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Construction and Building Materials 22 (2008) 286–294

Construction and Building MATERIALS

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# Comparison of rutting resistance of unmodified and SBS-modified Superpave mixtures by accelerated pavement testing

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Received 27 December 2005; received in revised form 12 August 2006; accepted 30 August 2006
Available online 24 October 2006

**Abstract**

Superpave asphalt mixtures have been used in highway pavements in the US since the late 1990s. Modified binders have also been used in some of the Superpave mixtures in an effort to increase the cracking and rutting resistance of these mixtures. Due to the short history of these mixtures, it is still too early to assess the long-term performance of these Superpave mixtures and the benefits from the use of the modified binders. This paper presents the results of a full-scale pavement-testing program to evaluate the rutting resistance of Superpave mixtures with and without polymer modification using a Heavy Vehicle Simulator.

Results from the HVS tests showed that the pavement sections with two 5-cm lifts of SBS-modified mixture clearly outperformed those with two 5-cm lifts of unmodified mixture, which had two to two and a half times the rut rate. The pavement sections with a lift of SBS-modified mixture over a lift of unmodified mixture practically had about the same performance as the sections with two lifts of SBS-modified mixture when tested at ambient temperature, and had only about 20% higher rutting than those with two lifts of modified mixture when tested at 50 °C. The test section with two lifts of SBS-modified mixture and tested at 65 °C still outperformed the test sections with two lifts of unmodified mixture and tested at 50 °C. Rutting of the unmodified mixture was observed to be due to a combination of densification and shoving, while that of the SBS-modified mixture was due primarily to densification.


*Keywords:* Rutting; SBS; Heavy Vehicle Simulator; Superpave

## 1. Introduction

Florida Department of Transportation (FDOT) started the use of Superpave mixtures on its highway pavements in 1995. Modified binders have also been used in some of the Superpave mixtures in an effort to increase the cracking and rutting resistance of these mixtures. Due to the short history of these mixtures, it is still too early to assess the long-term performance of these Superpave mixtures and the benefits from the use of the modified binders. There is a need to evaluate the long-term performance of these mixtures and the benefits obtained from the use of modified binders, so that the Superpave technology and the selection of modified binders to be used could be effectively applied.

The FDOT Materials Office recently acquired a Heavy Vehicle Simulator (HVS) [1,2] and constructed an Accelerated Pavement Testing (APT) facility (Fig. 1), which uses this Heavy Vehicle Simulator. The HVS can simulate 20

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0950-0618/$ - see front matter 
doi:10.1016/j.conbuildmat.2006.08.018

Fig. 1. Photo of the test track (APT facility).

years of interstate traffic on a test pavement within a short period of time [3]. This study was to use the accelerated pavement testing facility to evaluate the long-term performance of Superpave mixtures and SBS-modified Superpave mixtures with particular emphasis on the rutting resistance of these mixtures. This research work was a cooperative effort between the FDOT and the University of Florida.

The main objectives of this study are as follows:

- To evaluate the rutting performance of a typical Superpave mixture used in Florida and that of the same Superpave mixture modified with a SBS polymer.
- To evaluate the relationship between mixture properties and the rutting performance.
- To evaluate the difference in rutting performance of a pavement using two lifts of modified mixture versus a pavement using one lift of modified mixture on top of one lift of unmodified mixture and two lifts of modified mixture versus a pavement using two lifts of unmodified mixture.

## 2. Experimental design

### 2.1. Materials

The two asphalt mixtures, which were placed in the test pavements, were (1) a Superpave mixture using PG67-22 asphalt and (2) a Superpave mixture using PG67-22 asphalt modified with a SBS polymer (3% by weight of the total binder), which had an equivalent grading of PG76-22. Both mixtures were made with the same aggregate blend having the same gradation, and had the same effective asphalt content. The types and gradation of the aggregate (Florida limestone) blend used were similar to those of an actual Superpave mixture, which had recently been placed in Florida. These mixtures can be classified as 12.5 mm fine Superpave mixes, with a nominal maximum aggregate size of 12.5 mm and the gradation plotted above the restricted zone. The gradation of the aggregate used in the asphalt mixtures is given in Fig. 2. Design of the Superpave mixture was done according to the Superpave mix design procedure and criteria using a design traffic level of 10–$30\times10^6$ 80-kN (18-kip) Equivalent Single Axle Loads (ESALs) [4]. The binder contents and volumetric properties for these two mixtures are shown in Table 1.

### 2.2. Testing parameters and sequence

The main testing program was to be run on Test Lanes 1–5, which had a total of 15 test sections. The testing parameters and sequence to be used for the main testing program are shown in Fig. 3. The testing program was divided into two phases. Phase I was conducted at ambient condition on five test sections, 1C–5C. Phase II was conducted with temperature control on the other ten test sections. In Phase II, Lanes 1 and 2, which have two 5-cm lifts of SBS-modified Superpave mixture were tested at controlled pavement temperatures of 50 and 65 °C. The rest of the test sections in Phase II were tested at only one temperature, namely 50 °C. The testing sequence was arranged such that the effects of time on each lane could be averaged out. It was also arranged such that the HVS vehicle would not have to drive over a test section, which has not been tested in order to minimize damage to the test sections.

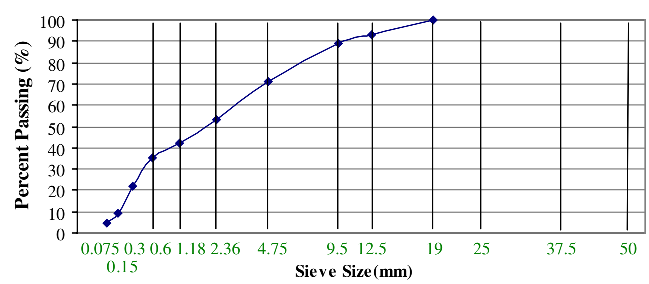


Fig. 2. Gradation of aggregate used in the asphalt mixture.

Table 1
Volumetric properties of the asphalt mixtures

| Mix properties | Mix type | |
|---|---|---|
| | Superpave mix (compacted at 149 °C) | Modified Superpave mix (compacted at 163 °C) |
| Asphalt binder | PG67-22 | PG76-22 |
| % Binder | 8.2 | 7.9 |
| $V_a@N_{design}$ (Air voids) (%) | 4.0 | 3.8 |
| VMA (Voids in the mineral aggregate) (%) | 14.5 | 14.2 |
| VFA (Voids filled with Asphalt) (%) | 72 | 73 |
| $P_{be}$ (Effective asphalt content) (%) | 4.97 | 4.90 |
| $G_{mm}$ (Maximum specific gravity of the mix) | 2.276 | 2.273 |

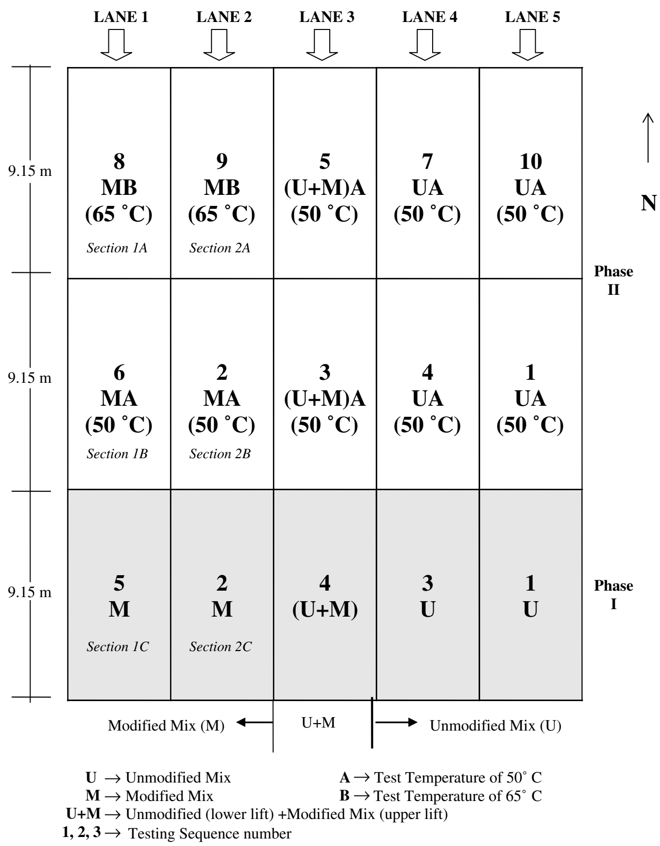


Fig. 3. HVS testing sequence (Plan view).

## 2.3. Temperature control and monitoring system

The temperature distributions in the test pavements were monitored by means of Type K thermocouples installed at various depths and locations in the test pavements. Type K thermocouple was selected to be used in consideration of its relatively high sensitivity (40 μV/°C), high range of operation (−200 to 200 °C), reliability and low cost. A total of eight thermocouples were installed for each test section. For each test section, three thermocouples were placed on top of the base course, three were placed on top of the first lift of asphalt mixture, and two were placed on the surface. Temperature readings were taken every 15 min and recorded in the PC during each test.

A temperature control system to control the temperature of the HVS test pavements was installed at the end of Phase I and used in Phase II of the testing program. It consisted mainly of (1) insulating panels to cover the pavement area to be tested, (2) radiant heaters to heat the pavement surface, and (3) thermocouples to monitor the pavement temperature and to control the heaters. The temperature measured at a depth of 5 cm was used to control the turning-on and turning-off of the heaters. The temperature measured on the surface was used to turn off the heaters when it exceeded a set amount.

## 2.4. Laser profiler

A laser profiler was installed on the HVS at the end of Phase I and used in Phase II of the testing program in order to enable more frequent and consistent measurement of the pavement profile during the HVS tests. The laser profiler used was a SLS 5000™ manufactured by LMI Selcom. It consisted of two lasers. The specified ambient temperature surrounding the laser should be 0–50 °C, while the temperature of objects to be measured can be below 0 °C and up to 1600 °C. Each of the two lasers was mounted on each side of the test carriage at a distance of 76 cm away from one another.

In making a profile measurement of a tested pavement, the test carriage holding the two lasers would travel (610 cm) longitudinally from one end to another, and then move diagonally back to the other end with a lateral incremental shift of 2.5 cm. In each pass, 58 data points would be collected, with each data point representing the average reading from every 10-cm sweep. This process would be repeated 30 and 1/2 times until each laser would sweep over a lateral distance of 76 cm. The last sweep of the right laser would overlap with the first sweep of the left laser. The total lateral distance covered by the two lasers would be 152 cm. The longitudinal profiles as measured would be used to determine the lateral profiles, which would in turn be used to determine the rut depth.

## 2.5. HVS testing configuration

The accelerated pavement testing was performed using a Heavy Vehicle Simulator (HVS), Mark IV Model. The main HVS testing program was run using a mode of unidirectional travel with 10-cm wander in 2.5-cm increments, which was determined to be the optimum testing configuration from the trial tests. The applied load was a 4082 kg and 793 kPa super single wheel traveling at a speed of 12.9 km/h. For each test section, HVS loading was applied until the rut depth was judged to be more than 12 mm.

## 2.6. Laboratory testing program

A laboratory-testing program was performed to characterize the Superpave and modified Superpave mixtures, which were placed on the test sections, to evaluate the potential performance of these mixes based on the laboratory results, and to evaluate the correlation between the laboratory test results with the performance of the test sections.

For each material and lift of pavement, enough samples of the mixtures were collected at the mixing plant to conduct tests performed by (1) Gyratory Testing Machine, (2) Servopac Gyratory Compactor, and (3) Asphalt Pavement Analyzer. In addition, cores taken from the test sections were evaluated for their density and other volumetric properties. The resilient modulus and tensile strength were also evaluated by performing the Indirect

Tensile Test. Moreover, the asphalt binders were extracted and recovered from the cores, and viscosity test were performed on the recovered binders.

## 3. Results from phase I HVS testing

### 3.1. Temperature measurement

Table 2 presents the average pavement temperatures of all of the five test sections in Phase I as measured by thermocouples placed between the two 5-cm lifts of asphalt mixtures on the test sections. It can be seen that the average daily maximum temperatures of sections 2C–5C were very close to one another, while the average daily maximum temperature of section 1C was slightly lower than the rest.

### 3.2. Rut measurement

Section 1C, which had two 5-cm lifts of SBS-modified Superpave mixture, received 329953 wheel passes over a 31-day period. Section 2C, which had the same mixture as Section 1C, was tested for 28 days with a total of 295950 passes. In addition, Section 3C, which had a 5-cm lift of SBS-modified Superpave mixture over a 5-cm lift of unmodified Superpave mixture, was trafficked for 25 days with a total of 253425 wheel passes. Section 4C, which had two 5-cm lifts of unmodified Superpave mixture, was tested for 27 days with a total of 281123 wheel passes. Finally, Section 5C, which had the same mixture as Section 4C, was applied with a total of 164525 wheel passes over 14 test days.

For each test pavement, five transverse profiles were measured on a daily basis by means of a profiler placed across the pavement at five fixed locations evenly spaced across the test section. A straight line was drawn on the profile plot such that it touched the highest point on each side of the wheel track. The maximum distance between the straight line and the measured profile was determined as the rut depth. This procedure is similar to how rut depths are usually determined in the field, and is called the "Surface Profile Method" in this paper.

Fig. 4 shows the comparison of the change in rut depth (as measured by the surface profile method) versus number of wheel passes for all of the five test sections in Phase I. It can be seen that sections 4C and 5C, which had two lifts of unmodified mixture, had substantially (2–3 times) higher rate of rut development than the other three test sections which had an SBS-modified mixture at the top lift. Section 3C, which had a lift of SBS-modified mixture over a lift of unmodified mixture, had a similarly low rut rate as that of sections 1C and 2C, which had two lifts of SBS-modified mixture.

Table 2
Temperatures of test pavements in Phase I as measured by thermocouples placed at 5-cm depth

| | Uni-directional loading with 10-cm Wander in 2.5-cm increments | | | |
|---|---|---|---|---|
| | Thermo-couple 4 | Thermo-couple 5 | Thermo-couple 6 | Average |
| *Section 1C* | | | | |
| Avg. Daily Min. Temp (°C) | 23.8 | 23.2 | 22.5 | 23.2 |
| Avg. Daily Max. Temp (°C) | 30.4 | 30.5 | 32.2 | 31.0 |
| Overall Min. Temp (°C) | 19.1 | 17.3 | 16.6 | 17.7 |
| Overall Max. Temp (°C) | 34.2 | 34.7 | 39.0 | 36.0 |
| *Section 2C* | | | | |
| Avg. Daily Min. Temp (°C) | 27.6 | 27.2 | 27.8 | 27.5 |
| Avg. Daily Max. Temp (°C) | 39.5 | 35.7 | 40.0 | 38.4 |
| Overall Min. Temp (°C) | 25.5 | 25.6 | 24.9 | 25.3 |
| Overall Max. Temp (°C) | 46.9 | 39.4 | 46.0 | 44.1 |
| *Section 3C* | | | | |
| Avg. Daily Min. Temp (°C) | 26.5 | 26.8 | 27.9 | 27.1 |
| Avg. Daily Max. Temp (°C) | 40.5 | 34.2 | 35.8 | 36.8 |
| Overall Min. Temp (°C) | 21.5 | 21.9 | 24.0 | 22.5 |
| Overall Max. Temp (°C) | 48.4 | 54.0 | 48.2 | 50.2 |
| *Section 4C* | | | | |
| Avg. Daily Min. Temp (°C) | 37.4 | 28.8 | 29.4 | 31.9 |
| Avg. Daily Max. Temp (°C) | 39.5 | 37.9 | 39.5 | 39.0 |
| Overall Min. Temp (°C) | 30.6 | 30.7 | 31.3 | 30.9 |
| Overall Max. Temp (°C) | 44.1 | 41.7 | 44.5 | 43.4 |
| *Section 5C* | | | | |
| Avg. Daily Min. Temp (°C) | 27.1 | 26.2 | 26.9 | 26.7 |
| Avg. Daily Max. Temp (°C) | 41.9 | 39.1 | 37.8 | 39.6 |
| Overall Min. Temp (°C) | 25.0 | 23.8 | 24.2 | 24.3 |
| Overall Max. Temp (°C) | 48.5 | 46.4 | 41.8 | 45.6 |

## 4. Results from phase II HVS testing

### 4.1. Temperature control and monitoring

The temperature of the test pavements in Phase II was controlled by a temperature control system as described earlier. The target pavement temperature measured at a depth of 5-cm was 50 °C for eight test sections and 65 °C for the other two, as shown in Fig. 5. Before each HVS testing, the pavement was pre-heated until the desired temperature was reached. HVS testing was started when the temperature at 5-cm depth reached the target temperature in a steady condition.

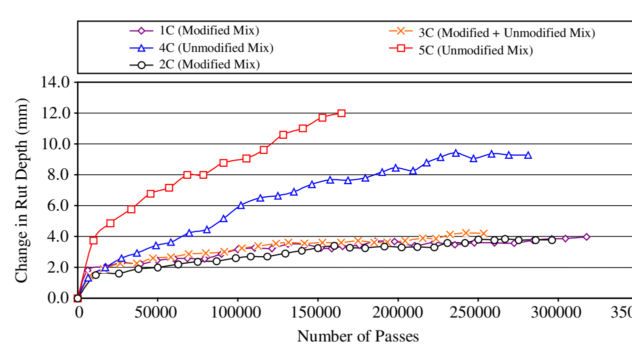


Fig. 4. Comparison of change in rut depth as measured by the surface profile method vs. number of passes in Phase I.

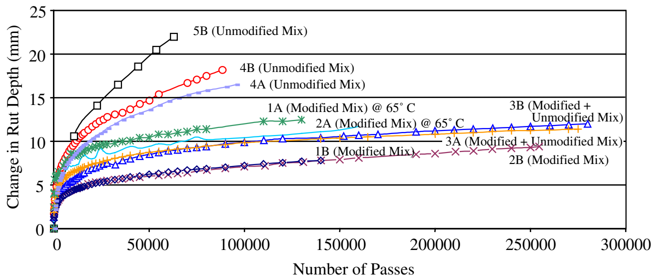


Fig. 5. Comparison of change in rut depth as measured by the differential surface profile method vs. number of passes in Phase II.

### 4.2. Rut measurement

A laser profiler was used to measure the pavement surface profiles of the test pavements before, during and after the HVS testing. Two different methods of analysis were used. In the first method, the initial transverse surface profile (before test) was subtracted from the transverse surface profile to obtain the "differential surface profile." A straight line is drawn over the "differential surface profile" and touching it at two highest points. The greatest distance between this straight line and the "differential surface profile" is taken to be the change in rut depth of the tested pavement relative to its initial condition. Fig. 5 shows the plots of change in rut depth as determined by this method.

In the second method, a straight line was drawn over the measured surface profile and touching it at two highest points. The greatest distance between this straight line and the surface profile was taken to be the rut depth of the test pavement. The rut depth of the pavement at its initial condition (before testing) was also determined in the same manner. The change in rut depth of the tested pavement relative to its initial condition was determined by subtracting the initial rut depth from the determined rut depth at the specified time. Fig. 6 shows the plots of change in rut depth as determined by this method.

The pavement sections with two lifts of SBS-modified mixture clearly outperformed those with two lifts of unmodified mixture. Sections 4B and 4B (with two lifts of unmodified mixture) had about two times the rut rate as compared with that of sections 1B and 2B (with two lifts of modified mixture). Section 5B (with two lifts of unmodified mixture) had about two and a half times the rut rate as compared with sections 1B and 2B.

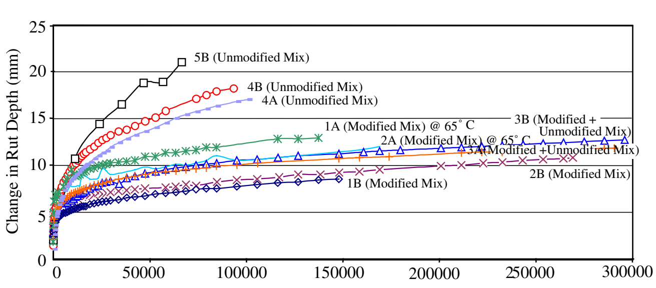


Fig. 6. Comparison of change in rut depth as measured by the surface profile method vs. number of passes in Phase II.

The pavement sections with a lift of SBS-modified mixture over a lift of unmodified mixture (Sections 3B and 3B) had only about 20% higher rutting than those with two lifts of modified mixture (1 and 2B) when tested at 50 °C.

Test Sections 1A and 2A, which had two lifts of SBS-modified mixture and tested at 65 °C still outperformed and had much lower rutting than the pavements with the unmodified mixture at tested at 50 °C (Sections 4A, 4B and 5B).

## 5. Results from the laboratory testing program

### 5.1. Results from the tests on the plant-collected mixtures

#### 5.1.1. Results from GTM tests

Plant-collected mixture samples were compacted in accordance with ASTM D 3387-83 standard test method. Three samples from each lift of the unmodified and the SBS-modified mixtures were compacted to ultimate density (when the change in density is equal to or less than 8 kg/m$^3$ per 50 revolutions) under a 827 kPa vertical ram pressure in the Gyratory Testing Machine (GTM). The unmodified mixture samples were compacted at 149 °C, whereas the SBS-modified asphalt mixtures were compacted at 163 °C. These two different compaction temperatures were used to simulate the actual placement temperatures of these two mixtures on the test roads. The Gyratory Stability Index (the ratio of the maximum gyratory angle to the minimum gyratory angle) was also determined at the end of the test.

No identifiable correlation with rutting performance could be observed from the gyratory shear values. The gyratory shear value of the unmodified mix-lift 2, modified mix-lift 1 and lift 2 were very close to one another. The unmodified mix-lift 1 had slightly higher gyratory shear values than those of the other three mixtures.

The Gyratory Stability Index (GSI) value of each specimen was calculated from the gyrograph and displayed in Table 3. It can bee seen that the GSI values of the SBS-modified mixtures were very close to 1.0. The unmodified mixtures had GSI values of 1.18 and 1.21 for lifts 1 and 2, respectively. An increase in the GSI value beyond 1.0 usually indicates instability of the mixture under the applied ram pressure. Therefore, this result could mean that the unmodified mixture (with a GSI of more than 1.0) was relatively less stable than the SBS-modified mixture (with a GSI close to 1.0).

#### 5.1.2. Results from servopac gyratory compactor tests

Three asphalt specimens were compacted in the Servopac Gyratory Compactor for each of the following materials and testing configuration:

1. Unmodified mixture-lift 1 using 1.25° gyratory angle.
2. Unmodified mixture-lift 1 using 2.5° gyratory angle.

3. SBS-modified mixture-lift 1 using 1.25° gyratory angle.
4. SBS-modified mixture-lift 1 using 2.5° gyratory angle.
5. SBS-modified mixture-lift 2 using 1.25° gyratory angle.
6. SBS-modified mixture-lift 2 using 2.5° gyratory angle.

One specimen was compacted to $N_{design}$ (100) gyrations, and two specimens were compacted to $N_{max}$ (160) gyrations. The unmodified mixtures were compacted at 149 °C while the SBS-modified mixtures were compacted at 163 °C.

No identifiable correlation with rutting performance could be observed from the gyratory shear values as obtained from the Servopac Gyratory Compactor. The unmodified mixture had higher gyratory shear values than those of the SBS-modified mixtures.

Table 3
GSI values of the four mixtures evaluated in the Gyratory Testing Machine

| Sample no. | Unmodified mix | Unmodified mix | Modified mix | Modified |
|---|---|---|---|---|
| | Lift 1 | Lift 2 | Lift 1 | Lift 2 |
| 1 | 1.15 | 1.20 | 1.00 | 1.00 |
| 2 | 1.23 | 1.19 | 1.05 | 1.00 |
| 3 | 1.17 | 1.23 | 1.00 | 1.12 |
| Average | 1.18 | 1.21 | 1.02 | 1.04 |

#### 5.1.3. Results from APA tests

Cylindrical specimens were compacted to between 6.5% and 7.5% air voids with the Superpave Gyratory Compactor. A 45-kg load was applied by a wheel to a hose placed on top of the specimens in the APA. The rut depth was measured at two locations after 8000 wheel passes. Final rut depth was calculated by subtracting the rut depth after 8000 wheel passes by the rut depth after 25 wheel passes. A total of six specimens of the unmodified mixture-lift 1 and four specimens of each of the other mixtures were evaluated in the APA. A summary of rut measurements is shown in Table 4. It can be seen that the average rut depth for the unmodified asphalt mixtures (8.7 mm) was about 50% higher than that for the SBS-modified asphalt mixtures (5.75 mm).

### 5.2. Summary of findings from tests on plant-collected mixtures

The only two laboratory test results which were related to rutting performance of the mixtures were (1) rut measurement from the APA and (2) GSI as measured by the GTM. A mixture with a higher rut depth in the APA will be likely to rut more in the actual pavement. A mixture with a GSI of more than 1.0 as measured by the GTM will be likely to rut more than one with a GSI close to 1.0.

Table 4
Summary of rut depth measurements in the APA evaluation of the four mixtures

| Sample no. | Measurement | Unmodified mix-lift 1 | | | Unmodified mix-lift 2 | | |
|---|---|---|---|---|---|---|---|
| | | Rut measurement (mm) | | | Rut measurement (mm) | | |
| | | 25 passes | 8000 passes | Rut depth | 25 passes | 8000 passes | Rut depth |
| 1 | 1 | 20.2 | 11.8 | 8.4 | 19.8 | 12.6 | 7.2 |
| | 2 | 20.6 | 11.1 | 9.5 | 20.3 | 11.9 | 8.4 |
| 2 | 1 | 20.8 | 10.8 | 10.0 | 20.6 | 12.6 | 8.0 |
| | 2 | 20.6 | 11.3 | 9.3 | 20.1 | 13.1 | 7.0 |
| 3 | 1 | 20.5 | 9.4 | 11.1 | 20.3 | 13.0 | 7.3 |
| | 2 | 20.7 | 9.6 | 11.1 | 20.4 | 12.6 | 7.8 |
| 4 | 1 | 20.8 | 10.4 | 10.4 | 20.4 | 13.4 | 7.0 |
| | 2 | 20.0 | 11.0 | 9.0 | 18.5 | 14.5 | 4.0[a] |
| 5 | 1 | 20.8 | 11.1 | 9.7 | | | |
| | 2 | 20.4 | 9.8 | 10.6 | | | |
| 6 | 1 | 20.8 | 10.6 | 10.2 | | | |
| | 2 | 21.0 | 12.0 | 9.0 | | | |
| Overall average (mm) | | | | 9.9 | | | 7.5 |
| | | Modified mix-lift 1 | | | Modified mix-lift 2 | | |
| 1 | 1 | 20.6 | 14.4 | 6.2 | 21.0 | 16.1 | 4.9 |
| | 2 | 20.8 | 14.5 | 6.3 | 21.0 | 15.8 | 5.2 |
| 2 | 1 | 20.7 | 14.4 | 6.3 | 21.2 | 16.4 | 4.8 |
| | 2 | 20.9 | 14.8 | 6.1 | 21.0 | 15.6 | 5.4 |
| 3 | 1 | 20.5 | 15.4 | 5.1 | 21.1 | 16.0 | 5.1 |
| | 2 | 21.1 | 14.8 | 6.3 | 21.2 | 15.2 | 6.0 |
| 4 | 1 | 21.3 | 14.3 | 7.0 | 21.3 | 15.7 | 5.6 |
| | 2 | 20.9 | 14.8 | 6.1 | 21.1 | 15.6 | 5.5 |
| Overall average (mm) | | | | 6.2 | | | 5.3 |

[a] Not considered in the overall average because the value is an outlier.

Table 5
Bulk densities of cores from wheel path and edge of wheel path from the test sections

| Sections | | Bulk density (g/cm$^3$) | | | | Thickness (mm) | |
|---|---|---|---|---|---|---|---|
| | | No. 1 | No. 2 | Average | % Difference | Average | % Difference |
| 7C | Wheelpath | 2.171 | 2.171 | 2.171 | 2.56 | 84.58 | 8.16 |
| | Edge of wheelpath | 2.109 | 2.122 | 2.116 | | 92.09 | |
| 2C | Wheelpath | 2.181 | 2.181 | 2.181 | 2.61 | 81.06 | 2.06 |
| | Edge of wheelpath | 2.129 | 2.119 | 2.124 | | 82.77 | |
| 3C | Wheelpath | 2.134 | 2.133 | 2.134 | 1.03 | 74.66 | 5.24 |
| | Edge of wheelpath | 2.119 | 2.104 | 2.112 | | 78.79 | |
| 4C | Wheelpath | 2.168 | 2.099 | 2.134 | 4.78 | 80.84 | 8.59 |
| | Edge of wheelpath | 2.092 | 1.971 | 2.032 | | 88.44 | |
| 5C | Wheelpath | 2.154 | 2.155 | 2.155 | 3.30 | 77.84 | 11.36 |
| | Edge of wheelpath | 2.071 | 2.096 | 2.084 | | 87.82 | |
| 2B | Wheelpath | 2.184 | 2.189 | 2.187 | 2.68 | 73.53 | 5.17 |
| | Edge of wheelpath | 2.125 | 2.131 | 2.128 | | 77.54 | |
| 3B | Wheelpath | 2.175 | 2.182 | 2.179 | 3.37 | 71.62 | 10.10 |
| | Edge of wheelpath | 2.097 | 2.113 | 2.105 | | 79.67 | |
| 4B | Wheelpath | 2.184 | 2.187 | 2.186 | 4.35 | 78.08 | 13.08 |
| | Edge of wheelpath | 2.080 | 2.101 | 2.091 | | 89.83 | |
| 5B | Wheelpath | 2.178 | 2.171 | 2.175 | 4.02 | 80.95 | 18.06 |
| | Edge of wheelpath | 2.099 | 2.075 | 2.087 | | 98.79 | |
| 3A | Wheelpath | 2.173 | 2.164 | 2.169 | 3.30 | 78.59 | 10.35 |
| | Edge of wheelpath | 2.092 | 2.102 | 2.097 | | 87.66 | |

Table 6
Comparison of air voids of cores before and after HVS testing

| Sections | Samples | Gmb (BSG of compacted mixture) | Gmm (Max. specific gravity of the mix) | Average air voids (%) | % Change in air voids |
|---|---|---|---|---|---|
| 2C | Original | 2.112 | 2.263 | 6.7 | |
| | Tested (edge of wheelpath) | 2.124 | 2.263 | 6.1 | −0.53 |
| | Tested (wheelpath) | 2.181 | 2.263 | 3.6 | −3.05 |
| 3C | Original | 2.097 | 2.271 | 7.7 | |
| | Tested (edge of wheelpath) | 2.112 | 2.271 | 7.0 | −0.66 |
| | Tested (wheelpath) | 2.134 | 2.271 | 6.0 | −1.63 |
| 4C | Original | 2.122 | 2.280 | 6.9 | |
| | Tested (edge of wheelpath) | 2.032 | 2.280 | 10.9 | 3.95 |
| | Tested (wheelpath) | 2.134 | 2.280 | 6.4 | −0.53 |
| 5C | Original | 2.118 | 2.276 | 7.0 | |
| | Tested (edge of wheelpath) | 2.084 | 2.276 | 8.4 | 1.47 |
| | Tested (wheelpath) | 2.155 | 2.276 | 5.3 | −1.65 |
| 2B | Original | 2.104 | 2.268 | 7.2 | |
| | Tested (edge of wheelpath) | 2.128 | 2.263 | 6.0 | −1.27 |
| | Tested (wheelpath) | 2.187 | 2.263 | 3.4 | −3.87 |
| 3B | Original | 2.100 | 2.275 | 7.7 | |
| | Tested (edge of wheelpath) | 2.105 | 2.271 | 7.3 | −0.38 |
| | Tested (wheelpath) | 2.179 | 2.271 | 4.1 | −3.64 |
| 4B | Original | 2.125 | 2.278 | 6.7 | |
| | Tested (edge of wheelpath) | 2.091 | 2.280 | 8.3 | 1.57 |
| | Tested (wheelpath) | 2.186 | 2.280 | 4.1 | −2.59 |
| 5B | Original | 2.121 | 2.277 | 6.9 | |
| | Tested (edge of wheelpath) | 2.087 | 2.276 | 8.3 | 1.45 |
| | Tested (wheelpath) | 2.175 | 2.276 | 4.4 | −2.41 |
| 3A | Original | 2.104 | 2.268 | 7.2 | |
| | Tested (edge of wheelpath) | 2.097 | 2.271 | 7.7 | 0.43 |
| | Tested (wheelpath) | 2.169 | 2.271 | 4.5 | −2.74 |

BSG: Bulk Specific Gravity.

## 6. Results of tests on the cored samples

### 6.1. Results of thickness and density evaluation

For each of the cores taken from the test sections, the thickness profile in the direction perpendicular to the wheel path was determined. This was done by drawing a line across the face and through the center of the core, in a direction judged to be perpendicular to the wheel path. The thickness of the core along the marked line was then measured with a caliper at a spacing of 12 mm.

The average thickness of the cores from the wheel path and the cores from the outside edge of the wheel path for each test section were calculated and shown in Table 5. The density of all the cores were also measured and shown also in Table 5. The percents difference in thickness and density between the cores from the wheel path and the cores from the outside edge of the wheel path were also computed and shown in Table 5.

The data show that all the cores from the wheel paths are thinner and denser than the cores from the edges of wheel paths. In comparing the percent difference in thickness with the percent difference in density between these two groups of cores, it can be seen that, except for section 2C (which had two layers of SBS-modified mixture), the percent difference in thickness was much greater than the percent difference in density. If the changes in density of the asphalt mixtures were due primarily to vertical densification, the percent increase in density should be approximately equal to the percent decrease in thickness. The greater difference in thickness as compared with the difference in density indicate that materials might be shoved from the wheel path to the edge, giving the wheel-path cores a higher density which could not be accounted for from their changes in thickness.

The specific gravities and air voids of these cores (which were obtained after HVS testing) were also compared with those of the cores obtained at the time of construction. Table 6 shows the comparison of the specific gravities and air voids of the cores at the time of construction with those of the cores after HVS testing. The percent change in air voids for each group was also computed and shown in Table 6. For all of the test sections, the cores from the wheel paths showed a reduction in air voids (or an increase in density). However, two different trends can be observed on the changes of density of the cores from the edge of wheel path. For the cores from the edge of wheel path from the test sections with the SBS-modified mixture (2C, 3C, 2B, 3B) with the exception of Section 3A, there was generally a small decrease in air voids (or increase in density). For those from the sections with two lifts of unmodified mixture, there was generally an increase in air voids (or decrease in density).

From the changes in thickness and density of the cores from these test sections, it can be inferred that, for pavements with the unmodified mixture, rutting was caused by a combination of densification and shoving. For the pavements with the SBS-modified mixture, rutting was due primarily to densification of the mixture. This could explain why the SBS-modified mixture rutted less than the unmodified mixture though the SBS-modified mixture was densified by the same amount or more than the unmodified mixture.

### 6.2. Summary of findings from resilient modulus and indirect tensile strength tests on cores

The cores obtained from the test sections contained two 5-cm layers of asphalt mixture, which were bonded together. Each core was cut into two slices by a mechanical saw at the interface between the two layers. The sliced specimens were tested for resilient modulus at 5 and 25 °C and indirect tensile strength at 25 °C. The SHRP IDT test system as developed and improved by Roque et al. [5] was used to measure the resilient modulus and indirect tensile strength of the specimens. The detailed description of specimen preparation, testing procedure and analysis procedure can be found in the report by Roque et al. [5].

The test results showed that the resilient modulus at 25 °C of the SBS-modified mixture was not significantly different from that of the unmodified mixture. The average indirect tensile strength at 25 °C of the SBS-modified mixture was higher than that of the unmodified mixture by about 10%.

### 6.3. Summary of findings from viscosity tests on recovered binders

Asphalt binder was extracted and recovered from the mixtures to evaluate the binder viscosity. The Reflux Asphalt Extraction procedure in accordance with ASTM D 2171-95 standard test method was used to extract the asphalt binder from the cores. The asphalt binders were then recovered from the solvent using Trichloroethylene (TCE) in accordance with ASTM D 5404-97 standard test method. The Brookfield viscosity test was performed on the recovered binders at 60 °C. The standard testing procedure for the Brookfield viscosity test is described in ASTM D 4402-95. Three replicate tests were run per sample.

The viscosity at 60 °C of the recovered binders from the SBS-modified mixture (with an average of 38 113 Poises) was two to three times that of the recovered binders from the unmodified mixture (with an average of 15 060 Poises).

## 7. Summary of findings

Results from the HVS tests showed that the pavement sections with two lifts of SBS-modified mixture clearly outperformed those with two lifts of unmodified mixture, which had two to two and a half times the rut rate. The pavement sections with a lift of SBS-modified mixture over a lift of unmodified mixture had only about 20% higher rutting than those with two lifts of modified mixture when tested at 50 °C. Test Section with two lifts of SBS-modified mixture and tested at 65 °C showed high rutting resistance and had much lower rutting as compared with that of the test section with two lifts of unmodified mixture and tested at 50 °C.

Results from the laboratory testing program showed that a mixture with a higher rut depth in the APA will be likely to rut more in the actual pavement. A mixture with a GSI of more than 1.0 as measured by the GTM will be likely to rut more than one with a GSI close to 1.0.

From the observation of the changes in thickness and density of the cores from these test sections, it can be inferred that, for pavements with the unmodified mixture, rutting was caused by a combination of densification and shoving. For the pavements with the SBS-modified mixture, rutting was due primarily to densification of the mixture.

The resilient modulus at 25 °C of the SBS-modified mixture was not significantly different from that of the unmodified mixture. The average indirect tensile strength at 25 °C of the SBS-modified mixture was only slightly higher than that of the unmodified mixture (by about 10%). The viscosity at 60 °C of the recovered binders from the SBS-modified mixture was two to three times that of the recovered binders from the unmodified mixture. The higher viscosity of the SBS-modified binder was one of the main reasons for the higher rutting resistance of the SBS-modified mixture.

## Acknowledgements

This research project was funded by the Florida Department of Transportation. The technical support of the following personnel was duly acknowledged: Messrs. Tom Byron, Steve Ross, Gale Page, Jim Musselman, Patrick Upshaw, Howard Moseley and Greg Sholar of Florida DOT. Drs. Reynaldo Roque, David Bloomquist, and Byron Ruth of the University of Florida.

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