considering the CRM as aggregate fines and accounting its gradation in the Trial and Error method calculations. No modification was made to the unmodified aggregate gradation used in the wet process. The Job Mix Formula (JMF) for all the 7 mixes yielded an aggregate gradation which satisfied both the AHTD Type II surface course specifications and the SHRP restricted zone and control points criteria. Figure 1 shows the gradation of the aggregates adopted for the design of the seven mixes and the Superpave gradation specifications.

The design of the mixes by Marshall method was done in accordance with the specifications given by the Asphalt Institute[8]. The design/optimum binder contents were selected at 4% air-void level. Five different sizes of aggregates and the CRM (for RUMAC and A-R mixes only) were blended to obtain an aggregate batch (1180 grams) in accordance with the Job Mix Formula. The mixes were designed for heavy traffic (75 blows/side) conditions at temperatures conforming to viscosity standards outlined in the MS-2 specifications[8]. The average mixing temperature for the unmodified and dry process mixes was 156 C and the compaction temperature was 143 C. For the "wet" process mixes the temperatures were
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168C and 149 C respectively.

**SHRP Level I Mix Design**

This part of the study was to determine the design asphalt content for the mixes using traffic levels comparable to that assumed for the Marshall mix design and for environmental conditions typical to the State of Arkansas (design 7-day maximum air temperature less than 39 C). In the SHRP process, the maximum number of gyrations to which the mixes are compacted depends upon the traffic and environmental conditions [6]. The design number of gyrations \( N_{\text{design}} \) comparable to the traffic conditions used in Marshall procedure and satisfying the Arkansas environmental criteria was 96. Corresponding values for the initial \( N_{\text{initial}} \) and Final \( N_{\text{final}} \) number of gyrations were 8 and 152 respectively.

The SHRP gyratory compaction specification M 002 [6] recommends that the samples be compacted to a height between 49-51 mm. However, the authors wanted to take advantage of the mold size and prepare samples of 150 mm in height to obtain two Marshall-sized specimens for use in performance tests. Shortage of aggregates gave an option to prepare samples of 50 mm in height for mix design and 150 mm samples for the preparation of samples at OAC. At this stage, it was suspected that the samples compacted to different heights at a given number of gyrations could yield different volumetric properties. A separate study [9] initiated to investigate the effect of sample heights on the volumetric properties of unmodified, A-R, and RUMAC mixes indicated that the variation in air voids could be as high as 3-8% for a given mix which is compacted using specimen sizes of 2000 to 6500 grams at the same number of gyrations. Figure 2 indicates the effect of sample height/weight on the air-voids of a given mix. Since the effect of specimen size on volumetric properties was negligible for larger specimen sizes, it was decided to prepare samples using 6500 grams of mix to obtain samples of about 150 mm in height. Two samples were prepared at each binder
content using the mixing and compaction temperature adopted in the Marshall mix design procedure. The mixes were aged and brought to appropriate compaction temperature and compacted. A correction factor for the bulk specific gravity estimated at each gyration was calculated using the measured bulk specific gravity (AASHTO T166) and the final height of the sample [10].

The theoretical maximum density of the mixes (AASHTO T 209) was determined at each asphalt content and the density-void analysis were performed to develop plots of percent voids, VMA, and VFA against their corresponding binder content. The optimum asphalt content (OAC) was determined at 4% air voids level.

COMPARISON OF MIX DESIGNS USING PERFORMANCE RELATED TESTS

Sample Preparation

Test samples were prepared at design asphalt contents corresponding to both Marshall and SHRP Level I design procedures for the following conditions:

1. Unaged mixes at Marshall optimum asphalt content (OAC) using Marshall compaction
2. Aged mixes at Marshall OAC using Gyratory compaction
3. Aged mixes at SHRP OAC using Gyratory compaction

Establishment of a Basis for Comparison

Even though the Marshall mix design procedure does not use aged mixes and a compaction procedure that simulates field compaction, mixes produced in the field (using the Marshall mix design) will be subjected to aging before compaction. The aging of the mix and the use of a compaction procedure that simulates field compaction is incorporated in the SHRP mix design. Hence, to compare the two mix designs from performance related properties, it was decided to age the mixes prepared at the Marshall OAC (as per SHRP provisions).
Three samples of each mix type were prepared using gyratory compaction at the optimum asphalt content obtained from the Marshall and Superpave Level I methods. Since SHRP Level II and III performance test procedures and equipment are still being evaluated and refined, it was decided to evaluate the two mix designs using more traditional tests like the repeated load dynamic compression, resilient modulus (ASTM D 4123) and indirect tensile strength tests.

Also, the difference between the sizes of traditional Marshall and SHRP specimens was resolved by sawing and coring the SHRP gyratory compacted specimens. Gyratory compacted samples (150 mm dia and 150 mm height) were sawed into two samples of 62.5 mm in height, each of which were cored to a diameter of 100 mm. Thus one gyratory compacted sample (150 mm height and 150 mm dia) produced two Marshall-sized samples (100 mm dia and 62.5 mm in height). Six samples prepared at Marshall and SHRP level I OAC were tested for the performance-related tests previously listed.

**Details of the Tests Conducted in this Study**

Repeated load dynamic compression tests were conducted on the test samples at 40 C using an MTS "Closed Loop" servo- hydraulic system with a haversine loading. The test samples were subjected to seating and dynamic loads of 3.4 Kpa (0.5 psi) and 103.4 Kpa (15 psi) respectively for 10,000 load repetitions. The total duration of each load repetition was 0.1 seconds with a rest period of 1.9 seconds. The permanent deformation at 10,000 repetitions was divided by the gauge length of the extensiometer to obtain the corresponding permanent strain.

Resilient modulus tests were conducted at 25 C on three samples of each mix type and compaction method using a pneumatic loading system. The resilient deformation was determined by applying an impulse loading on the diametral axis of the specimen. The duration
of application of the load was 0.1 seconds. The resilient modulus at 25 C was estimated using the empirical relation given in Reference 11.

The samples used in the resilient modulus study were used to determine the indirect tensile strength test at 25 C. The tensile loading was applied on the diametral axis of the specimen using the MTS system at a rate of (50 mm/min). The indirect tensile stress was estimated using the relationship used by Shatnawi [12].

DISCUSSION OF TEST RESULTS

Analysis of SHRP PG Classification Results

The performance grading of the unmodified and rubber modified asphalt (Table 2) shows that the blending of crumb rubber broadened the range of applicability of the asphalt. The high temperature increased from 64 C to 80 C with 10 and 15% A-R rubber blends and the low temperature decreased from -22 C to -34 C with 15% A-R blends. There was however, no indication of improvement in load-associated fatigue resistance. Among the asphalt-rubber blends binders tested in this study the 15% A-R blend marginally (3.1 pa-s) exceeded the viscosity limits (3 Pa-s).

Analysis of the Marshall Mix Design Results

Table 3 lists the Marshall mix design results. These results indicate that for the “dry” process, the GF-80 crumb rubber added at 1 and 2% CRM had no significant effect on the optimum asphalt content, VMA or VFA; however, stability decreased with increasing rubber percentages (17124 N unmodified, 15034 N at 1%, and 9875 N at 2%). With 3% CRM the optimum asphalt content increased from 5.1 to 5.7%, VMA increased (15.5 to 16.2%), VFA decreased (73 to 65%), and the Marshall stability continued its decrease (7828 N). It can be seen that the effect of CRM on the optimum asphalt content and volumetric properties is significant for RUMAC mixes with 3% CRM. This expected behavior of the "dry" process
mixes could be attributed to the absorption of asphalt by the CRM which increases the asphalt content requirements for the mix to attain the required volumetric properties (in this case, the air voids). Blending of asphalt and rubber prior to mixing with the aggregates (e.g. A-R mixes) ensures adequate reaction between the two materials. As such, the OAC of the A-R mixes will be less affected by the absorption of the asphalt by the CRM. The optimum asphalt contents of the asphalt-rubber mixes and their consistent Marshall stability values indicated in Table 3 reinforces this conclusion.

The decrease in the Marshall stability of the rubber modified mixes (dry process) with an increase in the percentage of CRM in the mix may be an early indication that 2 minutes of mixing and limited aging of the mix does not permit adequate reaction between the asphalt and rubber to produce a modified blend as proposed [5] by the CRM producer. The crumb rubber in the dry process mixes seems to reduce the stiffness of the resulting mixes.

Analysis of the SUPERPAVE Level I Mix Design Results

From Table 4, it can be seen that for the aggregate, crumb rubber type and the aggregate gradation used in this study, the Level I mix design procedure yields a lower OAC compared to the Marshall method. The difference in the OAC ranges from 1.0 to 1.3% AC for the dry process and 0.8 to 1.1% AC for the wet process. The reason could be attributed to the reduction in the effective asphalt content due to the absorption of asphalt by the aggregates and the crumb rubber during the aging process. The reduction in the VMA and VFA of the Level I Mixes reinforces this observation. A similar study[2], in which unmodified and rubber modified mixes (aged for 1 hour at 160 C) were designed by the Marshall method did not report consistent trends in the OAC relative to Level I mix design.

However, a significant observation from the mix design process is that all the SHRP mixes (1 unmodified and 6 modified) designed for an $N_{design}$ of 96 gyrations (comparable with
the Marshall Heavy Compaction calculated lesser VMA at the design asphalt content when compared with the Marshall mixes. This observation has also been reported by D'Angelo et al [3] for the same \( N_{\text{design}} \) and Marshall compaction used in this study. While some researchers may argue that the differences between the volumetric properties of the mixes designed by the two methods are unreasonable because the two mix design methods mixes have the same ideology that the compacted to the unit weight which they are expected to reach after 2-3 years. The authors offer the following arguments in favor of their results:

a. Even though the basic premise behind the two mix design procedures are the same, the mix design procedures adopt totally different mix preparation procedure. It is suspected that short-term curing of the SHRP mixes (1 unmodified and 6 crumb rubber modified) could increase the asphalt absorption by the aggregates and the crumb rubber when compared with the no aging adopted in the Marshall method. This could significantly affect the volumetric properties of the mixes.

b. The \( N_{\text{Max}} \) and \( N_{\text{Design}} \) gyrations (ESAL < \( 10^7 \)) for the Level I mix design method were selected to yield a mix compatibility that was comparable with the Marshall heavy traffic compaction (ESAL > \( 10^6 \)). There is however no published research to correlate the compatibility produced by the gyratory compacted mixes with the Marshall mixes.

This and a similar study by other researchers[3] confirms that an \( N_{\text{Design}} \) of 96 yields lesser VMA less than that produced by the Marshall 75 blow compactor and that the compatibility at \( N_{\text{Design}} \) of 96 may not be comparable with the Marshall compaction. The determination of a gyratory compactive effort that would produce a compactibility equivalent to the marshall compaction was beyond the scope of this study.
Comparisons Based on Performance Related Properties

General Philosophy behind Mix Comparisons

One of the objectives of this study was to evaluate the effect of crumb rubber as an additive in the asphalt mixes using performance related properties. Accordingly, the mixes were designed using the conventional Marshall method and the emerging Superpave Level I method. The mixes were prepared at the Marshall and Level I design asphalt content for four different conditions as indicated in Table 4 through 6. Recognizing the fact that the SHRP mixes did not meet the VMA criteria, the results from the performance tests will be strictly used to identify the trends in the behavior of the mixes with an increasing percentage of crumb rubber in the mixes and not for comparing the performance related properties of the mixes designed by the two methods.

Permanent Strain

From Table 5 it can be seen that the unmodified mixes designed by both methods show higher permanent strain in comparison to the CRM modified mixes. The dry process RUMAC mixes show a slight reduction in the permanent strain at 2% CRM relative to 1% CRM; at 3% CRM content the mixes exhibit substantially higher permanent strain. For the mixes designed by wet process, the unaged Marshall-compacted mixes showed a reduction in the permanent strain with an increase in the percent CRM in the blend. However, similar trends were not evident for aged, gyratory-compacted mixes. A general trend from the Table 5 is that the SHRP mixes show higher permanent strains compared to the Marshall mixes.

Resilient Modulus

For the seven mixes designed in this study, the unmodified, aged and gyratory-compacted mixes show higher modulus in comparison with the CRM mixes (Table 6). There were no evident trends in the modulus data for the unaged, Marshall-compacted RUMAC mixes. The
dry process RUMAC mixes (aged and SHRP compacted) show a decrease in the modulus with an increase in the CRM content. The gyratory compacted A-R mixes prepared at Marshall OAC indicated similar trends but the SHRP Level I A-R mixes did not show any appreciable reduction/variation in the modulus values. The difference in the performance properties of the SHRP Level I A-R mixes was statistically evaluated using the Students ‘t’ test. The test confirmed that the mean resilient modulus values of the SHRP Level I A-R mixes were significant at 5% level of significance.

**Tensile Strength Characteristics**

From Table 7 it can be seen that the unmodified mixes exhibited tensile strengths comparable with the RUMAC 1% and A-R 5% mixes. However, the general trend was that an increase in the % CRM in the mix resulted in a reduction in the tensile strengths. The reduction in the tensile strengths for the RUMAC mixes (both Marshall and SHRP designs) were significant at 5% level of significance; however, the reduction was not significant for the Marshall (aged and gyratory compacted) and the SHRP A-R mixes.

**Unmodified vs CRM Modified Mixes**

From Table 5, it can be seen that CRM mixes prepared in accordance with aging and gyratory compaction specifications exhibit higher resistance to rutting (reduced permanent strain) compared to the unmodified mixes. This indicates that the incorporation of CRM into HMAC mixes can be beneficial in reducing rutting. This conclusion is supported by improvements in the PG classification of the A-R binders with respect to rutting resistance. It should be noted, however, that relatively higher levels of CRM could lead to a reduction in the rutting resistance of the mixes.

The incorporation of CRM into HMAC mixes did not improve the resilient or tensile properties at 25 C. This stresses the need for conducting these tests at temperatures lower
than 25°C to quantify the contribution of the CRM in enhancing the resilient and tensile properties of the mixes.

**SUMMARY AND CONCLUSIONS**

For the aggregate, asphalt, CRM type and aggregate gradations evaluated, this study offers the following conclusions:

1. For the unmodified and crumb rubber modified mixes designed in this study using the Marshall and Superpave Level I methods, the Superpave Level I method yields lower design asphalt content and VMA when compared with the Marshall method.

2. This study confirms that the compactive effort produced by the SHRP gyratory compactor at an $N_{design}$ of 96 may not yield the volumetric properties (VMA) equivalent to the 75 blow Marshall compaction. Unless studies are conducted to correlate the volumetric properties of the Marshall mixes with the SHRP mixes at different levels of gyratory compaction, valid comparisons between the two mix design methods cannot be made for any traffic level.

3. The dry process of incorporating the CRM in the asphalt mixes tends to reduce the stiffness of the resulting mix and it may not enhance the mix properties when compared to the wet process.

4. Blending of crumb rubber with asphalt enhances the rutting resistance of the mixes prepared to simulate the field preparation (aging) and compaction (gyratory). However, there were no appreciable benefits to the resilient modulus and tensile strength of the mixes at the test temperature of 25°C.

5. The resilient modulus and the tensile strength of the RUMAC mixes generally decreased with an increase in the CRM content in the mix. However, the A-R mixes designed by SHRP Level I method did not show a statistically significant reduction in
the properties with an increase in CRM content in the blend.

6. A better understanding of the asphalt-rubber reaction is needed to identify the appropriate range of temperatures to evaluate the properties the CRM is purported to improve/impart to the mix.

7. Statistical analysis indicates that confining the RUMAC samples for 24 hours or paraffin coating the molds did not have significant effect on the mix design properties.

8. In SHRP mix design, small specimen sizes (for both unmodified and CRM mixes) can affect the volumetric properties of the mix. A specimen size of at least 3500 grams is recommended for the preparation of the SHRP gyratory samples.

This study adds to the data base of the volumetric and performance related properties of unmodified and CRM modified mixes designed by SHRP Level I and Marshall methods, for the environmental conditions typical to the State of Arkansas and for traffic and compaction levels comparable with "heavy traffic" Marshall mix design. Continued research is essential to broaden the data base by performing mix designs for temperature conditions typical to other states/climatic regions of the U.S. while accounting for the essential variables such as range of traffic levels, aggregate types, binder and modifier types, etc.

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study. The authors are responsible for the accuracy of the data presented in this paper and the views expressed in this paper are those of the authors and do not necessarily reflect the official views of the MBTC or AHTD. This paper does not constitute a standard or a specification.

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8. The Asphalt Institute Manual Series No 2 (MS-2) "Mix Design Methods for Asphalt


Table 1 Marshall Mix Design Parameters for RUMAC Mixes for Paraffin Coated/Non-coated and Sample Confined/Unconfined Conditions

<table>
<thead>
<tr>
<th>Mix Type</th>
<th>Condition</th>
<th>% OAC</th>
<th>%VMA</th>
<th>%VFA Range 65-75%</th>
<th>Stability Min 8000 N</th>
<th>Flow (1/100&quot;)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unmodified</td>
<td>No Paraffin Unconfined</td>
<td>5.15</td>
<td>15.5</td>
<td>75</td>
<td>17124</td>
<td>11</td>
</tr>
<tr>
<td>RUMAC 1% CRM</td>
<td>No Paraffin Confined</td>
<td>5.1</td>
<td>15.2</td>
<td>74</td>
<td>14223</td>
<td>12</td>
</tr>
<tr>
<td>RUMAC 1% CRM</td>
<td>No Paraffin Unconfined</td>
<td>5.1</td>
<td>15.2</td>
<td>75</td>
<td>15034</td>
<td>12</td>
</tr>
<tr>
<td>RUMAC 1% CRM</td>
<td>Paraffin Confined</td>
<td>5.15</td>
<td>15.3</td>
<td>75</td>
<td>12632</td>
<td>11</td>
</tr>
<tr>
<td>RUMAC 1% CRM</td>
<td>Paraffin Unconfined</td>
<td>5.1</td>
<td>15.1</td>
<td>74</td>
<td>12854</td>
<td>11</td>
</tr>
<tr>
<td>RUMAC 2% CRM</td>
<td>No Paraffin Confined</td>
<td>5.05</td>
<td>15.1</td>
<td>76</td>
<td>10141</td>
<td>11</td>
</tr>
<tr>
<td>RUMAC 2% CRM</td>
<td>No Paraffin Unconfined</td>
<td>5.1</td>
<td>15.1</td>
<td>76</td>
<td>9785</td>
<td>12</td>
</tr>
<tr>
<td>RUMAC 2% CRM</td>
<td>Paraffin Unconfined</td>
<td>5.1</td>
<td>15.1</td>
<td>76</td>
<td>9385</td>
<td>11</td>
</tr>
<tr>
<td>RUMAC 3% CRM</td>
<td>No Paraffin Confined</td>
<td>5.6</td>
<td>16.1</td>
<td>76</td>
<td>8406</td>
<td>16</td>
</tr>
<tr>
<td>RUMAC 3% CRM</td>
<td>No Paraffin Unconfined</td>
<td>5.7</td>
<td>16.2</td>
<td>76</td>
<td>7828</td>
<td>15.5</td>
</tr>
</tbody>
</table>
Table 2: Statistical Analysis showing the Effect of Sample Confining and Paraffining on the VMA of the Rubber Modified Asphalt Concrete (RUMAC) Mixes at 5.5% Asphalt Content

<table>
<thead>
<tr>
<th>Mix I.D</th>
<th>Effect Evaluated</th>
<th>n</th>
<th>Mean</th>
<th>S.D</th>
<th>t)Cal</th>
<th>t)0.05</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>RUMAC 1% @ 5.5% AC</td>
<td>EFFECT OF CONFINEMENT (Non Paraffin Coated)</td>
<td>3</td>
<td>15.03</td>
<td>0.13</td>
<td>0.42</td>
<td>2.78</td>
<td>Effect of sample confinement is not significant at 5%</td>
</tr>
<tr>
<td>Unconfined</td>
<td></td>
<td></td>
<td>15.03</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Confined</td>
<td></td>
<td></td>
<td>15.07</td>
<td>0.10</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RUMAC 2% @ 5.5% AC</td>
<td>EFFECT OF CONFINEMENT (Non Paraffin Coated)</td>
<td>3</td>
<td>15.02</td>
<td>0.23</td>
<td>0.21</td>
<td>2.78</td>
<td>Effect of sample confinement is not significant at 5%</td>
</tr>
<tr>
<td>Unconfined</td>
<td></td>
<td></td>
<td>15.02</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Confined</td>
<td></td>
<td></td>
<td>15.05</td>
<td>0.056</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RUMAC 1% @ 5.5% AC</td>
<td>EFFECT OF CONFINEMENT (Non Paraffin Coated)</td>
<td>3</td>
<td>16.45</td>
<td>0.06</td>
<td>0</td>
<td>2.78</td>
<td>Effect of sample confinement is not significant at 5%</td>
</tr>
<tr>
<td>Unconfined</td>
<td></td>
<td></td>
<td>16.45</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Confined</td>
<td></td>
<td></td>
<td>16.45</td>
<td>0.10</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RUMAC 1 @5.5% AC</td>
<td>EFFECT OF PARAFFIN COATING</td>
<td>3</td>
<td>15.1</td>
<td>0.12</td>
<td>1.108</td>
<td>2.78</td>
<td>Effect of Mold Paraffining is not significant at 5%</td>
</tr>
<tr>
<td>Unconfined</td>
<td></td>
<td></td>
<td>15.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Confined</td>
<td></td>
<td></td>
<td>15.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RUMAC 2% @ 5.5% AC</td>
<td>EFFECT OF PARAFFIN COATING</td>
<td>3</td>
<td>15.1</td>
<td>0.15</td>
<td>0</td>
<td>2.78</td>
<td>Effect of Mold Paraffining is not significant at 5%</td>
</tr>
<tr>
<td>Unconfined</td>
<td></td>
<td></td>
<td>15.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Confined</td>
<td></td>
<td></td>
<td>15.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 3 Performance Grade Classification of the Binders Used in this Study

<table>
<thead>
<tr>
<th>PG Classification Criteria</th>
<th>Unmodified AC-30</th>
<th>AR 5%</th>
<th>AR 10%</th>
<th>AR 15%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brookfield Viscosity</td>
<td>0.42 Pa-s</td>
<td>0.75 Pa-s</td>
<td>1.66 Pa-s</td>
<td>3.1 Pa-s</td>
</tr>
<tr>
<td>20 rpm, 135 C, Max 3 Pa-s</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dynamic Shear Rheometer (Unaged)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$G'/\sin(\delta)$ Kpa @ 10 rad/sec</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature (C)</td>
<td>64</td>
<td>70</td>
<td>80**</td>
<td>80**</td>
</tr>
<tr>
<td>Dynamic Shear Rheometer (TFO)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$G'/\sin(\delta)$ Kpa @ 10 rad/sec</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature (C)</td>
<td>64</td>
<td>70</td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td>Dynamic Shear Rheometer</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$G'/\sin(\delta)$ Kpa @ 10 rad/sec</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature (C)</td>
<td>25</td>
<td>25</td>
<td>25</td>
<td>22</td>
</tr>
<tr>
<td>Bending Beam Rheometer</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stiffness (S) Mpa @ 60 Sec</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slope of the Master Curve (m) @ 60 sec</td>
<td>-12</td>
<td>-18</td>
<td>-18</td>
<td>-24</td>
</tr>
<tr>
<td>Temperature (C)</td>
<td>64 - 22</td>
<td>70 - 28</td>
<td>80 - 28</td>
<td>80 - 34</td>
</tr>
</tbody>
</table>

* indicates the blend was constituted by 5% CRM by weight of the asphalt cement binder
** indicates that it was not possible to test the binders beyond 80 C
Table 4: Mix Design Results for Unmodified, Rubber Modified and Asphalt-Rubber Mixes
(Marshall Mix Design)

<table>
<thead>
<tr>
<th>Mix Design Parameters at 4% Voids</th>
<th>Unmodified Mix</th>
<th>Rubber-Modified Mixes (Dry Process)</th>
<th>Asphalt-Rubber Mixes (Wet Process)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1% CRM</td>
<td>2% CRM</td>
</tr>
<tr>
<td>Optimum AC %</td>
<td>5.1</td>
<td>5.1</td>
<td>5.1</td>
</tr>
<tr>
<td>VMA (%) Min. 15.2%</td>
<td>15.5</td>
<td>15.4</td>
<td>15.1</td>
</tr>
<tr>
<td>VFA (%) Range 65-75%</td>
<td>73</td>
<td>74.0</td>
<td>74.0</td>
</tr>
<tr>
<td>Marshall Stability (N) Min 8000 N</td>
<td>17,124</td>
<td>15,034</td>
<td>9,785</td>
</tr>
<tr>
<td>Sp. Gr of AC/Blend</td>
<td>1.033</td>
<td>1.033</td>
<td>1.033</td>
</tr>
</tbody>
</table>

* Percentage of CRM in the mix expressed as the total weight of the aggregate blend
** Percentage of CRM in the A-R Blend expressed as a total weight of the asphalt cement binder
Table 5 Comparison of Marshall and SHRP Level I Mix Designs for Unmodified, Rubber Modified and Asphalt-Rubber Mixes

<table>
<thead>
<tr>
<th>Mix Design Parameters at 4% Voids</th>
<th>Unmodified Mix</th>
<th>Rubber-Modified Mixes (Dry Process)</th>
<th>Asphalt-Rubber Mixes (Wet Process)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1% CRM</td>
<td>2% CRM</td>
</tr>
<tr>
<td>Optimum AC %</td>
<td>5.1</td>
<td>4.1</td>
<td>5.1</td>
</tr>
<tr>
<td>VMA (%) 15.2%</td>
<td>15.5</td>
<td>11.5</td>
<td>15.4</td>
</tr>
<tr>
<td>VFA (%) Min 65% Max. 75%</td>
<td>73</td>
<td>65</td>
<td>74</td>
</tr>
</tbody>
</table>

* Percentage of CRM expressed as the total weight of the aggregates
** Percentage of CRM expressed as the total weight of the asphalt cement binder
Table 6 Permanent Deformation Characteristics of the Mixes Tested in this Study

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N</td>
<td>Mean mm/mm</td>
<td>Std.Dev mm/mm</td>
</tr>
<tr>
<td>Unmodified</td>
<td>3</td>
<td>0.020</td>
<td>0.0025</td>
</tr>
<tr>
<td>RUMAC 1% CRM</td>
<td>3</td>
<td>0.030</td>
<td>0.0003</td>
</tr>
<tr>
<td>RUMAC 2% CRM</td>
<td>3</td>
<td>0.033</td>
<td>0.0025</td>
</tr>
<tr>
<td>RUMAC 3% CRM</td>
<td>3</td>
<td>0.056</td>
<td>0.005</td>
</tr>
<tr>
<td>A-R 5% Blend</td>
<td>3</td>
<td>0.046</td>
<td>0.010</td>
</tr>
<tr>
<td>A-R 10% Blend</td>
<td>3</td>
<td>0.022</td>
<td>0</td>
</tr>
<tr>
<td>A-R 15% Blend</td>
<td>3</td>
<td>0.018</td>
<td>0.013</td>
</tr>
</tbody>
</table>

* Percentage of CRM in the mix expressed as the total weight of the aggregate blend
** Percentage of CRM in the A-R Blend expressed as a total weight of the asphalt cement binder
Table 7  Resilient Characteristics of the Mixes Evaluated in this Study

<table>
<thead>
<tr>
<th></th>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N</td>
<td>Mean (Kpa)</td>
<td>S.D (Kpa)</td>
<td>N</td>
</tr>
<tr>
<td>Unmodified</td>
<td>6</td>
<td>1881</td>
<td>42.3</td>
<td>5</td>
</tr>
<tr>
<td>RUMAC 1% CRM</td>
<td>6</td>
<td>1908</td>
<td>30.2</td>
<td>4</td>
</tr>
<tr>
<td>RUMAC 2% CRM</td>
<td>6</td>
<td>2219</td>
<td>39.5</td>
<td>4</td>
</tr>
<tr>
<td>RUMAC 3% CRM</td>
<td>6</td>
<td>1174</td>
<td>84.5</td>
<td>4</td>
</tr>
<tr>
<td>A-R 5% Blend</td>
<td>6</td>
<td>3233</td>
<td>208.6</td>
<td>4</td>
</tr>
<tr>
<td>A-R 10% Blend</td>
<td>6</td>
<td>2917</td>
<td>154.8</td>
<td>3</td>
</tr>
<tr>
<td>A-R 15% Blend</td>
<td>6</td>
<td>1605</td>
<td>225</td>
<td>6</td>
</tr>
</tbody>
</table>

* Percentage of CRM in the mix expressed as the total weight of the aggregate blend
** Percentage of CRM in the A-R Blend expressed as a total weight of the asphalt cement binder
Table 8 Tensile Strength Characteristics of the Mixes Tested in this Study

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N</td>
<td>Mean Kpa</td>
<td>Std.Dev Kpa</td>
<td>N</td>
</tr>
<tr>
<td>Unmodified</td>
<td>3</td>
<td>938</td>
<td>20.5</td>
<td>3</td>
</tr>
<tr>
<td>RUMAC 1% CRM</td>
<td>3</td>
<td>978</td>
<td>20.5</td>
<td>3</td>
</tr>
<tr>
<td>RUMAC 2% CRM</td>
<td>3</td>
<td>805</td>
<td>27.1</td>
<td>3</td>
</tr>
<tr>
<td>RUMAC 3% CRM</td>
<td>3</td>
<td>627</td>
<td>15.5</td>
<td>3</td>
</tr>
<tr>
<td>A-R 5% Blend</td>
<td>3</td>
<td>1276</td>
<td>66.2</td>
<td>3</td>
</tr>
<tr>
<td>A-R 10% Blend</td>
<td>3</td>
<td>1201</td>
<td>68.5</td>
<td>3</td>
</tr>
<tr>
<td>A-R 15% Blend</td>
<td>3</td>
<td>1175</td>
<td>68.0</td>
<td>3</td>
</tr>
</tbody>
</table>

* Percentage of CRM in the mix expressed as the total weight of the aggregate blend
** Percentage of CRM in the A-R Blend expressed as the total weight of the asphalt cement binder
Figure 1 Gradation used in Study with AHTD and SHRP Gradation Specifications
Figure 2 Effect of Specimen Size on the Volumetric Property (% Gmm) of a Given Mix