EVALUATION OF COMPACTION BENEFITS OF FOAMED ASPHALT MIXTURES
AT VARYING PRODUCTION TEMPERATURES

By
Brian D. Prowell, Ph.D., P.E.
Principal Engineer
Advanced Materials Services, LLC
2515 E. Glenn Ave., Suite 107
Auburn, AL 36830 U.S.A.
1 (334) 246-4428
Fax 1 (334) 408-4854
Brian@amsllc.us
(Corresponding Author)

Richard J. Schreck
Executive Vice President
Virginia Asphalt Association
6900 Patterson Ave.
Richmond, VA 23226 U.S.A.
1 (804) 288-3169
Fax 1 (804) 288-4551
RSchreck@VAAsphalt.com

Shohei Sasaki
Chief Engineer
Technical Development Division
NIPPO CORPORATION
6-70, Mihashi, Nishi-ku
Saitama, 331-0052 Japan
+81-48-624-0095
Fax +81-48-622-3028
Sasaki_Shouhei@nippo-c.jp

September 8, 2011

Word Count = 3,597
ABSTRACT

A large number of contractors have adopted free-water foaming systems to produce warm mix asphalt (WMA). The foaming nozzles of early models were prone to clogging if contractors did not foam when producing hot mix asphalt (HMA). Consequently, many contractors ran their foaming systems regardless of whether or not they were producing WMA. Contractors may also wish to produce foamed asphalt mixtures to improve workability and compaction during cold weather or increase haul distances. In these situations, the contractor may wish to increase the temperature of the foamed asphalt above typical warm mix temperatures (<135 °C (<275° F)).

Research on foamed asphalt indicates that the half-life of the foam or the time it takes the initial volume of the foamed asphalt to decrease by one-half, decreases with increasing temperature even though the initial expansion ratio may be larger at higher temperatures. This suggests that the improved ability to compact foamed WMA could be diminished as the mix temperature increased.

Most of NIPPO CORPORATION’s asphalt mixtures contain high percentages of RAP, with minimum RAP contents of approximately 30 percent and maximum RAP contents of 60 percent for surface mixes and 80 percent for base mixtures. Currently, the Japanese government will not allow temperature reduction for HMA, except when producing trial projects. NIPPO CORPORATION was interested in implementing foamed asphalt systems on their plants, but they were concerned that the benefits would be minimal due to elevated production temperatures.

An experimental design was developed to evaluate the compactability of foamed asphalt mixes produced at 132–138°C (270-280°F) and 160-166°C (320-331°F). Companion, non-foamed HMA control mix was produced at 160-166°C (320-331°F). Both a virgin mix and a mix containing 30 percent reclaimed asphalt pavement (RAP) were included in the study. The mixes were produced using an Astec Double Barrel™ Green plant. Twenty-five to thirty samples of each mix/production temperature combination were compacted in an on-site laboratory over a 40 to 70°C (72 to 126°F) temperature range. Japan still specifies the Marshall method. Both Marshall and a lesser number of companion gyratory samples were prepared. The time to compact a given set of samples typically exceeded 100 minutes. Attempts were made to stratify temperature across storage time.

The data were analyzed for the effects of production temperature and storage time on compacted sample density. The data indicate that foamed mixes, produced at both WMA and HMA temperatures, improved sample density over the control. Compacted samples produced with foamed asphalt mixtures have a more consistent relationship with compaction temperature compared to HMA samples. There is evidence of a time effect with foamed virgin mixes produced at warm mix temperatures and RAP mixtures produced at both warm mix and conventional hot mix temperatures. It is expected that the mechanisms behind these observations are different for the virgin and RAP mixes. RAP mixes produced with four stockpiles, including the fractionated, coarse RAP, were more consistent in terms of gradation and asphalt content than the virgin mixes were.

INTRODUCTION

Various technologies were introduced over ten years ago as compaction aids for asphalt mixtures. These compaction aids allow a reduction in the temperature at which asphalt mixtures are produced, laid, and compacted. Temperature reductions result in decreased fuel usage, stack
emissions and fumes. Other benefits include the potential for increased haul distances, paving in cooler weather, and the utilization of higher percentages of reclaimed asphalt pavement (RAP), shingles, or a combination thereof while still maintaining workability and allowing required compaction. Generically, these technologies are termed warm mix asphalt (WMA).

When considering long-term production, economic analyses indicate that foaming systems are the most cost effective warm mix technology (1). Foamed asphalt is produced when water is introduced into hot asphalt (>100°C (212°F)). The water will turn to steam and expand approximately 1,600 times. When the steam is encapsulated in hot asphalt, the volume of the foamed asphalt increases by 10 to 16 times, depending on such factors as the amount of water added, asphalt temperature and asphalt grade (Figure 1). This expansion allows better coating of the aggregate, improved workability, and improved compaction.

![Graph showing expansion ratio and half-life of foamed asphalt.](image)

**FIGURE 1** Expansion ratio and half-life of foamed asphalt (*2 in 3*).

Astec’s Double Barrel® Green system was one of the first commercially available systems in the United States for producing foamed asphalt using an asphalt plant. The first generation foaming nozzles were prone to clogging when the foaming system was not being used. Since the cost of the “additive,” e.g. water, used with foaming systems is inexpensive, many contractors report foaming all of their warm mix and hot mix asphalt mixtures, regardless of production temperature. This prevented clogging of the nozzles. Astec reports that the nozzles in the second generation manifold were simplified to prevent clogging.

Contractors may also wish to produce foamed asphalt mixtures to improve workability and compaction during cold weather or increase haul distances. In these situations, the contractor may wish to increase the temperature of the foamed asphalt above typical warm mix temperatures (<135°C (275°F)). Examination of Figure 1 indicates that the half-life of the foam,
or the time for the foamed asphalt to subside from its maximum volume (best workability) to half of its maximum volume, decreases with increasing temperature. This raises the question as to whether or not foaming asphalt at higher production temperatures actually provides any benefit in terms of improved compaction.

**EXPERIMENTAL PLAN**

NIPPO CORPORATION, Japan’s largest asphalt contractor, owns and operates over 150 asphalt plants. Most of NIPPO CORPORATION’s asphalt mixtures contain high percentages of RAP, with minimum RAP contents of approximately 30 percent and maximum RAP contents of 60 percent for surface mixes and 80 percent for base mixtures. For a number of years, NIPPO CORPORATION has been investigating the use of WMA-type foaming additives as compaction aids. Currently, the Japanese government will not allow temperature reductions except trial projects when producing asphalt mixtures. However, NIPPO CORPORATION is still interested in investigating the benefits of WMA technologies for cold-weather paving and longer haul distances. NIPPO CORPORATION developed an experimental plan to assess the effectiveness of foamed asphalt as a compaction aid at higher production temperatures. The experimental plan is shown in Table 1.

**TABLE 1 Test Matrix**

<table>
<thead>
<tr>
<th>Mix</th>
<th>Target Production Temperature</th>
<th>132 – 138°C (270 – 280°F)</th>
<th>160 - 166°C (320 – 330°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Foamed WMA</td>
<td>HMA¹</td>
<td>Foamed WMA</td>
</tr>
<tr>
<td>Virgin</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>30% RAP</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
</tbody>
</table>

¹ Non-foamed hot mix asphalt (HMA).

The Marshall mix design procedure, supplemented with performance tests, is used to design asphalt mixtures in Japan. The Marshall hammer is a constant-stress compaction device which is sensitive to the affects of compaction temperature. Rollers are also constant stress devices for given levels of ballast and inflation pressure (rubber-tire rollers), although certain rollers using intelligent compaction technology can adjust vibratory amplitude as the stiffness of the mix changes. Experience indicates field compaction is sensitive to compaction temperature. This does not insinuate that the Marshall Hammer simulates field compaction. Therefore, NIPPO CORPORATION selected Marshall compacted samples to assess the sensitivity of foamed and non-foamed (HMA) mixtures.

Twenty-five to thirty samples of a given mix were compacted over a wide range of compaction temperatures. A total of 225 Marshall and gyratory samples were compacted as part of the experiment (Figure 2). Early trials conducted as part of this experiment indicated elapsed time after sampling might affect the compacted sample density. Therefore, an attempt was made to compact samples over a range of temperatures at different times after sampling. The elapsed time and compaction temperature of each sample was recorded. The mix was stored in sealed 23-liter (6-gallon) buckets in an oven set at the production temperature until needed.
A secondary experiment was conducted with a limited number of gyratory samples. The mixes used in the experiment were originally designed as Marshall mixes for commercial use. Virginia Department of Transportation specifies 65 N_{design} gyrations for all traffic levels. Samples were compacted at 65 gyrations to assess volumetric properties. The Superpave gyratory compactor (SGC) applies a constant shear strain (4). It is designed to hold the specified angle of gyration (1.16 degrees) and vertical pressure (600 kPa) regardless of the stiffness of the mix. Therefore, it would be expected that more compaction energy would be applied to a colder sample. It was believed, however, that the SGC might be sensitive to compaction temperature when using a lower number of gyrations. Initially 50 gyrations were used. This was later reduced to 30 gyrations. Asphalt mixtures are typically placed at three to four times nominal maximum aggregate size (NMAS). For the 9.5 mm (3/8 in) NMAS mixture used in this study a thickness of 29 to 38 mm (1.15 to 1.50 in) would be appropriate. Full-height gyratory samples are 115 mm (4.5 in) tall, whereas Marshall samples are 64 mm (2.5 in) tall. It was hypothesized that thinner samples would be more sensitive to compaction temperature. The mass of the SGC samples compacted at reduced gyrations was reduced to produce a sample height of approximately 63 mm (2.5 in).

MIX DESIGNS

Two 9.5 mm (3/8 in) nominal maximum aggregate size Superpave mixtures were used for the experiment, one virgin and one containing 30 percent fractionated RAP. The RAP was fractionated into two stockpiles, the coarse fraction was used in this study. The mixtures were produced by L. H. Sawyer in Salem, VA using a Double Barrel® Green plant with second generation foaming nozzles (Figure 3). The mix produced for the experiments generally represented small production runs. The mix was generally discharged into a front-end loader. The mix was dumped on the ground and the top of the pile flattened by the loader. The mix was
sampled with a shovel from the flattened pile and then tested in Sawyer’s on-site laboratory. The asphalt content and gradation of each sample were tested according to AASHTO T308 and T30, respectively. The maximum specific gravity of each sample was tested according to AASHTO T209. SGC samples were compacted to N\textsubscript{design} (65 gyrations) according to AASHTO T312 and the volumetric properties measured according to AASHTO T166 and T169. The job mix formulas and production gradation, asphalt content, and SGC volumetric properties are summarized in Table 2.

### TABLE 2 Job Mix Formula, Production Gradation, Asphalt Content, and Volumetric Properties

<table>
<thead>
<tr>
<th>Stockpile</th>
<th>Virgin</th>
<th>RAP</th>
</tr>
</thead>
<tbody>
<tr>
<td># 8 Limestone</td>
<td>50</td>
<td>43</td>
</tr>
<tr>
<td>#10 Limestone</td>
<td>35</td>
<td>14</td>
</tr>
<tr>
<td>Nat. Sand</td>
<td>15</td>
<td>13</td>
</tr>
<tr>
<td>Coarse RAP(^2)</td>
<td>0</td>
<td>30</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sieve Size, mm</th>
<th>JMF 169°C</th>
<th>HMA 179°C</th>
<th>Foam 132°C</th>
<th>Foam 165°C</th>
<th>JMF 161°C</th>
<th>HMA 161°C</th>
<th>Foam 138°C</th>
<th>Foam 168°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.5</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>99</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>9.5</td>
<td>94</td>
<td>95</td>
<td>94</td>
<td>97</td>
<td>96</td>
<td>94</td>
<td>91</td>
<td>92</td>
</tr>
<tr>
<td>4.75</td>
<td>60</td>
<td>58</td>
<td>54</td>
<td>66</td>
<td>64</td>
<td>60</td>
<td>51</td>
<td>53</td>
</tr>
<tr>
<td>2.36</td>
<td>45</td>
<td>47</td>
<td>42</td>
<td>55</td>
<td>52</td>
<td>44</td>
<td>41</td>
<td>42</td>
</tr>
<tr>
<td>1.18</td>
<td>34</td>
<td>35</td>
<td>30</td>
<td>41</td>
<td>37</td>
<td>33</td>
<td>32</td>
<td>33</td>
</tr>
<tr>
<td>0.600</td>
<td>25</td>
<td>27</td>
<td>23</td>
<td>31</td>
<td>28</td>
<td>26</td>
<td>26</td>
<td>26</td>
</tr>
<tr>
<td>0.300</td>
<td>11</td>
<td>14</td>
<td>11</td>
<td>16</td>
<td>15</td>
<td>12</td>
<td>13</td>
<td>13</td>
</tr>
<tr>
<td>0.150</td>
<td>6</td>
<td>8</td>
<td>6</td>
<td>9</td>
<td>9</td>
<td>7</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>0.075</td>
<td>4.5</td>
<td>6.3</td>
<td>4.7</td>
<td>6.6</td>
<td>7.2</td>
<td>5.0</td>
<td>5.0</td>
<td>5.2</td>
</tr>
<tr>
<td>AC%</td>
<td>5.3</td>
<td>5.01</td>
<td>5.14</td>
<td>5.25</td>
<td>5.25</td>
<td>5.3</td>
<td>4.98</td>
<td>5.10</td>
</tr>
<tr>
<td>SGC Air Voids, %</td>
<td>3.7</td>
<td>4.2</td>
<td>6.2</td>
<td>2.7</td>
<td>3.7</td>
<td>3.8</td>
<td>2.8</td>
<td>2.3</td>
</tr>
<tr>
<td>SGC VMA, %</td>
<td>15.2</td>
<td>15.0</td>
<td>17.1</td>
<td>14.4</td>
<td>15.3</td>
<td>15.0</td>
<td>12.9(^1)</td>
<td>13.0(^1)</td>
</tr>
</tbody>
</table>

\(^1\) VMA of Marshall compacted sample ranged from 15.2 to 19.2 for HMA; 16.0 to 17.8 for Foam at 138 °C; and 14.5 to 18.9 for Foam at 168 °C. \(^2\) The asphalt content of the Coarse RAP was 5.9 percent.

Note: 1 °C = 1.8 °F

The production of the mixes with 30 percent RAP appears to be more consistent than the virgin mixes were. For the virgin foamed mix produced at 132°C (270°F), the volumetric properties do not follow expectations based on the gradation and asphalt content. Although the mix is finer on the 2.36 and 1.18 mm (No. 8 and No. 16) sieves, it appears as if the foamed asphalt may be contributing to the lower voids in mineral aggregate (VMA) and air voids. Although the VMA of SGC compacted samples for the RAP mixes were low, the VMA for Marshall compacted samples were greater than 15 percent with the exception of 2 of 25 samples of the Foam mix produced at 168 °C (334°F). Previous experience indicates WMA technologies can result in a reduction in VMA. This is most likely due to better aggregate orientation.
RESULTS AND DISCUSSION

Virgin Mix

Figure 3 shows the relationship between compaction temperature and percent maximum density for the virgin mixes. The foamed mix produced at 132°C (270°F) has the best compaction as a function of temperature, followed by the foamed mix produced at 165°C (325°F). There is a higher amount of scatter in the HMA as indicated by the lower $R^2$ value and more scatter in the Foam produced at 132 °C (270°F) compared to the Foam produced at 165°C (325°F). The effect of the scatter is to magnify the difference between the foamed and non-foamed (HMA) mix produced at the higher production temperatures.

One trial batch of the virgin HMA had a higher than design asphalt content (5.7 percent). A number of density samples were produced before the asphalt content was determined. Figure 4 shows a comparison between the HMA produced at the various measured asphalt contents. Of note is the fact that the scatter in the data between compaction temperature and percent density is reduced at the higher asphalt content similar to that observed for the foamed mixes. Gradation differences (Table 2), particularly the percents passing the 0.075 mm (No. 200) sieve affect the relative density between the mix produced with 5.01 and 5.14 percent asphalt. The larger volume of the foamed asphalt may reduce the total asphalt absorbed and facilitate compaction similar to the higher asphalt in a non-foamed mix.
As indicated in Figure 1, the half-life of the foam should decrease with increasing temperature. In production, this may result in a loss of workability with time as the foam collapses and moisture is driven from the mix. Figure 5 investigates the possibility of this phenomenon. Figure 5a indicates a trend of decreasing density with elapsed time for the foam mix produced at 132°C (270°F). There does not seem to be a trend for the HMA or foam mix produced at 165°C (325°F). For the foamed mixes, the distribution of compaction temperature with elapsed time was good (Figure 5b); however, for the HMA few samples were compacted at higher temperatures between 60 and 100 elapsed minutes.
To further investigate these trends, multiple linear regressions were performed using compaction temperature and elapsed time as predictors for sample density. The results are summarized in Table 3. The $p$-values in Table 3 indicate the significance of the variable (compaction temperature or elapsed time) on sample density based on analysis of variance. $P$-values less than 0.05 indicate the variable has a significant effect on compacted sample density. As expected, all three mixes are sensitive to compaction temperature. The influence of compaction temperature, as indicated by the coefficient, is approximately the same for the HMA and foam mix produced at 132°C (270°F); however, the foamed mix produced at 165°C (325°F) is less sensitive to changes in compaction temperature. This matches observations in Figure 3. Only the foamed mix produced at 132°C (270°F) is significantly affected by elapsed time. The coefficient indicates decreasing sample density with increasing time after production similar to the trend shown in Figure 5a. This would correspond to the concept of half-life shown in Figure 1 that for foamed mix produced at reduced temperatures, compaction benefits will dissipate as the foam dissipates.

**TABLE 3 Multiple Linear Regression Results for Virgin Mixes**

<table>
<thead>
<tr>
<th>Mix</th>
<th>Constant</th>
<th>Compaction Temperature, °C</th>
<th>Elapsed Time, minutes</th>
<th>R², %</th>
<th>Standard Error</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Coefficient</td>
<td>$p$-value</td>
<td>Coefficient</td>
<td>$p$-value</td>
</tr>
<tr>
<td>HMA</td>
<td>86.2</td>
<td>0.048</td>
<td>0.009</td>
<td>0.004</td>
<td>0.621</td>
</tr>
<tr>
<td>Foam 165°C</td>
<td>90.1</td>
<td>0.029</td>
<td>0.000</td>
<td>0.000</td>
<td>0.947</td>
</tr>
<tr>
<td>Foam 132°C</td>
<td>90.0</td>
<td>0.046</td>
<td>0.000</td>
<td>-0.013</td>
<td>0.000</td>
</tr>
</tbody>
</table>

Note: 1°C = 1.8°F

Additional gyratory samples were compacted to 50 gyrations with a target height of 63 mm (2.5 in) to match the height of Marshall compacted samples. Experience producing performance test samples targeting 93 percent density indicates the SGC is apparently sensitive to compaction temperature at reduced sample heights when compacted to low numbers of gyrations. Figure 6 shows a comparison of the sample densities for samples compacted from the three mixtures described previously. At 50 gyrations and a 50 mm (2.0 in) height, the SGC seems to have little sensitivity to compaction temperature over a range of 30 to 40°C (54 to 72°F). The foamed mix produced at 132°C (270°F) did result in slightly higher sample densities,
but not to the same extent as shown in Figure 3. Unfortunately, the height data could not be printed or digitally collected for further analyses.

![Image](image.png)

**FIGURE 6** Percent density versus compaction temperature for virgin mixes compacted using SGC.

**RAP Mix**

Figure 7 shows the relationships between compaction temperature and samples density for the mixes containing 30 percent RAP. In this case, the foamed mix produced at 168°C (334°F) provides the highest density as a function of temperature, followed by the foam mix produced at 138°C (280°F) and then the HMA produced at 161°C (322°F). As observed with the virgin mixes, there is more scatter in the HMA data than in the foamed mix data. This may indicate that foamed mix should result in more consistent in-place density in the field.
Similar to the virgin mixes, multiple linear regressions were performed using compaction temperature and elapsed time as predictors for sample density. The results are summarized in Table 4 and shown graphically in Figure 8. Again, compaction temperature is significant for all three mixes. The coefficient for elapsed time is negative for all three mixes, indicating some reduction in compaction with elapsed time after production. However, the effect of elapsed time is only significant for the foamed mix produced at 168°C (334°F). The reasons for this are unclear. Possible explanations may include the stiffness of the RAP binder, increased blending and therefore stiffness of the combined virgin and RAP binders with time, or an effect from residual moisture in the mixture resulting from the high RAP percentage.

**TABLE 4 Multiple Linear Regression Results for RAP Mixes**

<table>
<thead>
<tr>
<th>Mix</th>
<th>Constant</th>
<th>Compaction Temperature, °C</th>
<th>Elapsed Time, minutes</th>
<th>R², %</th>
<th>Standard Error</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Coefficient</td>
<td>p-value</td>
<td>Coefficient</td>
<td>p-value</td>
</tr>
<tr>
<td>HMA</td>
<td>89.0</td>
<td>0.019</td>
<td>0.005</td>
<td>-0.008</td>
<td>0.089</td>
</tr>
<tr>
<td>Foam 168°C</td>
<td>88.7</td>
<td>0.052</td>
<td>0.000</td>
<td>-0.011</td>
<td>0.000</td>
</tr>
<tr>
<td>Foam 138°C</td>
<td>87.8</td>
<td>0.050</td>
<td>0.000</td>
<td>-0.005</td>
<td>0.232</td>
</tr>
</tbody>
</table>

Note: 1°C = 1.8°F
Samples of the foamed RAP mix were compacted with 30 gyrations in the SGC to a target sample height of 63 mm (2.5 in). Samples of the HMA with RAP were not prepared due to insufficient material. The data are presented graphically in Figure 9. Figure 9 indicates the relative insensitivity of the SGC to compaction temperature even at reduced gyrations.
CONCLUSIONS

Based on the data collected in this study, the following conclusions can be drawn:

- Foamed asphalt mixtures improve compacted sample density at both warm mix and conventional hot mix temperatures,
- Compacted samples produced with foamed asphalt mixtures have a more consistent relationship with compaction temperature compared to HMA samples. This may be due to the increased lubricity, resulting from higher film-thicknesses, of the foamed mix,
- There is evidence of a time effect with foamed virgin mixes produced at warm mix temperatures and RAP mixtures produced at both warm mix and conventional hot mix temperatures. It is expected that the mechanisms behind these observations are different for the virgin and RAP mixes,
- The Superpave gyratory compactor is relatively insensitive to compaction temperature even considering lower gyration levels (30 to 50) and shorter specimen heights (63 mm), and
- The RAP mixtures produced with four stockpiles, including the fractionated, coarse RAP, were more consistent in terms of gradation and asphalt content than the virgin mixes were. It should be noted that L. H. Sawyer rarely produces virgin mixes.

REFERENCES