GEORGIA DOT RESEARCH PROJECT 15-03
FINAL REPORT

EVALUATION OF GEORGIA ASPHALT MIXTURE PROPERTIES USING A HAMBURG WHEEL-TRACKING DEVICE

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Evaluation of Georgia Asphalt Mixture Properties Using a Hamburg Wheel-Tracking Device

Final Report

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16. Abstract

This study used a Hamburg Wheel-Tracking Device (HWTD) to evaluate the resistance of Georgia asphalt mixtures to rutting and stripping. It aimed to develop an HWTD test procedure and criteria aligned with GDOT's asphalt materials and mixture design.

Aggregates, reclaimed asphalt pavement (RAP), and asphalt binders from four representative hot mix asphalt plants A1, A2, A3 and A4 - were selected for the test. All mixtures contained RAP. Asphalt binders of performance grade (PG) 64-22 and PG 76-22 were used, and four nominal maximum aggregate size (NMAS) Superpave mix types (25 mm, 19 mm, 12.5 mm, 9.5 mm T1 and T2), a 4.75 mm dense-graded and a 12.5 mm SMA mixtures were selected for this study. For Superpave and dense-graded mixtures, 30% RAP was used for A1 and A2 sources, and 25% RAP for A3 and A4. For SMA mixtures, 15% RAP was used regardless of source. Three temperatures of 50, 64, and 70°C were selected for each asphalt mix type. In total, 216 mixture samples were made by Superpave gyratory compactor (SGC), and 216 sets were tested by HWTD.

The results are as follows: 1) Rut depths were very small - less than 5 mm, even after 20,000 wheel passes at 50°C and increased remarkably at the higher test temperatures; most mixtures reached 20.0 mm within 20,000 wheel passes at 70°C. 2) Rut depths may reflect the influence of the type and size of the aggregates and the binders at test temperatures of 64°C and higher. 3) Rut depths from the mixtures with NMAS of 25 mm and 19 mm were obviously lower than those from NMAS of 12.5 mm, 9.5 mm, and 4.75 mm. 4) Rut depths increased and stripping inflection point (SIP) decreased as the NMAS of the gradation decreased. 5) Overall, mixtures using modified binders had lower rut depths than those using unmodified binders; in addition, the rut depths of 12.5 mm SMA using modified binders was much higher than those of 12.5 mm Superpave mixtures. 6) The raw material sources of aggregate and RAP had an apparent effect on rutting and stripping performance. 7) RAP preprocessing methods during laboratory mixing– either not heating or preheating in a 110°C oven for 2 hours before the RAP was mixed with the virgin aggregates and binder - affected rutting and stripping performance, regardless of temperature and mix type. 8) HWTD test procedures were proposed for evaluating Georgia asphalt mixtures.

17. Key Words Hamburg Wheel-Tracking Device, Asphalt Mixtures, RAP, Temperature, Rut depth, Stripping Inflection Point	18. Distribution Statement N/A

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EXECUTIVE SUMMARY

Background

Hot weather and moisture conditions may affect the rutting and anti-stripping properties of Georgia asphalt pavements more than other vulnerabilities. They are sporadic but concerning problems, leading to premature pavement failures. Like other DOTs, GDOT uses the asphalt pavement analyzer (APA) and the tensile strength ratio (TSR) to evaluate asphalt mixtures' resistance to rutting and stripping. However, questions have arisen as to whether the APA provides adequate severity and consistent test results. Additionally, evaluating moisture susceptibility using the TSR includes a conditioning procedure that takes a relatively long time to finish. Therefore, GDOT is now evaluating the Hamburg Wheel-tracking Device (HWTD) for implementation in lieu of the APA.

Many previous studies have evaluated the rutting and stripping resistance of asphalt mixtures using HWTD but at limited test temperatures, generally 50°C. In summer, most of Georgia is exposed to temperatures higher than 50°C. Asphalt mixtures may be more susceptible to stripping when reclaimed asphalt pavement (RAP) is used under high temperature and moisture conditions; RAP and modified binders make asphalt mixtures stiffer. Therefore, the rutting and stripping resistance of mixtures containing RAP and modified binders must be evaluated over a broader range of testing temperatures.

Objectives and Scope

This study aimed to use an HWTD to explore the performance of asphalt mixtures typically used in Georgia. Consequently, one objective was to develop an HWTD test procedure along with criteria aligned with GDOT's asphalt materials and mixture design procedures. The detailed main objectives were to determine:

1) testing temperatures appropriate to establishing criteria for evaluating the rutting and anti-stripping properties of Georgia asphalt mixtures;
2) appropriate load-pass numbers and corresponding rut depth criteria for Georgia asphalt mixtures; and
3) the number of wheel passes at the inflection point, when stripping is initiated.

To this end, Superpave, SMA and dense-graded asphalt mixture specimens were fabricated with aggregates from four different sources in Georgia, including both virgin and RAP, two asphalt binder grades - unmodified PG 64-22 and modified PG 76-22, and four nominal maximum aggregate size (NMAS) for Superpave, one for dense-graded and one for SMA, for a total of 216 mixture samples. HWTD tests were conducted on each at 50, 64, and 70°C. In the project, 70°C, not 76°C was selected as testing temperature for mixtures using modified binders of PG 76-22, after the rutting results at 64°C were reviewed, and it was determined that 76°C would be too severe.

Major Findings

1) When the test temperature increased from 50°C to 70°C, the rut depths of the asphalt mixtures increased, and the stripping inflection point (SIP) decreased, regardless of the type of aggregates and binders used. When tests were conducted at 50°C, rut depths were less than 5 mm, even at 20,000 wheel passes. This finding held true for all mixtures, regardless of binder type and size and mix type or gradation. No obvious SIP appeared on the curves of rut depth and wheel passes.

2) When tests were conducted at 64°C, rut depths were deeper than those found at 50°C and, most important, their values reflected the influence of the binders and mix type and size of

aggregates. Rut depths for coarse graded mixtures with nominal maximum aggregate size (NMAS) 25 mm and 19 mm were consistently lower than those with fine graded aggregates of NMAS 12.5 mm, 9.5 mm, and 4.75 mm. Most of the curves of rut depth and wheel passes showed SIP.

3) When tests were conducted at 70°C, the rut depths for the unmodified asphalt mixtures were very severe; most specimens resulted in over 20.0 mm rut depths, the limit set for the tests after very few wheel passes. Rut depths for mixtures using modified binder were still lower than 8.0 mm, even at 20,000 wheel passes. That finding held true for all the mixtures, regardless of the aggregate size and mix type. Similarly, when rut depth was low, no SIP appeared on the rut depth/wheel pass curves.

4) The effect of aggregate size on the performance of the asphalt mixtures was obvious. Rut depth increased as NMAS decreased, and SIP increased for the NMAS mixtures. Rut performance could be distinguished between large NMAS mixtures (25 mm and 19 mm) and small NMAS mixtures (12.5 mm, 9.5 mm, and 4.75 mm). This finding was especially apparent at 64°C.

5) When a modified binder (PG 76-22) was used in the 12.5 mm SMA and 12.5 mm Superpave and 4.75 mixtures, the rut depths were generally very low. The rut depths of the 12.5 mm Superpave and 4.75 mm mixtures using modified binders were much lower than those of the 12.5 mm Superpave and 4.75 mm mixtures using an unmodified binder (PG 64-22), even at 70°C. The SIPs were generally very high, above 20,000 wheel passes, which was the test limit for this research. In addition, the 12.5 mm SMA showed higher rut depth than 12.5 mm Superpave and 4.75 mm dense-graded mixture, regardless of the test temperature. This finding was true for all the aggregate sources and sizes used in the project.

6) The aggregate source influenced rutting and stripping performance. Generally, the mixtures using A1 and A3 aggregates had lower rut depths than those using A2 and A4. Asphalt mixtures containing RAP sourced from A1 with the lowest asphalt content had the lowest rut depth among the other sources. This finding was true, regardless of test temperature and the type of the binder used.

7) RAP preprocessing methods (i.e., preheating at 110°C for 2 hours in an oven or no preheating) before mixing the RAP with the virgin aggregate and binder affected rutting performance, regardless of test temperatures. It was found that asphalt mixtures containing the RAP with preheating process produced less rut depths. The proposed Hamburg test procedure and criteria for the asphalt mixture containing RAP with preheating were modified from those containing RAP without the preheating.

8) Since the rut depth and the SIP were significantly affected by the test temperature and the number of wheel passes, correlations were well-established among rut depth, SIP, temperature, and wheel passes for developing testing procedures and criteria.

Recommendations:

For asphalt mixtures using asphalt binder of PG 64-22 and containing RAP (25%-30%):

1) The combination of 18,500 wheel pass number at 58°C is recommended for the NMAS of 25 and 19 mm mixtures for a maximum rut depth of 12.5 mm. The number of the SIP is recommended to be at least 18,500.
2) The combination of 15,000 wheel pass number at 58°C is recommended for the NMAS of 12.5, 9.5T1, 9.5T2 and 4.75 mm mixtures for a maximum rut depth of 12.5mm. The number of the SIP is at least 15,000.

For asphalt mixtures using asphalt binder of PG 76-22 and containing RAP (25%-30%):

1) A test temperature of 64°C and 20,000 wheel passes are recommended for achieving no more than 6.0 mm rut depth for modified SMA 12.5, Superpave 12.5 and dense-graded 4.75 mm.
2) No SIP is allowed to appear before 20,000 passes at the test temperature of 64°C.

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Chapter 1 Introduction

1.1 Introduction

Rutting due to heavy and/or slow moving vehicle loads, and stripping due to moisture damage caused by climate conditions are typical asphalt pavement distresses. Severe rutting and stripping can considerably reduce a pavement's service life. Contributors to these distresses are traffic conditions, the quality of the materials, mix design, construction conditions, and other factors. To function properly under dynamic environmental conditions and increasing traffic, asphalt pavements must have adequate stiffness and flexibility at extreme temperatures, proper asphalt cement binders for climate conditions, good production and placement practices, and sufficient bond strength between the aggregate and the binder. Otherwise, pavements may rut, strip, and crack prematurely.

In an effort to lengthen the service life of asphalt pavement and promote sustainability, the use of modified asphalt binders has increased over the past decades (1). Reclaimed asphalt pavement (RAP) from construction and maintenance projects is a very valuable paving material. Though aged by traffic and climate conditions, it contains recyclable aggregate and asphalt cement binder. Nationally, the percentage of RAP incorporated into asphalt mixtures for pavements has increased up to as much as 100 percent in some applications based on its application, environmental, and economic benefits.

Given the extreme hot and humid weather conditions in Georgia, ascertaining accurate rutting and moisture damage susceptibility of its mixtures is very important to the Georgia Department of Transportation (GDOT). Hot weather and moisture conditions may affect the rutting and anti-stripping properties of Georgia asphalt pavements more than other factors. They have been sporadic but concerning problems, leading to premature pavement failures. Like other DOTs, GDOT uses the asphalt pavement analyzer (APA) and the tensile strength ratio (TSR) to evaluate asphalt mixtures' resistance to rutting and anti-stripping. However, questions have arisen as to whether the APA provides adequate severity and consistent test results. Additionally, evaluating moisture susceptibility using the TSR includes a conditioning procedure that takes a relatively long time to finish. GDOT is now evaluating the Hamburg Wheel-Tracking Device (HWTD) for implementation in lieu of the APA.

Although many previous studies have evaluated the rutting and stripping resistance of asphalt mixtures containing RAP or modified binder using the HWTD, they used a limited range of test temperatures. A pavement's surface layer is exposed to higher temperatures and adverse weather events more than the other layers within its structure. Asphalt surface mixtures, even those modified with RAP, may be more susceptible to rutting and stripping than other mixtures lower in the pavement structure. Most research on asphalt performance features, such as rutting and moisture damage, using the HWTD were conducted at a test temperature of 50°C. In the Georgia summer, most areas are exposed to high air temperatures with many consecutive days in the 32.2°C range; consequently, the temperature at a depth of 2.0 cm below the pavement surface is at least 54°C. The addition of RAP contributes positively in that it helps to stiffen asphalt mixtures like the modified binders but without the elasticity provided by the polymers. Investigations on use of the HWTD must consider higher temperature conditions. At the same time, GDOT must develop an HWTD test procedure and criteria that are aligned with its asphalt materials and mixture design procedures.

1.2 Objectives and Scope

The study used the HWTD to explore the performance of asphalt paving materials typically used in Georgia. Laboratory tests using the HWTD were conducted on various asphalt mixtures manufactured with typical Georgia materials to determine the influence of test temperature, mix type, RAP content, aggregate size, and asphalt cement performance grade. More specifically, the material variables included four aggregate sources designed at four hot mix asphalt plants with

RAP; mixtures consisting of six nominal maximum aggregate sizes (NMAS; i.e., 25 mm, 19 mm, 12.5 mm, 9.5 mm T1, 9.5 mm T2, 4.75mm); and unmodified and modified asphalt.

Figures 1-1 and 1-2 depict the work flow and the organization of the material combinations, including control mixtures, for testing. The suffix SP means Superpave design, and SMA means stone mastic asphalt mixtures. Testing was conducted at 50, 64, and 70°C, and four replicates for each test were conducted. Thus, testing six groups from four aggregate sources with nine kinds of mixture (unmodified and modified) at three test temperatures in four replicates resulted in a total of 432 samples.

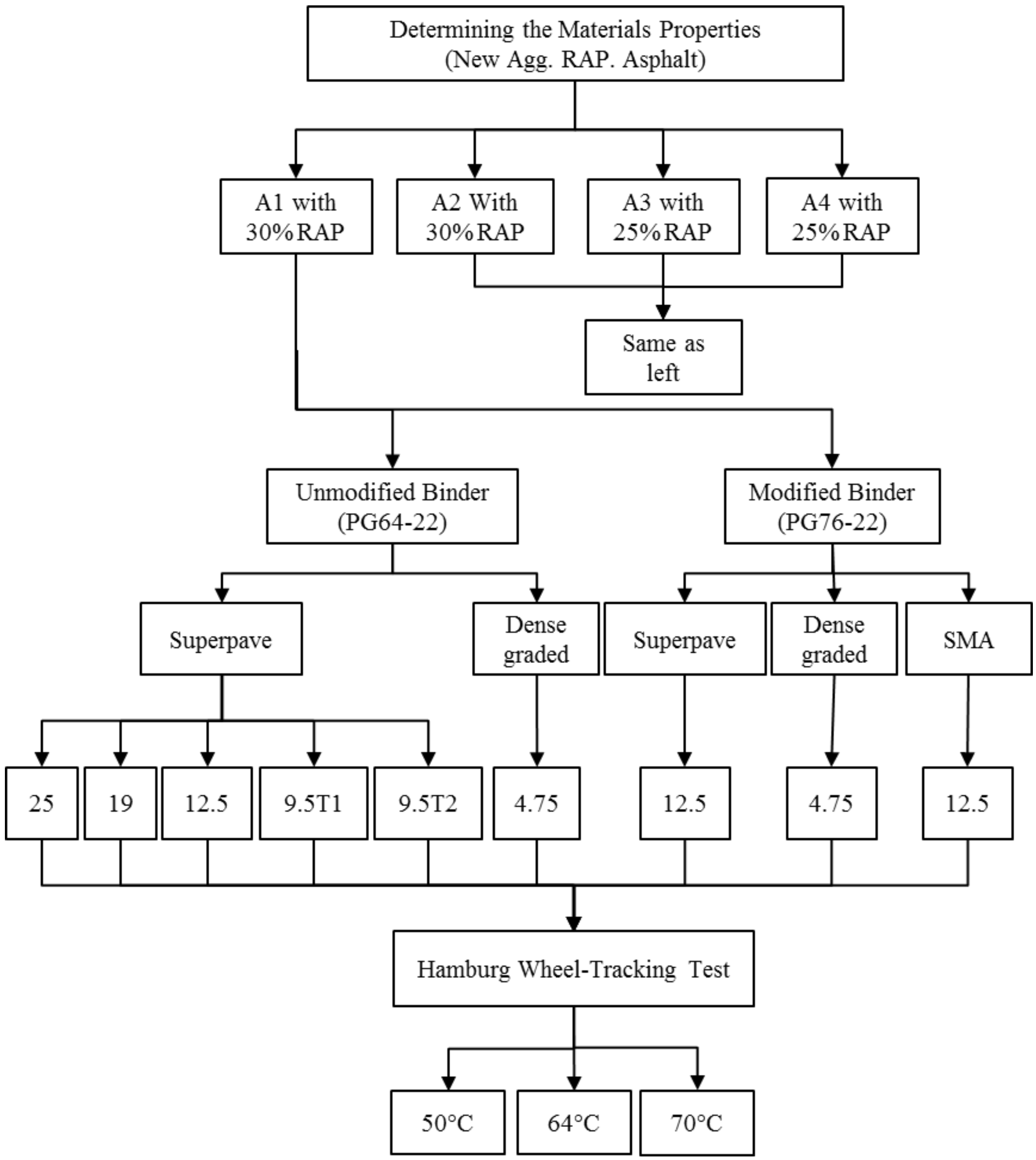


Figure 1-1 Flow chart of the study process

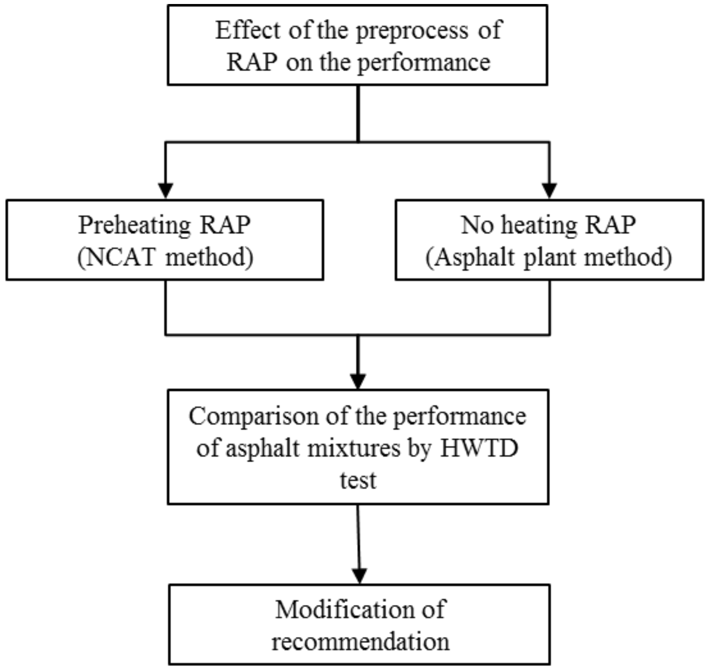


Figure 1-2 Modification of preheating of RAP effect on the HWTD test results

1.3 Literature Review

Over the past decades, national and state research programs have studied ways to alleviate rutting and stripping in asphalt pavements, resulting in innovative mix design methods, materials selection and management, and quality assurance systems. *Superpave*, the primary product of the Strategic Highway Research Program (SHRP), greatly affected the pavement industry's characterization of asphalt binders and aggregates, asphalt mixture designs, pavement performance analysis, and pavement serviceability maintenance (2).

Several mechanical methods are available to evaluate rutting and moisture damage or stripping of asphalt pavement. Traditionally, rutting was tested by static and dynamic creep, unconfined compression, and resilient modulus, and the tensile strength test evaluated moisture damage susceptibility. In recent years, more sophisticated methods using advanced equipment have been introduced - the asphalt pavement analyzer (APA), French rutting tester (FRT), asphalt mixtures performance tester (AMPT), and the Hamburg wheel-tracking device (HWTD) - and the rutting test results correlate reasonably well with field performance (3, 4, 5, 6).

HWTD is believed to measure the combined effects of rutting resistance and anti-stripping more reliably and accurately than APA, even at relatively higher temperatures. Additional research shows that this equipment meticulously captures the effects of aggregate sources and gradations, asphalt sources and grade, short-term aging (STA) duration, and compaction temperatures. The test data have proven consistent and replicable and correlate well with in-situ testing of rutting and stripping characteristics (7, 8, 9, 10).

Ever since the HWTD, developed in Germany, was introduced to the United States by pavement engineers and officials following a European asphalt study tour for technology transfer in the early 1990s, some states have adopted it to evaluate rutting and stripping potential. The customary test temperature for the HWTD is 50°C (11, 12).

The test evaluates the resistance to rutting and moisture damage of various asphalt pavement mixes at different temperatures. The deformation, or rut depth, of the mixes produced by the Hamburg loading wheel is plotted as a function of the number of wheel passes. An abrupt increase in the rate of deformation, known as the stripping inflection point (SIP), indicates that the asphalt mixture has experienced a failure possibly caused by binder having stripped from the aggregate (13). Results are influenced by several factors, including test temperature, asphalt-cement type, air-void content, the mix's aging, and the presence of lime. Controlling these variables in the laboratory is important for accurate results and determining the stripping inflection point in order to statistically ensure repeatability. Figure 1-3 shows a typical HWTD result, depicting the relationship between wheel passes and deformation.

Based on these benefits, several HWTD studies were conducted to evaluate the rutting potential of various modified asphalt mixtures. A Texas research report on SBS, SBR, tire rubber, and Elvaloy in PG 70-22 and PG 76-22 indicates that all the modifiers significantly increased the mixtures' rutting resistance. The final rut depth after 20,000 wheel passes at 50°C was less than 5 mm, which meets Texas specifications (14).

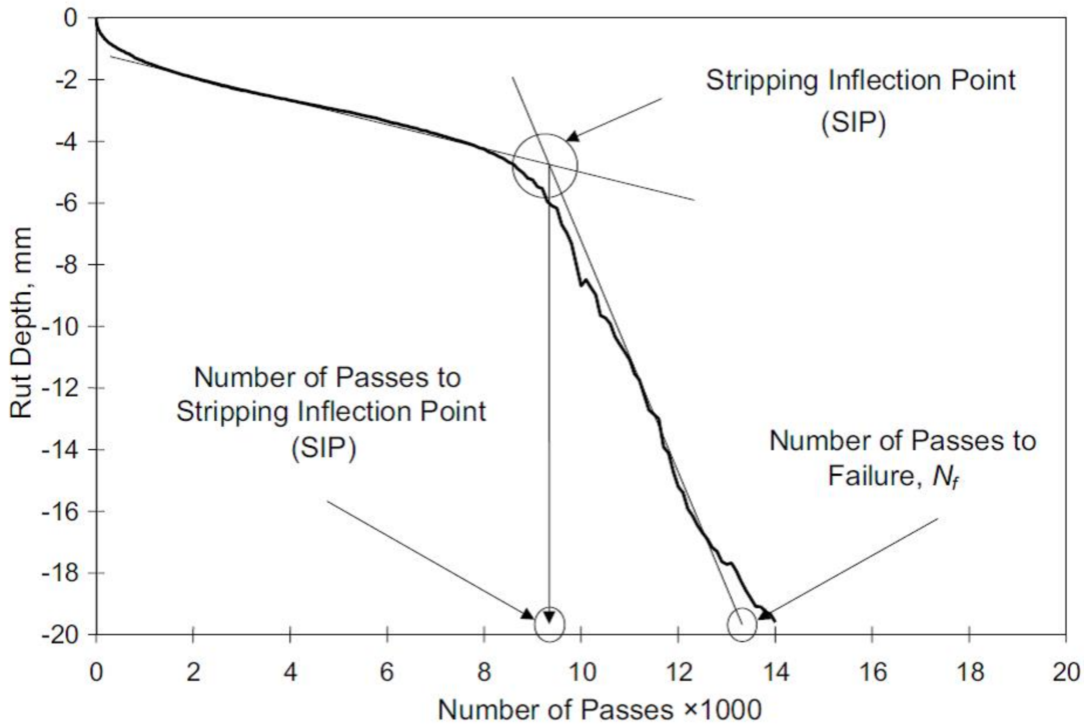


Figure 1-3 Typical curve from HWTD test (AASHTO T 324)

Another HWTD study confirmed that using modifiers decreases rut susceptibility; when a tire-rubber mixture modified with PG 76-22 and SBS mixtures modified with PG 76-22 were subjected to 20,000 passes at 50°C, they presented final rut depths of 1.3 and 1.4 mm, respectively (15). HWTD results can also reflect the compaction temperature and use of anti-stripping agents, such as hydrated lime and liquid anti-stripping additives, when asphalt mixture samples are made (16).

A Texas study reported that polymer-modified asphalt mixtures were superior to unmodified mixtures in terms of rutting potential and general stiffness when evaluated by such laboratory test methods as HWTD, flexural beam fatigue, and indirect tensions (17). Accelerated pavement testing indicated that styrene butadiene styrene (SBS) modified mixtures outperformed unmodified mixtures at 50°C and 65°C (18). Other reports showed that the performance of modified asphalt mixtures is enhanced even when they include RAP (19, 20, 21). HWTD has been increasingly used by many agencies and institutions around the world to measure rutting and stripping parameters and their effects on asphalt mixtures in a temperatures range of normally 45-55°C (12, 22).

Several studies have addressed the relationship between aggregate gradation/size and the rutting potential of asphalt mixtures. Auburn University's National Center for Asphalt Technology evaluated five asphalt mixtures using different nominal maximum aggregate sizes (3/8, ½, ¾, 1.5 inches) with respect to four mix stiffness properties, including Marshall stability and indirect tensile strength, and results indicated that asphalt mixes designed with larger aggregates are generally stronger and more resistant to rutting (23, 24). However, maximum aggregate size is not the only factor in mixture stiffness. Other influential attributes were excessive use of fine-grained aggregate or natural rounded aggregate (25). The shape of the aggregate gradation curve and the percentage of crushed coarse particles were found to have a significant effect on the rutting potential of asphalt mixtures (26).

In 1994, the Colorado DOT compared the rutting and moisture susceptibility of lab-manufactured hot mix asphalt (HMA) mixes with field mixes using the HWTD test. The study found that the stripping performance of the HMA pavement depended strongly on the material (i.e., asphalt cements and aggregates), the quality of the aggregate components in the mixture, and their interactions. It also found that the stripping inflection point was correlated to the known level of stripping performance; the lower the stripping inflection point, the worse the stripping was in the field (27).

Kansas State University carried out a study to assess whether different performance graded (PG) binders had any impact on premature rutting (2003). This study used four binder grades, PG 52-28, PG 58-28, PG 64-22, and PG 70-28, at a test temperature of 45°C. They found that PG 70-28 performed better than the other grades in terms of rutting distress, and its Superpave mixes showed a significant difference in the number of wheel repetitions to reach a maximum 20 mm rut depth and the stripping inflection point. The study also assessed the effect of compaction in Superpave mixes and showed that those with fewer air voids of 7% performed better than those with only 2 percent more of 9% (28).

The Texas Transportation Institute (Texas A&M University) studied whether the HWTD could test durability like the magnesium sulfate soundness (MSS) and Micro-Deval (MD) tests, but the correlation between their results was insignificant. This finding might be explained by the effect of other variables, such as binder type, test temperature, aggregate angularity, particle shape, or surface texture, which were not included in the database (29).

Texas A&M University evaluated the HWTD test, dynamic modulus (DM), and uniaxial repeated load permanent deformation (RLPD) to characterize the rutting potential of various HMA mixes (e.g., PG 64-22, PG 70-22, PG 70-28, and PG 76-22) and relate it to field performance. The HWTD test was conducted at a loading weight of 158 pounds, 52 passes per minute, and 50℃ in a water bath. DM correlated well with the RLPD and HWTD test results. High DM values indicated low RLPD accumulated strain and high resistance to rutting, consistent with HWTD results, which were found most replicable, least variable (coefficient of variance < 10%), and best suited for routine HMA mix-design and performance evaluations, including stripping and rutting performance (30).

Utah DOT and the University of Utah studied whether the HWTD test can produce consistent and repeatable results that can be used in pavement design and, eventually, field acceptance tests. Their statistical analysis indicated that non-uniform density in the test specimen due to the compaction process can cause results to vary. They stressed the importance of calculating and measuring or weighing the materials; compacting them on top of the mold for uniformity; and timing the heating of the compaction plates from the oven to loading and compacting the mold. With a proper compaction procedure, the HWTD will provide consistent results (31).

The Hamburg test can also evaluate the moisture damage susceptibility of asphalt mixes. According to a 2007 National Lime Association report, moisture damage to HMA pavements is not so much a problem in itself but represents a conditioning problem after which several distresses may occur one at a time or simultaneously. Moisture first destroys the bond between the aggregate and the asphalt binder or the binder's internal cohesion. As the HMA weakens, the stresses generated by traffic loads increase significantly and lead to fatigue cracking or rutting of the HMA layer. In terms of environmental stresses, the weaker HMA layer cannot resist the thermal stresses that lead to transverse cracking and aging stresses that create block cracking (32). In 1999, Texas DOT used the HWTD to evaluate moisture damage to HMA mixes treated with hydrated lime and liquid additives. Six HMA mixes were evaluated, all using AC-20 asphalt binder, in a controlled, lime-treated, and liquid-treated condition. Optimal binder content for each was established on the untreated mixes following TxDOT design methods. All the HWTD samples were compacted in the Superpave gyratory compactor (6.0-inch diameter cylinders) with air voids of 7 ±1%. Two 6.0-inch cylinders were then fitted side-by-side and loaded with the wheel. The tests were conducted at 40°C and 50°C. Based on the HWTD data, the researchers concluded that 50°C was too close to the softening point of the AC-20 binder to yield reliable results. However, the mixes with hydrated lime performed best, followed by those modified with liquid anti-stripping additive. Mixes without anti-stripping additive at 40°C performed worst (33).

Table 1-1 HWTD test specifications (34)

<table>
<tr><th rowspan="2">State DOTs</th><th colspan="4">HWTD Test Criteria</th></tr>
<tr><th>Asphalt Grade</th><th colspan="2">Minimum Number of Passes at 0.5 inch rut depth</th><th>Test Temperature (°C)</th></tr>
<tr><td rowspan="4">California</td><td>PG 58</td><td colspan="2">10,000</td><td>45</td></tr>
<tr><td>PG 64</td><td colspan="2">15,000</td><td>50</td></tr>
<tr><td>PG 70</td><td colspan="2">20,000</td><td>55</td></tr>
<tr><td>PG 76 or higher</td><td colspan="2">25,000</td><td></td></tr>
<tr><td rowspan="4">Illinois</td><td>PG 58 or lower</td><td colspan="2">5,000</td><td rowspan="4">50</td></tr>
<tr><td>PG 64</td><td colspan="2">7,500</td></tr>
<tr><td>PG 70</td><td colspan="2">15,000</td></tr>
<tr><td>PG 76 or Higher</td><td colspan="2">20,000</td></tr>
<tr><td rowspan="3">Louisiana</td><td>PG 58</td><td colspan="2">12,000</td><td rowspan="3">50</td></tr>
<tr><td>PG 64</td><td colspan="2">20,000</td></tr>
<tr><td>PG 70 (OGFC)</td><td colspan="2">7,500</td></tr>
<tr><td rowspan="4">Montana</td><td></td><td>Produced Plant Mix</td><td>Mix Design</td><td></td></tr>
<tr><td>PG 58</td><td>10,000</td><td>15,000</td><td>44</td></tr>
<tr><td>PG 64</td><td>10,000</td><td>15,000</td><td>50</td></tr>
<tr><td>PG 70</td><td>10,000</td><td>15,000</td><td>56</td></tr>
<tr><td rowspan="3">Texas</td><td>PG 64 or lower</td><td colspan="2">10,000</td><td rowspan="3">50</td></tr>
<tr><td>PG 70</td><td colspan="2">15,000</td></tr>
<tr><td>PG 76 or higher</td><td colspan="2">20,000</td></tr>
<tr><td rowspan="4">Wisconsin</td><td>PG 58</td><td colspan="2">5,000</td><td rowspan="4">50</td></tr>
<tr><td>PG 64</td><td colspan="2">10,000</td></tr>
<tr><td>PG 70</td><td colspan="2">15,000</td></tr>
<tr><td>PG 76</td><td colspan="2">20,000</td></tr>
<tr><td rowspan="4">Colorado</td><td>PG 58</td><td colspan="2" rowspan="4">Maximum rut depth >4.0 mm before 10,000 passes is considered a failure</td><td>45</td></tr>
<tr><td>PG 64</td><td>50</td></tr>
<tr><td>PG 70</td><td>55</td></tr>
<tr><td>PG 76</td><td>55</td></tr>
</table>

Chapter 2 Materials and Methods

2.1 Materials

The materials considered in our research include aggregates, asphalt binders, and RAP along with two additives: hydrated lime and cellulose fiber. This section describes the properties of each as measured in the Georgia Southern University laboratory and reported by the suppliers.

2.1.1 Aggregate

The mineral aggregates used to manufacture our specimens were supplied by the following asphalt mix plants located across the state of Georgia: Aggregate source 1 (A1), Aggregate source 2 (A2), Aggregate source 3 (A3), and Aggregate source 4 (A4). The aggregates were transported to the GSU asphalt laboratory where a series of tests were conducted to measure aggregate-related physical properties, including specific gravities (bulk, saturated surface dry, and apparent), absorption, and abrasion loss. Tables 2-1(a) to (d) summarize the results and the relevant ASTM standards. The properties presented in the tables were measured separately for coarse aggregates (greater than 4.75 mm) and fine aggregates (less than 4.75 mm). Figures 2-1(a) to (d) are photographs of aggregate stockpiles at the four sources. In general, A1 has the least L.A. abrasion loss, and A2, the most, but A2 has the highest Specific Gravity (S.G.), and A1, the smallest.

Table 2-1(a) Properties of aggregate sources for A1

Aggregate number	NMAS (mm)	Specific Gravity (ASTM C 127, 128)			Absorption (ASTM C 127, 128) (%)	L.A. Abrasion Loss (ASTM C 533) (%)
		Bulk	S.S.D	APP.		
#005	25	2.602	2.619	2.647	0.55	30.5
#006	19	2.600	2.617	2.644	0.63	33.0
#007	12.5	2.580	2.605	2.645	0.95	30.8
#089	9.5	2.566	2.593	2.637	1.06	29.8
#810	4.75	2.632	2.646	2.668	0.5	-
#W10	4.75	2.631	2.652	2.670	0.9	-

Table 2-1(b) Properties of aggregate sources for A2

Aggregate number	NMAS (mm)	Specific Gravity (ASTM C 127, 128)			Absorption (ASTM C 127, 128) (%)	L.A. Abrasion Loss (ASTM C 533) (%)
		Bulk	S.S.D	APP.		
#005	25	2.640	2.653	2.675	0.5	33.8
#006	19	2.643	2.656	2.676	0.5	36.4
#007	12.5	2.610	2.633	2.671	0.9	42.7
#089	9.5	2.575	2.627	2.717	2.0	34.4
#810	4.75	2.629	2.653	2.693	0.9	-
#W10	4.75	2.659	2.667	2.680	0.3	-

Table 2-1(c) Properties of aggregate sources for A3

Aggregate number	NMAS (mm)	Specific Gravity (ASTM C 127, 128)			Absorption (ASTM C 127, 128) (%)	L.A. Abrasion Loss (ASTM C 533) (%)
		Bulk	S.S.D	APP.		
#005	25	2.601	2.618	2.647	0.7	31.6
#006	19	2.600	2.620	2.652	0.8	36.7
#007	12.5	2.579	2.609	2.658	1.5	34.7
#089	9.5	2.521	2.583	2.688	2.4	36.7
#810	4.75	2.640	2.646	2.654	0.2	-
#W10	4.75	2.631	2.639	2.652	0.3	-

Table 2-1(d) Properties of aggregate sources for A4

Aggregate number	NMAS (mm)	Specific Gravity (ASTM C 127, 128)			Absorption (ASTM C 127, 128) (%)	L.A. Abrasion Loss (ASTM C 533) (%)
		Bulk	S.S.D	APP.		
#005	25	2.607	2.622	2.647	0.6	25.9
#006	19	2.630	2.647	2.676	0.7	36.4
#007	12.5	2.596	2.618	2.655	0.9	36.1
#089	9.5	2.587	2.625	2.688	1.5	34.5
#810	4.75	2.618	2.632	2.653	0.5	-
#W10	4.75	2.640	2.646	2.654	0.2	-

(a)

(b)

(c)

(d)

Figure 2-1 Stockpiles at (a) A1, (b) A2, (c) A3, and (d) A4

2.1.2 RAP

The RAP materials used in this study were delivered to the GSU laboratory from the hot mix asphalt plants shown in Figure 2-1. Several RAP properties were measured, including aggregate gradation before and after asphalt-content extraction using the Abson recovery method (ASTM D 1856), the extracted asphalt cement content (Figures 2-4 and 2-5), and other physical properties of the RAP binder using a dynamic shear rheometer (DSR), (AASHTO T 315) and a rotational viscometer (RV, AASHTO T 316).

Table 2-2 and Figure 2-2 present the results of sieve analyses of the RAP from each source, with gradation determined before and after the asphalt binder was extracted. At every sieve size (from 19.0 mm to 0.075 mm), the percent of RAP passing after asphalt cement extraction was higher than that before extraction, which is expected since aggregate particles without asphalt coating are smaller. Since all RAP materials passed through the 19 mm sieve and 0.4 to 8.1% remained in the 12.5 mm sieve, the NMAS of the RAP was classified as 12.5 mm.

The difference between the gradations of the RAP before and after the RAP binders are extracted varies by the RAP source. For A1, there was no significant difference between the percent passing in the 12.5 mm or coarser sieves before and after extraction, while the percent passing in the 4.75 mm or smaller sieves increased to a range of 7.1 ~ 11.4% before and after extraction. For A2, there was a 7.4% increase after extraction in percent passing in the 9.5mm sieve, and a 7.8 to 25.4% increase in percent passing in the 4.75 mm or smaller sieves after extraction. For A3, no significant difference in the percent passing in 12.5 mm or larger sieves was observed, while an increase of 6.7 to 14.9% in the 4.75 mm or smaller sieves after extraction was observed. In the case of A4, it was found that there was an increase of 9.2% and 12.9% for 12.5 and 9.5 mm sieves, respectively, and an increase of 5.4 to 19.6% for 4.75 mm or smaller sieves.

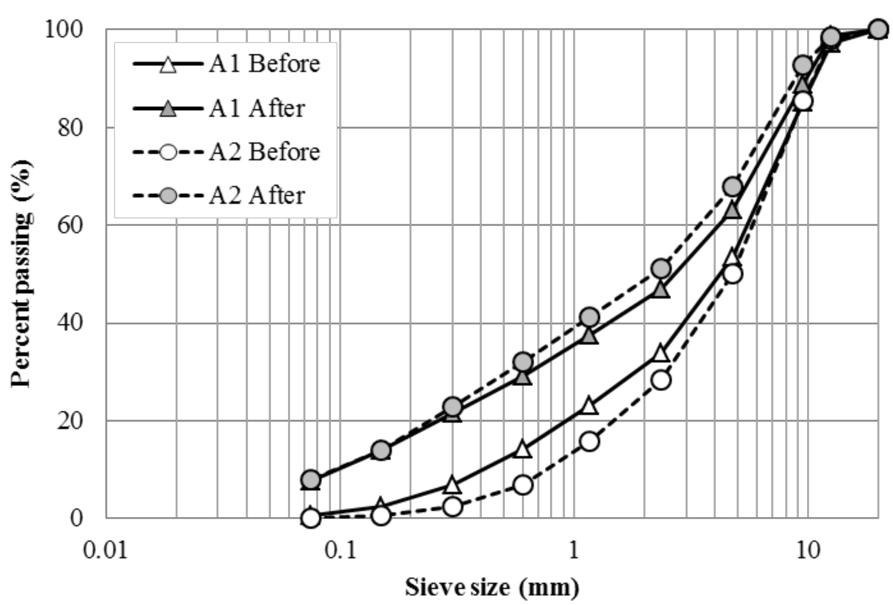
As Table 2-2 shows, A4 had the highest asphalt cement content (AC), and A1, the least. The AC of these RAP sources differed significantly. RAP gradation before and after extraction also differed significantly, regardless of the source.

Table 2-2 Asphalt content and RAP gradations before and after extraction

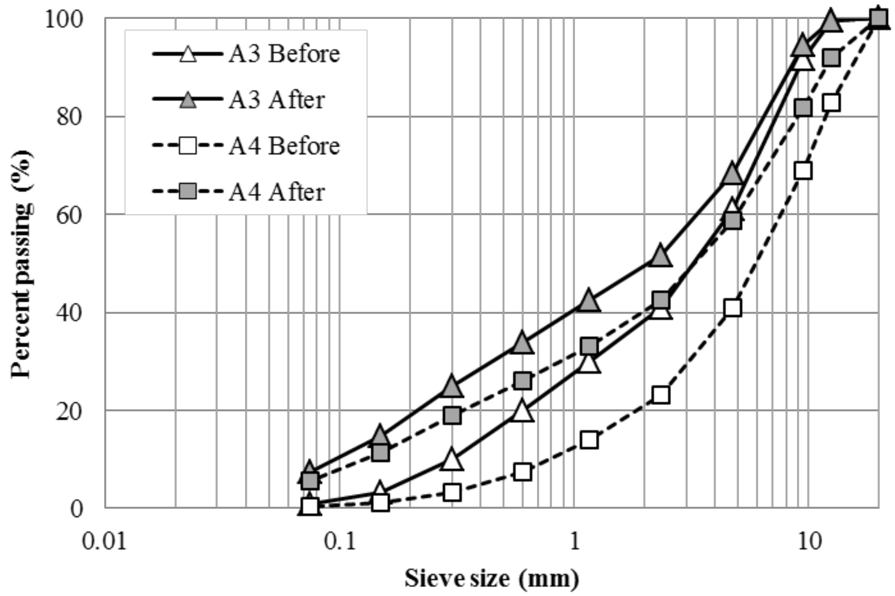
Source	Asphalt Content (%)	Passing percent of RAP aggregate before* and after** extraction										
		Sieve Size (mm)	19	12.5	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
A1	4.97	Before	100	97.3	85.1	53.5	33.9	23.2	14.3	6.9	2.5	0.7
		After	100	98.7	88.7	63.0	47.0	37.6	29.2	21.7	13.9	7.8
A2	6.17	Before	100	98.0	85.4	50.0	28.2	15.8	6.9	2.5	0.7	0.1
		After	100	98.6	92.8	68.0	51.2	41.2	31.9	22.8	14.0	7.9
A3	5.25	Before	100	99.5	91.8	61.0	41.0	30.0	20.0	10.0	3.2	0.8
		After	100	99.6	94.6	68.5	51.7	42.4	34.0	24.9	14.7	7.5
A4	5.89	Before	100	82.7	68.9	40.9	23.0	13.8	7.4	3.2	1.1	0.2
		After	100	91.9	81.8	58.7	42.6	33.0	25.9	18.9	11.3	5.6

* Dried RAP in lab included old asphalt.

** Remaining pure RAP aggregate after extraction by the Abson recovery method.



(a) A1 and A2



(b) A3 and A4

Figure 2-2 Gradation of RAP aggregate before and after extraction

The asphalt binder extracted from RAP was tested to obtain DSR properties (G*/sin δ). The results are summarized in Table 2-3 and Figure 2-3.

Table 2-3 DSR results (G*/sin δ) using recovered binder at drying conditions

Preprocess	RAP, dried in laboratory at room temperature but no preheating				RAP, heated @ 110°C for 2 hrs after drying at 60°C for 12 Hrs.			
Test temp. (°C)	A1	A2	A3	A4	A1	A2	A3	A4
58	3.15	3.76	4.52	4.92	7.32	9.78	4.75	8.88
64	2.16	2.64	3.01	2.93	4.92	5.45	3.22	5.76
70	1.35	1.56	1.86	1.72	1.70	2.96	1.98	3.01
76	0.83	0.98	1.12	1.01	1.05	1.64	1.24	1.61
82	-	-	0.68	0.61	0.68	0.93	0.89	1.01
84	-	-	-	-	-	-	-	0.59

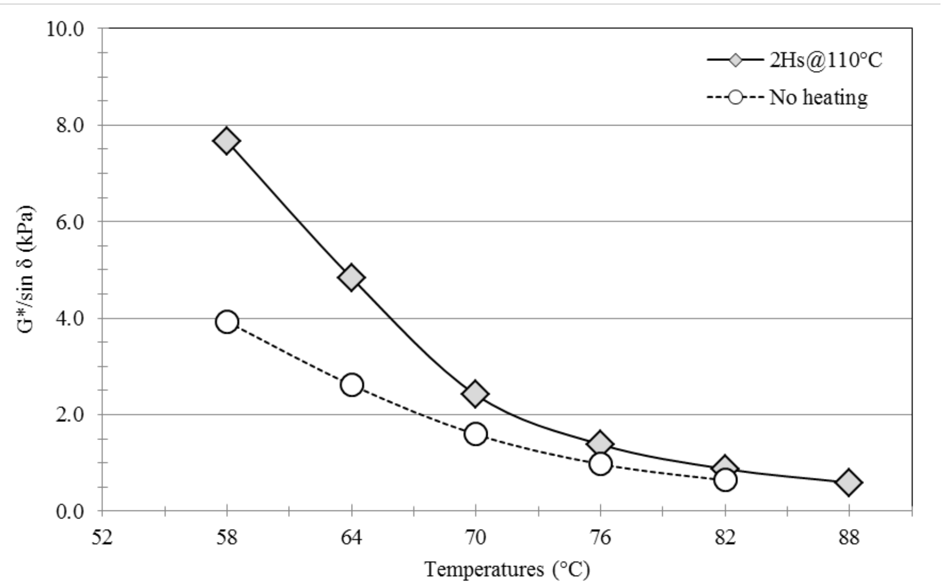


Figure 2-3 G*/sin δ of recovered binders by drying condition (average values of four sources)

Figure 2-4 Centrifuge for RAP extraction

Figure 2-5 Abson recovery system

2.1.3 Hydrated lime

Hydrated lime, shown in Figure 2-6, is an additive widely used in hot mix asphalt (HMA) production to reduce stripping and improve stiffness (38). This study used hydrated lime provided by the four plants. Their size and purity met the GDOT specifications. We used 0.9% hydrated lime by mixture weight as an anti-stripping agent.

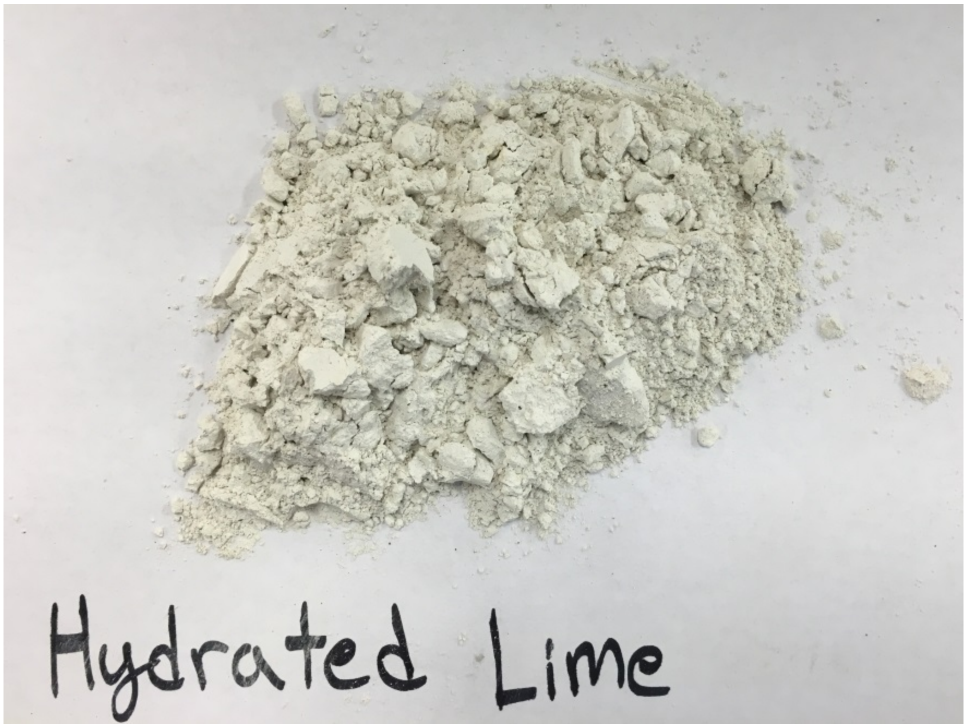


Figure 2-6 Hydrated lime for anti-stripping

2.1.4 Cellulose fiber

Cellulose fiber (Fig. 2-7) is also used as an additive for asphalt mixtures. The fiber is incorporated in asphalt mixtures to help to prevent drain-down which is the tendency for the asphalt in the mixtures, especially for SMA, to drain to the bottom due to high asphalt content as the mix sits in storage silos, transport trucks, or in the field. We used 0.3% fiber by mixture weight.

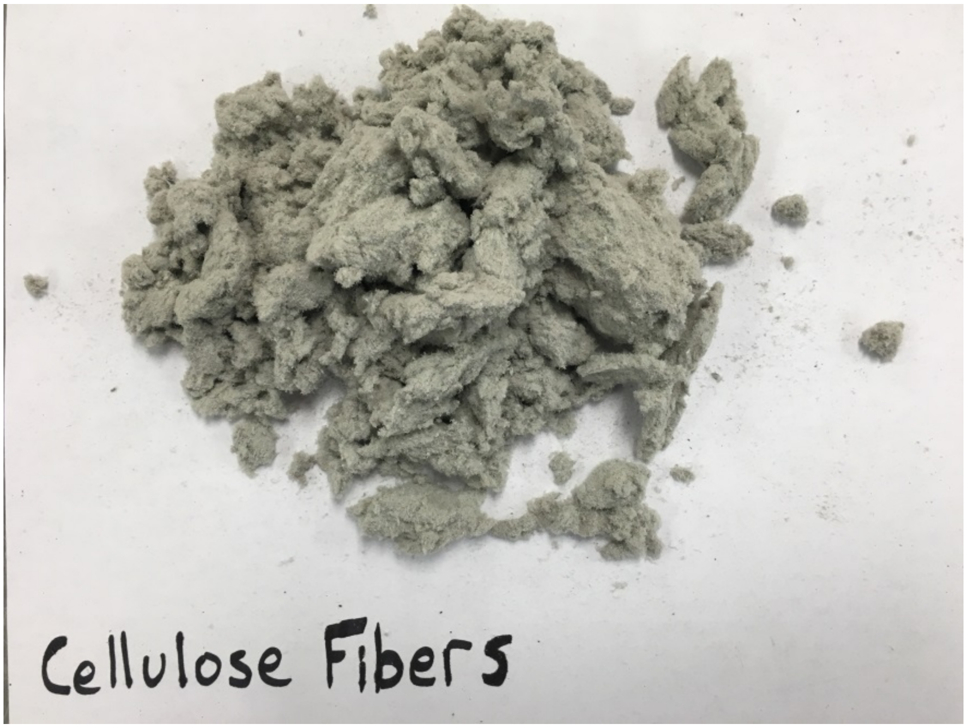


Figure 2-7 Cellulose fibers for SMA mixtures

2.1.5 Asphalt cement

Asphalt cements used in this study were provided by the same four asphalt plants. Two performance grades, PG 64-22 (unmodified) and PG 76-22 (modified), were used to manufacture asphalt mixtures in the laboratory. Table 2-4 shows the properties of virgin asphalt binder under three different aging conditions (original, RTFO, and PAV) reported by the suppliers. They include specific gravity, flashpoint, viscosity, G*/sin (δ), and phase angle for the original binder; mass loss and G*/sin (δ) for the short-term aged binder; and G*/sin (δ), creep stiffness, and m-value for the long-term aged binder.

Table 2-4 Properties of virgin asphalt binders provided by the four asphalt plants

Test Item	Temp. (°C)	Requirement	PG 64-22				PG 76-22			
			A1	A2	A3	A4	A1	A2	A3	A4
ORIGINAL										
Specific Gravity	25.0	-	1.030	1.032	1.035	1.035	1.045	1.034	1.033	1.033
Flashpoint	-	230 min	319	268.3	324	324	317	273.9	321	321
Viscosity, Pa*s	135.0	3.0 max	0.420	0.518	0.443	0.443	2.480	1.217	1.299	1.299
DSR, G*/sin (δ), kPa	64.0	1.0 min	1.17	1.64	1.46	1.46	-	-	-	-
	76.0	1.0 min	-	-	-	-	3.28	1.129	1.19	1.19
Phase angle, δ	76.0	75 max. if modified	-	-	-	-	68.3	72.9	73.8	73.8
RTFO residual										
Mass loss, %		0.5 max	0.443	0.208	0.137	0.137	0.214	0.263	0.218	0.218
DSR, G*/sin (δ), kPa	64.0	2.2 min	3.31	3.77	3.56	3.56	-	-	-	-
	76.0	2.2 min	-	-	-	-	6.55	2.32	2.69	2.69
PAV residual										
DSR, G*/sin (δ), kPa	25.0	5000 max	3,470	3,800	3,540	3,540	-	-	-	-
	31.0	5000 max	-	-	-	-	2.070	1556	1520	1520
Creep Stiffness, MPa @60sec	-12.0	300 max	168	199	169	169	158	157	154	154
m-Value @ 60sec	-12.0	0.300 min	0.320	0.349	0.324	0.324	0.305	0.360	0.327	0.327

2.2 Asphalt Mix Design (provided by mix plants)

The asphalt mix design used in this research followed the designs provided by the plants in that test specimens would be consistent with GDOT approved mixtures. A total of nine types of mixture per asphalt plant source were considered (Table 2-5). Nominal maximum aggregate sizes (NMAS) of 25, 19, 12.5, 9.5, and 4.75 mm were considered with 30% RAP (A1 and A2) or 25% RAP (A3 and A4). Unmodified asphalt binder was used for all these NMAS, and modified binder with 12.5 and 4.75 mm NMAS designs. One SMA mixture with 12.5 mm NMAS incorporating 15% RAP was added to each source. Specimen preparation followed AASHTO PP 60-14. The batch of asphalt mixture for preparing specimens was calculated based on the proportions shown in the Table 2-5.

It should be noted that GDOT does not credit the RAP binders with 100% binder replacement. Previous research conducted by GDOT resulted in specification giving RAP binder only 75% replacement credits. As an alternative to original asphalt content (OAC), corrected asphalt cement content (COAC) was established for asphaltic concrete mix designs using RAP in Georgia. The value of COAC equals the value of OAC obtained from the mixture designs at four percent air void content of the fabricated specimens (Table 2-5) plus that value of 25% of the RAP binder replacement content.

2.3 Test Flow Chart

Figure 2-8 shows the experimental design. The flow chart shows the sequence of the mixture preparation and the temperature conditions for each material type (aggregate, asphalt cement, and RAP) for both unmodified and modified asphalt mixtures. The following sections provide more information on the sample preparation and HWDT testing.

Table 2-5 Job mix formula provided by four asphalt mix plants

Material Source	Mixture Designation*	RAP (%)	Percent Passing (Combined gradation, %)											OAC (%)	COAC (%)
			25mm	19	12.5	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075		
A1	25U30R	30	99	84	69	59	45	33	25	19	14	8	4.9	4.10	4.47
	19U30R	30	100	100	88	68	43	33	26	20	14	9	4.9	4.50	4.87
	12.5U30R	30	100	100	99	85	59	45	34	26	18	10	5.9	5.10	5.47
	9.5T1U30R	30	100	100	100	97	73	53	40	30	20	11	6.2	5.60	5.97
	9.5T2U30R	30	100	100	100	97	65	45	34	26	18	10	5.6	5.50	5.87
	4.75U30R	30	100	100	100	98	82	60	46	34	24	14	8.7	6.00	6.37
	12.5M30R	30	100	100	100	85	60	44	35	27	19	11	6.0	5.00	5.37
	4.75M30R	30	100	100	100	98	82	60	46	34	24	14	8.7	6.00	6.37
	12.5SMA15R	15	100	100	90	66	25	16	14	13	12	10	9.4	6.10	6.27
A2	25U30R	30	100	89	70	56	43	33	24	18	12	8	5	4.20	4.66
	19U30R	30	100	97	88	70	44	33	25	19	13	8	5.5	4.38	4.84
	12.5U30R	30	100	100	98	87	61	45	32	23	14	8	5.4	5.00	5.46
	9.5T1U30R	30	100	100	98	91	65	44	33	23	14	10	5.7	5.50	5.96
	9.5T2U30R	30	100	100	99	97	69	48	35	26	18	12	6.5	5.68	6.14
	4.75U30R	30	100	100	100	97	83	62	45	34	23	15	8.3	6.00	6.46
	12.5M30R	30	100	100	97	84	58	41	30	21	13	9	5.5	5.23	5.69
	4.75M30R	30	100	100	100	97	83	62	45	34	23	15	8.3	6.00	6.46
	12.5SMA15R	15	100	100	88	63	28	22	19	16	14	12	11.5	6.07	6.53
A3	25U25R	25	99	88	69	65	47	33	25	20	14	8	4.7	3.98	4.31
	19U25R	25	100	98	79	74	51	34	27	21	15	9	5.3	4.37	4.70
	12.5U25R	25	100	100	98	87	62	45	35	27	18	10	5.8	4.93	5.26
	9.5T1U25R	25	100	100	100	99	68	45	35	27	18	10	6.0	5.43	5.76
	9.5T2U25R	25	100	100	100	99	74	53	40	31	20	10	6.0	5.93	6.26
	4.75U25R	25	100	100	100	97	80	63	47	36	25	15	9.0	6.00	6.33
	12.5M25R	25	100	100	99	89	58	43	31	23	15	9	5.6	4.95	5.28
	4.75M25R	25	100	100	100	97	80	63	47	36	25	15	9.0	6.00	6.33
	12.5SMA15R	15	100	100	96	66	24	19	17	16	13	12	10.4	6.50	6.83
A4	25U25R	25	99	89	70	60	40	32	25	20	15	8	4.8	4.50	4.87
	19U25R	25	100	100	89	72	49	34	29	25	15	10	5.3	4.50	4.87
	12.5U25R	25	100	100	97	86	59	44	35	27	19	12	5.9	5.40	5.77
	9.5T1U25R	25	100	100	99	98	68	45	36	28	20	13	6.3	5.72	6.09
	9.5T2U25R	25	100	100	100	99	73	52	40	32	22	12	6.4	6.07	6.44
	4.75U25R	25	100	100	100	98	82	64	51	39	27	13	10.1	6.20	6.57
	12.5M25R	25	100	100	98	85	52	39	31	25	20	10	6.2	5.20	5.57
	4.75M25R	25	100	100	100	98	82	64	51	39	27	13	10.1	6.20	6.57
	12.5SMA15R	15	100	100	88	56	24	17	16	15	13	12	11.3	6.40	6.77

* first number (25… 4.75) = nominal maximum aggregate size; SP = Superpave design; 15R = 15% RAP; 25R = 25% RAP; 30R = 30% RAP; U = unmodified asphalt (PG 64-22); M = modified asphalt (PG 76-22); SMA = stone mastic asphalt

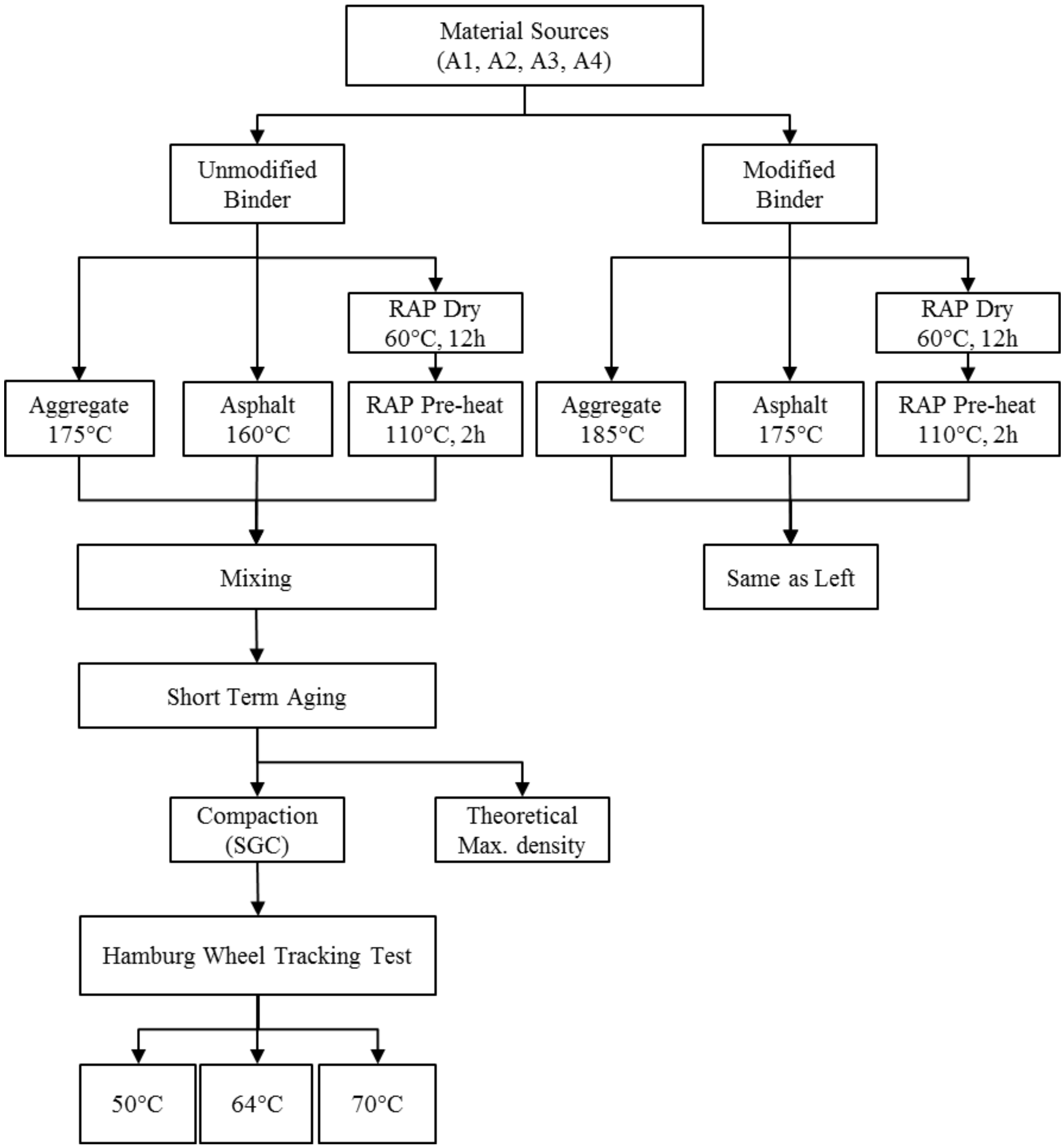


Figure 2-8 Flow chart of the experiment used in the project

2.4 Sample Preparation for HWTD Testing

2.4.1 Mixing and compacting

All the new aggregates and RAP were dried in the oven to remove moisture. Drying temperatures were controlled to approximately 110±5°C for virgin aggregates and 60° for RAP, following the suggestions of several national studies (35, 36, 37). When unmodified asphalt mixtures were manufactured, the materials (asphalt binder, aggregates, and RAP) were heated in the oven as follows: asphalt at 160°C for 2 hours; aggregates at 170°C for 4 hours; and RAP at 110°C for 2 hours. When modified asphalt mixtures were manufactured, the materials (asphalt binder, aggregates, and RAP) were heated as follows: asphalt at 175°C for 2 hours; aggregates at 185°C for 4 hours; and RAP at 110°C for 2 hours.

After mixing, loose asphalt mixtures were subjected to short-term aging (STA) according to AASHTO R 30: 4 hours at 135°C for unmodified, and 4 hours at 155°C for modified. Modified mixtures were subjected to the higher temperature because their behavior is more viscous, and require a higher compaction temperature (39). The short-term aged loose mixtures were then compacted using a Superpave gyratory compactor (SGC) following AASHTO T 312 (40). Figures 2-9 and 2-10 are photographs of mixing and compaction in the GSU laboratory.

A portion of each type of loose mixture was used to measure its theoretical maximum density (G_{mm}) according to AASHTO T 209. The G_{mm} values of all portions were then used to calculate the air voids of test specimens. Figures 2-11 and 2-12 show the loose materials and an apparatus for G_{mm}.

It is worth noting that mixing virgin aggregates, asphalt binder and RAP without a preheating process in asphalt plants is commonly found in the United States. However, previous studies suggested that RAP mixtures be oven-dried at 60°C for 12 hours before mixing to completely remove moisture followed by oven-heating at 110°C for equal or less than two hours for a better mixing with new aggregates (35, 36, 37). After concluding the experiments following references of this suggestion (i.e., the preheating option), the research team conducted an additional set of HWTD tests under the without-preheating option. The purpose of this extra experiment was to find a possible discrepancy that might exist between the asphalt plant practice (i.e., no preheating RAP) and the academia practice (i.e., preheating RAP). The detail on this subject is discussed in Chapter 4.

Figure 2-9 Asphalt Mixing

Figure 2-10 Superpave Gyratory Compactor (SGC)

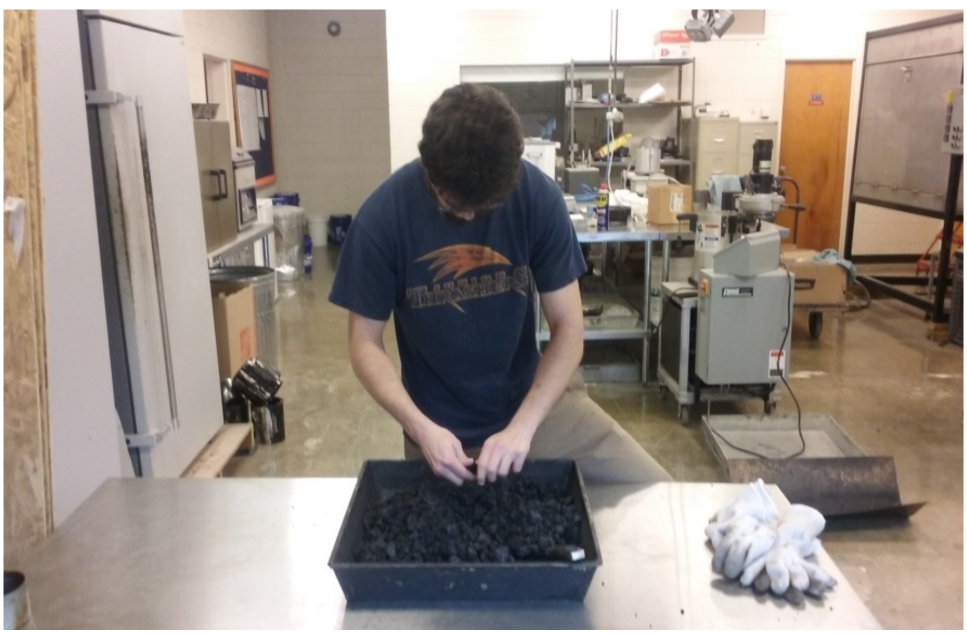


Figure 2-11 Separating aggregate in asphalt mixtures

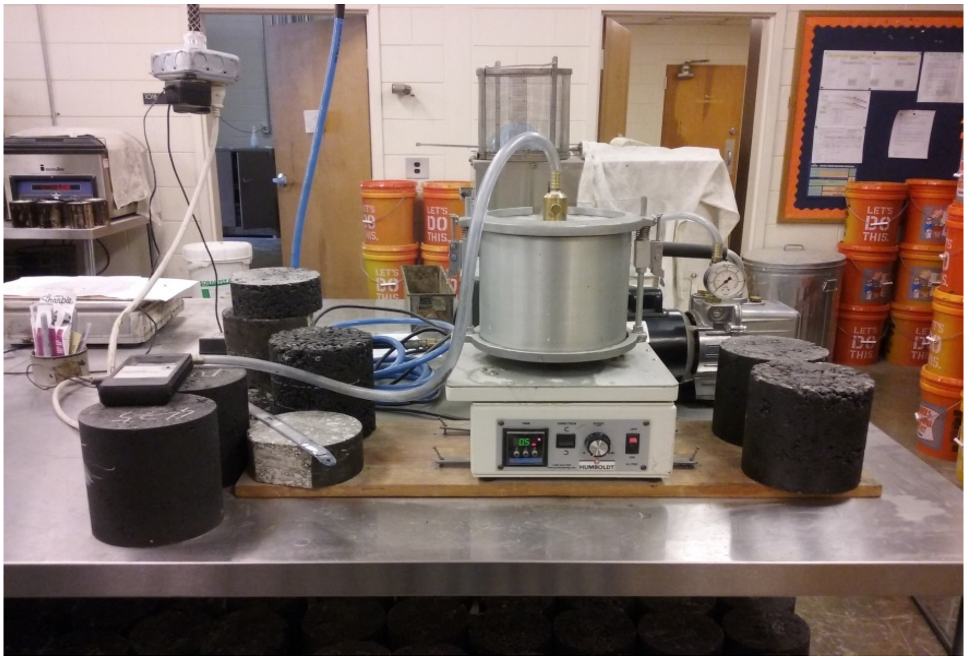


Figure 2-12 Apparatus for Measuring Theoretical Maximum Density

2.4.2 Volumetric properties

Volumetric properties of compacted samples were calculated according to AASHTO T 312. They include bulk density, air voids, voids in mineral aggregate (VMA), and voids filled with asphalt (VFA). The allowable air-void level specified in AASHTO T 324 for HWTD testing is 7±1%, and any specimens out of this range were discarded. Table 2-6 summarizes the average measurement of each volumetric property for the mix designs.

Table 2-6 Average volumetric properties for HWTD test of SGC samples

Material Source	Mixture Designation	Bulk Density (g/cm^3)	Air void (%)	VMA (%)	VFA (%)
A1	25U30R	2.312	6.5	16.4	60.6
	19U30R	2.294	6.6	17.4	61.9
	12.5U30R	2.274	6.8	18.8	63.7
	9.5T1U30R	2.232	7.5	20.4	62.9
	9.5T2U30R	2.264	6.8	19.6	65.1
	4.75U30R	2.245	6.9	20.7	66.7
	12.5M30R	2.261	7.3	18.9	61.4
	4.75M30R	2.248	6.8	20.6	67.3
	12.5SMA15R	2.234	6.9	20.6	66.1
A2	25U30R	2.336	6.2	16.4	62.1
	19U30R	2.308	6.9	17.6	60.9
	12.5U30R	2.277	7.2	19.2	62.4
	9.5T1U30R	2.268	6.8	19.8	65.5
	9.5T2U30R	2.280	6.5	19.9	67.4
	4.75U30R	2.259	7.2	21.1	66.1
	12.5M30R	2.284	6.9	19.4	64.3
	4.75M30R	2.263	7.1	21.0	66.4
	12.5SMA15R	2.275	7.2	19.3	72.5
A3	25U25R	2.302	6.8	16.5	58.5
	19U25R	2.300	7.0	17.5	59.9
	12.5U25R	2.262	7.5	19.2	60.7
	9.5T1U25R	2.268	7.1	19.7	64.2
	9.5T2U25R	2.253	7.0	20.7	66.2
	4.75U25R	2.252	6.9	20.8	66.9
	12.5M25R	2.305	6.2	18.1	65.7
	4.75M25R	2.237	7.1	20.9	66.0
	12.5SMA15R	2.291	6.5	19.3	73.4
A4	25U25R	2.316	6.2	17.0	63.7
	19U25R	2.297	6.7	17.6	62.3
	12.5U25R	2.293	6.1	18.8	67.6
	9.5T1U25R	2.264	6.8	20.1	66.1
	9.5T2U25R	2.240	7.2	21.1	66.1
	4.75U25R	2.282	6.4	20.8	69.1
	12.5M25R	2.268	6.2	20.5	69.8
	4.75M25R	2.296	6.2	18.5	66.4
	12.5SMA15R	2.200	6.4	20.1	68.0

2.5 Hamburg Wheel-Tracking Device Test

2.5.1 Test conditions

The specimens prepared by SGC (150 mm diameter by 150 mm height) were cut into two pieces, 63 (±0.5) mm high, for HWTD testing, following AASHTO T 324. The tests were conducted with a Troxler PMW Wheel Tracker with embedded 6.0 software under a 705N load at a 0.35 m/s wheel speed for all prepared specimens. When the number of passes reached 20,000 or the rut depth reached 20 mm, the wheel stopped automatically, and the test ended. Figures 2-13 and 2-14 show a sample cutting and the equipment with the mounted specimens ready for HWTD testing, respectively.

2.5.2 Data collection and analysis

The HWTD software collected all the measured rut depth data during testing. The rut depth and the wheel pass number were recorded for specimens prepared at each of the three predetermined testing temperatures (50, 64, and 70°C). While testing, rut depths were recorded at 11 spots on the surfaces of two specimens under one wheel. Since two wheels operated, rut depths on a total of 22 spots on four specimens were recorded as a function of the number of wheel passes. Among 22 rut depth curves, a single curve that has the maximum rut depth was chosen for further data analyses. The parameters of rut depth and SIP are found in a typical rutting curve. Figure 2-15 illustrates an example of the curve. It should be noted that the number of wheel pass is displayed up to 20,000.

(a) (b)

Figure 2-13 (a) Sample cutting, and (b) mounting specimens into the mold

Figure 2-14 Hamburg Wheel-Tracking Device

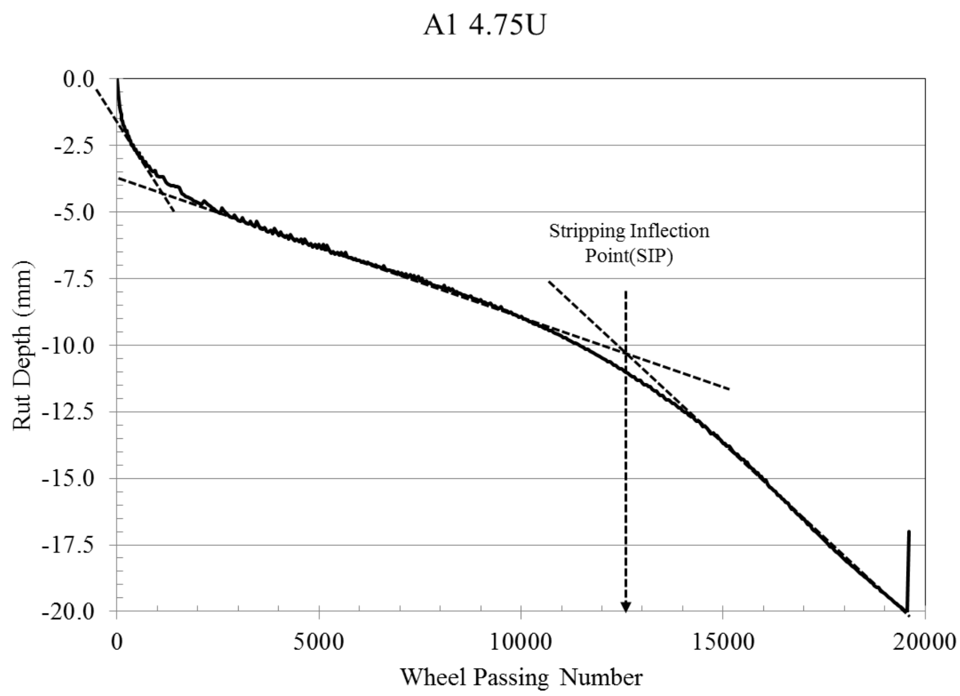


Figure 2-15 Typical HWTD test rutting curve for the number of wheel passes and rut depth at 64°C

Chapter 3 Test Results and Discussions

The Hamburg wheel-tracking device testing was conducted with 432 Hamburg test specimens of nine different mix types fabricated with aggregates from the four sources. As mentioned earlier, the different mix types included four Superpave mixtures with varying NMAS (25 mm to 9.5 mm), one dense-graded with NMAS of 4.75 mm, and one 12.5 mm SMA mixture. All the mix types were evaluated using PG 64-22, and several mixtures were also evaluated using PG 76-22. All mix types were tested at three testing temperatures of 50, 64, and 70°C. Rut depth results presented in this chapter is the deepest rut measurement achieved at 20,000 wheel passes. In case the rut depth reached 20.0 mm prior to a wheel pass of 20,000, the test ended. The profiles (i.e., rut depth versus wheel pass) were used to determine the maximum rut depth and SIP in relation to the number of wheel passes. Figure 3-1 outlines the process used to determine these parameters. Figure 3-2 shows an example of the 22 measuring points of rut depth on the left (L1 to L11) and right (R1 to R11) wheels, i.e., 11 points for each wheel.

The following subsections present the profiles obtained at the three test temperatures for the unmodified and modified asphalt binder mixtures separately.

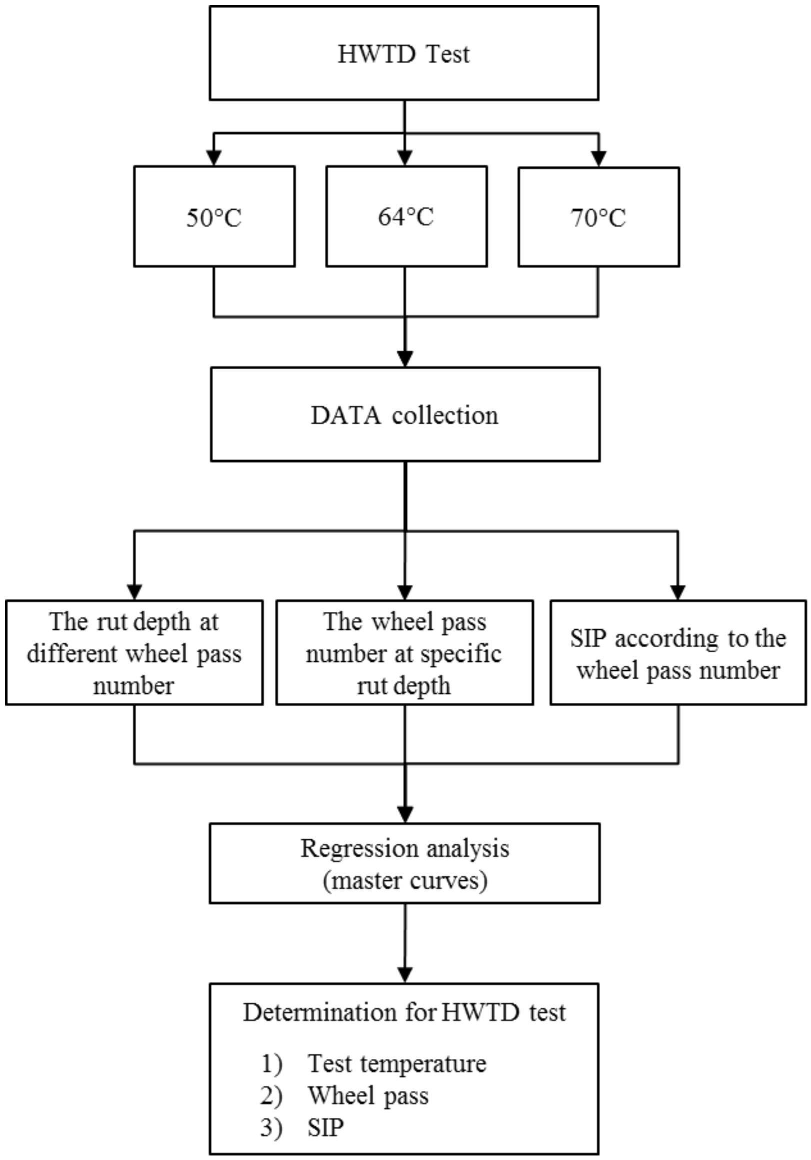
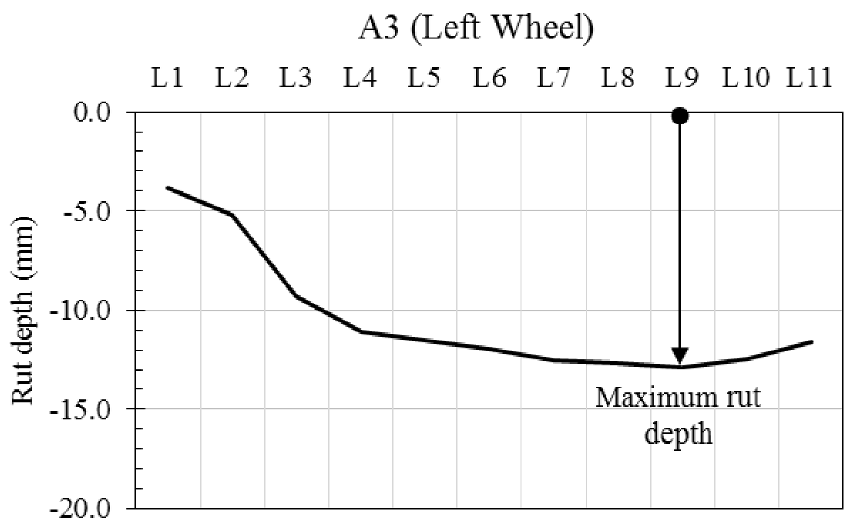


Figure 3-1 Process for determining HWTD test conditions



(a)

(b)

Figure 3-2 Example of measuring a maximum rut depth (a) Left Wheel and (b) Right Wheel

3.1 Unmodified Asphalt Mixtures

3.1.1 Test results at 50°C

3.1.1.1 Profiles of rut depth vs. wheel passes at 50°C

Figures 3-3 to 3-8 show the changes in rut depth with different NMAS (25, 19, 12.5, 9.5T1, 9.5T2, and 4.75 mm) in unmodified asphalt mixtures at 50°C. Overall, the rut depths of all the mixtures using unmodified binders were very low, less than 6.0 mm, even when wheel passes reached the loading limit of 20,000. It was found that the rut depths were affected by the sources; A2 and A4 had slightly higher rut depths than A1 and A3. All the curves showed initial rutting at the very beginning under loading, which is attributed to initial compaction/condensation. No SIP was observed for all mixtures tested at this temperature.

Figure 3-3 represents all the unmodified 25 mm Superpave mixtures, showing a very low rut depth of less than 4.5 mm at 20,000 wheel passes. The mixtures using aggregate from A1, A2, A3, and A4 had rut depths of 2.38, 3.47, 3.22, and 4.33 mm, respectively. As mentioned, the curves showed no SIP.

Figure 3-4 represents all the unmodified 19 mm Superpave mixtures, likewise showing a very low rut depth of less than 3.5 mm at 20,000 wheel passes. The A1, A2, A3, and A4 aggregates had rut depths of 2.98, 3.17, 1.58, and 2.29 mm, respectively and showed no SIP. It is noted that the rut depths of the 19 mm Superpave were slightly less than those of the 25 mm Superpave mixtures, except for A1.

Figure 3-5 represents all the unmodified 12.5 mm Superpave mixtures, showing a low rut depth of less than 5.0 mm at 20,000 wheel passes. Mixtures using aggregates from A1, A2, A3, and A4 had rut depths of 3.64, 4.60, 2.69, and 4.10 mm, respectively and showed no SIP. It is also noted that the rut depths for the 12.5 mm Superpave exceeded those of the 19 mm Superpave mixtures.

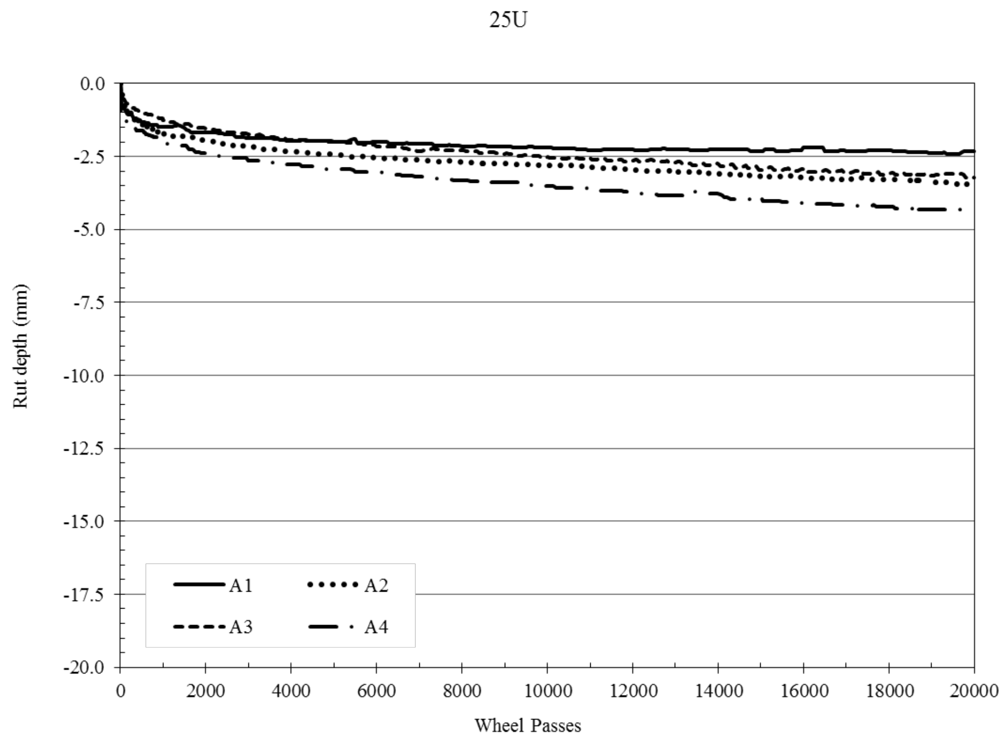


Figure 3-3 Rut depth vs. number of wheel passes for unmodified 25 mm mixtures at 50°C

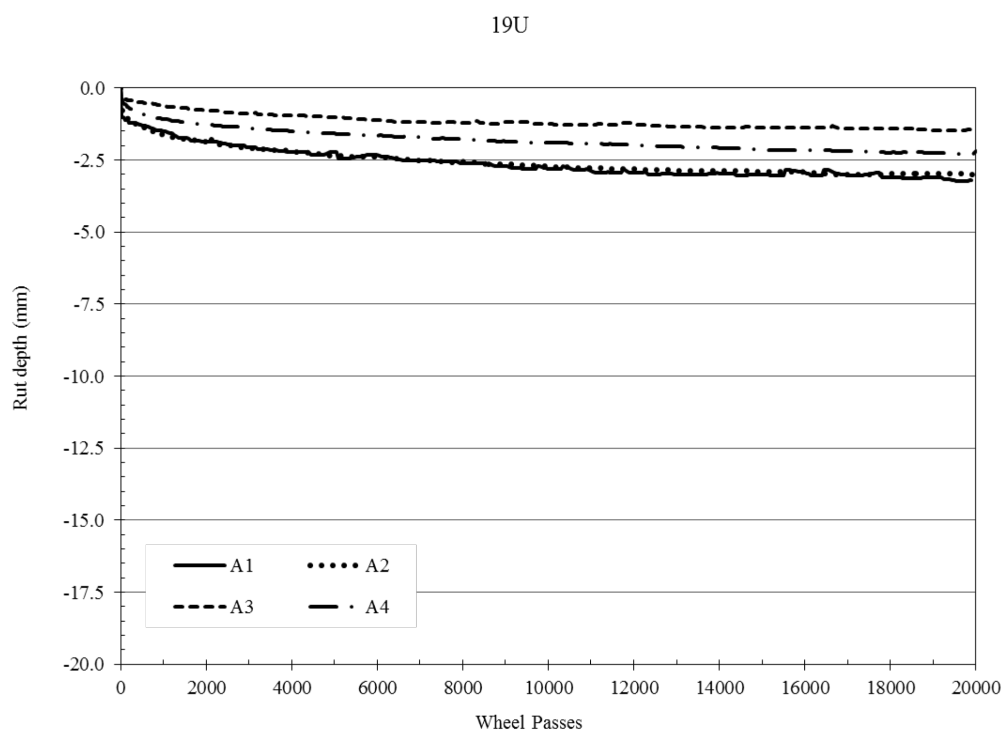


Figure 3-4 Rut depth vs. number of wheel passes for unmodified 19 mm mixtures at 50°C

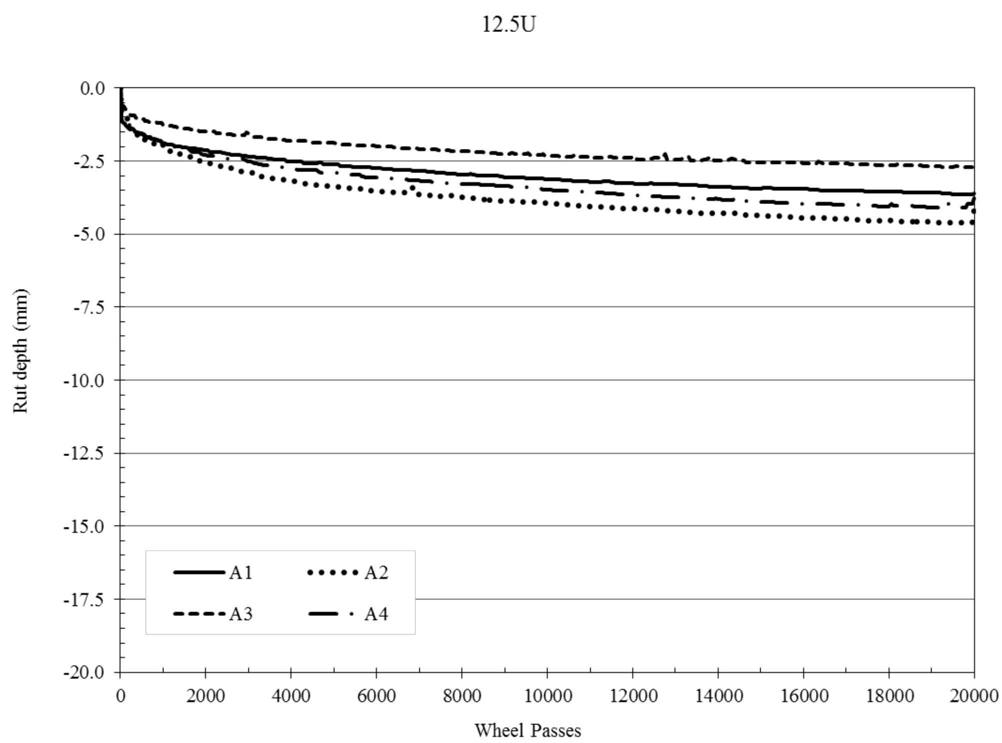


Figure 3-5 Rut depth vs. number of wheel passes for unmodified 12.5 mm mixtures at 50°C

Figure 3-6 represents all the unmodified 9.5 mm T1 Superpave mixtures, showing a rut depth of less than 5.0 mm at 20,000 wheel passes. Mixtures using aggregates from A1, A2, A3, and A4 had rut depths of 3.6, 3.92, 2.95, and 4.66, respectively and showed no SIP. It is noted that the rut depths for the 9.5 mm T1 Superpave were, on average, greater than those of the 12.5 mm Superpave mixtures.

Figure 3-7 represents all the unmodified 9.5 mm T2 Superpave mixtures, showing a rut depth slightly over 5.0 mm at 20,000 wheel passes. Mixtures using aggregates from A1, A2, A3, and A4 had rut depths of 3.21, 4.80, 2.85, and 5.15 mm, respectively and showed no SIP. It is noted that the average rut depths for the 9.5 mm T2 Superpave showed a similar pattern as those for the 9.5 mm T1 Superpave mixtures.

Figure 3-8 represents all the unmodified 4.75 mm dense-graded mixtures, showing a maximum rut depth of 5.0 mm at 20,000 wheel passes. Mixtures using aggregates from A1, A2, A3, and A4 had rut depths of 5.0, 3.33, 4.02, and 4.10 mm, respectively and showed no SIP. It is noted that the average rut depths for the 4.75 mm mixtures were similar as those for the 9.5 mm T2 Superpave mixtures.

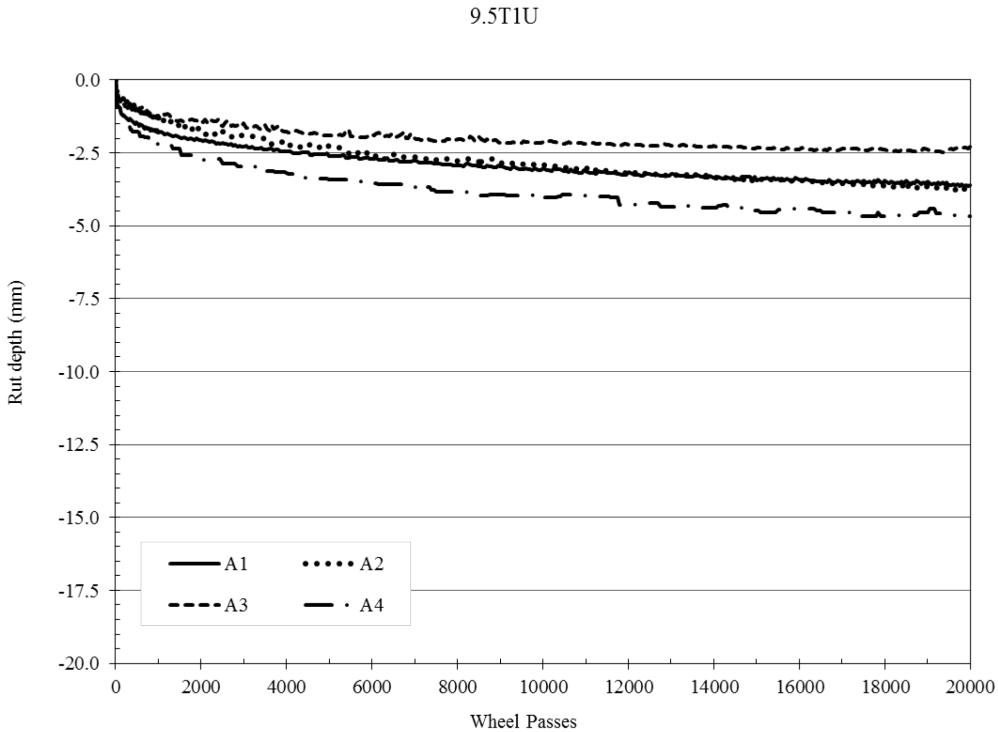


Figure 3-6 Rut depth vs. number of wheel passes for unmodified 9.5 mm T1 mixtures at 50°C

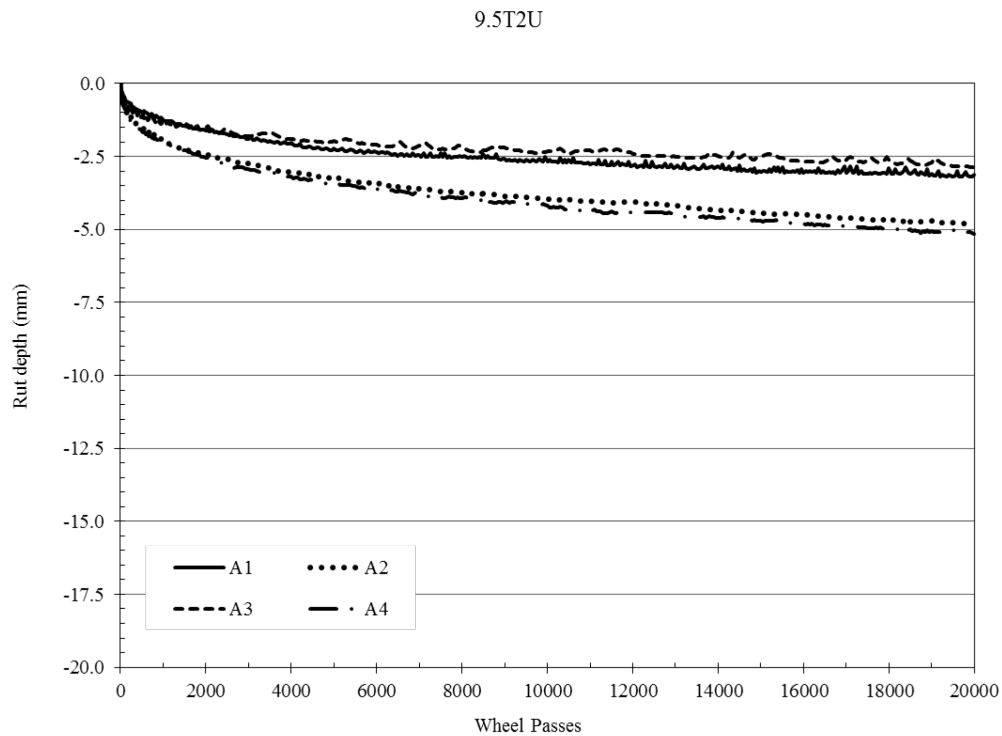


Figure 3-7 Rut depth vs. number of wheel passes for unmodified 9.5 mm T2 mixtures at 50°C

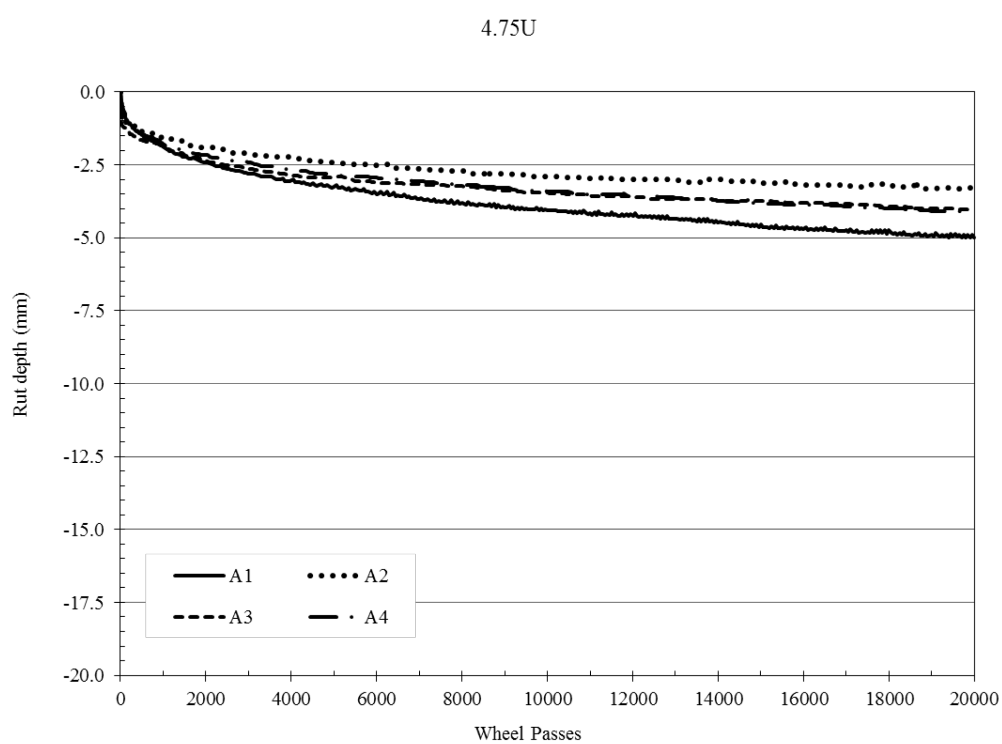


Figure 3-8 Rut depth vs. number of wheel passes for unmodified 4.75 mm mixtures at 50°C

3.1.1.2 Rut depth and SIP changes with wheel passes

To evaluate rutting performance, the mixtures were divided into two groups: NMAS 25 to 19 mm and NMAS 12.5 to 4.75 mm. Table 3-1 shows the parameters calculated.

Figures 3-9 to 3-12 are bar charts comparing the rut depths of the asphalt mixtures tested at 50°C. All mixtures, regardless of mix type, aggregate source and gradation, asphalt grade, or RAP content, had rut depths under 5.15 mm. Mixtures containing aggregates from A1 (Fig. 3-9), A2 (Fig. 3-10), A3 (Fig. 3-11), and A4 (Fig. 3-12) had rut depths ranging from 2.38-5.0, 3.17-4.8, 1.58-4.02, to 2.29-5.15 mm, respectively.

As indicated earlier, none of the profiles exhibited SIP. After an initial densification up to 1,000 wheel passes, the curves were found to be nearly straight lines at this temperature. This results were consistent for all mixtures.

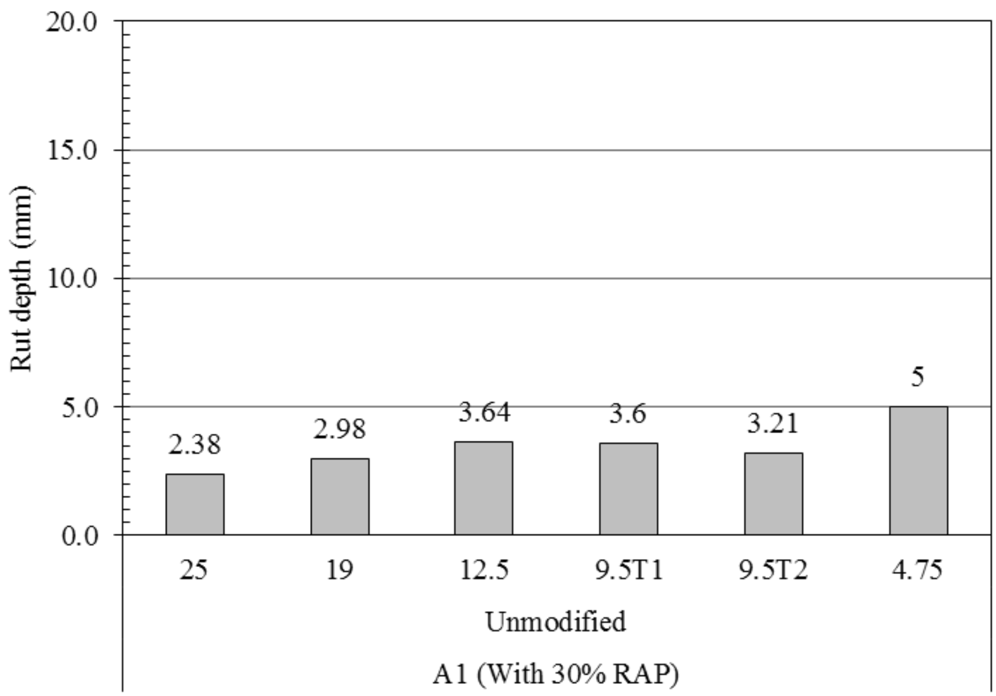


Figure 3-9 Rut depth of A1 mixtures at 50°C and 20,000 wheel passes

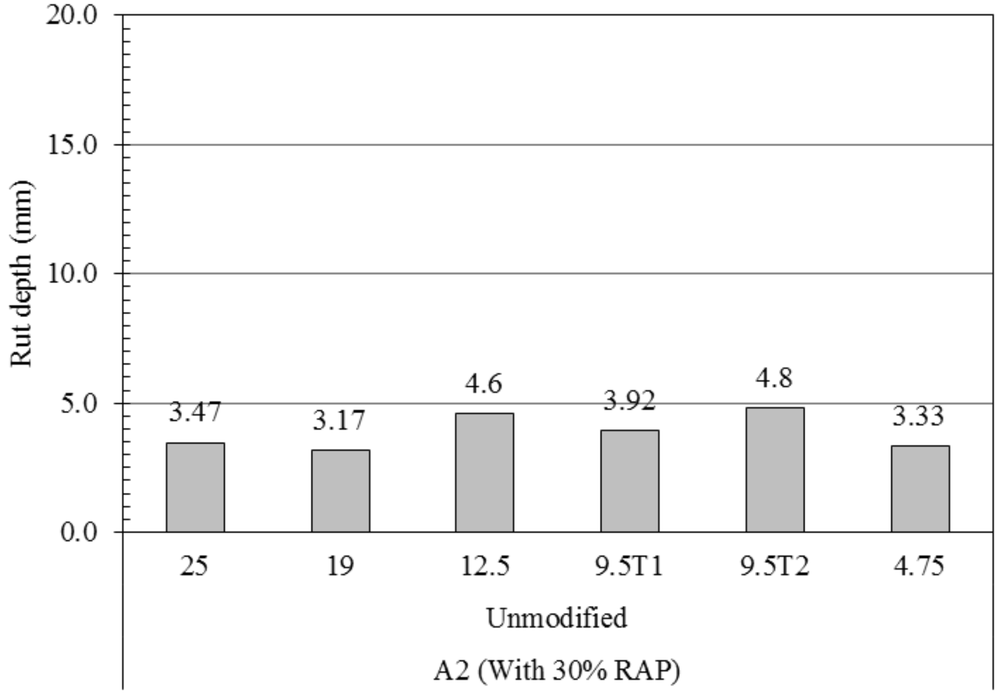


Figure 3-10 Rut depth of A2 mixtures at 50°C and 20,000 wheel passes

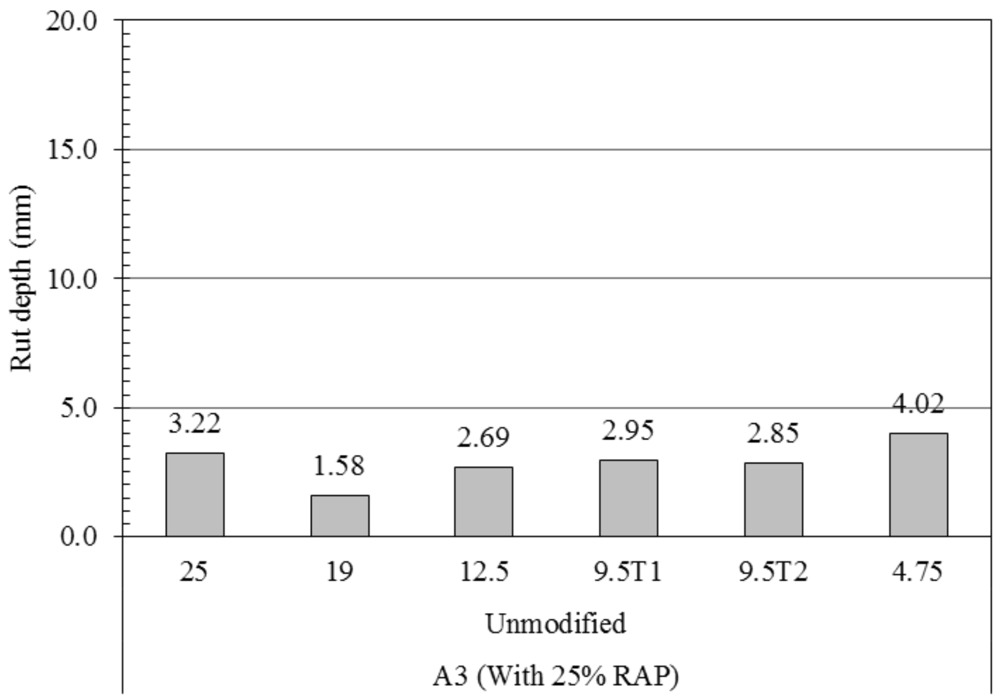


Figure 3-11 Rut depth of A3 mixtures at 50°C and 20,000 wheel passes

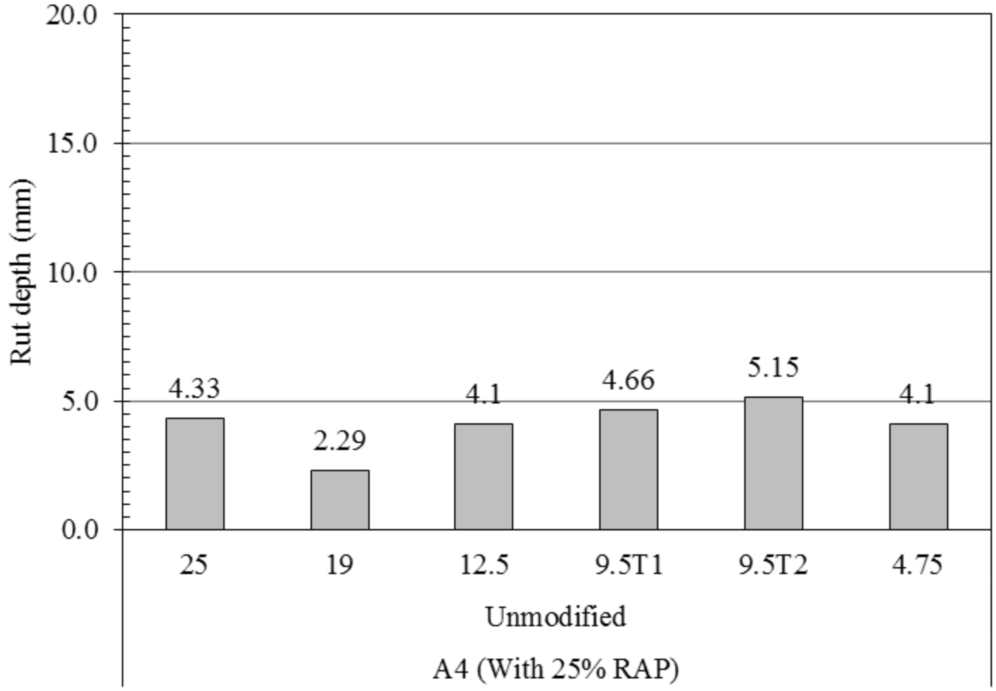


Figure 3-12 Rut depth of A4 mixtures at 50°C and 20,000 wheel passes

The rut depth and SIP were collected at five different wheel passes (20,000, 18,000, 15,000, 12,000, and 10,000) from the profiles presented in the previous section. Tables 3-1 to 3-5 contain the rut depths and SIP results at the five wheel passes. Since SIP did not appear, no SIP values are presented in the tables. The testing at this temperature did not show any tendency to rut or strip for the unmodified mixtures containing RAP with PG 64-22.

Table 3-1 Rut depth and SIP after 20,000 wheel passes at 50°C

Mixtures	Rut depth (mm)				SIP (passes)			
	A1(30R)	A2(30R)	A3(25R)	A4(25R)	A1(30R)	A2(30R)	A3(25R)	A4(25R)
25U	2.38	3.47	3.22	4.33	-	-	-	-
19U	2.98	3.17	1.58	2.29	-	-	-	-
12.5U	3.64	4.60	2.69	4.10	-	-	-	-
9.5T1U	3.60	3.92	2.95	4.66	-	-	-	-
9.5T2U	3.21	4.80	2.85	5.15	-	-	-	-
4.75U	5.00	3.33	4.02	4.10	-	-	-	-

Table 3-2 Rut depth and SIP after 18,000 wheel passes at 50°C

Mixtures	Rut depth (mm)				SIP (passes)			
	A1(30R)	A2(30R)	A3(25R)	A4(25R)	A1(30R)	A2(30R)	A3(25R)	A4(25R)
25U	1.90	3.28	3.09	4.78	-	-	-	-
19U	2.64	3.08	1.41	2.25	-	-	-	-
12.5U	3.48	4.40	2.36	5.32	-	-	-	-
9.5T1U	3.17	3.54	2.86	4.13	-	-	-	-
9.5T2U	3.21	4.65	260	4.96	-	-	-	-
4.75U	4.87	3.17	3.86	3.91	-	-	-	-

Table 3-3 Rut depth and SIP after 15,000 wheel passes at 50°C

Mixtures	Rut depth (mm)				SIP (passes)			
	A1(30R)	A2(30R)	A3(25R)	A4(25R)	A1(30R)	A2(30R)	A3(25R)	A4(25R)
25U	1.78	3.17	2.82	3.85	-	-	-	-
19U	2.52	3.02	1.25	2.07	-	-	-	-
12.5U	3.25	3.98	2.10	5.00	-	-	-	-
9.5T1U	3.12	3.66	2.75	3.77	-	-	-	-
9.5T2U	3.05	4.45	2.47	4.69	-	-	-	-
4.75U	4.63	2.72	3.72	3.66	-	-	-	-

Table 3-4 Rut depth and SIP after 12,000 wheel passes at 50°C

Mixtures	Rut depth (mm)				SIP (passes)			
	A1(30R)	A2(30R)	A3(25R)	A4(25R)	A1(30R)	A2(30R)	A3(25R)	A4(25R)
25U	1.71	2.96	2.64	3.21	-	-	-	-
19U	2.40	2.60	1.23	1.98	-	-	-	-
12.5U	3.02	3.45	2.00	4.80	-	-	-	-
9.5T1U	3.06	2.66	2.62	3.49	-	-	-	-
9.5T2U	2.81	3.97	2.40	4.41	-	-	-	-
4.75U	4.26	2.55	3.56	3.44	-	-	-	-

Table 3-5 Rut depth and SIP after 10,000 wheel passes at 50°C

Mixtures	Rut depth (mm)				SIP (passes)			
	A1(30R)	A2(30R)	A3(25R)	A4(25R)	A1(30R)	A2(30R)	A3(25R)	A4(25R)
25U	1.44	2.80	2.51	2.92	-	-	-	-
19U	1.57	2.60	0.97	1.96	-	-	-	-
12.5U	2.87	3.45	1.96	4.48	-	-	-	-
9.5T1U	2.92	2.66	2.55	3.24	-	-	-	-
9.5T2U	2.68	3.97	2.30	4.14	-	-	-	-
4.75U	4.06	2.55	3.38	3.32	-	-	-	-

3.1.2 Test results at 64°C

3.1.2.1 Profiles of rut depth vs. wheel pass number at 64°C

Figures 3-13 to 3-18 show the rut depths of unmodified asphalt mixtures at different wheel pass numbers and a test temperature of 64°C. It was found that overall, the rut depths were greater than those measured at 50°C. In some cases, the tests stopped automatically before 20,000 wheel passes because the rut depth reached the 20.0 mm limit. The rut depth ranged from 5.0 to 20.0 mm when wheel passes reached the loading limit of 20,000 and varied with the aggregate sources; A1 and A3 mixtures had lower values than A2 and A4 mixtures. In addition, the rut depth range was smaller in a group of NMAS 25 and 19 mm mixtures than a group of NMAS 12.5, 9.5, and 4.75 mm mixtures.

Figure 3-13 shows results for all the unmodified 25 mm Superpave mixtures. The mixtures using aggregates from A1, A2, A3, and A4 had rut depths of 5.87, 7.80, 4.97, and 10.7 mm, respectively. Rut depth was smallest in the A3 mixtures and highest in A4. The A3 mixtures had only half the rut depth of the A4 mixtures at 64°C.

Figure 3-14 presents results on all the unmodified 19 mm Superpave mixtures. The mixtures using aggregates from A1, A2, A3, and A4 had rut depths of 7.98, 7.57, 5.92, and 7.21 mm, respectively. The rut depths of all the 19 mm mixtures were less dependent on aggregate source, with an average rut depth of 7.17 mm and a standard deviation of 0.6 mm.

Figure 3-15 presents results on all the unmodified 12.5 mm Superpave mixtures. The mixtures using aggregate from A1, A2, A3, and A4 had rut depths of 11.0, 20.0, 8.13, and 20.0 mm, respectively. The results varied significantly by aggregate source, RAP, and mix design. Rut depths reached the 20.0 mm limit at 15,900 and 16,100 wheel passes for A2 and A4 mixtures, respectively; A1 and A3 were 11.0 and 8.13 mm, respectively, at 20,000 wheel passes. The effect of aggregate source on rutting resistance was similar for the 25 mm and 12.5 mm mixtures.

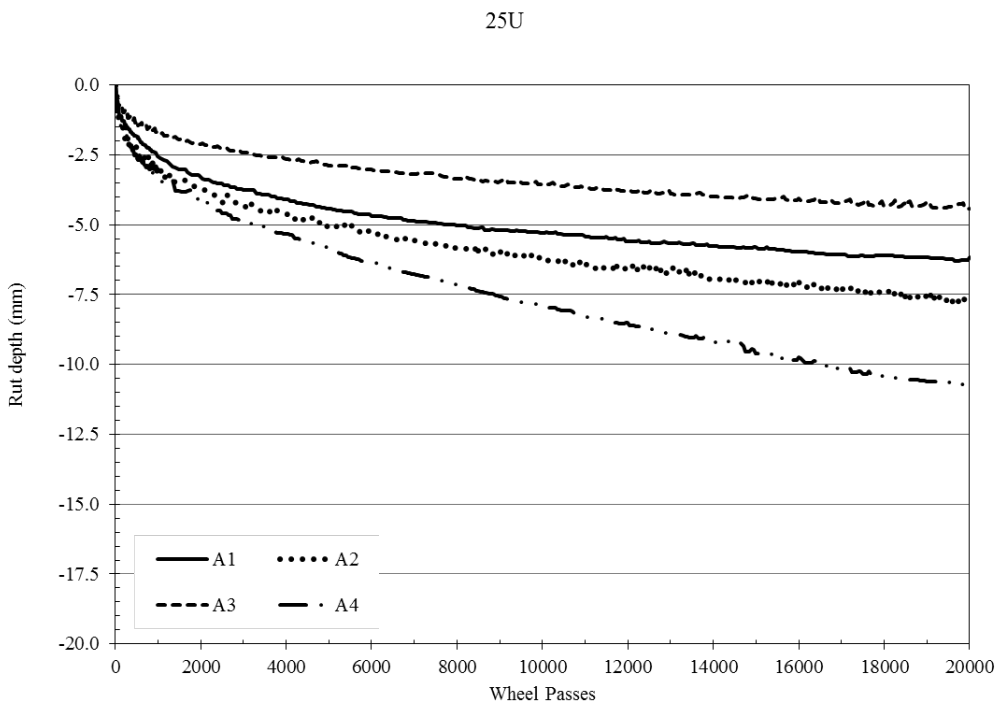


Figure 3-13 Rut depth vs. wheel passes for unmodified 25 mm mixtures at 64°C

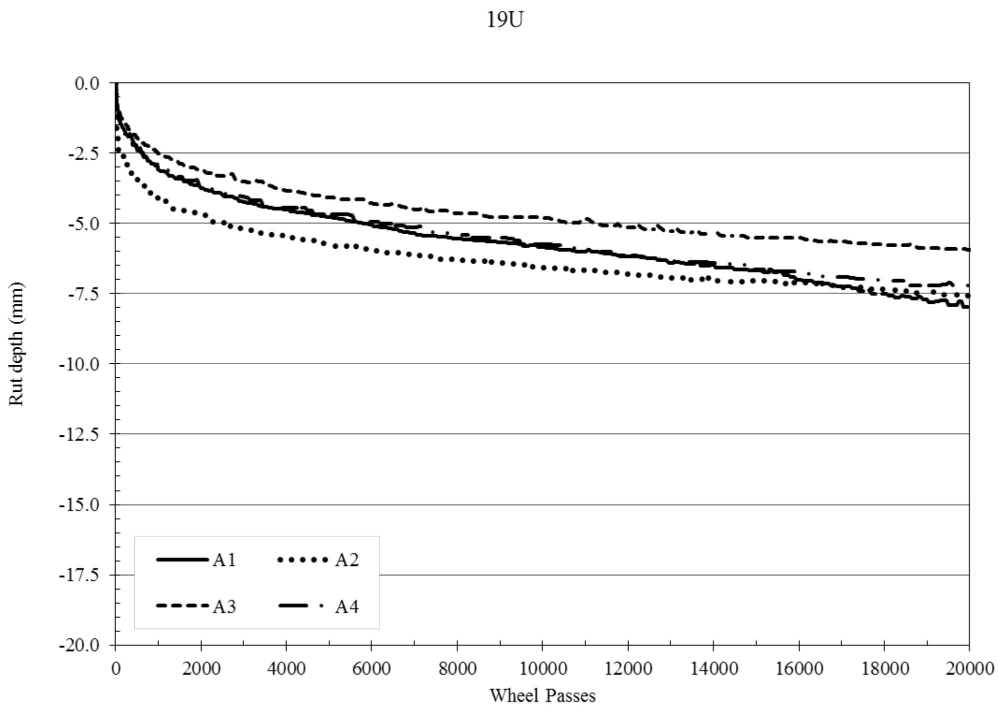


Figure 3-14 Rut depth vs. wheel passes for unmodified 19 mm mixtures at 64°C

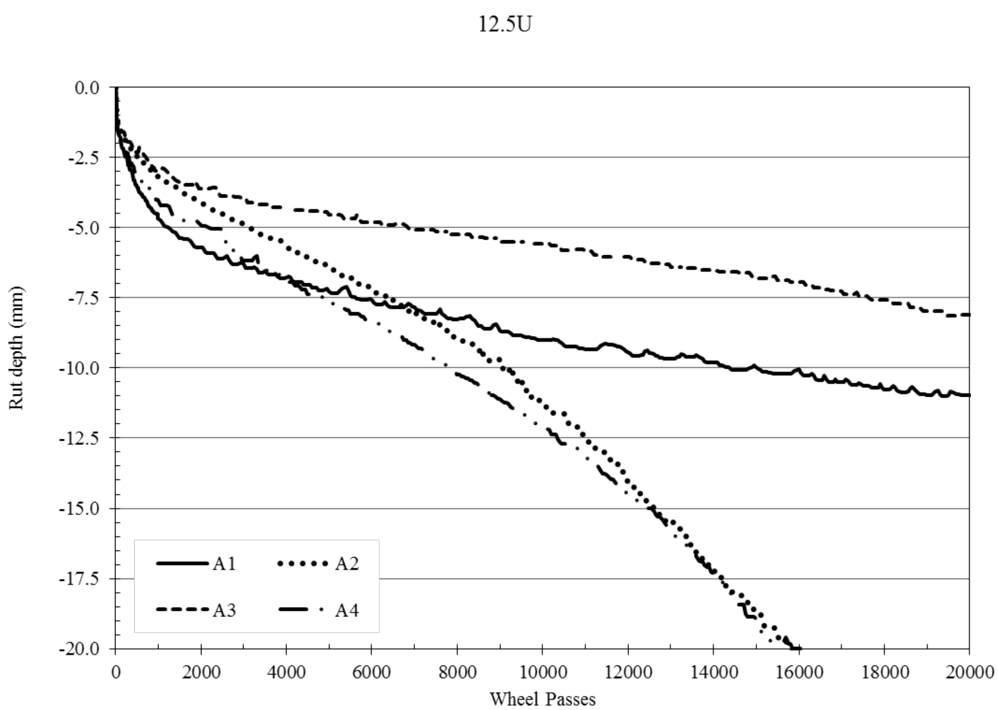


Figure 3-15 Rut depth vs. wheel passes for unmodified 12.5 mm mixtures at 64°C

Figure 3-16 presents results on all the unmodified 9.5 mm T1 Superpave mixtures. The A1, A2, A3, and A4 mixtures had rut depths of 8.33, 20.0, 10.5, and 20.0 mm, respectively. Rut resistance was highly dependent upon the source, mix type, AC, and RAP. Rut depths for mixtures using A2 and A4 aggregate reached the 20.0 mm limit at 12,650 and 10,050 wheel passes, respectively. Rut depths for A1 and A2 mixtures were 8.33 and 10.5 mm, respectively, at 20,000 wheel passes. The effect of aggregate source was similar to that of the 12.5 mm mixtures.

Figure 3-17 presents results on all the unmodified 9.5 mm T2 Superpave mixtures. The A1, A2, A3, and A4 mixtures had rut depths of 8.01, 20.0, 15.8, and 20.0 mm, respectively. Rut resistance was likewise highly dependent upon the source, mix type, asphalt content, and RAP. Rut depths reached the 20.0 mm limit at 13,850 and 11,700 wheel passes in the A2 and A4 mixtures, respectively; at 20,000 wheel passes, A1 and A3 mixtures had rut depths of 8.01 and 15.8 mm, respectively.

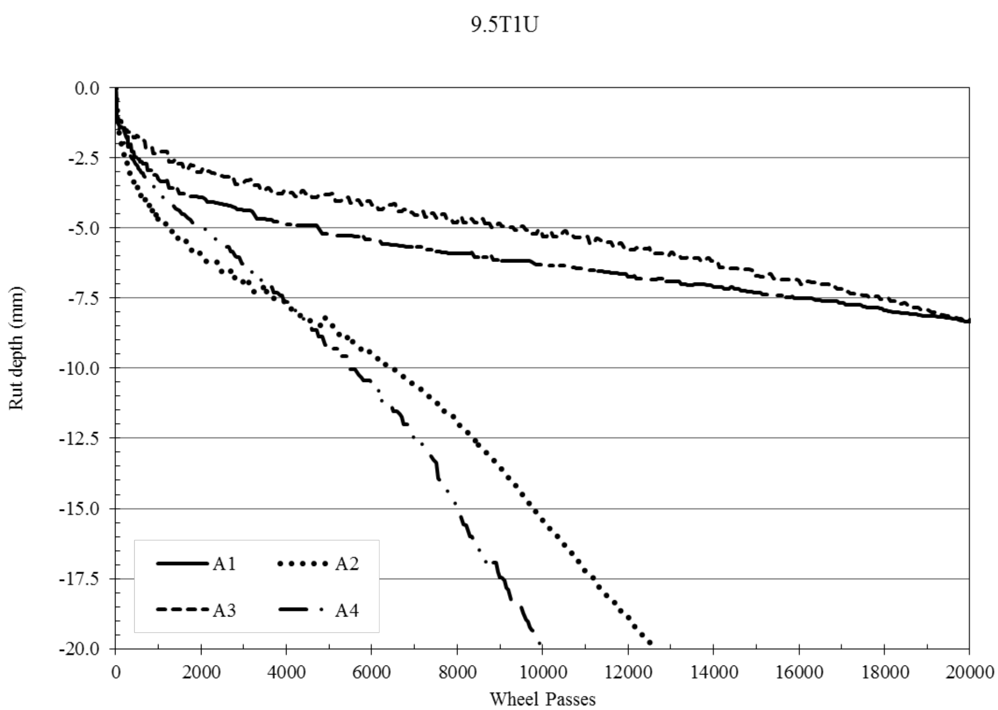


Figure 3-16 Rut depth vs. wheel passes for unmodified 9.5 mm T1 mixtures at 64°C

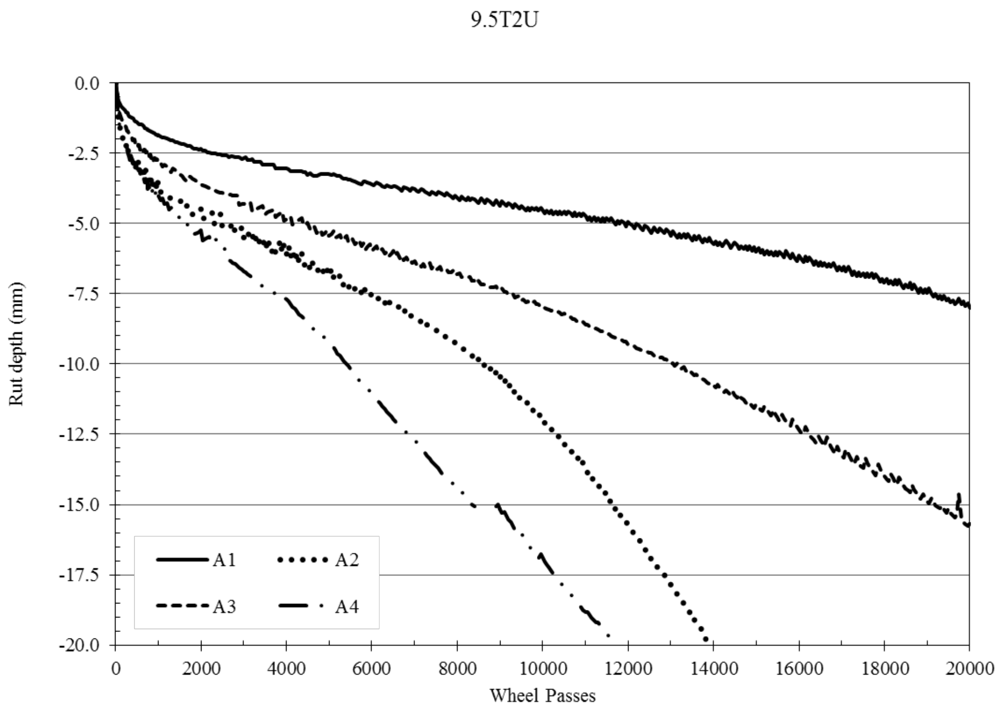


Figure 3-17 Rut depth vs. wheel passes for unmodified 9.5 mm T2 mixtures at 64°C

Figure 3-18 presents results on all the unmodified 4.75 mm dense-graded mixtures, showing a rut depth of 20.0 mm at 20,000 wheel passes. Aggregate source played an important role in the final rut depth and corresponding wheel passes. The number of wheel passes reaching the 20.0 mm limit for A1, A2, A3, and A4 was 19,950, 15,000, 14,850, and 6,740, respectively. The effects of aggregate source varied with fine and coarse graded mixtures. A1 was the most rut-resistible while A4 the least with fine gradations. For coarse aggregates, A3 was the most rut-resistible, while A4 the least.

4.75U

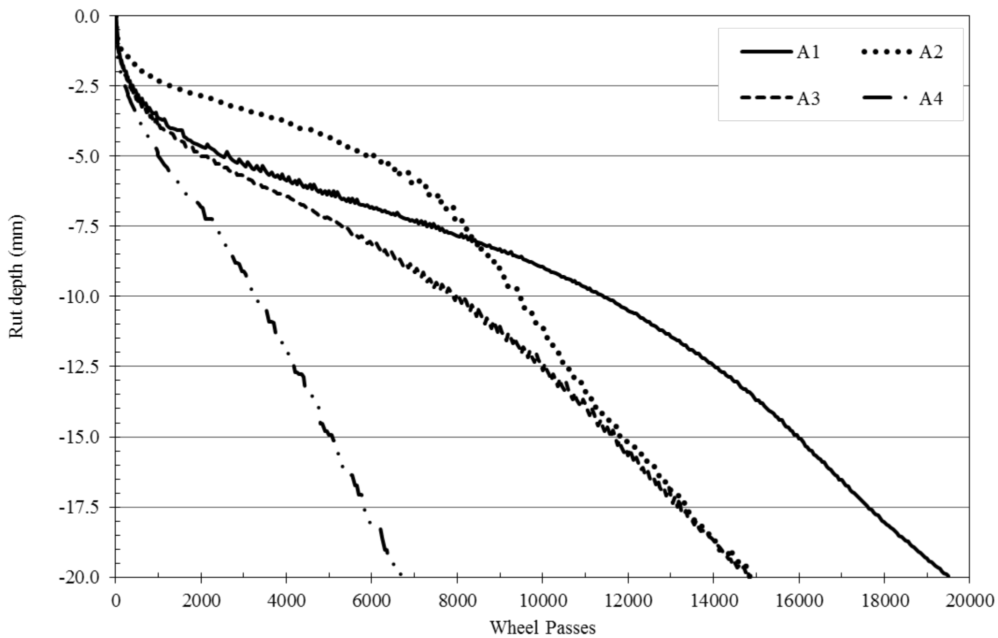


Figure 3-18 Rut depth vs. wheel passes for unmodified 4.75 mm mixtures at 64°C

3.1.2.2 Rut depth and SIP changes with wheel pass at 64°C

As the SIP analysis at 50°C, the mixtures were divided into two groups: NMAS 25 and 19 mm and NMAS 4.75, 9.5, and 12.5 mm for this temperature. Figures 3-19 to 3-22 show that rut depth varied by aggregate source, asphalt content, RAP, and mix type, and the differences were noticeable.

Figure 3-19 shows the rut depths of mixtures using A1 aggregate. The rut depth range for various gradations was 5 to 20 mm within 20,000 wheel passes. Overall it was observed that NMAS played an important role in rutting performance; the smaller the NMAS, the greater the rut depth. The 4.75 mm dense-graded mixture reached a test limit of 20.0 mm rut depth before 20,000 wheel passes for this source.

Figure 3-20 shows the rut depths of mixtures using A2 aggregate. The impact of NMAS is significant. The smaller NMAS group (12.5, 9.5 and 4.75 mm) reached the 20.0 mm limit before

20,000 wheel passes, while the larger NMAS group (25 and 19 mm) has a rut depth of 7.8 and 7.57 mm for 25 and 19 mm NMAS, respectively.

Figure 3-21 shows the rut depths of mixtures using A3 aggregate. Rut depths ranged from 4.97 to 20 mm for the various gradations, showing their clear influence. The 4.75 mm dense-graded mixture reached a test limit of 20.0 mm rut depth before 20,000 wheel passes. This pattern is similar to the A1 results.

Figure 3-22 shows the rut depths of the A4aggregate. The rut depth of 25 and 19 mm NMAS was 10.73 and 7.21 mm, respectively. For the smaller NMAS group, the rut depths reached the maximum limit (20 mm) before 20,000 wheel passes. This pattern is similar to that of the A2 results.

Overall, the rut depths of the 25 and 19 mm mixtures were much less than those of the other NMAS mixtures. It was observed that the NMAS 25 and 19 mm mixtures from all four sources did not reach the 20.0 mm rut depth with 20,000 wheel passes.

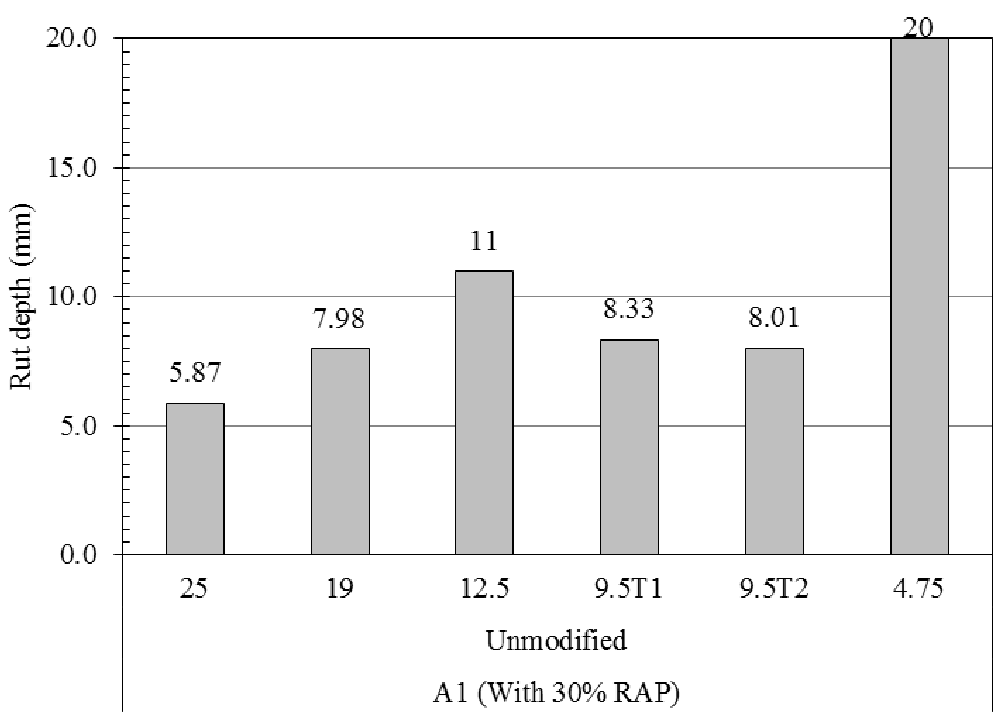


Figure 3-19 Rut depth of the A1 mixtures at 64°C and 20,000 wheel passes

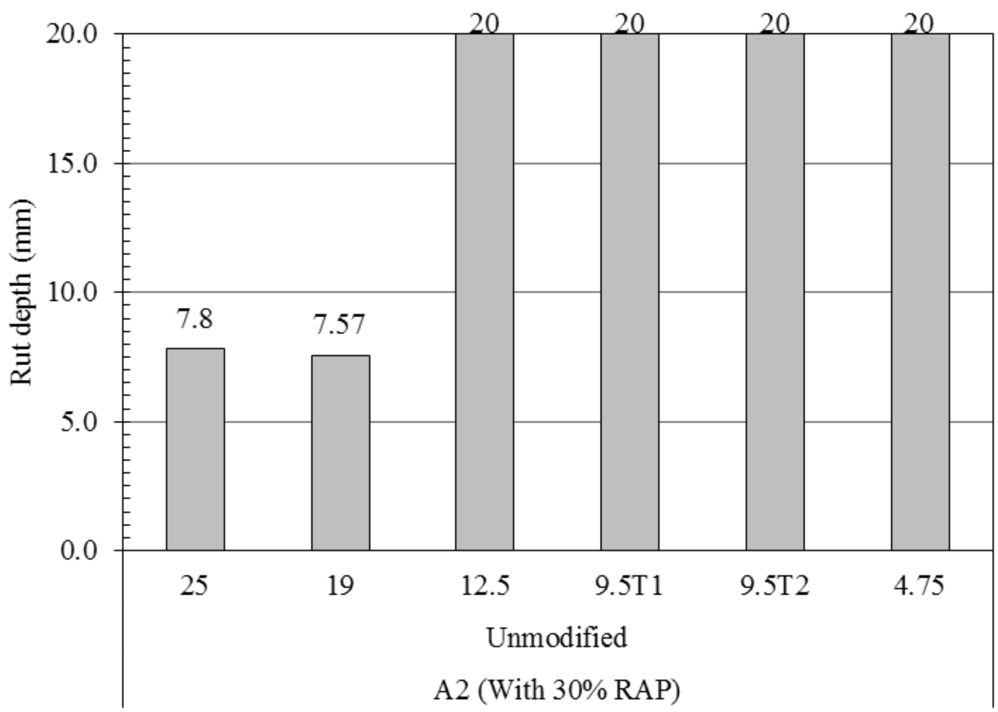


Figure 3-20 Rut depth of the A2 mixtures at 64°C and 20,000 wheel passes

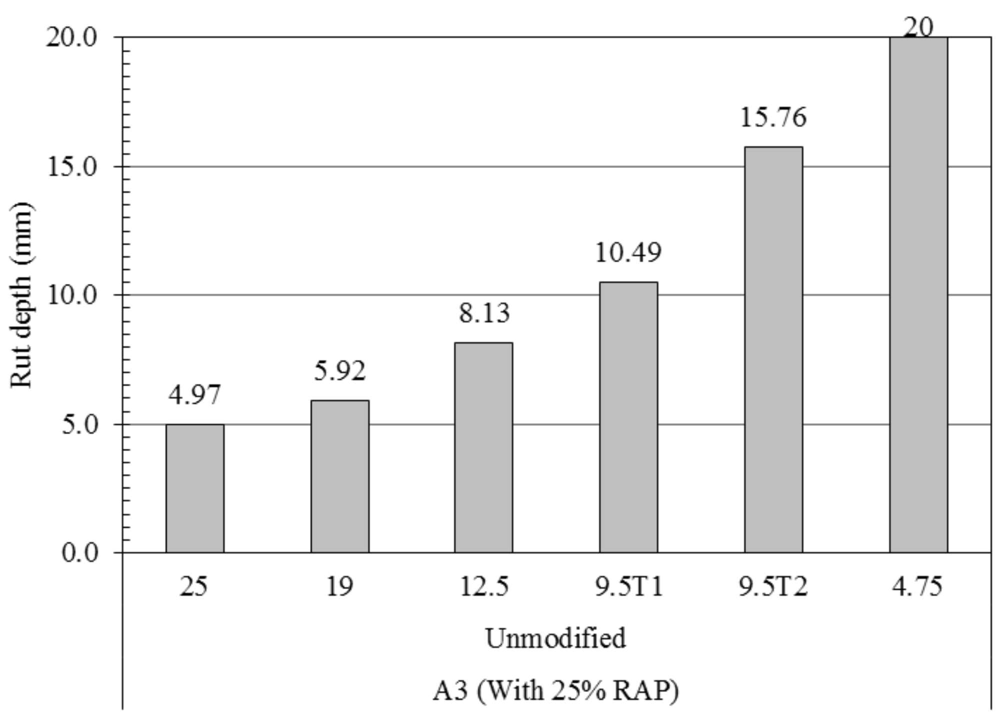


Figure 3-21 Rut depth of the A3 mixtures at 64°C and 20,000 wheel passes

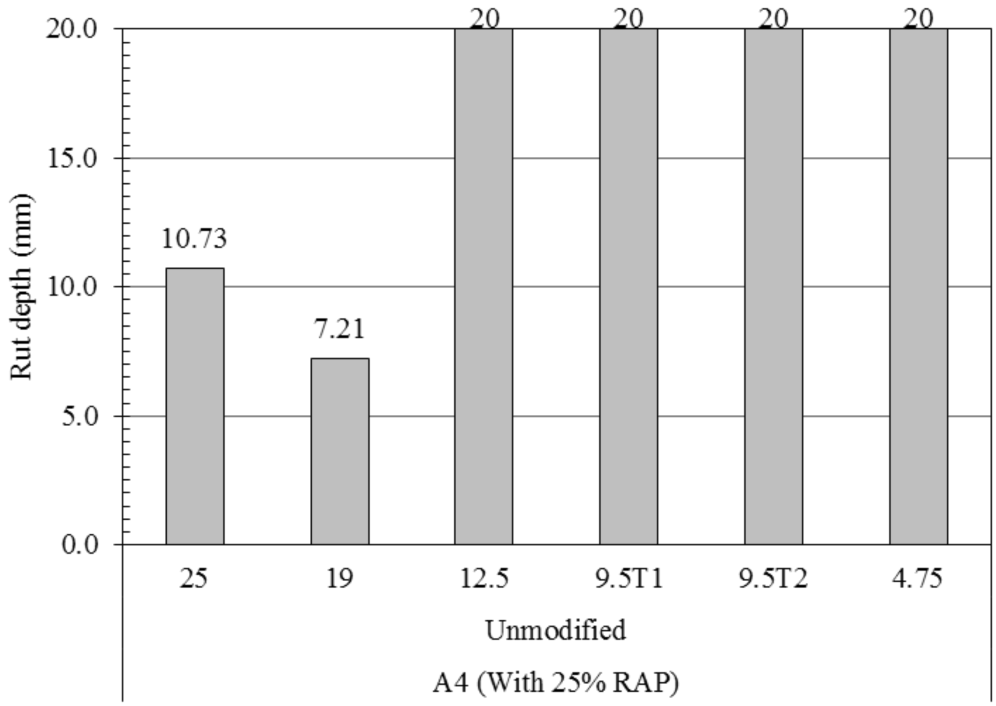


Figure 3-22 Rut depth of the A4 mixtures at 64°C and 20,000 wheel passes

Figure 3-23 shows SIP for A1 at 64°C. The SIP of the 25 mm mixture seemed to be higher than 20,000 passes. No SIP appeared for the 25 mm mixtures within 20000 wheel passes. For the 19, 12.5, T1, T2 and 4.75 mm mixtures, the SIP ranged from 10,800 to 15,650 passes. Obviously, SIP decreased with smaller NMAS.

Figure 3-24 shows SIP for A2 at 64°C. The SIP of the 25 and 19 mm mixtures was higher than 20,000 passes, No SIP appeared for 25 and 19 mm mixtures within 20,000 wheel passes. For the 12.5, 9.5T1, T2 and 4.75 mixtures, the SIP appeared 10,057, 7,752, 9,468, and 7,308 passes, respectively. Obviously, a smaller aggregate size has negative effects on the SIP.

Figures 3-25 and 3-26 show SIP for A3 and A4 mixtures, respectively, at 64°C. No SIP appeared for the 25 and 19 mm mixtures within 20,000 wheel passes. The SIP showed a similar trend as A1 and A2 mixtures.

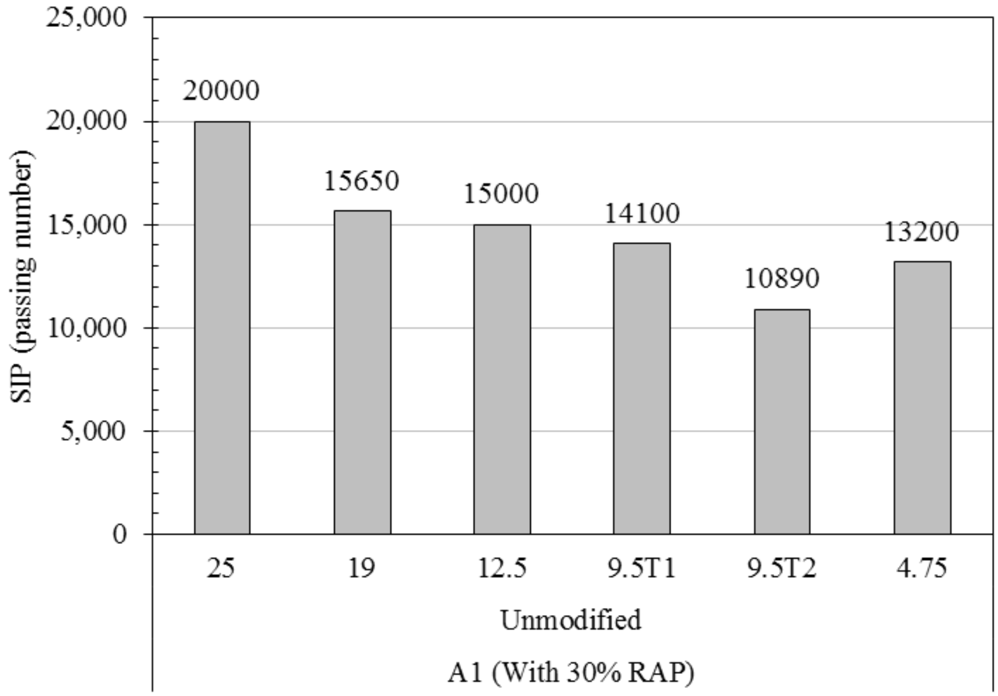


Figure 3-23 SIP of A1 mixtures at 64°C and 20,000 wheel passes

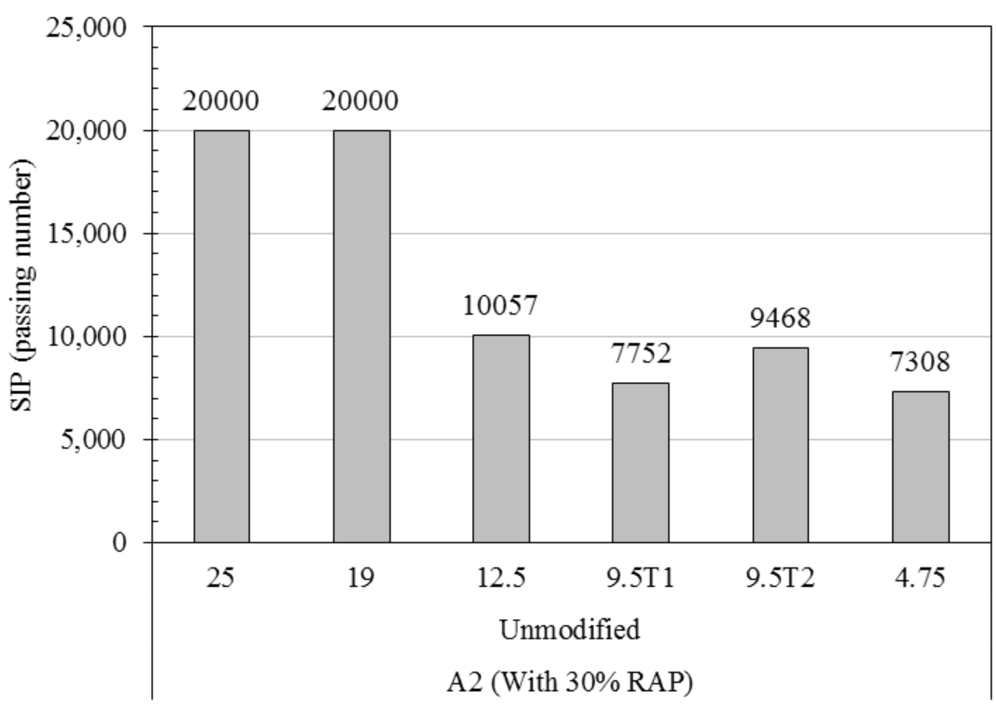


Figure 3-24 SIP of A2 mixtures at 64°C and 20,000 wheel passes

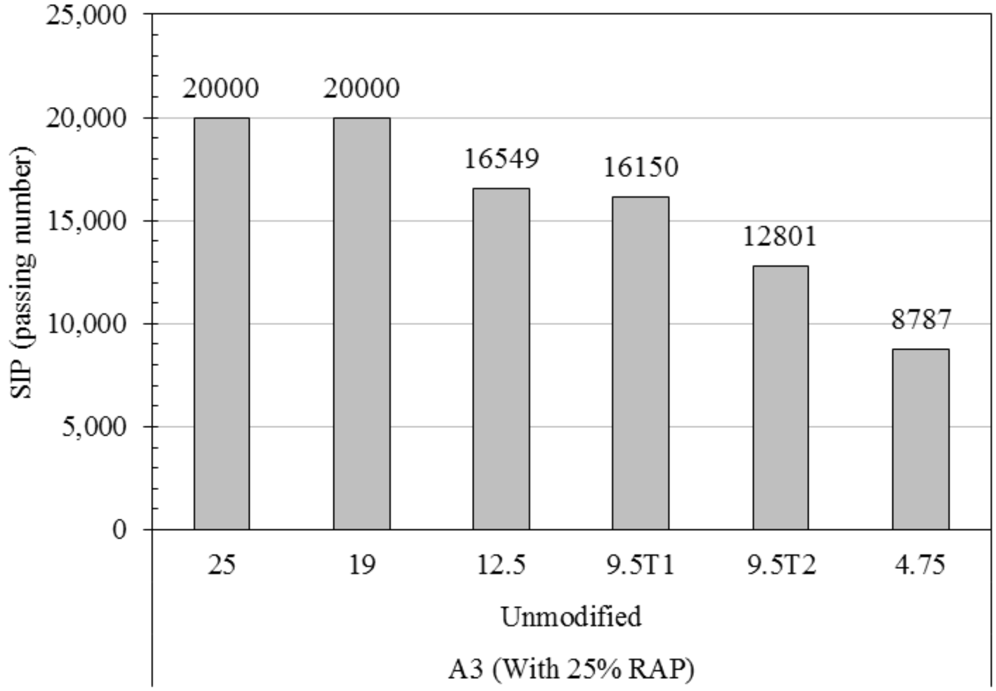


Figure 3-25 SIP of A3 mixtures at 64°C and 20,000 wheel passes

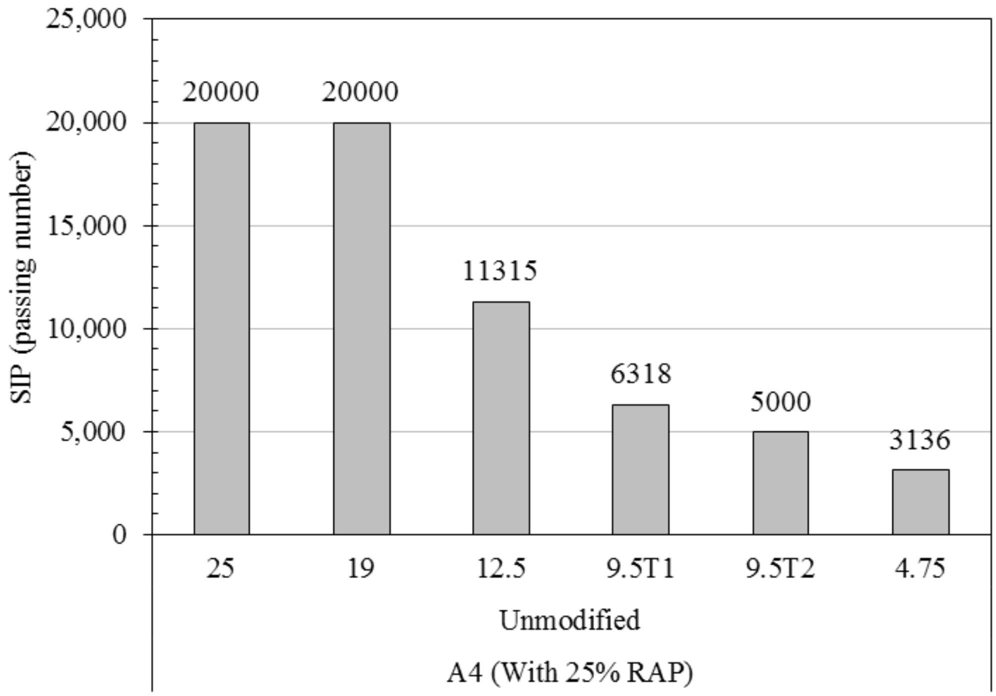


Figure 3-26 SIP of A4 mixtures at 64°C and 20,000 wheel passes

To take a more detailed look at the effect of wheel pass number on rut depth and SIP, these two parameters at 20,000, 18,000, 15,000, 12,000, and 10,000 wheel passes were collected using the profiles shown in the previous section. Tables 3-6 to 3-10 show the results.

As Table 3-6 shows, the NMAS 25 and 19 mm mixtures had rut values less than 10.7 mm, while most of the NMAS 12.5, 9.5 and 4.75 mm mixtures reached at the 20.0 mm limit. The 25 and 19 mm mixtures of all four sources showed there were no SIP values even after passing 20,000 wheel passes except 19 mm mixtures of A1.

Table 3-6 Rut depth and SIP after 20,000 wheel passes at 64°C

Mixtures	Rut depth (mm)				SIP (passes)			
	A1(30R)	A2(30R)	A3(25R)	A4(25R)	A1(30R)	A2(30R)	A3(25R)	A4(25R)
25U	5.87	7.80	4.97	10.7	-	-	-	-
19U	7.98	7.57	5.92	7.21	14,652	-	-	-
12.5U	11.0	>20.0	8.13	>20.0	15,000	10,057	15,500	11,315
9.5T1U	8.33	>20.0	10.5	>20.0	14,100	7,752	16,556	6,314
9.5T2U	8.01	>20.0	15.8	>20.0	15,600	9,468	12,801	5,000
4.75U	20.0	>20.0	>20.0	20.0	13,200	7,308	8,787	3,136

Table 3-7 shows the results at 18,000 wheel passes. The NMAS 25 and 19 mm mixtures had rut values less than 9.69 mm, while over 50% of the NMAS 12.5, 9.5, and 4.75 mm mixtures reached 20.0 mm. Besides, the 25 and 19 mm mixtures of all for sources showed that there was no SIP after passing 18,000 wheel pass except 19 mm mixtures of A1.

Table 3-7 Rut depth and SIP after 18,000 wheel passes at 64°C

Mixtures	Rut depth (mm)				SIP (passes)			
	A1(30R)	A2(30R)	A3(25R)	A4(25R)	A1(30R)	A2(30R)	A3(25R)	A4(25R)
25U	5.65	7.43	4.31	9.69	-	-	-	-
19U	7.49	7.35	5.72	6.56	14,652	-	-	-
12.5U	10.7	>20	7.09	>20	15,000	10,057	15,500	11,315
9.5T1U	7.88	>20	9.27	>20	14,100	7,752	16,556	6,314
9.5T2U	7.10	>20	14.0	>20	15,650	9,468	12,801	5,000
4.75U	18.02	>20	>20	>20	13,200	7,308	8,787	3,136

Table 3-8 shows the results at 15,000 wheel passes. The NMAS 25 and 19 mm mixtures had rut values less than 9.5 mm, while over 50% of the NMAS 12.5, 9.5, and 4.75 mm mixtures reached 20.0 mm. The 25 and 19 mm mixtures of all for sources showed that there was no SIP after 15,000 wheel passes except 19 mm mixtures of A1. The 12.5 mm mixtures of A1 and A3, 9.5T1 mixture of A3, and 9.5T2 mixture of A1 showed that there were no SIPs after 15,000 wheel passes.

Table 3-8 Rut depth and SIP after 15,000 wheel passes at 64°C

Mixtures	Rut depth (mm)				SIP (passes)			
	A1(30R)	A2(30R)	A3(25R)	A4(25R)	A1(30R)	A2(30R)	A3(25R)	A4(25R)
25U	5.39	7.09	4.07	9.5	-	-	-	-
19U	6.66	6.64	5.51	6.24	14,652	-	-	-
12.5U	9.91	18.0	6.48	19.8	-	10,057	-	11,315
9.5T1U	7.30	>20	8.43	>20	14,100	7,752	-	6,314
9.5T2U	5.99	>20	11.4	>20	-	9,468	12,801	5,000
4.75U	13.7	>20	>20	>20	13,200	7,308	8,787	3,136

Table 3-9 shows the results at 12,000 wheel passes. The NMAS 25 and 19 mm mixtures had values less than 8.51 mm, while the NMAS 12.5, 9.5, and 4.75 mm mixtures from A4 reached 20.0 mm. The 50% of the mixtures tested did not show an SIP within 12,000 wheel passes.

Table 3-9 Rut depth and SIP after 12,000 wheel passes at 64°C

Mixtures	Rut depth (mm)				SIP (passes)			
	A1(30R)	A2(30R)	A3(25R)	A4(25R)	A1(30R)	A2(30R)	A3(25R)	A4(25R)
25U	5.02	6.65	3.75	8.51	-	-	-	-
19U	6.15	6.45	5.13	5.67	-	-	-	-
12.5U	9.32	13.3	5.43	14.2	-	10,057	-	11,315
9.5T1U	6.63	18.8	7.41	>20	-	7,752	-	6,314
9.5T2U	5.09	15.7	9.29	>20	-	9,468	-	5,000
4.75U	10.5	14.7	15.7	>20	-	7,308	8,787	3,136

Table 3-10 shows the results at 10,000 wheel passes. The NMAS 25 and 19 mm mixtures had rut depth values less than 7.86 mm, while the NMAS 12.5, 9.5, and 4.75 mm mixtures of 4.75 from A4 reached 20.0 mm. A 62.5 percent of the mixtures tested did not show an SIP within 10,000 wheel passes, while some of A2 and A4 did.

Table 3-10 Rut depth and SIP after 10,000 wheel passes at 64°C

Mixtures	Rut depth (mm)				SIP (passes)			
	A1(30R)	A2(30R)	A3(25R)	A4(25R)	A1(30R)	A2(30R)	A3(25R)	A4(25R)
25U	4.81	6.23	3.55	7.86	-	-	-	-
19U	5.83	5.81	4.78	8.30	-	-	-	-
12.5U	8.99	11.0	5.20	11.8	-	-	-	-
9.5T1U	6.31	15.4	6.98	19.6	-	7,752	-	6,314
9.5T2U	4.64	11.9	7.94	16.9	-	9,468	-	5,000
4.75U	8.93	10.3	12.6	>20	-	7,608	8,787	3,136

The rutting resistances for the two gradation groups were distinct. Overall, the NMAS 25 and 19 mm mixtures had lower rut depths than the NMAS 12.5, 9.5, and 4.75 mm mixtures. Also, the SIP of the NMAS 25 and 19 mm mixtures was higher than that of the NMAS 12.5, 9.5, and 4.75 mm mixtures.

3.1.3 Test results at 70°C

3.1.3.1 Profiles of rut depth vs. wheel pass number at 70°C

Figures 3-27 to 3-32 present the rut depth of unmodified asphalt mixtures as a function of wheel passes at a test temperature of 70°C. Overall, the rut depths of all the mixtures using unmodified binders were greater than those tested at 64°C. For all the mixtures except for 25 mm mixtures of A1, 25 mm mixtures of A2, and 19 mm mixtures of A2, the rut depth reached 20.0 mm. The A1 and A3 mixtures had relatively lower rut depths and higher SIP than the A2 and A4 mixtures. Results also indicate there is an effect of aggregate size on rut depth. The NMAS 25 and 19 mm mixtures had considerably lower rut depths and higher SIP than the NMAS 12.5, 9.5, and 4.75 mm mixtures.

Figure 3-27 shows the test results for the unmodified 25 mm mixtures from all four sources. The A1, A2, A3, and A4 mixtures had final rut depths of 6.3, 20.0, 11.5, and 20.0 mm, respectively, indicating that the difference in rut depths is a function of the mix type, and RAP source. The A1 mixtures showed the lowest rut depth (6.3 mm) among others, while the A4 mixtures showed the highest (over 20.0 mm). For the A2 and A4 mixtures, rut depths reached the 20.0 mm limit at 18,850 and 14,550 wheel passes, respectively.

Figure 3-28 shows the test results for the unmodified 19 mm mixtures. Rut depth was approximately 20.0, 20.0, 16.3, and 20.0 mm for A1, A2, A3, and A4, respectively, showing the type and source-dependency on the rut depth. Rut depth reached 20.0 mm at 19,050, 18,950, and 17,650 passes for A1, A2, and A4, respectively, while for A3, it was 16.3 mm even at 20,000 passes.

Figure 3-29 presents the results for the unmodified 12.5 mm mixtures. Rut depth reached 20.0 mm at 9,200, 5,750, 14,550, and 6,100 wheel passes for A1, A2, A3, and A4, respectively. A2 and A4 showed a similar trend, while A3 reached 20.0 mm at the highest number of wheel passes.

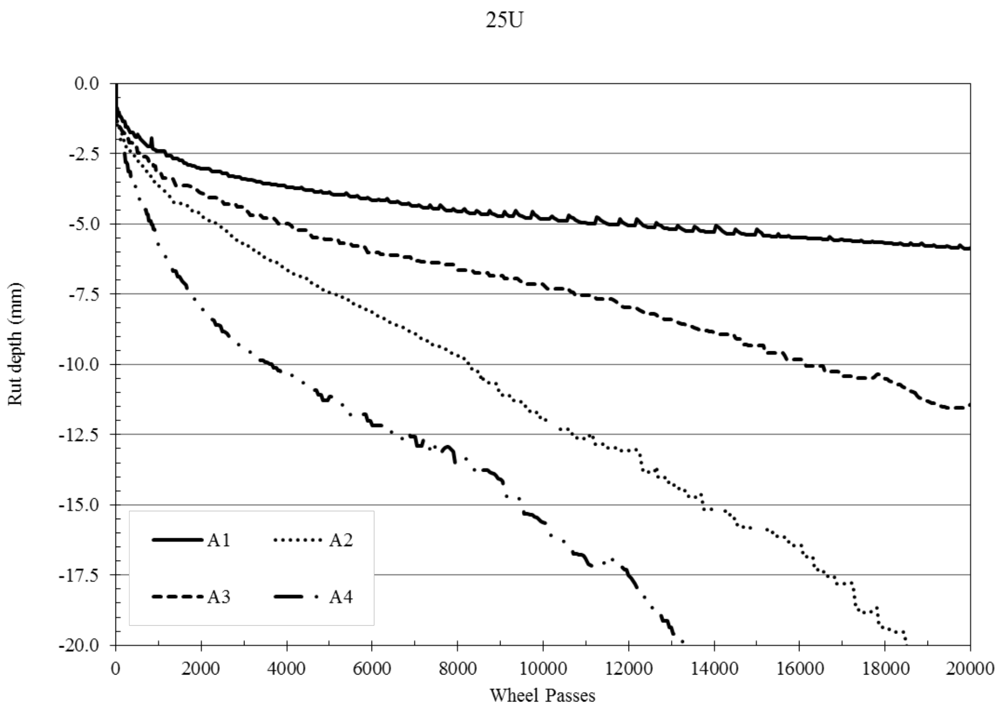


Figure 3-27 Rut depth vs. wheel passes for unmodified 25 mm mixtures at 70°C

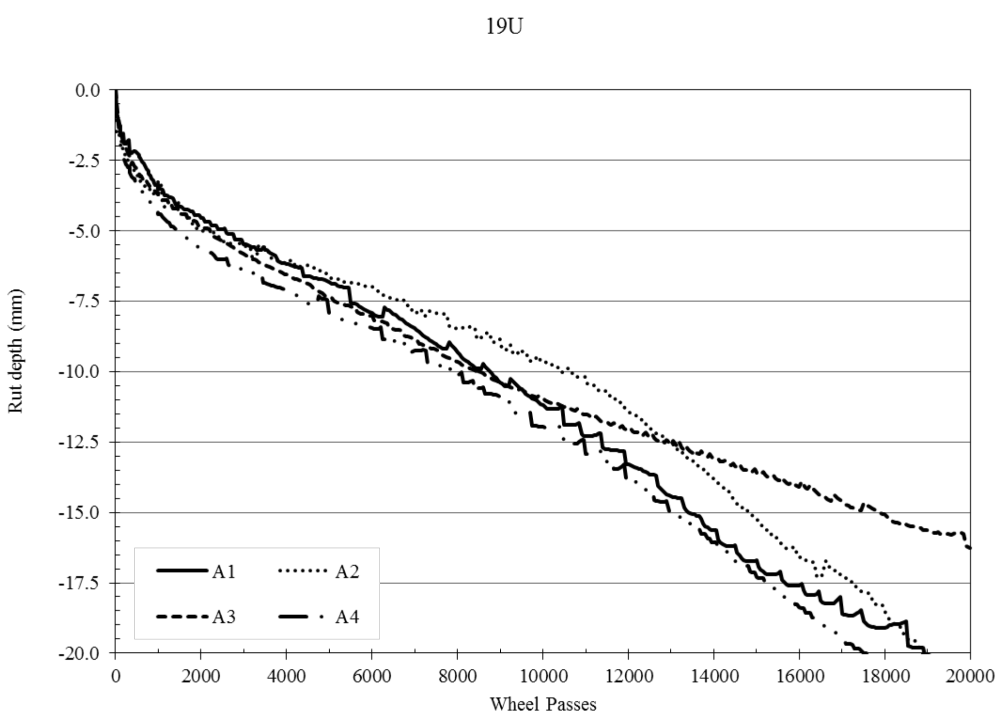


Figure 3-28 Rut depth vs. wheel passes for unmodified 19 mm mixtures at 70°C

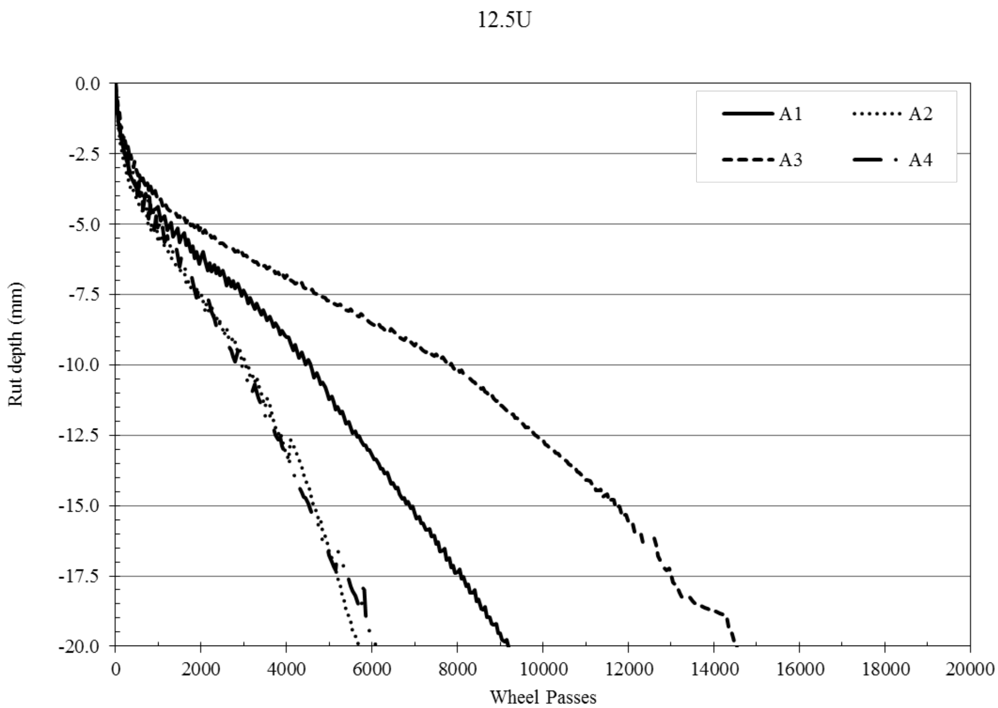


Figure 3-29 Rut depth vs. wheel passes for unmodified 12.5 mm mixtures at 70°C

Figure 3-30 presents results on all the unmodified, 9.5 mm T1 mixtures. Rut depths reached 20.0 mm at 7,850, 6,600, 11,000, and 3,300 wheel passes in A1, A2, A3, and A4, respectively, showing that performance depended on aggregate source. Wheel passes were highest for A3 and lowest for A4 mixtures.

Figure 3-31 presents results on all the unmodified, 9.5 mm T2 mixtures. Rut depths reached 20.0 mm at 13,050, 4,450, 9,150, and 5,000 wheel passes for mixtures using A1, A2, A3, and A4, respectively. Wheel passes were highest for A1 and lowest for A4.

Figure 3-32 presents results on all the unmodified, 4.75 mm dense-graded mixtures. Rut depths reached 20.0 mm at 5,650, 5,600, 4,950, and 4,050 wheel passes for A1, A2, A3, and A4, respectively. For this NMAS, the numbers of wheel passes to reach 20.0 mm were relatively close among different sources.

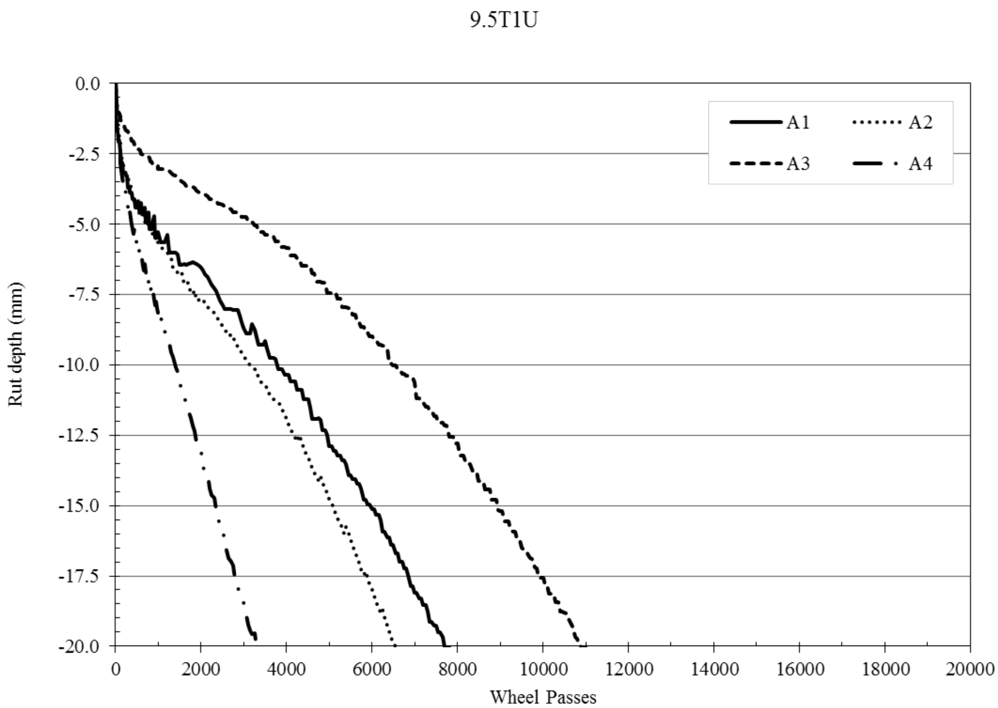


Figure 3-30 Rut depth vs. wheel passes for unmodified 9.5 mm T1 mixtures at 70°C

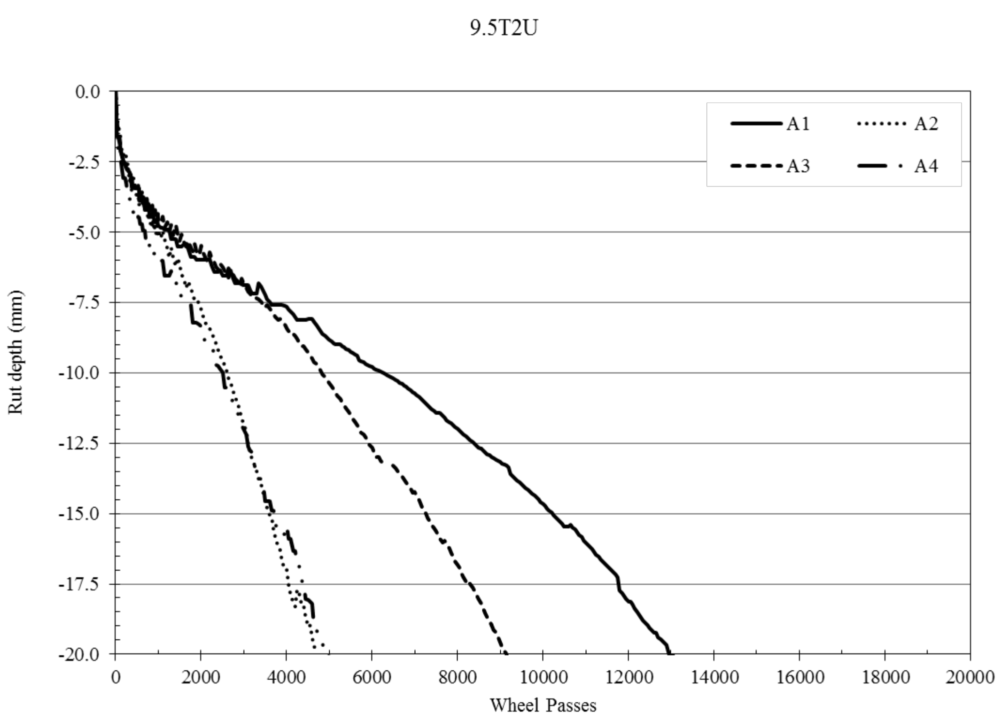


Figure 3-31 Rut depth vs. wheel passes for unmodified 9.5 mm T2 mixtures at 70°C

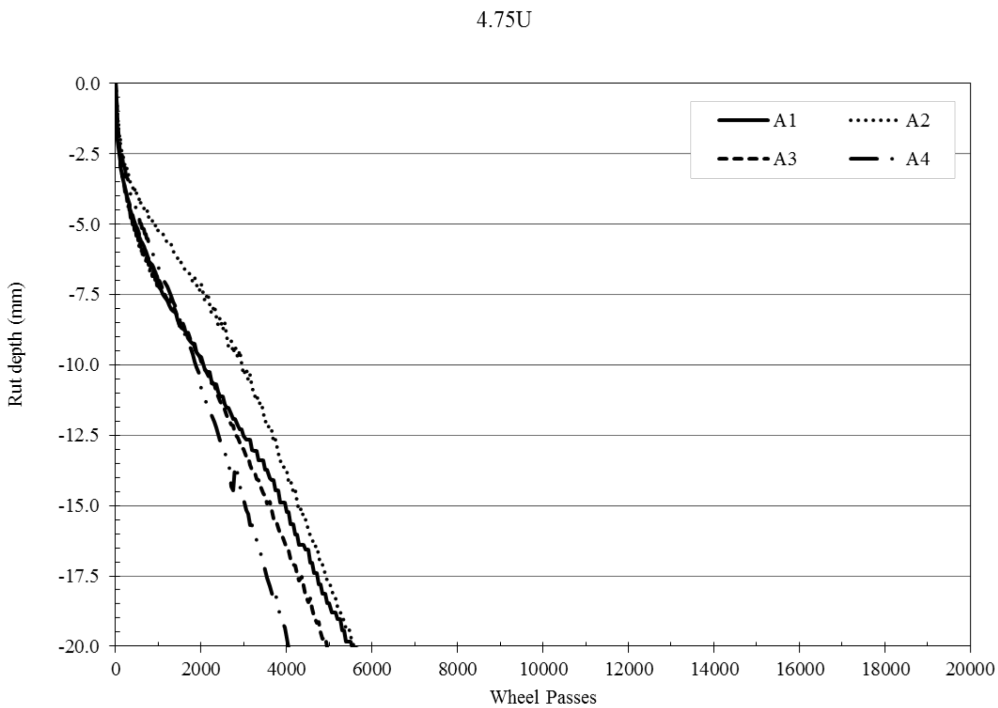


Figure 3-32 Rut depth vs. wheel passes for unmodified 4.75 mm mixtures at 70°C

3.1.3.2 Rut depth and SIP at 70°C

This section presents the test results described in the previous section in a bar chart format. The mixtures tested at 70°C were also divided into two groups: NMAS 25 and 19 mm and NMAS 12.5, 9.5, and 4.75 mm. As shown in the preceding section, most of the mixtures reached the maximum rut depth of 20.0 mm prior to 20,000 wheel passes, suggesting that 70°C may be an extreme temperature for the evaluation of the rutting resistance for unmodified asphalt mixtures.

Figures 3-33 to 3-36 show the rut depth results on each source. Except for the 25 mm mixture, all the other NMAS mixtures of A1 had a rut depth of 20.0 mm prior to 20,000 wheel passes (Fig. 3-33). All mixtures of A2 and A4 had rut depths of 20.0 mm prior to 20,000 wheel passes (Fig. 3-34 and 3-36). Except for 25 and 19 mm, all the other NMAS mixtures of A3 reached the 20.0 mm rut depth prior to 20,000 wheel passes (Fig. 3-35).

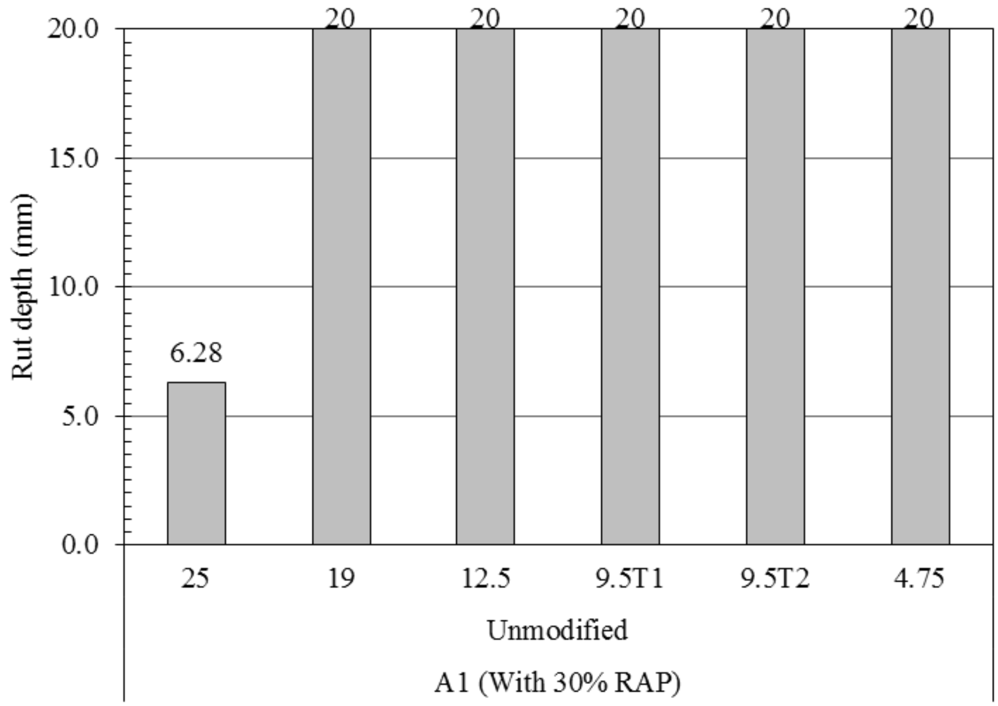


Figure 3-33 Rut depth of A1 mixtures at 70°C and 20,000 wheel passes

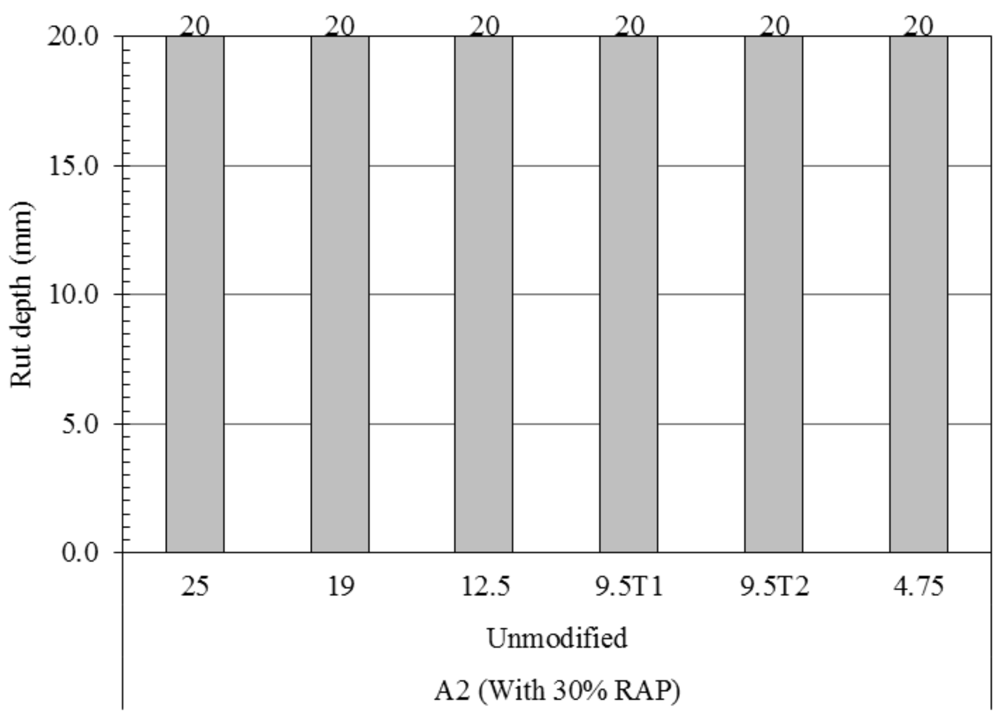


Figure 3-34 Rut depth of A2 mixtures at 70°C and 20,000 wheel passes

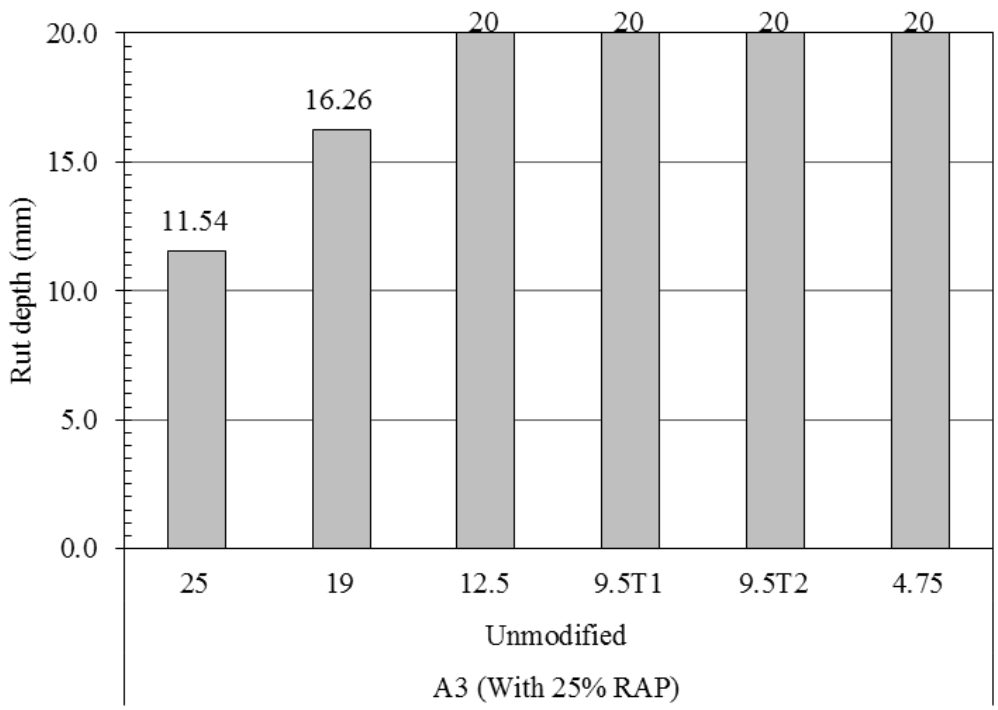


Figure 3-35 Rut depth of A3 mixtures at 70°C and 20,000 wheel passes

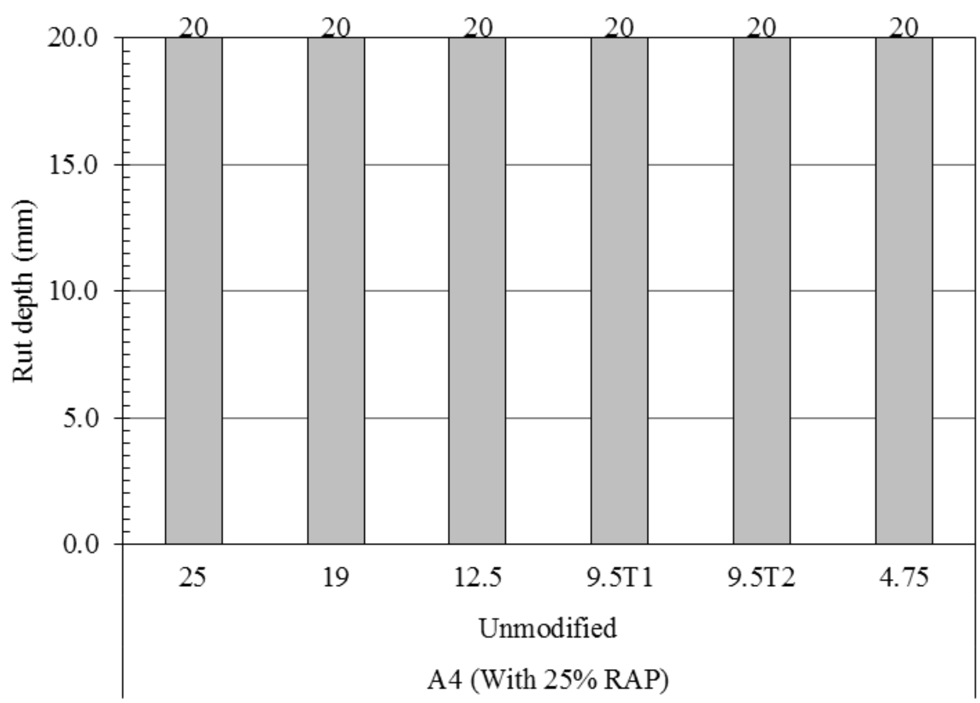


Figure 3-36 Rut depth of A4 mixtures at 70°C and 20,000 wheel passes

Figures 3-37 to 3-40 present the SIP results for various NMAS mixtures of each source. It was found that the SIP generally decreases with the decrease of NMAS. This tendency is consistent for all sources, although A1 and A3 show a higher SIP than A2 and A4. Overall, at 70°C, for all four sources, the NMAS 25 and 19 mm mixtures show a higher SIP than NMAS 12.5, 9.5, and 4.75 mm mixtures.

Figure 3-37 shows the SIP of A1 mixtures at 70°C. SIP did not appear in the 25 mm mixture at the loading limit of 20,000. The SIPs of the 19, 12.5, 9.5T1, 9.5T2 and 4.75 mm mixtures occurred at 10,550, 4,700, 4,577, 8,516, and 4,177 passes, respectively. Overall, the NMAS 25 and 19 mm mixtures had a higher SIP than the NMAS 12.5, 9.5, and 4.75 mm mixtures.

Figure 3-38 shows the SIP of A2 mixtures at 70°C. The SIPs of the 25, 19, 12.5, 9.5T1, 9.5T2 and 4.75 mm mixtures were 16,101, 11,065, 3,377, 4,926, 2,307, and 2,848 passes, respectively. NMAS 25 and 19 mm mixtures had a higher SIP than the NMAS 12.5, 9.5, and 4.75 mm mixtures.

Figure 3-39 shows the SIP of A3 mixtures at 70°C. The SIPs of the 25, 19, 12.5, 9.5T1, 9.5T2 and 4.75 mm mixtures were 14,136, 13,020, 8,818, 6,015, 4,567 and 2,876 passes, respectively. The figure clearly shows that as NMAS decreases, SIP decreases. Also, NMAS 25 and 19 mm mixtures had a higher SIP than NMAS 12.5, 9.5, and 4.75 mm mixtures.

Figure 3-40 shows the SIP of A4 mixtures at 70°C. The SIPs of the 25, 19, 12.5, 9.5T1, 9.5T2 and 4.75 mm mixtures were 7,564, 11,515, 3,016, 1,780, 2,377, and 1,836 passes, respectively. The NMAS 25 and 19 mm mixtures had a higher SIP than NMAS 12.5, 9.5, and 4.75 mm mixtures. A4 mixtures had the lowest SIP of all the mixtures.

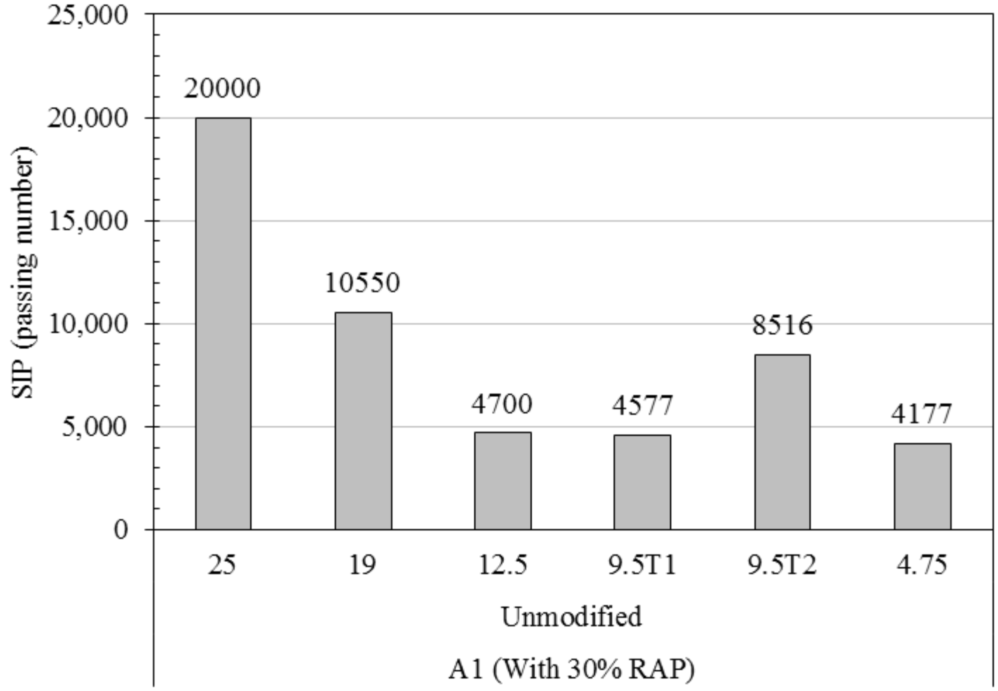


Figure 3-37 SIP of A1 mixtures at 70°C and 20,000 wheel passes

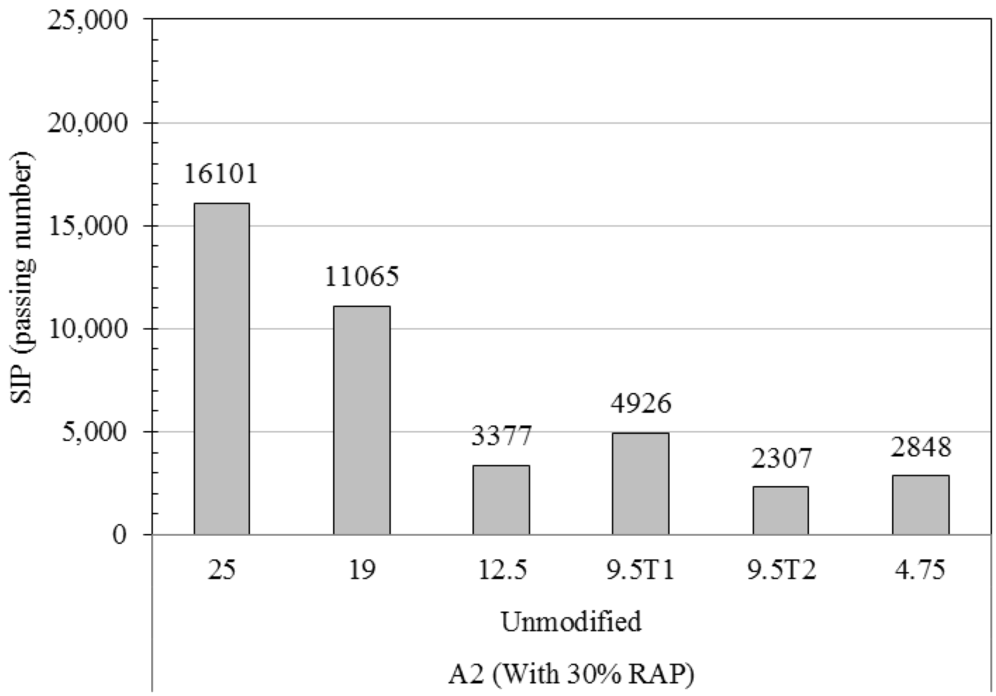


Figure 3-38 SIP of A2 mixtures at 70°C and 20,000 wheel passes

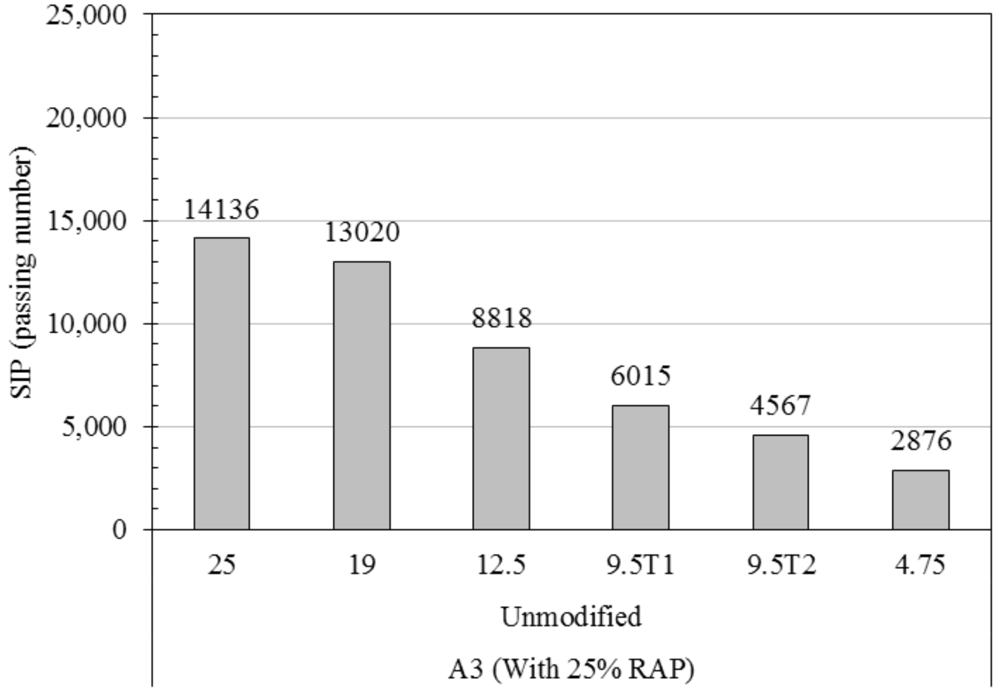


Figure 3-39 SIP of A3 mixtures at 70°C and 20,000 wheel passes

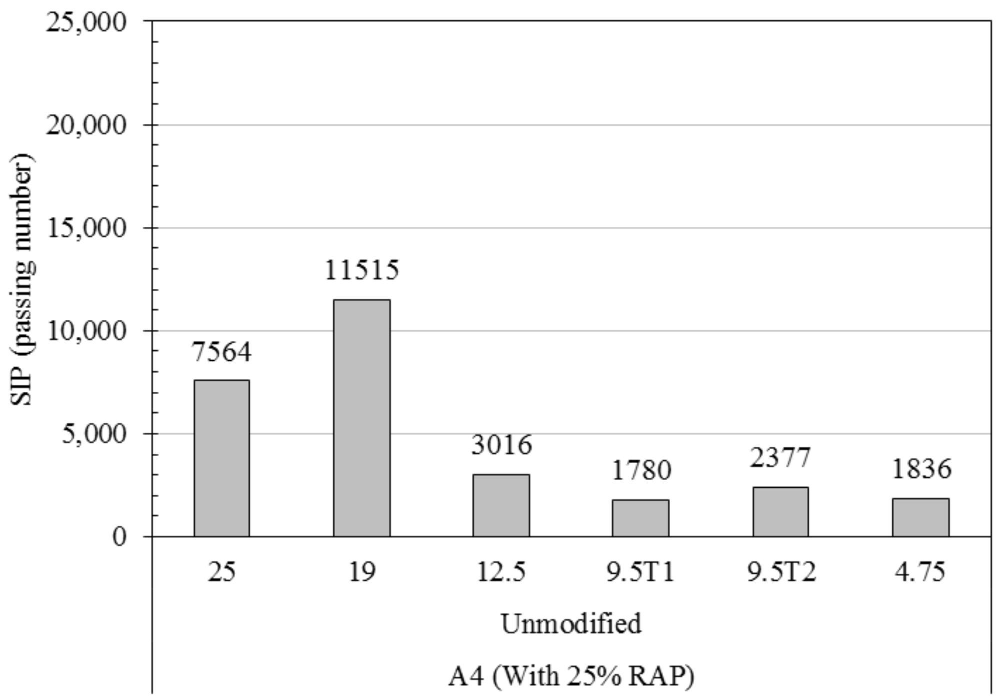


Figure 3-40 SIP of A4 mixtures at 70°C and 20,000 wheel passes

To see how rut depth and SIP are affected by test temperature and wheel pass number, the rut depths were collected at 20,000, 18,000, 15,000, 12,000, and 10,000 passes. As shown in Table 3-11, all the NMAS 12.5, 9.5, and 4.75 mm mixtures reached a rut depth of 20.0 mm within 20,000 passes. All the NMAS 25 and 19 mm mixtures had less rut depths, although some reached 20.0 mm; the rut depth of the 25 mm mixture of A1 mixture was as low as 6.3 mm. The SIP values also depended on aggregate source, mix type, asphalt content, RAP, and NMAS. As shown in Table 3-12, all the NMAS 12.5, 9.5, and 4.75 mm mixtures reached a rut depth of 20.0 mm within 18,000 wheel passes. The NMAS 25 and 19 mm mixtures had a rut depth of less than 20.0 mm. Table 3-13 shows the rut depth and SIP of all the mixtures at 15,000 wheel passes. All of the NMAS 12.5, 9.5, and 4.75 mm mixtures had rut depths over 20.0 mm; the NMAS 25 and 19 mm mixtures did not. As shown in Table 3-14, all the NMAS 12.5, 9.5, and 4.75 mm mixtures reached the rut depth of 20.0 mm within 20,000 wheel passes, except 12.5 mm mixture of A3. All the NMAS 25 and 19 mm mixtures showed a rut depth of less than 20.0 mm. Table 3-15 shows the rut depth and SIP at 10,000 wheel passes. All the NMAS 12.5, 9.5, and 4.75 mm mixtures, except 9.5T1 for A1, 12.5 for A3, and 9.5T1 for A3, reached 20.0 mm; NMAS 25 and 19 mm mixtures did not.

Table 3-11 Rut depth and SIP after 20,000 wheel passes at 70°C

Mixtures	Rut depth (mm)				SIP (passes)			
	A1(30R)	A2(30R)	A3(25R)	A4(25R)	A1(30R)	A2(30R)	A3(25R)	A4(25R)
25U	6.3	>20	11.5	>20	-	16,101	14,136	7,564
19U	>20	>20	16.3	>20	10,550	11,065	13,020	11,515
12.5U	>20	>20	>20	>20	4,700	3,377	8,818	3,016
9.5T1U	>20	>20	>20	>20	4,577	4,926	6,015	1,780
9.5T2U	>20	>20	>20	>20	8,516	2,307	4,567	2,377
4.75U	>20	>20	>20	>20	4,177	2,848	2,876	1,868

Table 3-12 Rut depth and SIP after 18,000 wheel passes at 70°C

Mixtures	Rut depth (mm)				SIP (passes)			
	A1(30R)	A2(30R)	A3(25R)	A4(25R)	A1(30R)	A2(30R)	A3(25R)	A4(25R)
25U	6.11	17.3	10.14	>20	-	16,101	14,136	7,564
19U	19.1	18.3	15.1	>20	10,550	11,065	13,020	11,515
12.5U	>20	>20	>20	>20	4,700	3,377	8,818	3,016
9.5T1U	>20	>20	>20	>20	4,577	4,926	6,015	1,781
9.5T2U	>20	>20	>20	>20	8,516	2,307	4,567	2,377
4.75U	>20	>20	>20	>20	4,177	2,848	2,878	1,868

Table 3-13 Rut depth and SIP after 15,000 wheel passes at 70°C

Mixtures	Rut depth (mm)				SIP (passes)			
	A1(30R)	A2(30R)	A3(25R)	A4(25R)	A1(30R)	A2(30R)	A3(25R)	A4(25R)
25U	5.09	13.94	9.07	>20	-	-	14,136	7,564
19U	16.7	15.1	13.6	17.2	10,550	11,065	13,020	11,515
12.5U	>20	>20	>20	>20	4,700	3,377	8,818	3,016
9.5T1U	>20	>20	>20	>20	4,577	4,926	6,015	1,781
9.5T2U	>20	>20	>20	>20	8,516	2,307	4,567	2,377
4.75U	>20	>20	>20	>20	4,177	2,848	2,876	1,868

Table 3-14 Rut depth and SIP after 12,000 wheel passes at 70°C

Mixtures	Rut depth (mm)				SIP (passes)			
	A1(30R)	A2(30R)	A3(25R)	A4(25R)	A1(30R)	A2(30R)	A3(25R)	A4(25R)
25U	5.51	13.1	7.65	17.3	-	-	-	7,564
19U	12.8	11.1	12.1	13.13	10,550	11,065	-	11,515
12.5U	>20	>20	15.63	>20	4,700	3,377	8,828	3,016
9.5T1U	>20	>20	>20	>20	4,577	4,926	6,015	1,781
9.5T2U	>20	>20	>20	>20	8,516	2,307	4,567	2,377
4.75U	>20	>20	>20	>20	4,177	4,177	2,876	1,868

Table 3-15 Rut depth and SIP after 10,000 wheel passes at 70°C

Mixtures	Rut depth (mm)				SIP (passes)			
	A1(30R)	A2(30R)	A3(25R)	A4(25R)	A1(30R)	A2(30R)	A3(25R)	A4(25R)
25U	5.29	11.1	6.00	15.5	-	-	-	7,564
19U	11.1	9.26	11.0	11.95	-	-	-	-
12.5U	>20	>20	12.69	>20	4,700	3,377	8,818	3,016
9.5T1U	>20	>20	17.6	>20	4,577	4,926	6,015	1,781
9.5T2U	14.5	>20	>20	>20	8,516	2,307	4,567	2,377
4.75U	>20	>20	>20	>20	4,177	2,848	2,876	1,868

3.1.4 Temperature effects on rut depth

This section discusses the effects of temperature on rut depth to determine proper HWTD test conditions (e.g., test temperature and wheel pass number) and asphalt mixture design criteria (e.g., rut depth and SIP). The analysis considered the various NMAS to form two groups: one group with 25 and 19 mm NMAS, and the other group with the rest of NMAS. The figures and tables in this section are presented based on the two groups.

Regression analyses were also performed to develop a statistical model to estimate the rut depths at various temperatures that are not used in the actual HWTD testing. The correlations between rut depth and the test temperatures of 50, 64, and 70°C were established at 10,000, 12,000, 15,000, 18,000, and 20,000 passes, depending on the maximum wheel passes at which the maximum rut depth of 20.00 mm was reached. Figures 3-41 to 3-45 show the regression analysis results. The values of the rut depth used in the regressions were the average rut depths from four aggregate sources of the larger NMAS group (25 - 19 mm), and the smaller NMAS group (12.5 - 4.75 mm). The figures were created for each selected wheel pass number from 20,000, 18,000, 15,000, 12,000, and 10,000.

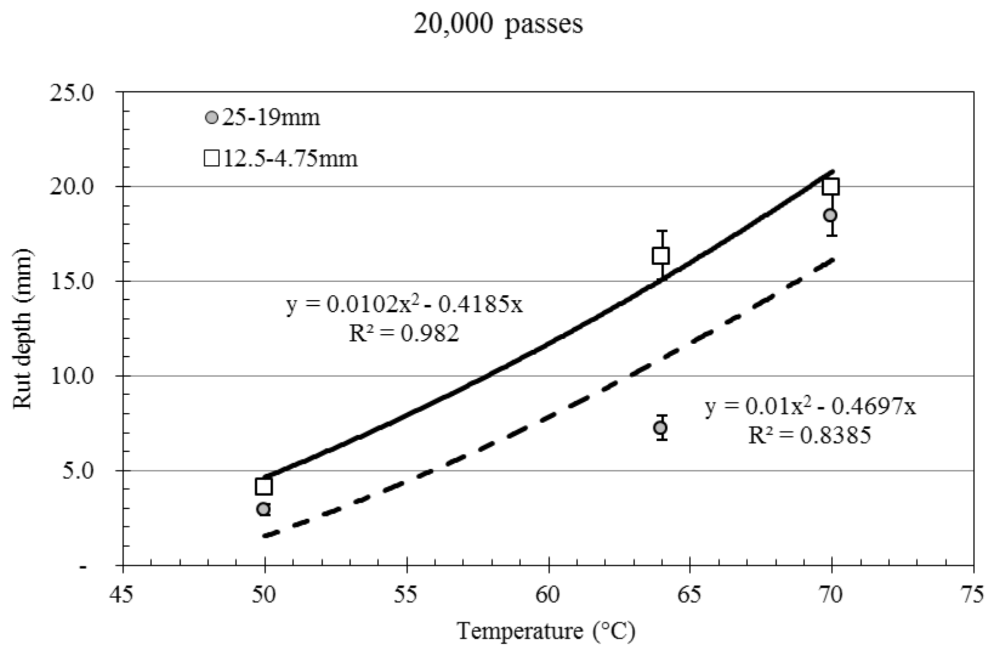


Figure 3-41 Test temperature vs. maximum rut depth at 20,000 wheel passes

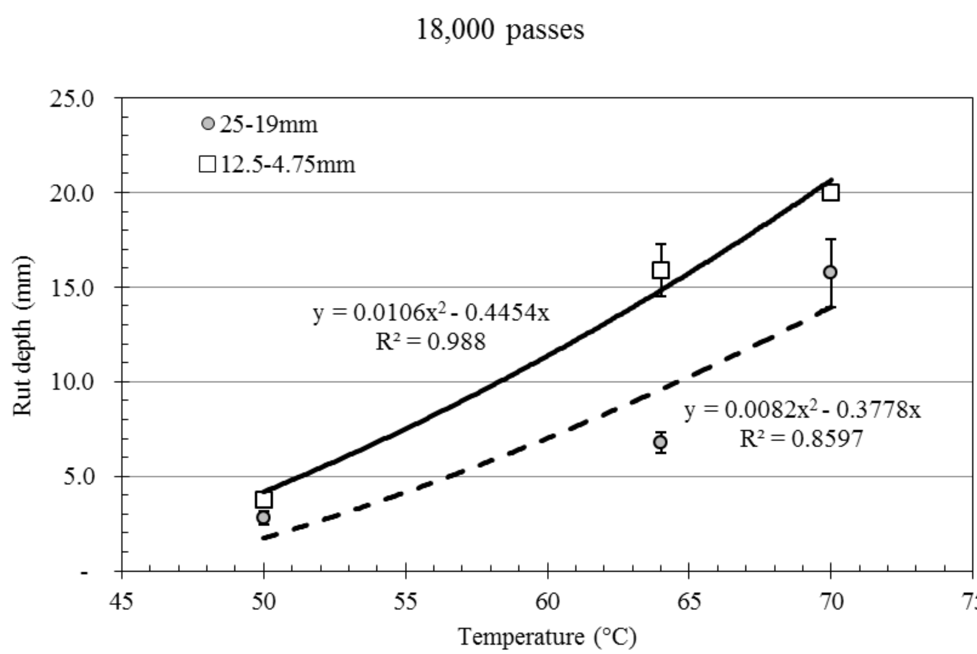


Figure 3-42 Test temperature vs. maximum rut depth at 18,000 wheel passes

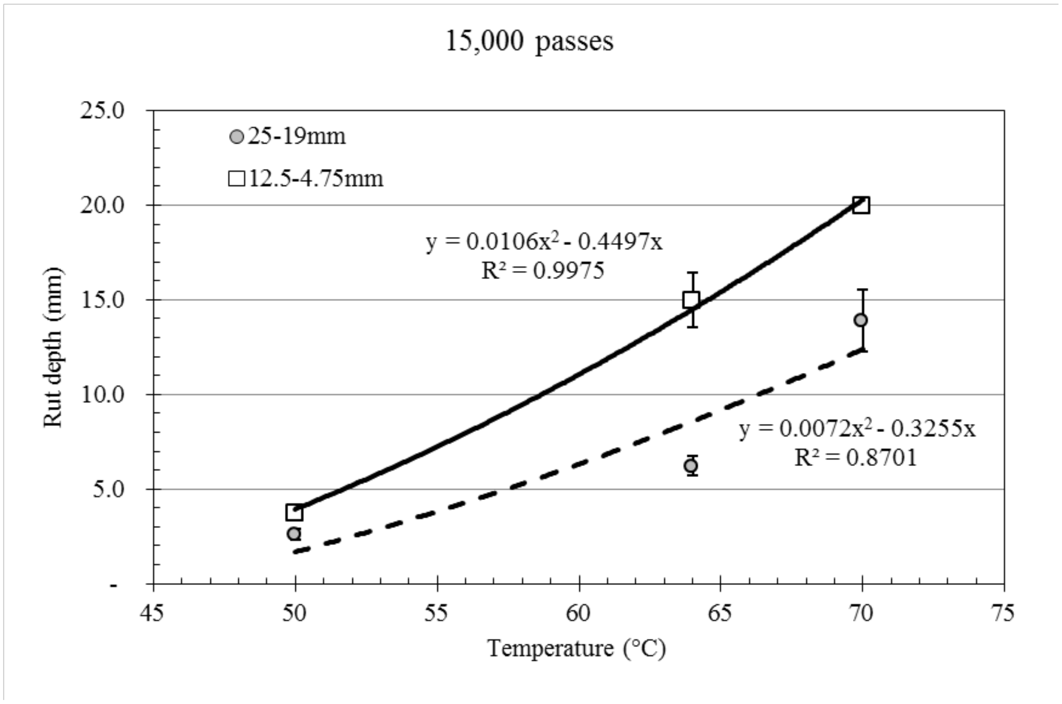


Figure 3-43 Test temperature vs. maximum rut depth at 15,000 wheel passes

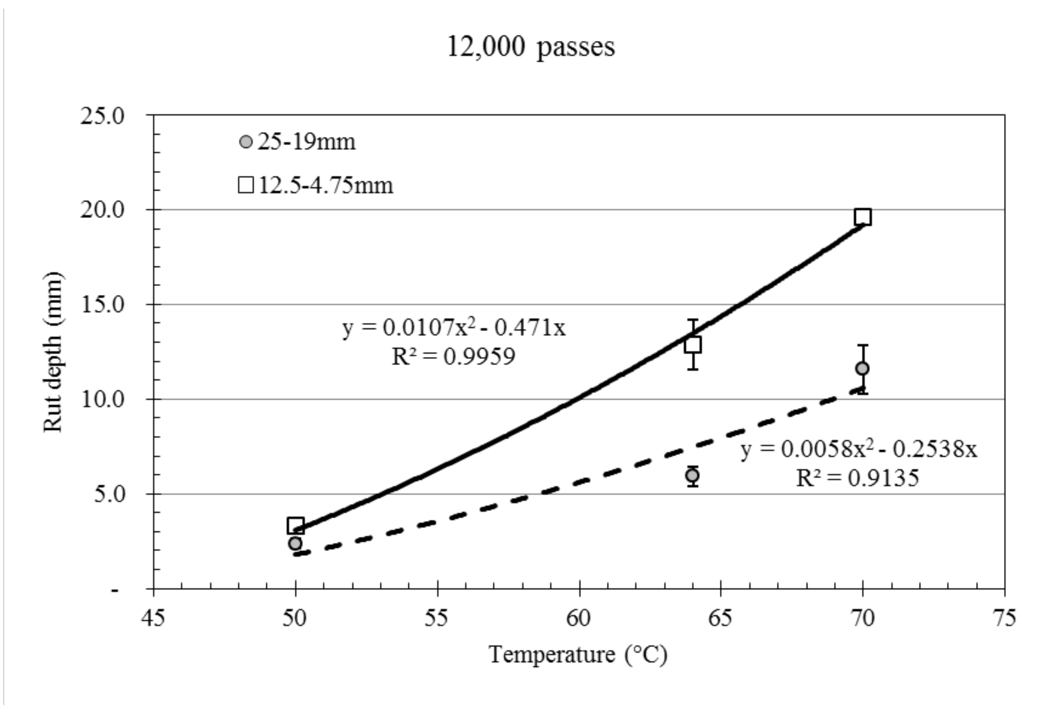


Figure 3-44 Test temperature vs. maximum rut depth at 12,000 wheel passes

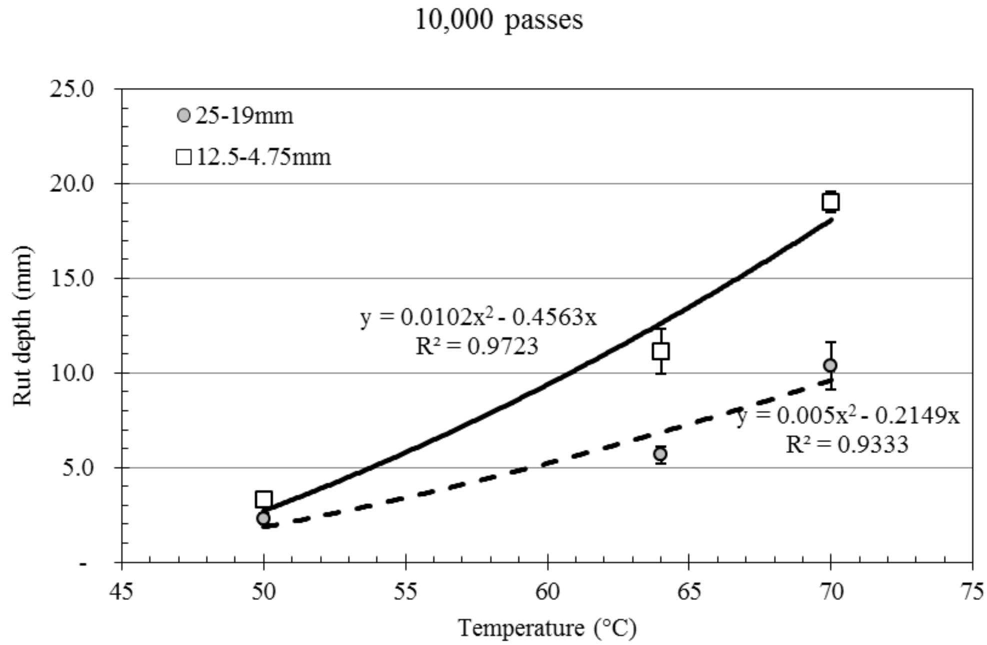


Figure 3-45 Test temperature vs. maximum rut depth at 10,000 wheel passes

Table 3-16 shows the regression models and the coefficient of determination (R^2). Using the regression equations, a rut depth at a given temperature can be estimated for any selected wheel pass number. All the regression curves are a parabola of temperature which is an independent variable. The R^2 values were found to range from 0.87 to 0.93, indicating good correlations of rut depth with test temperatures.

Table 3-16 Regression equations relating test temperature (X, °C) with maximun rut depth (Y, mm)

Mixture NMAS (mm)	Passes	Formula	R^2
25-19	20000	$Y=0.0100\ X^2 - 0.4697\ X$	0.8385
	18000	$Y=0.0082\ X^2 - 0.3778\ X$	0.8597
	15000	$Y=0.0072\ X^2 - 0.3255\ X$	0.8701
	12000	$Y=0.0058\ X^2 - 0.2538\ X$	0.9135
	10000	$Y=0.0050\ X^2 - 0.2149\ X$	0.9333
12.5-4.75	20000	$Y=0.0102\ X^2 - 0.4185\ X$	0.9820
	18000	$Y=0.0106\ X^2 - 0.4454\ X$	0.9880
	15000	$Y=0.0106\ X^2 - 0.4497\ X$	0.9975
	12000	$Y=0.0107\ X^2 - 0.4710\ X$	0.9959
	10000	$Y=0.01020\ X^2 - 0.4563\ X$	0.9723

Table 3-17 shows an example of estimated rut depths using the developed regression models for arbitrarily selected temperatures. For example, if the number of wheel passes is 20,000, the predicted rut depth for 19 mm Superpave mixture will be 6.4 mm, and will be 10.0 mm for 9.5 mm Superpave mixture at the test temperature of 58°C.

Table 3-17 Rut depth calculated for different temperatures at selected wheel passes

Mixture NMAS (mm)	Passes	Temperatures (°C)											
		50	54	55	56	57	58	60	62	64	66	68	70
25-19	20000	1.8	3.8	4.4	5.1	5.7	**6.4**	7.8	9.3	10.9	12.6	14.3	16.1
	18000	1.8	3.5	4.0	4.6	5.1	5.7	6.9	8.1	9.4	10.8	12.2	13.7
	15000	1.8	3.4	3.9	4.4	4.8	5.3	6.4	7.5	8.7	9.9	11.2	12.5
	12000	1.8	3.2	3.6	4.0	4.4	4.8	5.7	6.6	7.5	8.5	9.6	10.7
	10000	1.8	3.0	3.3	3.6	4.0	4.4	5.1	5.9	6.7	7.6	8.5	9.5
12.5-4.75	20000	4.6	7.1	7.8	8.6	9.3	**10.0**	11.6	13.3	15.0	16.8	18.7	20.7
	18000	4.2	6.9	7.6	8.3	9.1	9.8	11.4	13.1	14.9	16.8	18.7	20.8
	15000	4.0	6.6	7.3	8.1	8.8	9.6	11.2	12.9	14.6	16.5	18.4	20.5
	12000	3.2	5.8	6.5	7.2	7.9	8.7	10.3	11.9	13.7	15.5	17.4	19.5
	10000	2.7	5.1	5.8	6.4	7.1	7.8	9.3	10.9	12.6	14.3	16.1	18.0

3.1.5 Material source effects on rut depth

Since the 12.5, 9.5 and 4.75 mm mixtures of A2 and A4 reached 20.0 mm rut depth before the 20,000 wheel pass limit at test temperature of 64 and 70°C, it was decided to further analyze the rut depth by the source to evaluate the effect of the wheel passes at these temperatures in more detail. For this analysis, wheel passes were collected when a rut depth reached 5.0, 10.0, 12.5, 15.0 and 20.0 mm. This data collection was completed from all test results including all NMAS, the three temperatures, and all four sources.

3.1.5.1 Effect of aggregate source on rut depth at 50°C

Table 3-18 shows the wheel pass number at a specific rut depth for different NMAS at a test temperature of 50°C. More than 20,000 wheel passes were required to generate a rut depth of more than 5.0 mm, and this tendency was consistent for all aggregate sources. Therefore, it was unable to identify the effect of the sources and the NMAS at this temperature.

Table 3-18 Wheel pass number at specific rut depth of A1, A2, A3, and A4 mixtures at 50°C

Rut depth (mm)	Wheel pass number by mixtures					
	25	19	12.5	9.5T1	9.5T2	4.75
5.0	>20,000	>20,000	>20,000	>20,000	>20,000	>20,000
10.0	>20,000	>20,000	>20,000	>20,000	>20,000	>20,000
12.5	>20,000	>20,000	>20,000	>20,000	>20,000	>20,000
15.0	>20,000	>20,000	>20,000	>20,000	>20,000	>20,000
20.0	>20,000	>20,000	>20,000	>20,000	>20,000	>20,000

3.1.5.2 Effect of aggregate source on rut depth at 64°C

When the test temperature was 64°C, the rut depths of the mixtures were affected obviously, so the discussion of the effect of aggregates was made source by source. Table 3-19 and Figure 3-46 show the wheel pass number at reaching a rut depth of 5.0, 10.0, 12.5, 15.0 and 20.0 mm for the different NMAS of A1 mixtures at 64°C. The required wheel passes at 5.0 mm rut depth ranged from 1,400 to 12,400 for various NMAS. Wheel passes to reach a 10.0 mm rut depth were more than

20,000 passes for 25, 19 and 9.5 mm mixtures, for the 12.5 and 4.75 mm mixtures, 14,500 and 11,450 passes were required, respectively. The 25, 19, 12.5 and 9.5 mm mixtures required more than 20,000 wheel passes to reach a rut depth of 12.5, 15.0 and 20.0 mm. The 4.75 mm mixtures needed wheel passes of 14,050, 16,000 and 19,550 for 12.5, 15.0 and 20.0 mm rut depth, respectively.

Table 3-19 Wheel pass number at specific rut depth of A1 mixture at 64°C

Rut depth (mm)	Mixtures					
	25	19	12.5	9.5T1	9.5T2	4.75
5.0	12,400	6,050	1,400	5,750	11,900	2,450
10.0	>20,000	>20,000	14,500	>20,000	>20,000	11,450
12.5	>20,000	>20,000	>20,000	>20,000	>20,000	14,050
15.0	>20,000	>20,000	>20,000	>20,000	>20,000	16,000
20.0	>20,000	>20,000	>20,000	>20,000	>20,000	19,550

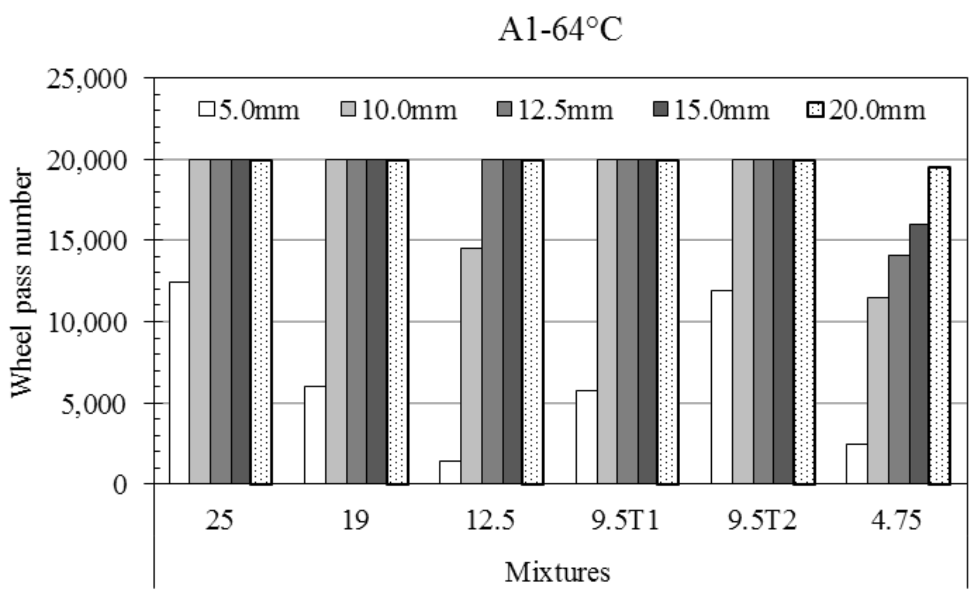


Figure 3-46 Wheel pass number at a specific rut depth for A1 mixture at 64°C

As shown in Table 3-20 and Figure 3-47, at 64°C, A2 mixtures reached a specific rut depth in a relatively early wheel pass as compared with A1 mixtures. The required wheel pass number at 5.0 mm rut depth ranged from 1,250 to 6,000. Wheel passes to reach 10.0, 12.5, 15.0 and 20.0 mm rut depth was more than 20,000 for 25 and 19 mm mixtures. The 12.5, 9.5 and 4.75 mm mixtures needed wheel passes between 6,450 and 15,900.

Table 3-20 Wheel pass number at specific rut depth of A2 mixture at 64°C

Rut depth (mm)	Mixtures					
	25	19	12.5	9.5T1	9.5T2	4.75
5.0	4,900	2,950	3,250	1,250	2,500	6,000
10.0	>20,000	>20,000	9,200	6,450	8,650	9,550
12.5	>20,000	>20,000	11,150	8,350	10,250	10,600
15.0	>20,000	>20,000	12,700	9,750	11,600	11,900
20.0	>20,000	>20,000	15,900	12,650	13,850	14,950

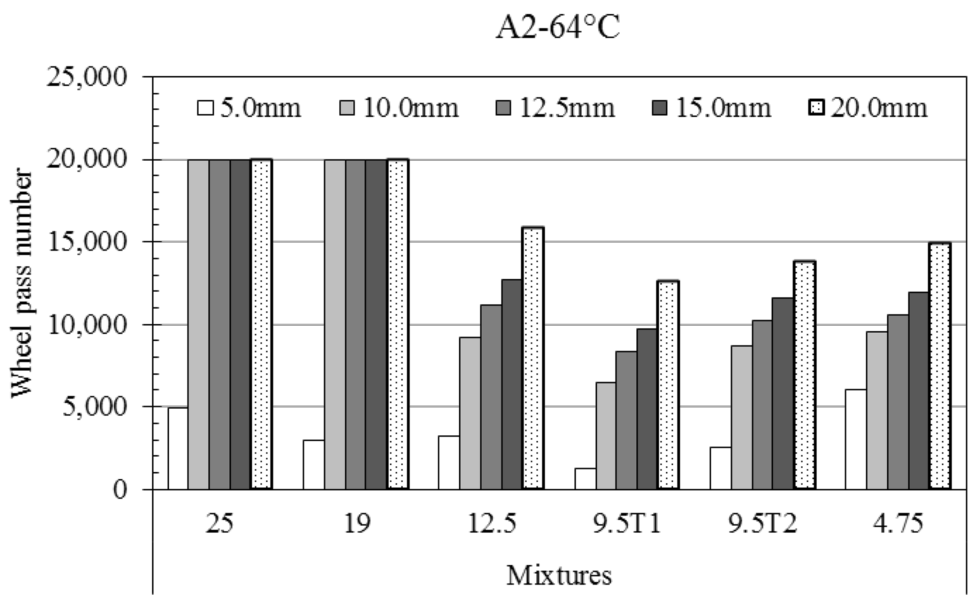


Figure 3-47 Wheel pass number at a specific rut depth for A2 mixture at 64°C

Table 3-21 and Figure 3-48 show the wheel pass number at reaching a rut depth of 5.0, 10.0, 12.5, 15.0 and 20.0 mm for the different NMAS of A3 mixtures at 64°C. Overall, the A3 mixtures required higher wheel passes to reach a specific rut depth as compared to A1 and A2 mixtures. The required wheel passes at 5.0 mm rut depth ranged from 2,050 to 20,000. Wheel passes to reach 10.0, 12.5, 15.0 and 20.0 mm rut depth were more than 19,250 for 25, 19, 12.5 and 9.5T1 mixtures, the 9.5T2 and 4.75 mm mixtures needed wheel passes from 7,950 to 20,000 passes.

Table 3-21 Wheel pass number at specific rut depth of A3 mixture at 64°C

Rut depth (mm)	Mixtures					
	25	19	12.5	9.5T1	9.5T2	4.75
5.0	>20,000	11,350	7,100	4,650	4,150	2,050
10.0	>20,000	>20,000	>20,000	19,250	13,000	7,950
12.5	>20,000	>20,000	>20,000	>20,000	16,100	10,000
15.0	>20,000	>20,000	>20,000	>20,000	19,200	11,600
20.0	>20,000	>20,000	>20,000	>20,000	>20,000	14,850

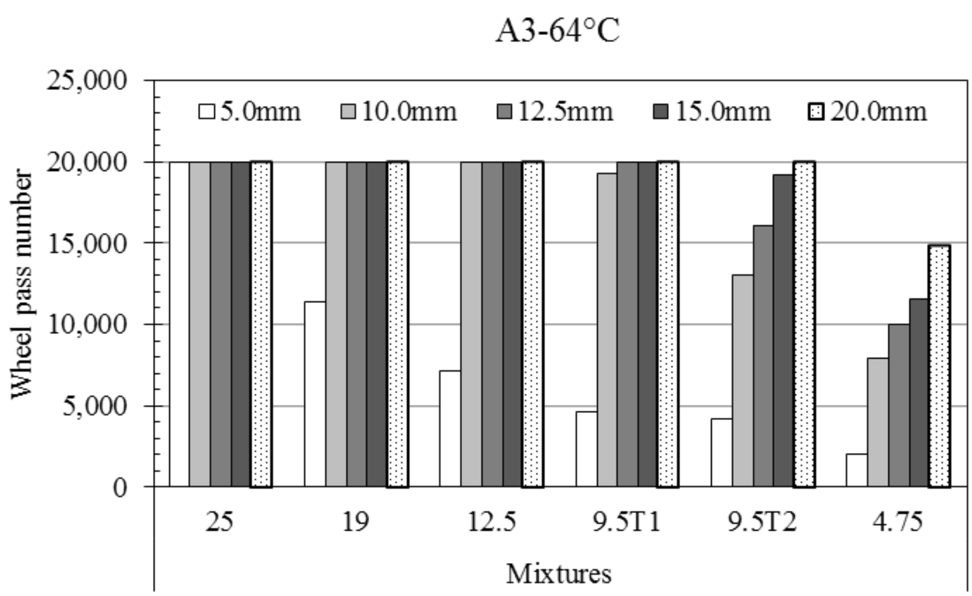


Figure 3-48 Wheel pass number at a specific rut depth for A3 mixture at 64°C

A specific rut depth of A4 mixtures occurred at lower wheel pass number than A1, A2 and A3 mixtures at 64°C as shown in Table 3-22 and Figure 3-49. The required wheel passes at 5.0 mm rut depth ranged between 1,050 and 3,350. Wheel passes to reach a 10.0 mm rut depth were more than 16,550 for the 25 and 19 mm mixtures, and the 12.5, 9.5T1, T2 and 4.75 mm mixtures needed 8,050, 5,600, 5,400 and 3,400 passes, respectively. Wheel passes to reach a 12.5, 15.0 and 20.0 mm rut depth were more than 20,000 passes for 25 and 19 mm mixtures, and for the mixtures of 12.5, 9.5 and 4.75 mm ranged from 4,300 to 16,100.

Table 3-22 Wheel pass number at specific rut depth of A4 mixture at 64°C

Rut depth (mm)	Wheel pass number by mixtures					
	25	19	12.5	9.5T1	9.5T2	4.75
5.0	3,350	7,050	2,350	2,100	1,650	1,050
10.0	16,550	>20,000	8,050	5,600	5,400	3,400
12.5	>20,000	>20,000	10,600	7,100	6,850	4,300
15.0	>20,000	>20,000	12,700	8,100	8,900	5,200
20.0	>20,000	>20,000	16,100	10,050	11,700	6,750

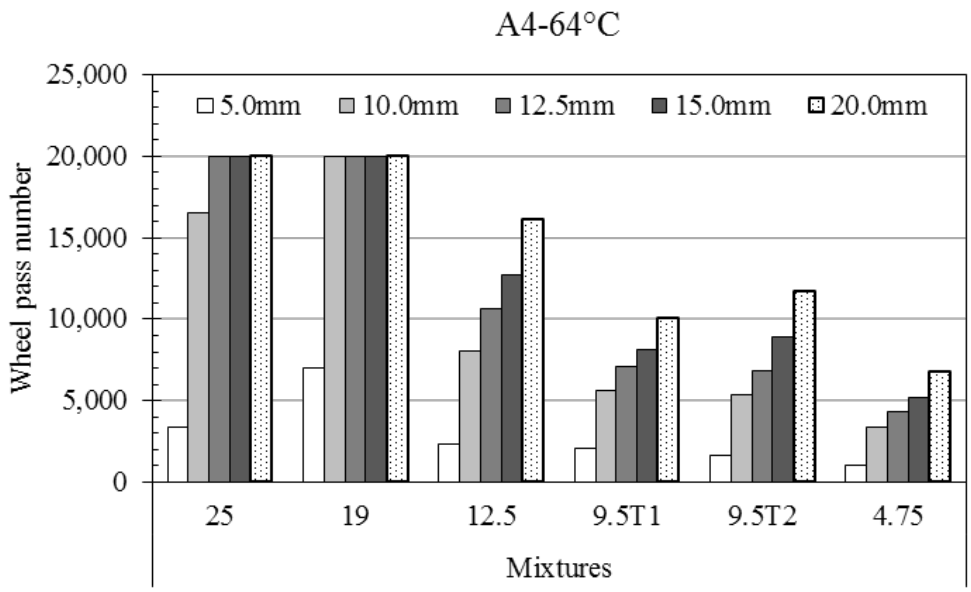


Figure 3-49 Wheel pass number at a specific rut depth for A4 mixture at 64°C

3.1.5.3 Effect of aggregate source on rut depth at 70°C

Similarly, when the test temperature was 70°C, the rut depths of the mixtures were affected obviously, so the discussion of the effect of aggregates was made source by source. Table 3-23 and Figure 3-50 show the wheel pass number at reaching a rut depth of 5.0, 10.0, 12.5, 15.0 and 20.0 mm of A1 mixtures at 70°C. The needed wheel passes of all mixtures to reach a specific rut depth were low as compared with the results of 64°C. The required wheel passes at 5.0 mm rut depth ranged from 500 to 9,200 for various NMAS. Wheel passes to reach 10.0, 12.5, 15.0 and 20.0 mm rut depth were more than 20,000 for 25 mm mixtures, the 12.5, 9.5 and 4.75 mm mixtures needed wheel passes a range from 2,200 to 9,200.

Table 3-23 Wheel pass number at specific rut depth of A1 mixture at 70°C

Rut depth (mm)	Mixtures					
	25	19	12.5	9.5T1	9.5T2	4.75
5.0	9,250	2,700	1,200	840	1,400	500
10.0	>20,000	8,900	4,600	3,900	6,350	2,200
12.5	>20,000	11,500	5,650	5,050	8,450	3,100
15.0	>20,000	13,500	6,900	6,000	10,300	4,100
20.0	>20,000	19,050	9,200	7,800	13,050	5,650

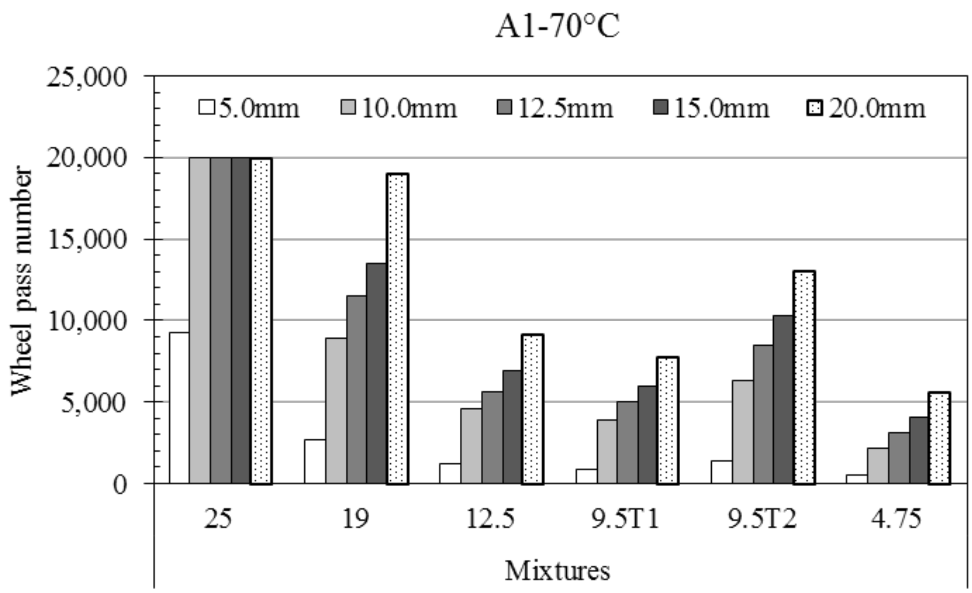


Figure 3-50 Wheel pass number at a specific rut depth for A1 mixture at 70°C

Table 3-24 and Figure 3-51 show the wheel pass number at a rut depth of 5.0, 10.0, 12.5, 15.0 and 20.0 mm of A2 mixtures at 70°C. The required wheel passes at 5.0 mm rut depth were 2,650 and 2,400 for 25 and 19 mm mixtures, respectively, the 12.5, 9.5 and 4.75 mm mixtures ranged from 760 to 880 passes. To reach a 10.0 mm rut depth, 25 and 19 mm mixtures needed 8,550 and 10,750 wheel passes, the 12.5, 9.5 and 4.75 mm mixtures required 2,650 to 3,150 passes. The 25 and 19 mm mixtures required wheel passes a range from 10,900 to 19,000 to generate a rut depth range from 12.5 to 20.0mm, the 12.5, 9.5 and 4.75 mm mixtures needed a range of 2,650 to 6,600 passes.

Table 3-24 Wheel pass number at specific rut depth of A2 mixture at 70°C

Rut depth (mm)	Mixtures					
	25	19	12.5	9.5T1	9.5T2	4.75
5.0	2,650	2,400	760	760	940	880
10.0	8,550	10,750	3,050	3,150	2,650	3,000
12.5	10,900	13,050	3,800	4,200	3,100	3,600
15.0	14,000	14,900	4,650	5,100	3,600	4,300
20.0	18,900	19,000	5,700	6,600	6,600	5,600

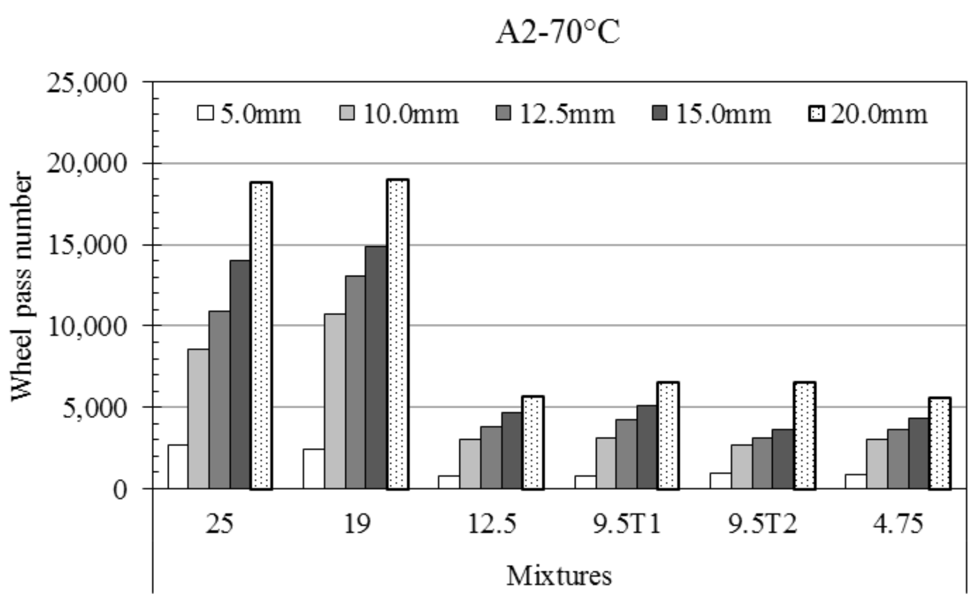


Figure 3-51 Wheel pass number at a specific rut depth for A2 mixture at 70°C

Table 3-25 and Figure 3-52 show the wheel pass number at a rut depth of 5.0, 10.0, 12.5, 15.0 and 20.0 mm of A3 mixtures at 70°C. The needed wheel passes at 5.0 mm rut depth were 4,450 and 2,250 for 25 and 19 mm mixtures, respectively, the 12.5, 9.5 and 4.75 mm mixtures required wheel pass from 400 to 3,350. To reach a 10.0 mm rut depth, 25 and 19 mm mixtures needed

16,500 and 8,550 wheel passes, and the 12.5, 9.5 and 4.75 mm mixtures required from 2,100 to 7,800 passes. The 25 and 19 mm mixtures needed wheel passes from 12,700 to 20,000 to generate a rut depth from 12.5 to 20.0 mm. And the 12.5, 9.5 and 4.75 mm mixtures required from 2,800 to 14,550 passes.

Table 3-25 Wheel pass number at specific rut depth of A3 mixture at 70°C

Rut depth (mm)	Mixtures					
	25	19	12.5	9.5T1	9.5T2	4.75
5.0	4,450	2,250	1,750	3,350	1,350	400
10.0	16,500	8,550	7,800	6,600	4,850	2,100
12.5	>20,000	12,700	9,850	7,900	6,300	2,800
15.0	>20,000	17,850	11,700	9,050	7,250	3,650
20.0	>20,000	20,000	14,550	11,000	9,150	4,950

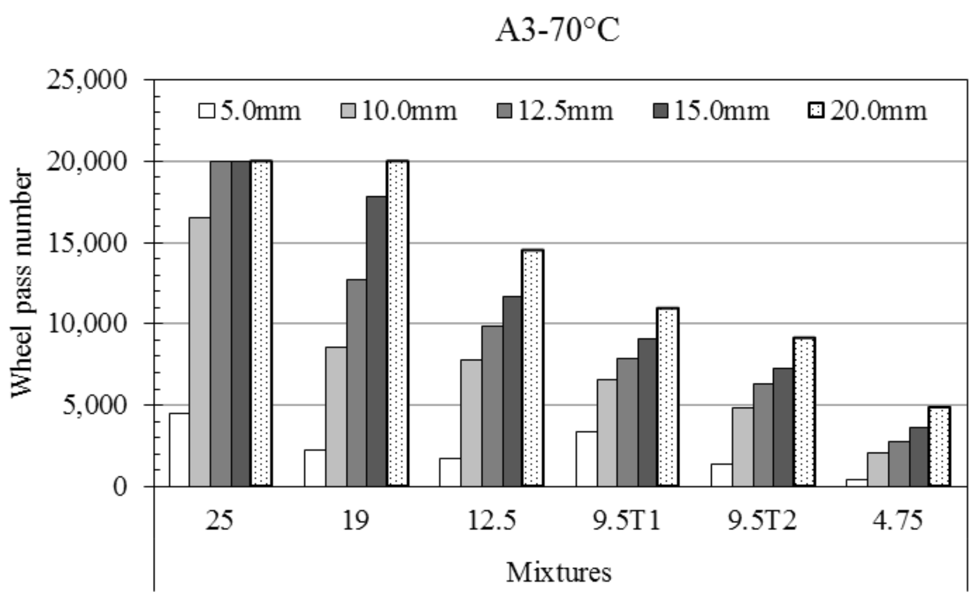


Figure 3-52 Wheel pass number at a specific rut depth for A3 mixture at 70°C

As shown in Table 3-26 and Figure 3-53**,** the wheel pass number at 5.0 mm rut depth range from 380 to 1,600 passes depended on the NMAS. Wheel passes at a 10.0 mm rut depth ranged from 1,400 to 7,950. Wheel passes to reach a 12.5 mm rut depth were from 1,900 to 10,600, and at 15.0 and 20.0 mm rut depth were from 2,350 to 13,250, and 3,300 to 17,650, respectively. The rut depth according to wheel passes was dependent on the NMAS of all mixtures.

Table 3-26 Wheel pass number at specific rut depth of A4 mixture at 70°C

Rut depth (mm)	Mixtures					
	25	19	12.5	9.5T1	9.5T2	4.75
5.0	880	1,600	840	380	680	580
10.0	3,700	7,950	2,950	1,400	2,600	1,900
12.5	7,000	10,600	3,750	1,900	3,200	2,400
15.0	9,650	13,250	4,550	2,350	3,850	3,050
20.0	13,400	17,650	6,100	3,300	5,000	4,050

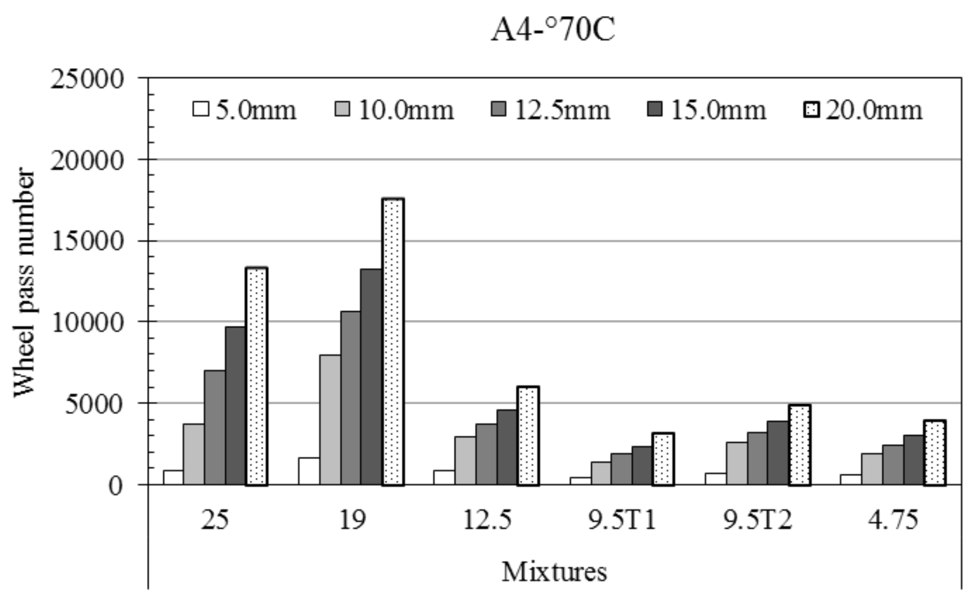


Figure 3-53 Wheel pass number at a specific rut depth for A4 mixture at 70°C

3.1.6 The NMAS effects on rut depth

3.1.6.1 Effect of the NMAS on rut depth at 50°C

As explained in the preceding section (Table 3-20**)**, the wheel pass number to require a rut depth of 5.0 mm for all mixtures was more than 20,000 at 50°C. Accordingly, an NMAS effect analysis on rut depth by wheel passes was unable at this temperature.

3.1.6.2 Effect of the NMAS on rut depth at 64°C

Overall, the wheel pass number to reach a specific rut depth can be clearly divided into two groups of A1 and A3, and A2 and A4. The 25 mm mixtures of A1, A2, A3 and A4 required 12,400, 4,900, 20,000 and 3,350 wheel passes to reach a rut depth of 5.0 mm, respectively. The wheel pass number that was needed to reach 10.0 mm rut depth demanded more than 20,000, except for the A4 mixtures. Also, to reach a 12.5, 15.0 and 20.0 mm of rut depth, more than 20,000 passes were required regardless of the material source (Figure 3-54).

The 19 mm mixtures required 6,050, 2,950, 11,350 and 7,050 wheel passes for A1, A2, A3 and A4 for the 5.0 mm rut depth, respectively. On reaching a rut depth of 10.0 to 20.0 mm, over 20,000 wheel pass number were required regardless of the material source (Figure 3-55).

For the 12.5 mm mixtures, the wheel pass number when reaching a specific rut depth was relatively lower compared to the 25 and 19 mm mixtures. To reach a 5.0 mm rut depth for the A1, A2, A3 and A4 mixtures, wheel passes were 1,400, 3,250, 7,100 and 2,350, respectively. To generate/create/cause a 10.0 mm rut depth, 14,500, 9,200, 20,000 and 8,050 wheel passes were required. Wheel passes for occurring the rut depth of 12.5, 15.0 and 20.0 mm were an over 20,000 passes for A1 and A3 mixture, and were more than 10,000, 12,000, and 16,000 passes for A2 and A4 mixture, respectively (Figure 3-56).

The 9.5 mm T1 mixture shows the rut depth difference between the A1, A3 and A2, A4 mixtures clearly. The wheel pass of 5,750, 1,250, 4,650 and 2,100 generated a 5.0 mm rut depth for mixtures of the A1, A2, A3 and A4, respectively. The A1 and A3 mixtures required more than

19,000 wheel passes to occur a 10.0 mm rut depth, and the A2 and A4 mixtures required 6,450 and 5,600 wheel passes. To reach a 12.5 mm rut depth, A1 and A3 mixture required more than 20,000 wheel passes, the A2 and A4 mixture required 8,350, 7,100 passes, respectively. To reach a 15.0 mm rut depth of A1 and A3 mixture required more than 20,000 passes, A2 and A4 mixture needed 9,750 and 8,100 passes. The A1 and A3 mixture needed more than 20,000 passes to occur a 20.0 mm rut depth, and the A2 and A4 mixture required 12,650 and 10,050 passes (Figure 3-57). As shown in Figure 3-58, wheel passes at generating a specific a rut depth for the 9.5 mm T2 mixture showed similar tendency to the 12.5 and 9.5 mm T1 mixture, and the rut depth difference according to the material source was obvious.

The 4.75 mm dense-graded mixture required wheel passes of 2,450, 6,000, 2,050 and 1,050 to reach a 5.0 mm rut depth for mixtures of the A1, A2, A3 and A4, and wheel passes to reach a 10.0 mm rut depth required 11,450, 9,550, 7,950 and 3,400, respectively. The required wheel passes at reaching a 12.5 mm rut depth were 14,050, 10,600, 10,000 and 4,300 for mixtures of the A1, A2, A3 and A4, and at 15.0 mm were 16,000, 11,900, 11,600 and 5,250 passes, respectively, for reaching 20.0 mm were 19,550, 14,950, 14,850 and 6,750 passes (Figure 3-59).

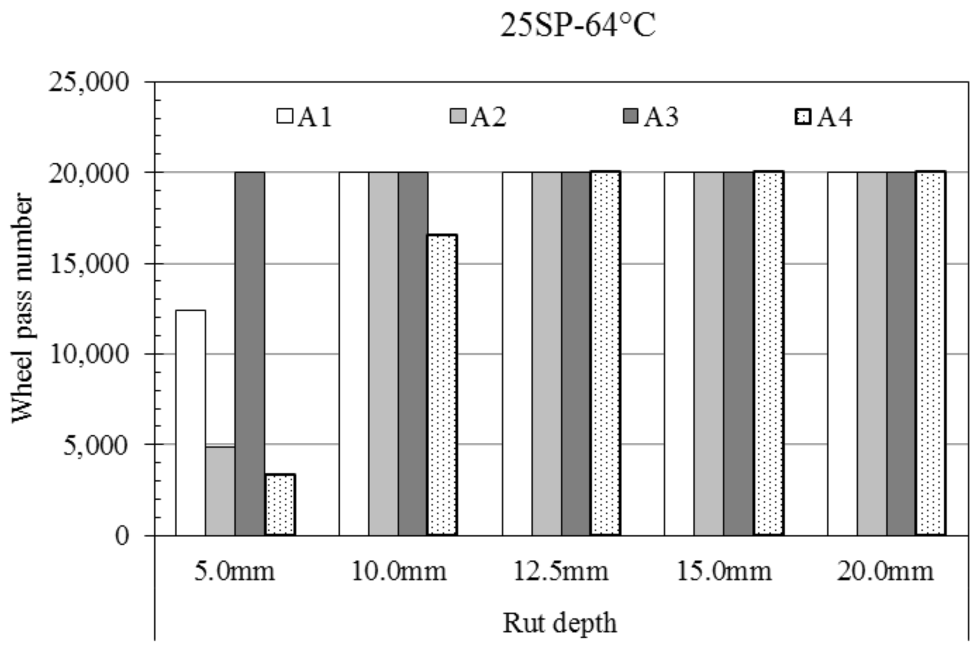


Figure 3-54 Wheel pass number for a specific rut depth for a 25 mm mixture at 64°C

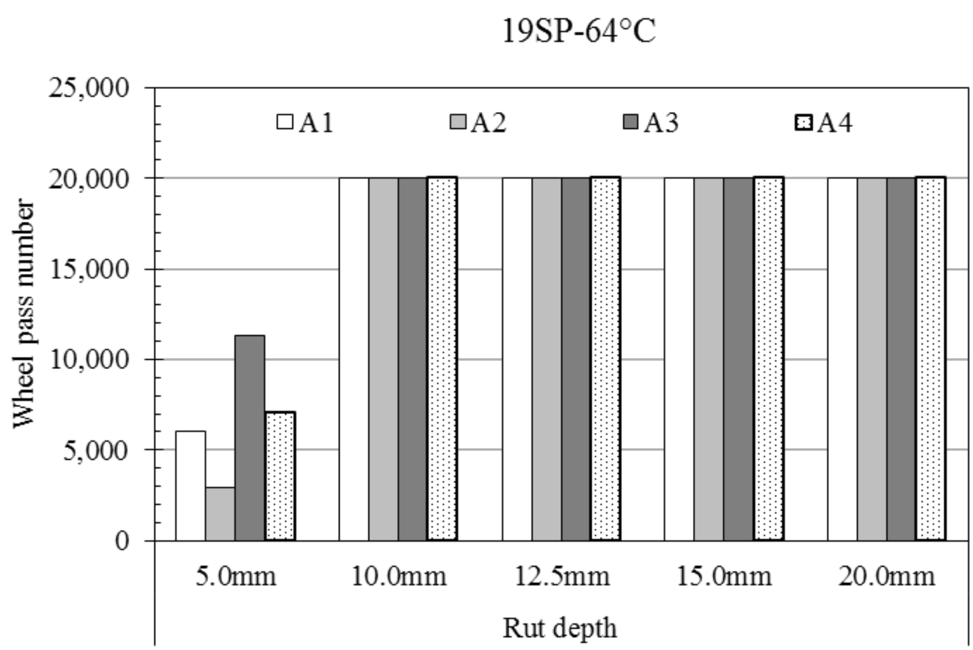


Figure 3-55 Wheel pass number for a specific rut depth for a 19 mm mixture at 64°C

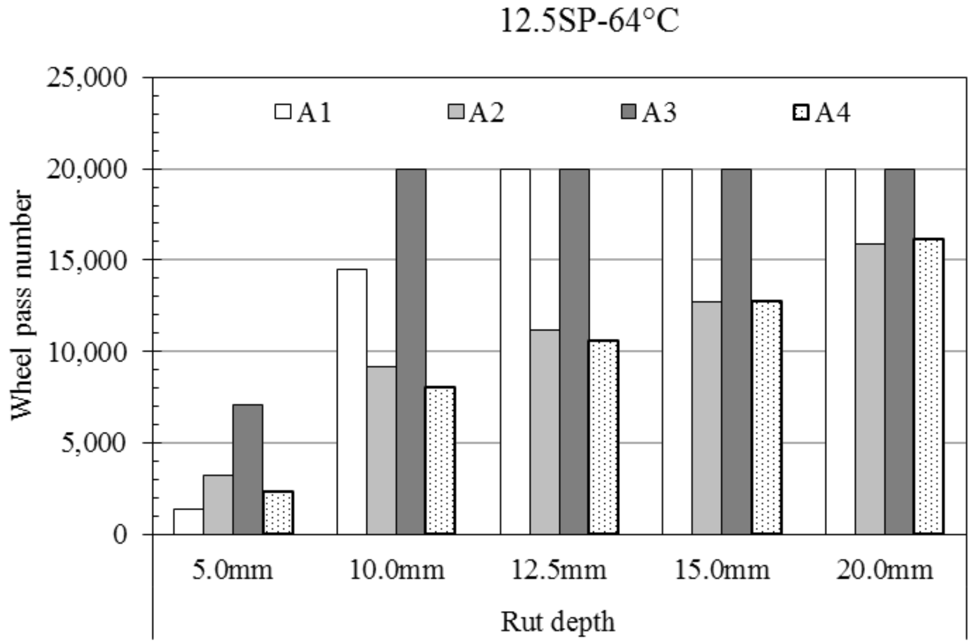


Figure 3-56 Wheel pass number for a specific rut depth for a 12.5 mm mixture at 64°C

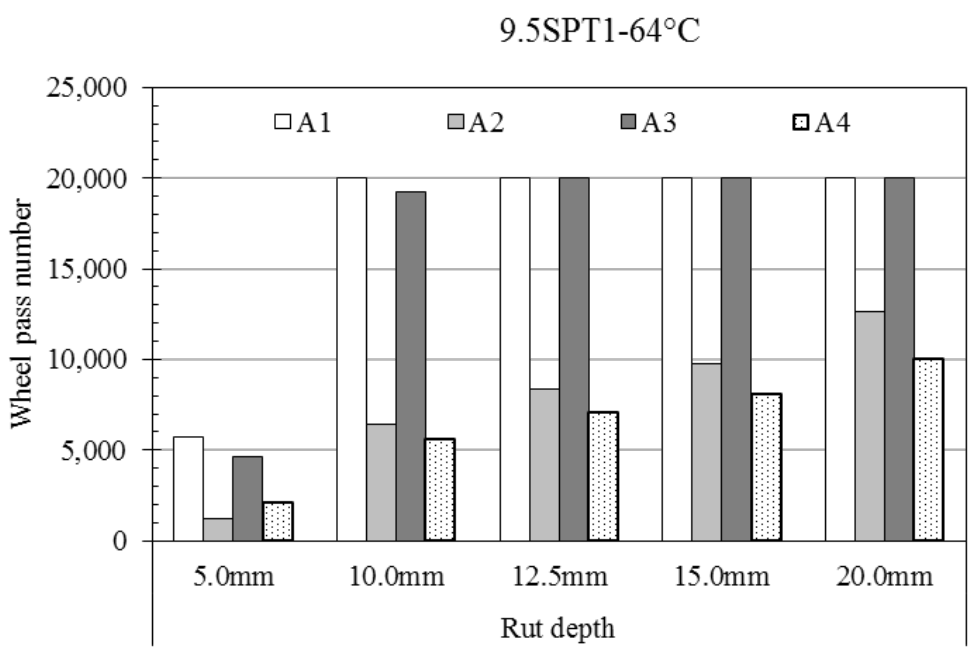


Figure 3-57 Wheel pass number for a specific rut depth for a 9.5 mm T1 mixture at 64°C

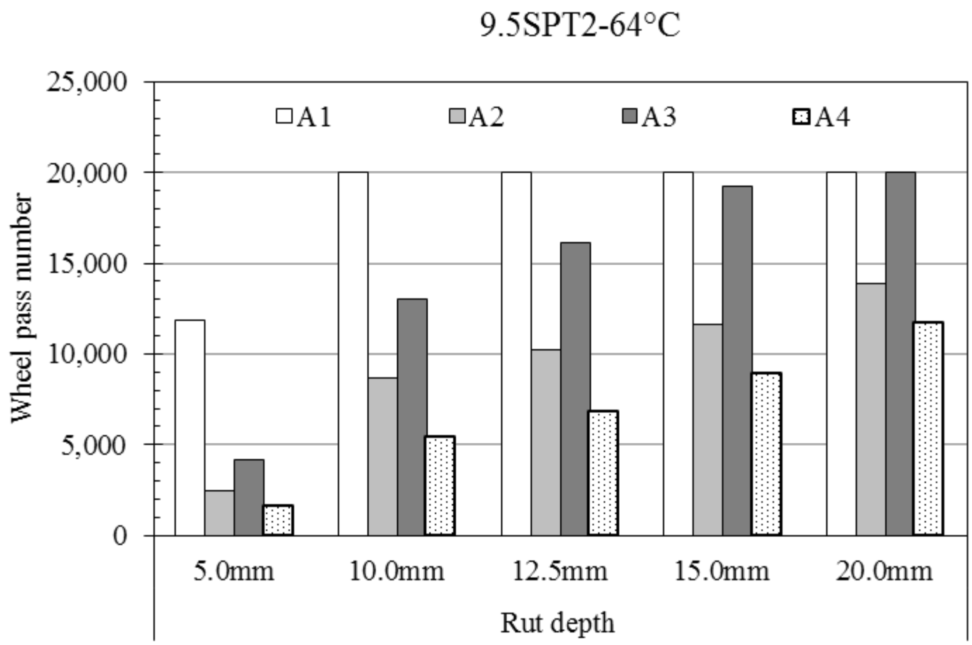


Figure 3-58 Wheel pass number for a specific rut depth for a 9.5 mm T2 mixture at 64°C

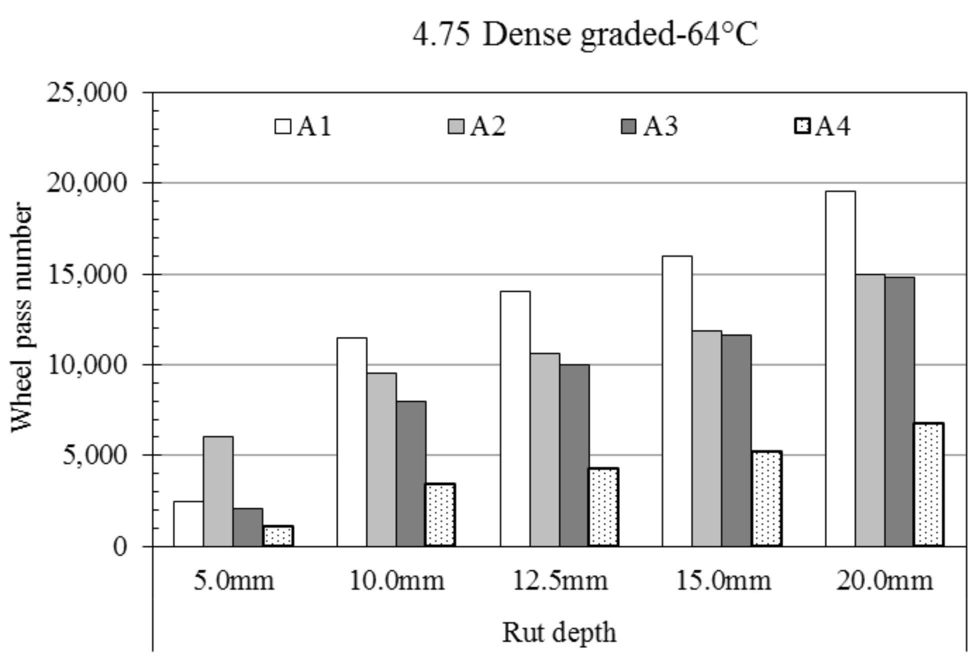


Figure 3-59 Wheel pass number for a specific rut depth for a 4.75 mm mixture at 64°C

3.1.6.3 Effect of the NMAS on rut depth at 70°C

At 70°C, the 25 mm mixtures required 880 to 9,250 wheel passes to occur a 5.0 mm rut depth, and at reaching a 10.0 mm rut depth were from 3,700 to 20,000 passes. To reach a 12.5 mm rut depth, wheel pass of 7,000 to 20,000 required, and a 15.0 mm rut depth required 9,650 to 20,000 passes. Wheel pass to occur a 20.0 mm rut depth were 13,400 to 20,000, these wheel passes were dependent on the NMAS and material sources (Figure 3-60).

The 19 mm mixture required 1,600 wheel passes or more to occur 5.0 mm rut depth, and 7,950 passes at 10.0 mm, 10,600 passes at 12.5 mm, 13,250 passes at 15.0 mm and 17,650 passes at 20.0 mm rut depth (Figure 3-61).

For the 12.5, 9.5T1, 9.5T2 and 4.75 mm mixture showed lower wheel passes at same rut depth as compared with the 25 and 19 mm mixtures. These mixtures required 400 to 3,350 wheel passes to generate a 5.0 mm rut depth, and 1,400 to 7,800 passes at 10.0 mm, 1,900 to 9,850 passes at 12.5 mm, 2,350 to 11,700 passes at 15.0 mm, and 3,300 to 14,550 passes at 20.0 mm (Figure 3-62 to 3-65).

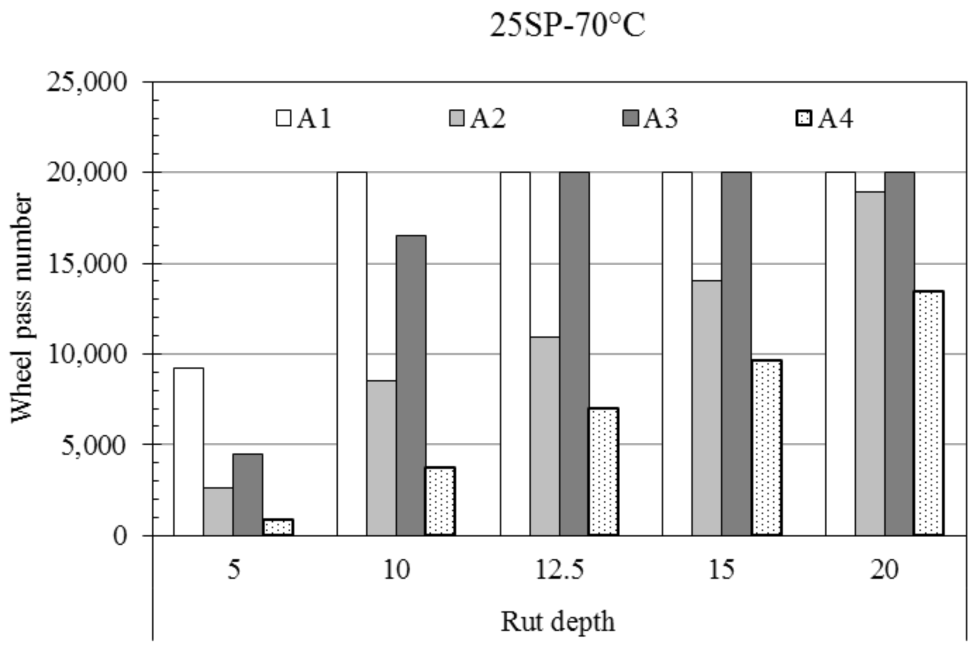


Figure 3-60 Wheel pass number for a specific rut depth for a 25 mm mixture at 70°C

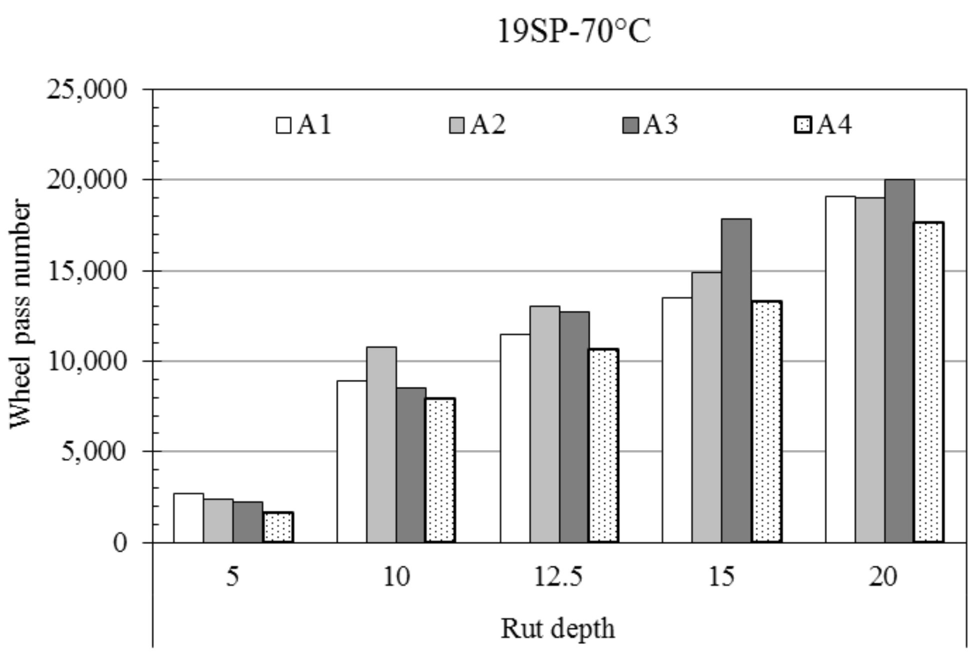


Figure 3-61 Wheel pass number for a specific rut depth for a 19 mm mixture at 70°C

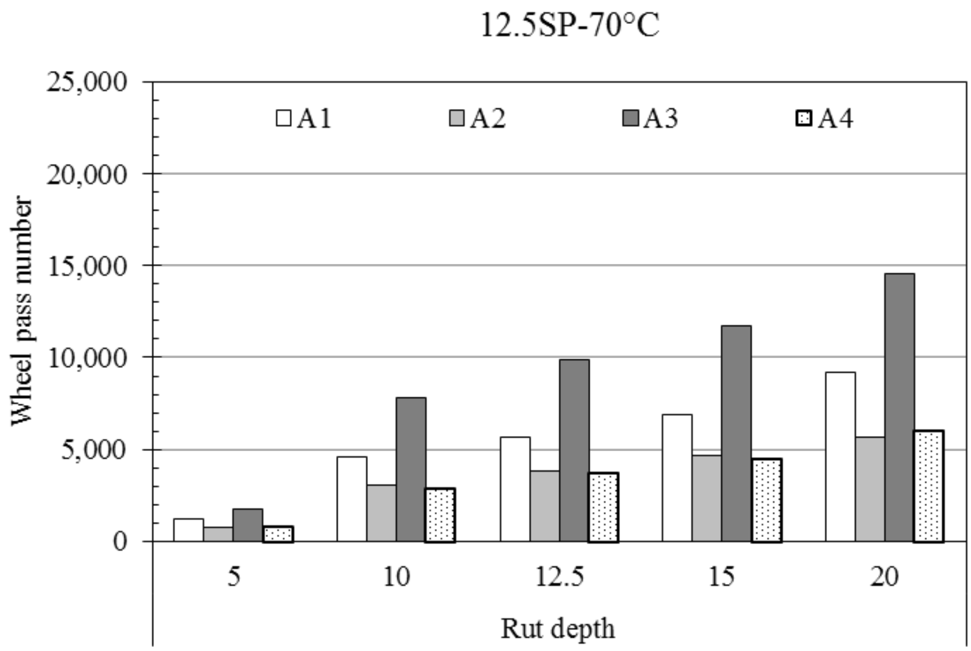


Figure 3-62 Wheel pass number for a specific rut depth for a 12.5 mm mixture at 70°C

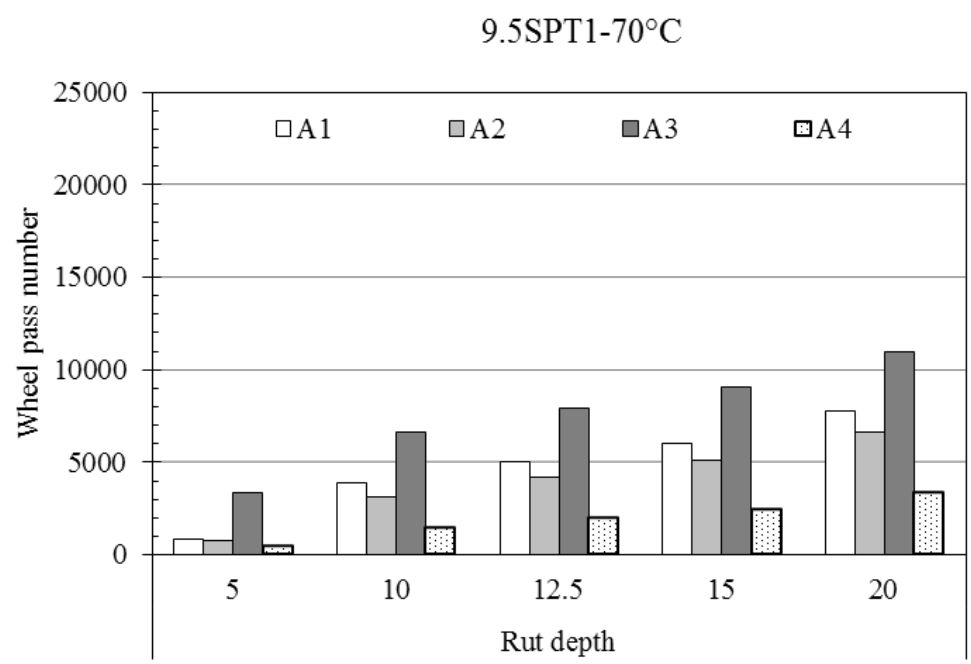


Figure 3-63 Wheel pass number for a specific rut depth for a 9.5 mm T1 mixture at 70°C

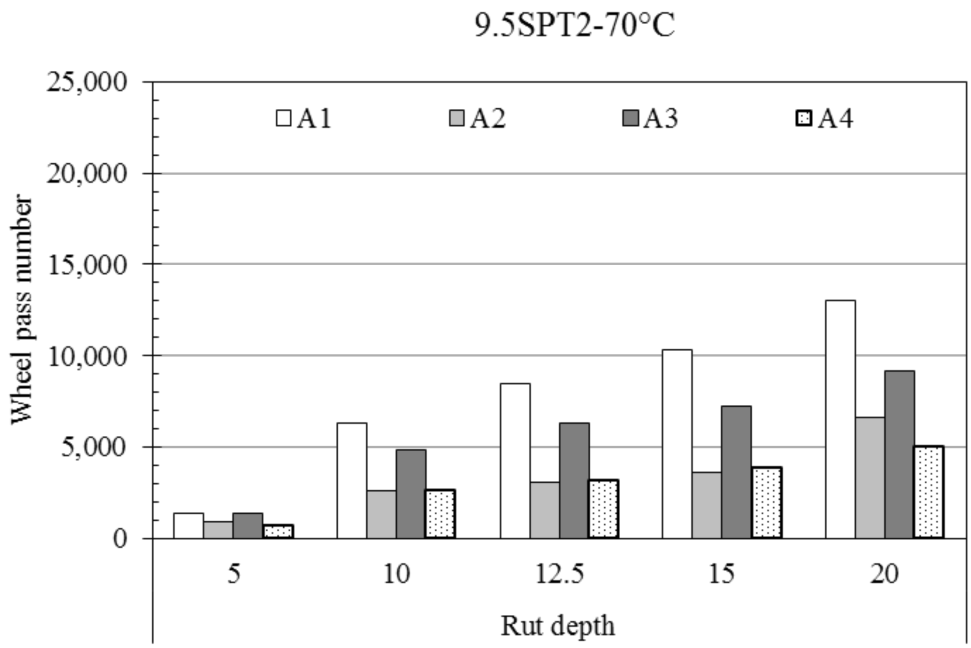


Figure 3-64 Wheel pass number for a specific rut depth for a 9.5 mm T2 mixture at 70°C

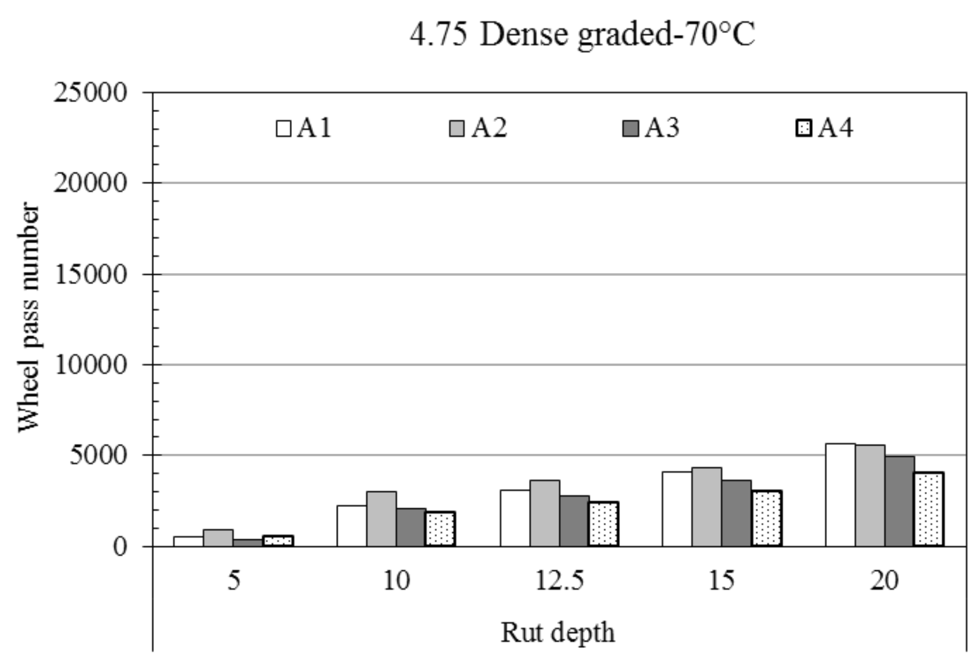


Figure 3-65 Wheel pass number for a specific rut depth for a 4.75 mm mixture at 70°C

3.1.7 Temperature-pass number superposition of rut depth

Trend lines between wheel passes and temperatures were established for selected rut depths for both groups (a group of NMAS 25 and 19 mm and another group of NMAS 12.5, 9.5, and 4.75 mm mixtures). The data used in the curves are the average values for the four sources. Overall, good-to-excellent correlations between temperature and wheel pass were achieved for the selected rut depths of 5, 10, 12.5, 15, and 20 mm. Table 3-27 presents the regression models with the R^2 values obtained from the relationships. Second-order polynomial equations were used for the regression analysis. Table 3-28 contains the wheel pass numbers predicted from the regression models at each of the selected rut depths.

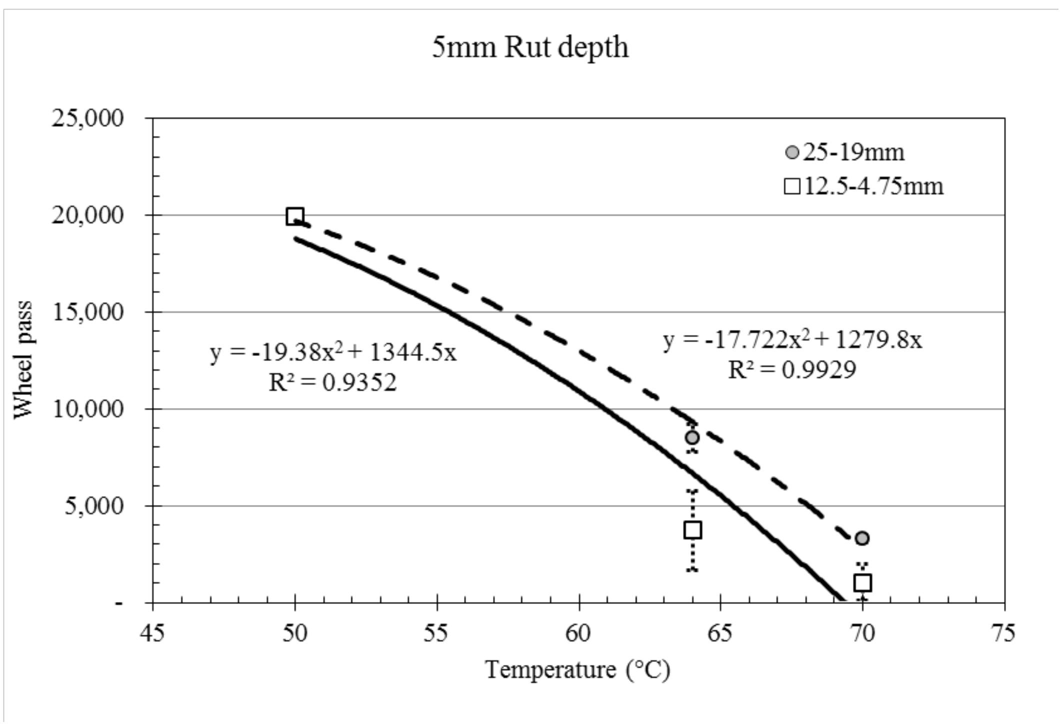


Figure 3-66 Combination of test temperature and pass number to reach 5.0 mm rut depth

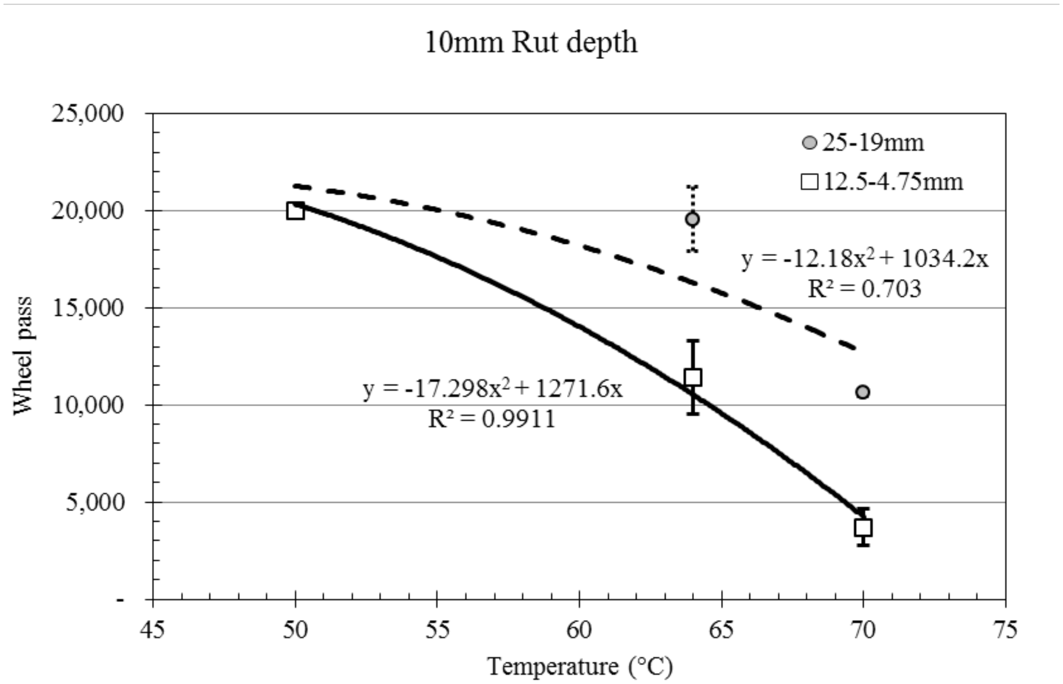


Figure 3**-67 Combination of test temperature and pass number to reach 10.0 mm rut depth**

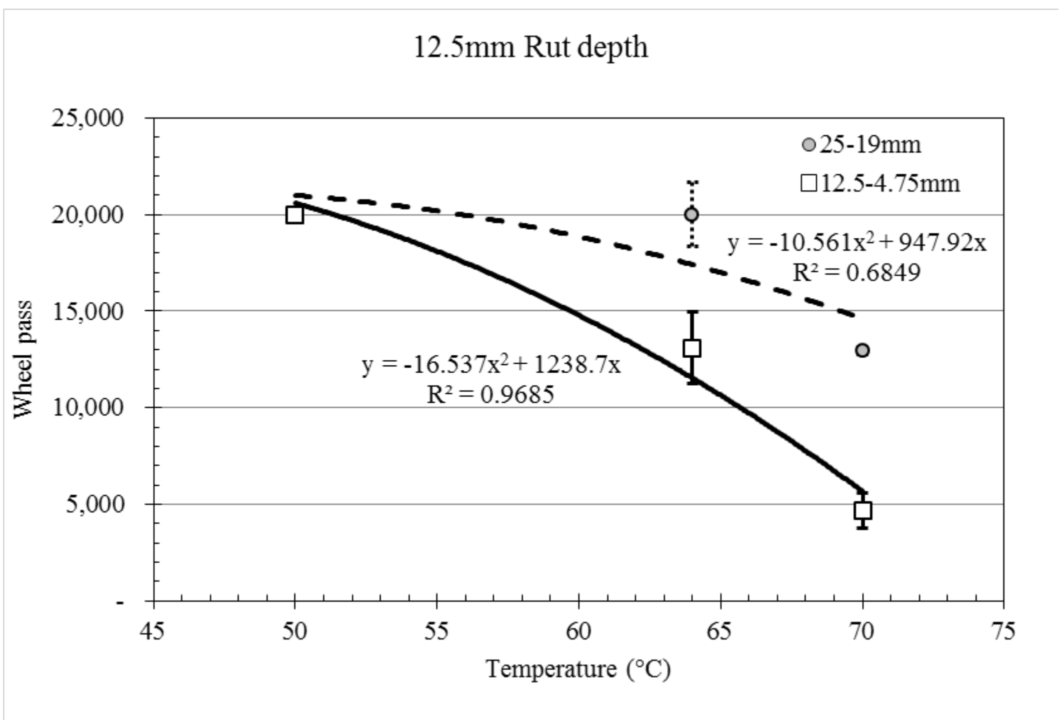


Figure 3-68 Combination of test temperature and pass number to reach 12.5 mm rut depth

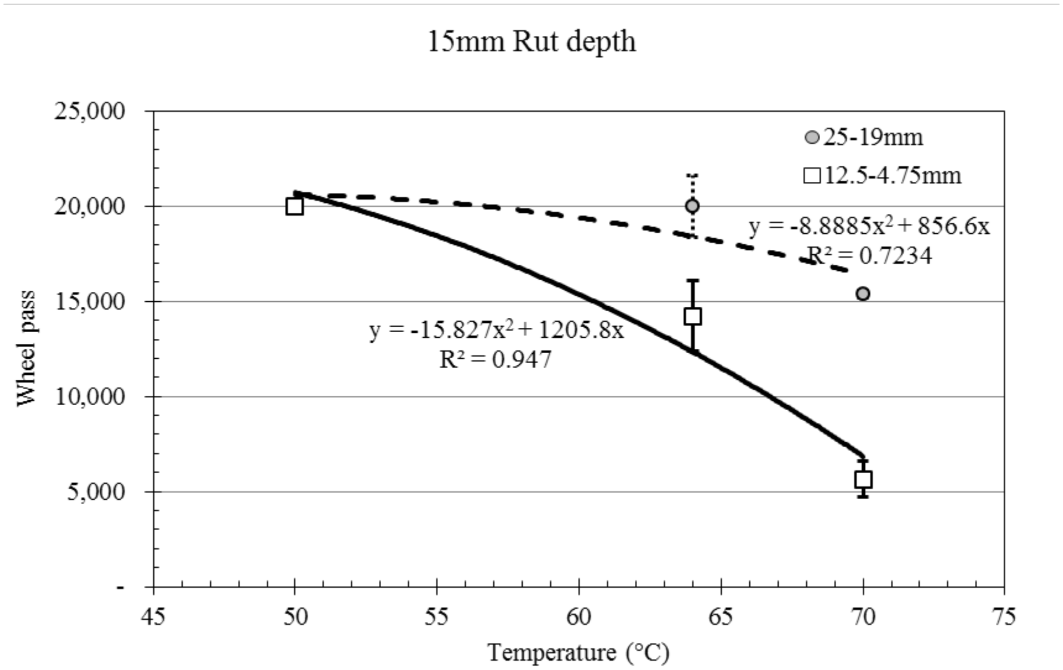


Figure 3-69 Combination of test temperature and pass number to reach 15.0 mm rut depth

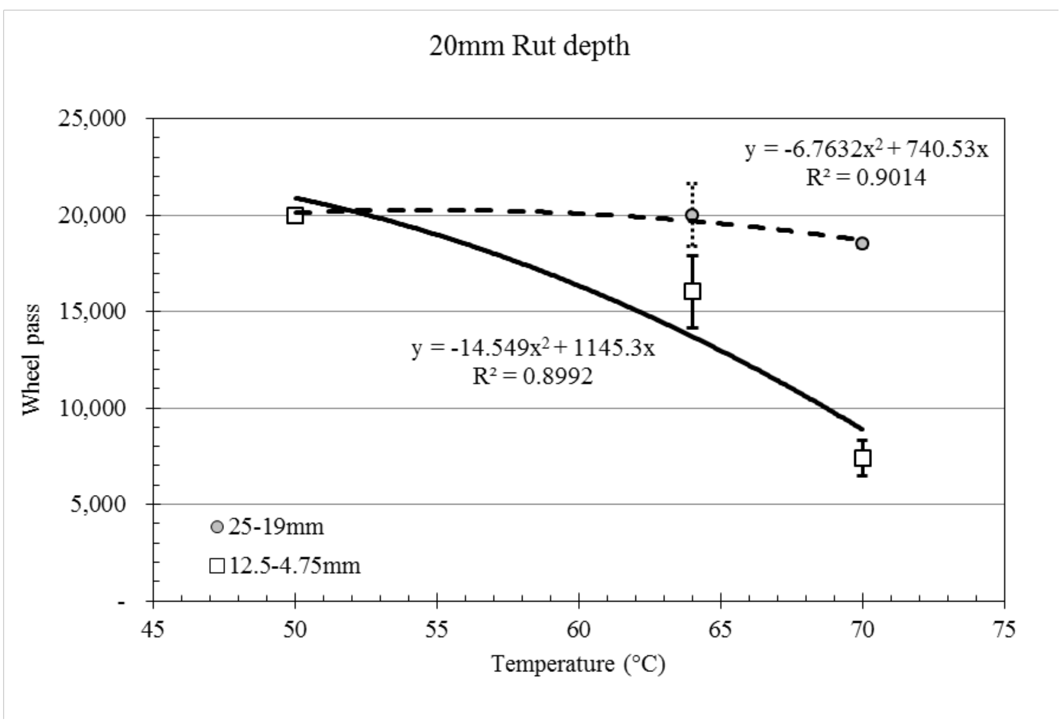


Figure 3-70 Combination of test temperature and pass number to reach 20.0 mm rut depth

Table 3-27 Regression equations for test temperatures (X, °C) and passing number (Y, wheel pass)

Mixture NMAS (mm)	Rut depth (mm)	Formula	R^2
25-19	5.0	$Y = -17.722 X^2 + 1279.8 X$	0.993
	10.0	$Y = -12.180 X^2 + 1034.2 X$	0.703
	12.5	$Y = -10.561 X^2 + 947.92 X$	0.685
	15.0	$Y = -14.772 X^2 + 1150.4 X$	0.856
	20.0	$Y = -6.7632 X^2 + 740.53 X$	0.901
12.5-4.75	5.0	$Y = -19.380 X^2 + 1344.5 X$	0.993
	10.0	$Y = -17.298 X^2 + 1171.6 X$	0.991
	12.5	$Y = -16.537 X^2 + 1238.7 X$	0.968
	15.0	$Y = -15.933 X^2 + 1199.6 X$	0.997
	20.0	$Y = -14.549 X^2 + 1145.3 X$	0.899

These wheel pass numbers, when specific rut depths occurred, were obtained using these regressions at various temperatures. For example, for a rut depth of 10.0 mm to occur, the expected wheel pass number for 19 mm Superpave mixtures is 19,010, and the expected wheel pass number for 9.5 mm Superpave mixtures is 15,562 at a test temperature of 58°C.

Table 3-28 Pass numbers at the specific rut depth at different temperatures (calculated from the master curves)

Mixture NMAS (mm)	Rut depth (mm)	Temperatures (°C)											
		50	54	55	56	57	58	60	62	64	66	68	70
25-19	5.0	19658	17342	16780	16093	15370	14612	12989	11224	9318	7270	5080	2748
	10.0	21260	20330	20037	19719	19377	19010	18204	17300	16300	15201	14005	12112
	12.5	20994	20392	20189	19964	19719	19452	18856	18175	17409	16559	15624	14606
	15.0	20609	20338	20225	20095	19947	19782	18942	18942	18415	17817	17148	16408
	20.0	20119	20267	20270	20260	20237	20199	19915	19915	19692	19414	19083	18697
12.5-4.75	5.0	18775	16091	15323	14516	13671	12787	10902	8862	6668	4318	1813	-
	10.0	20335	18225	17612	16963	16280	15562	14023	12346	10530	8576	6483	4252
	12.5	20593	18668	18104	17507	16877	16214	14789	13231	11541	9719	7765	5678
	15.0	20723	18962	18442	17891	17309	16694	15371	13921	12344	10640	8810	6864
	20.0	20893	19421	18981	18511	18012	17485	16342	15082	13706	12214	10606	8881

The rut depths varied obviously with the NMAS of the mixtures, i.e., mixtures with a large NMAS presented low rut depths and high SIPs. The finding provided the basis for the HWTD test criteria on the mixtures with different NMAS.

The results of wheel pass numbers at specific rut depths, and SIP were used to distinguish the mixture groups according to the NMAS, based on a cluster analysis at 64°C. The analysis is a method for creating a sub-cluster and grouping the expected clusters using the log-likelihood distance measurement. The cluster analysis results showed that centroid based on distance measures was higher for NMAS 25-19 mixtures (Average = 19,404.13, Standard Deviation = 1,137.36) compared to other mixture (12.5, 9.5 and 4.75, Average = 14,331.31, Standard Deviation = 5,786.45). Therefore, it was shown that the NMAS mix type was grouped into a large NMAS mix types (25-19 mm) and other mix types (12.5, 9.5 and 4.75 mm).

For NMAS 25 and 19 mm, results (Table 3-28) indicate that a rut depth of 12.5 mm could be reached at the following wheel pass number and temperature combinations: 19,452 at 58°C, 18,856 at 60°C, 18,175 at 62°C, 17,409 at 64°C, and 16,559 at 66°C. Since the 25 and 19 mm mixtures with unmodified asphalt binder (PG 64-22) were used in a base course layer, the combination of 19,000 at 58°C for HWTD testing of NMAS 25 and 19 mm mixtures is considered.

For NMAS 12.5, 9.5T1, 9.5T2 and 4.75 mm, the results (Table 3-28) indicate that a rut depth of 12.5 mm can be reached at the following wheel pass number and temperature combinations: 16,214 at 58°C, 14,785 at 60°C, 13,231 at 62°C, 11,541 at 64°C, and 9,719 at 66°C.

3.1.8 Influence of wheel pass number on SIP

The correlations between SIP at 50, 64, and 70°C at 20,000 wheel passes were also established for two groups, NMAS 25 and 19 mm, and NMAS 12.5, 9.5, and 4.75 mm since their SIPs differ greatly. Figure 3-71 shows regression analysis results, and Table 3-29 presents the regression models and their coefficients. Using the regression equations, the SIP can be predicted at a given temperature for any wheel pass number. Table 3-31 shows SIP for any temperature.

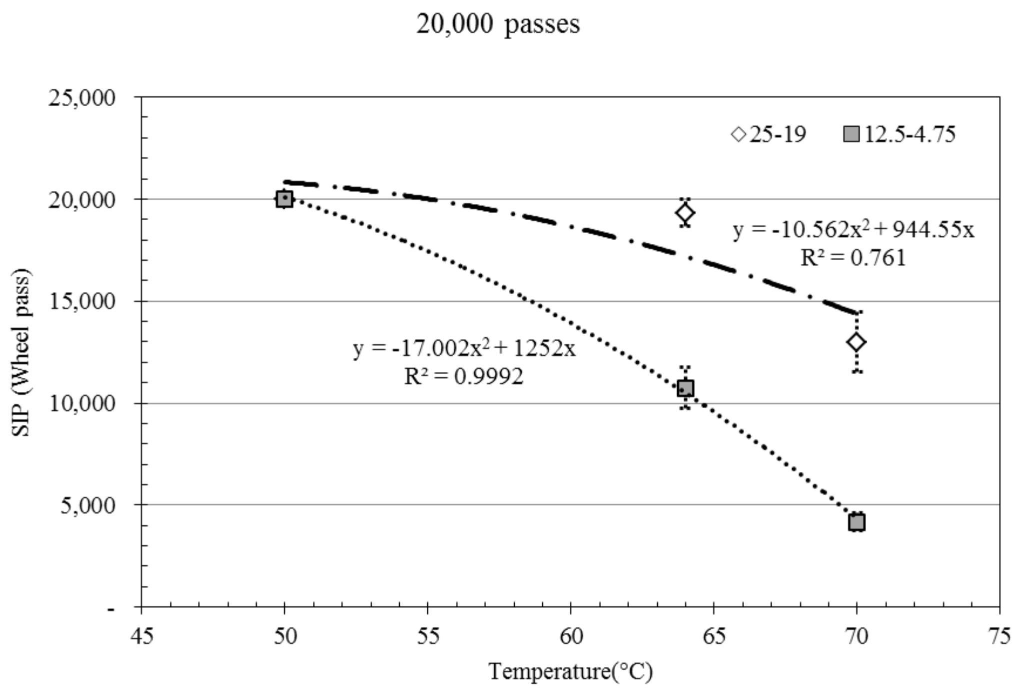


Figure 3-71 Test temperature vs. SIP at 20,000 wheel passes

Table 3-29 Regression equations for test temperatures (X, °C) and SIP (Y, pass)

Mixture (mm)	Passes	Formula	R^2
25-19	20000	$Y = -10.5620 X^2 + 944.55 X$	0.761
12.5-4.75	20000	$Y = -17.002 X^2 + 1252.00 X$	0.9992

Table 3-30 SIP calculated for different temperatures at selected wheel passes

Mixture (mm)	Passes	Temperatures (°C)										
		50	52	54	56	58	60	62	64	66	68	70
25-19	20000	20823	20557	20207	19772	19253	18650	17962	17189	16332	15391	14365
12.5-4.75	20000	20095	19131	18030	16794	15421	13913	12268	10488	8571	6519	4330

3.1.9 HWTD test criteria for unmodified asphalt mixtures

Based on our test results, the following HWTD test conditions were proposed for unmodified asphalt mixtures containing RAP. A maximum allowable rut depth of 12.5 mm is proposed as the criterion as usually selected by other state agencies (Table 1-1).

1) The combination of 19,000 at 58°C for HWTD testing of NMAS 25 and 19 mm mixtures is considered. Using Table 3-28, criteria, SIP was obtained at 19,000 passes at 58°C.
2) The combination of 16,000 at 58°C for HWTD testing of NMAS 12.5, 9.5T1, 9.5T2 and 4.75 mm mixtures is recommended. The SIP was obtained at 15,000 passes at 58°C.

3.2 Modified Asphalt Mixtures

This section describes HWTD test results in terms of the rutting resistance and anti-stripping properties of modified asphalt mixtures with RAP. The same test methods as used in unmodified asphalt mixtures and conditions were applied.

3.2.1 Tested profiles of modified asphalt mixtures

3.2.1.1 Testing temperature of 50°C

Figures 3-72 to 3-74 show rut depths over wheel passes for the four modified asphalt mixtures (A1, A2, A3, and A4) at 50°C. The results clearly indicate that the modified mixtures have a strong resistance to rutting at this temperature. At 20,000 wheel passes, the rut depths were less than 2.0 mm. SMA mixtures with 15% RAP showed a higher rut depth than Superpave modified mixtures with 25 and 30% RAP for all four sources (Fig. 3-57). SIP did not appear even with more than 20,000 passes for all the modified mixtures tested.

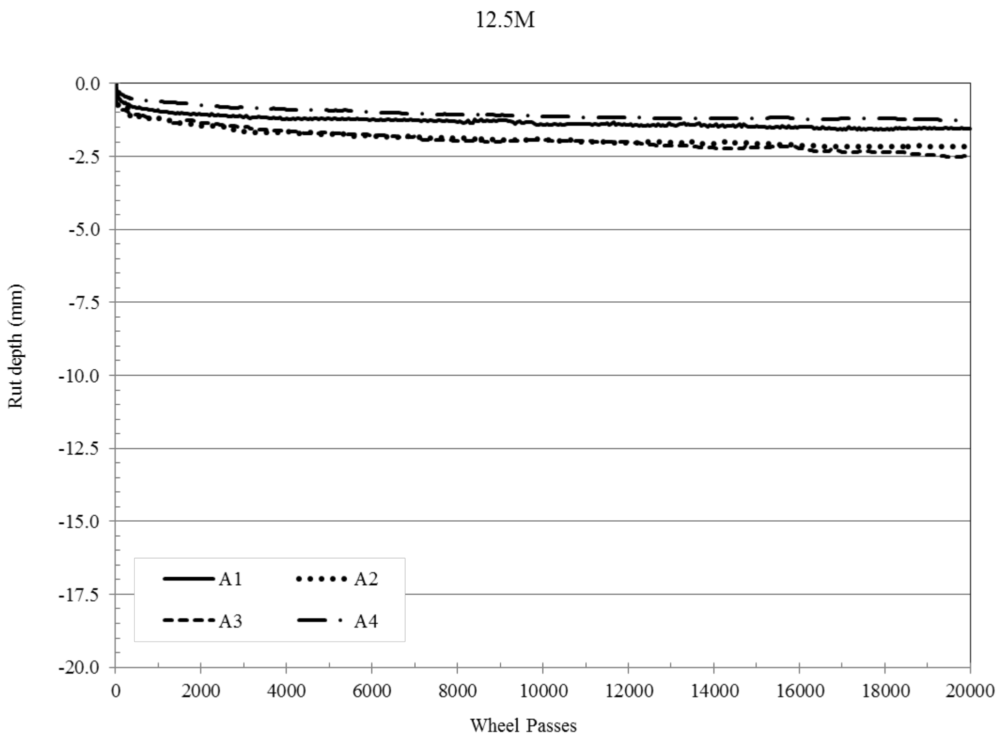


Figure 3-72 Rut depth profiles of modified 12.5 mm SP mixtures at 50°C

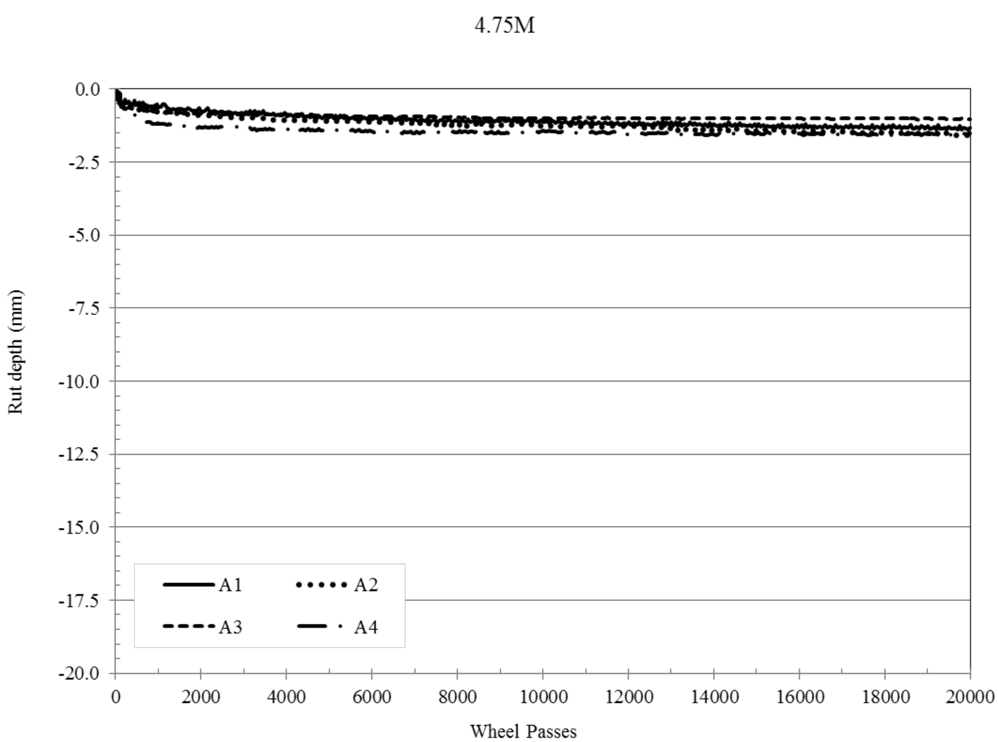


Figure 3-73 Rut depth profiles of modified 4.75 mm SP mixtures at 50°C

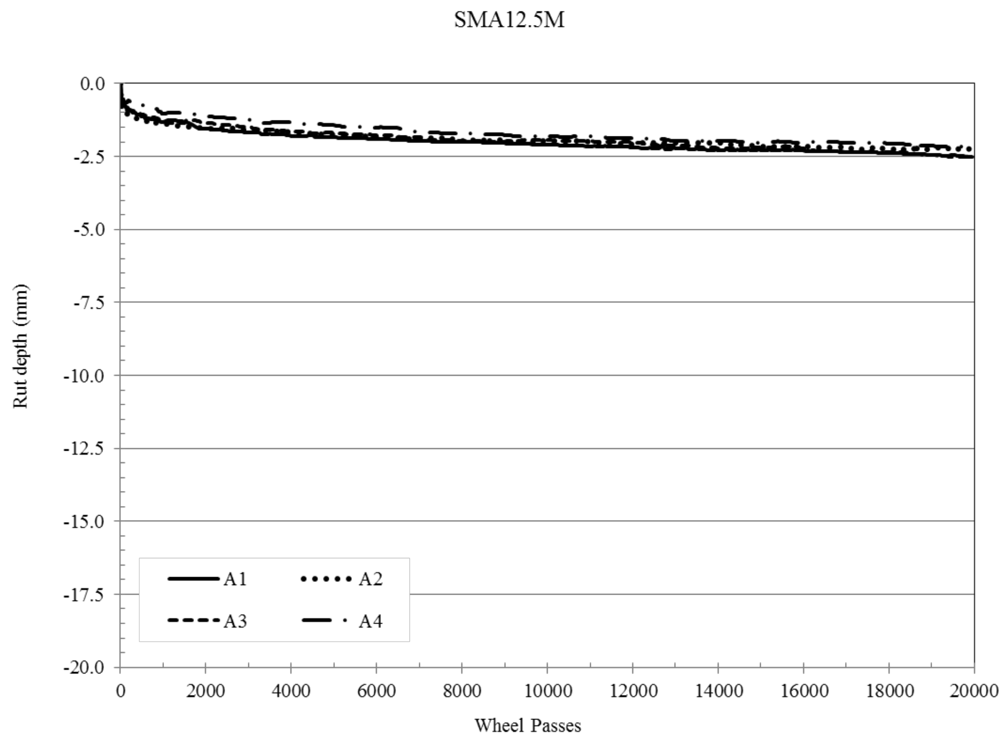


Figure 3-74 Rut depth profiles of modified 12.5 mm SMA mixtures at 50°C

3.2.1.2 Testing temperature of 64°C

Figures 3-75 to 3-77 show the HWTD test results for modified asphalt mixtures at 64°C. Naturally, there is more rutting at this temperature than at 50°C, but the final rut depths are still low, less than 6.0 mm at 20,000 passes. Rut depths in SMA mixtures with 15% RAP showed higher rut depth than that of 12.5 mm Superpave modified mixtures and 4.75 dense-graded modified mixtures. The SIP did not occur at even more than 20,000 passes for all the SMA and Superpave modified mixtures.

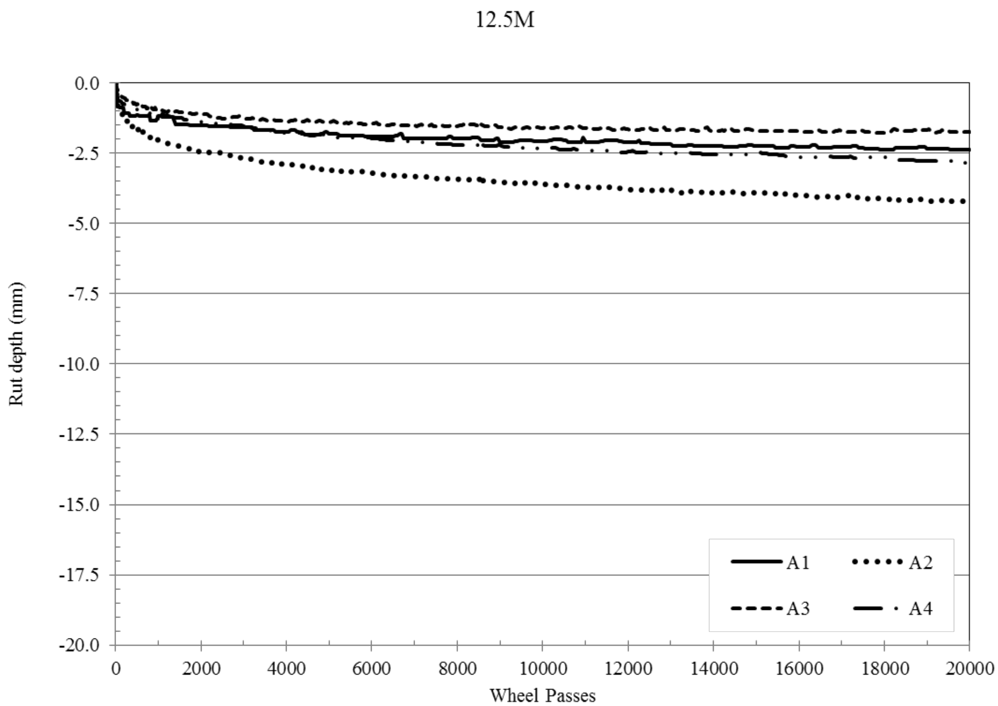


Figure 3-75 Rut depth profiles of modified 12.5 mm SP mixtures at 64°C

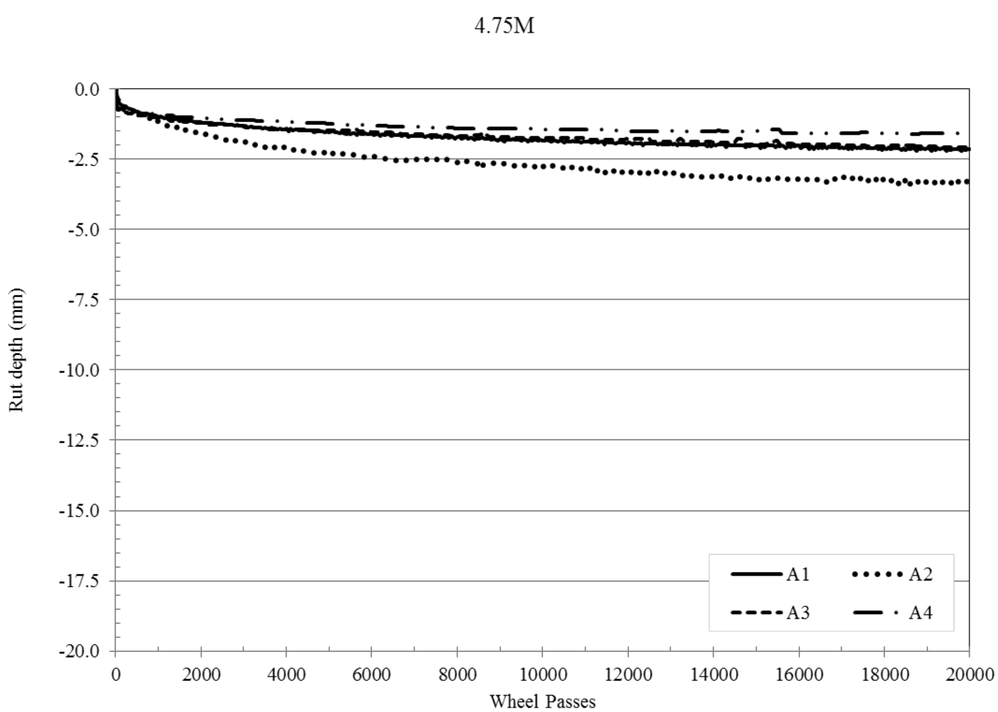


Figure 3-76 Rut depth profiles of modified 4.75 mm SP mixtures at 64°C

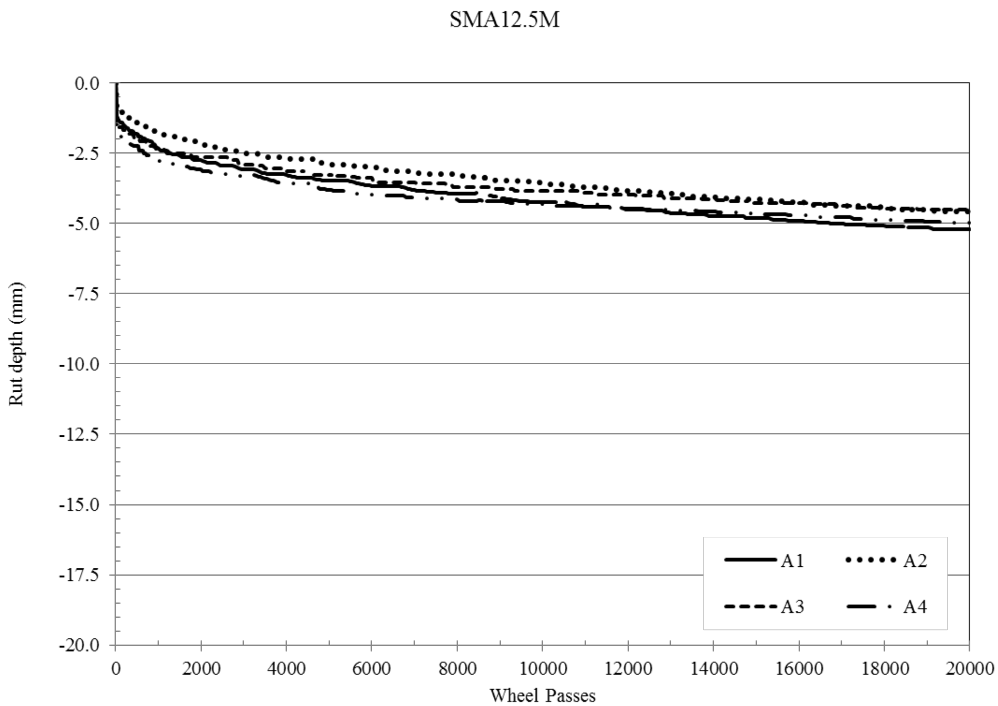


Figure 3-77 Rut depth profiles of modified 12.5 mm SMA mixtures at 64°C

3.2.1.3 Testing temperature of 70°C

Figures 3-78 to 3-80 show the rut depth profiles by wheel pass of modified mixtures at 70°C. A little more rutting is observed at this temperature. For Superpave mixtures, rut depths were less than 8.0 mm after 20,000 wheel passes. SIP did not appear. The SMA mixtures had deeper ruts. These trends held for all the modified asphalt mixtures, regardless of NMAS, RAP content, source and temperature.

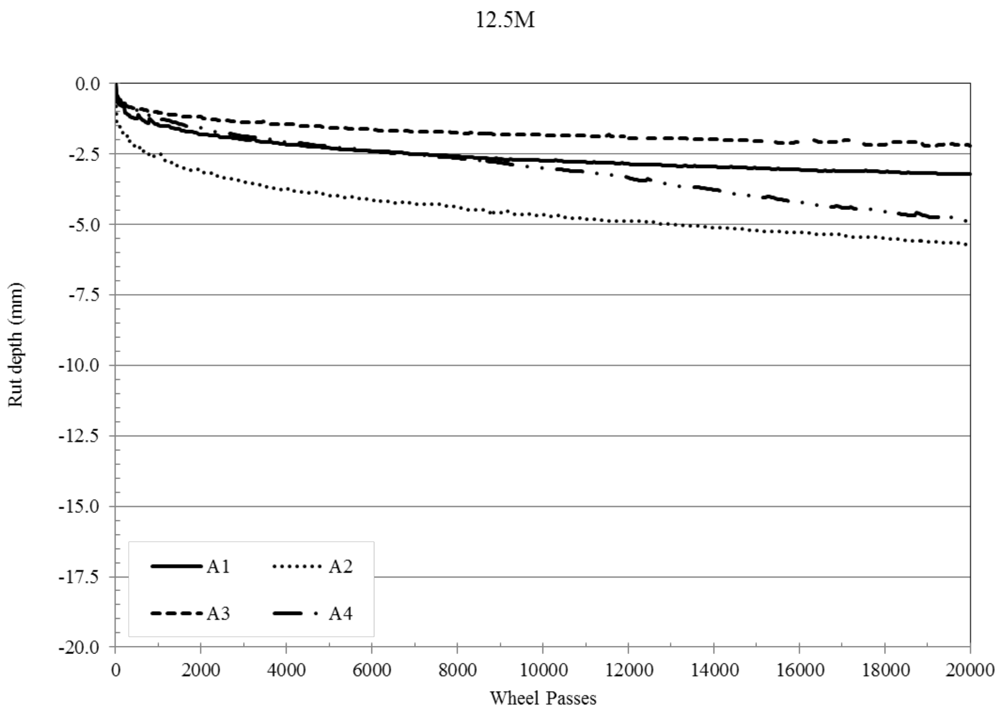


Figure 3-78 Rut depth profiles of modified 12.5 mm SP mixtures at 70°C

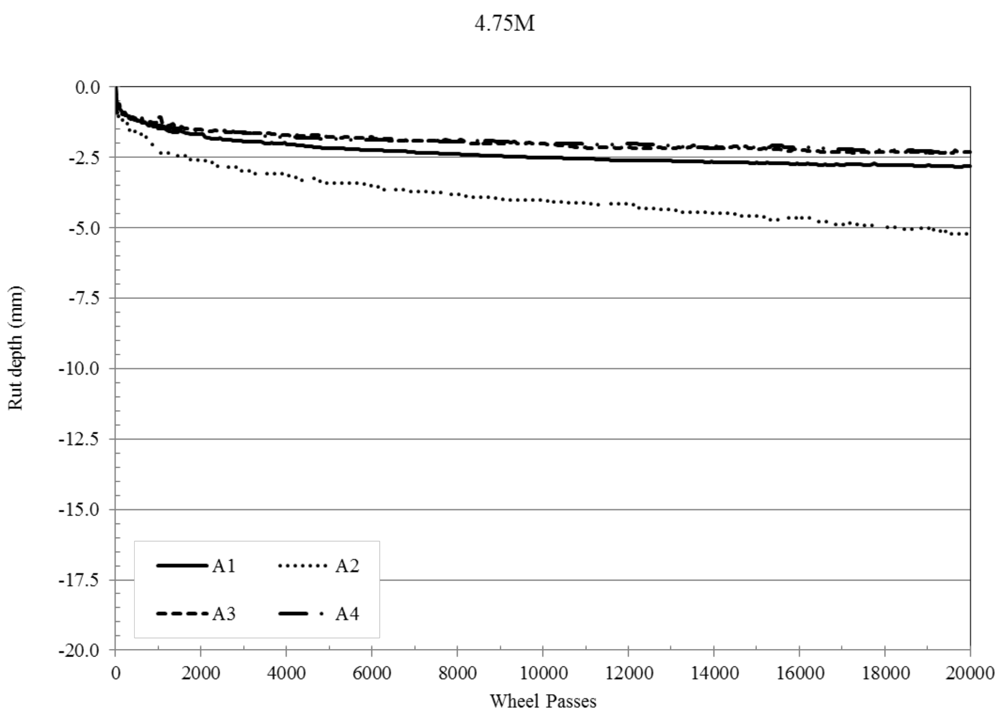


Figure 3-79 Rut depth profiles of modified 4.75 mm SP mixtures at 70°C

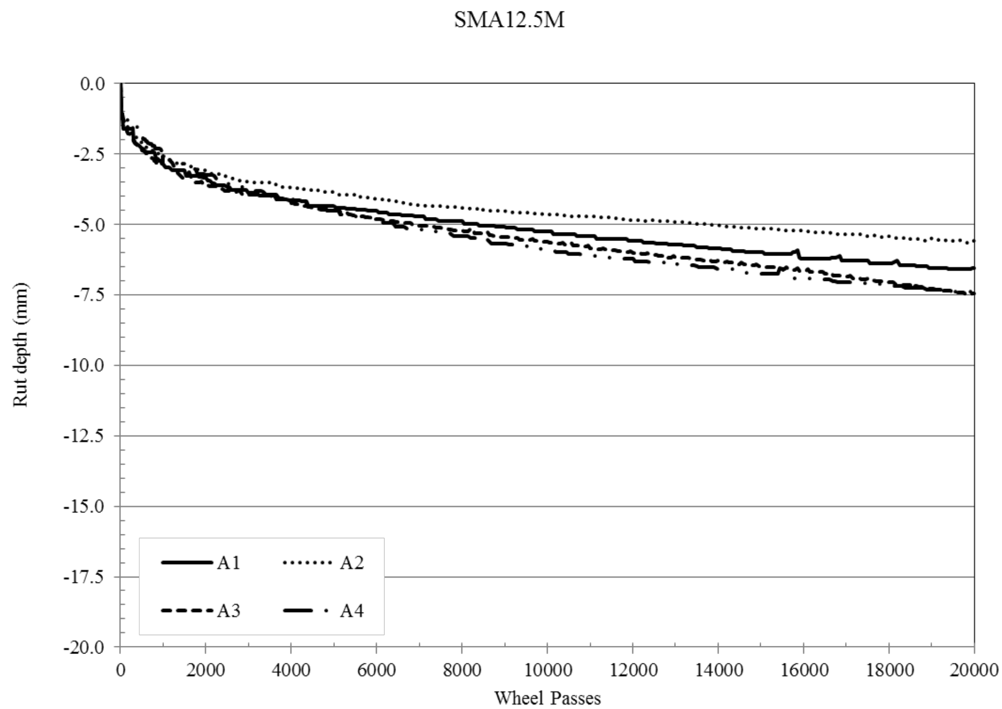


Figure 3-80 Rut depth profiles of modified 12.5 mm SMA mixtures at 70°C

3.2.2 Rut depth

Table 3-31 summarizes the final rut depth results of modified mixtures for all four sources at the three temperatures. As indicated in the previous section, overall, the rut depths of all modified mixtures are quite low. The SMA mixtures showed lower rutting resistance than the Superpave mixtures. More discussion on this result follows.

Table 3-31 Test results on rut depth at 50, 64 and 70°C

Sources / Mixtures		Rut depth (mm) at passing 20,000					
		A1 (30R)	A2 (30R)	A3 (25R)	A4 (25R)	Average	Standard Deviation
50°C	12.5M30R	1.58	2.16	1.01	1.26	1.50	0.43
	4.75M30R	1.65	1.60	1.05	1.56	1.47	0.24
	12.5SMA15R	2.53	2.24	2.51	2.16	2.36	0.16
64°C	12.5M30R	2.36	4.24	1.76	2.82	2.80	0.92
	4.75M30R	2.20	3.40	2.06	2.05	2.43	0.56
	12.5SMA15R	5.21	5.48	4.51	4.95	5.04	0.36
70°C	12.5M30R	3.22	5.87	2.20	4.87	4.04	1.42
	4.75M30R	2.84	5.20	2.36	2.30	3.18	1.19
	12.5SMA15R	6.57	5.79	7.48	7.38	6.81	0.68

Figures 3-81 to 3-83 show the rut depths of modified asphalt mixtures from the four sources at 50, 64, and 70°C. The test results at 50°C for modified 12.5 mm Superpave mixtures were very low. The average rut depth was only 1.5 mm with a standard deviation of 0.43 mm. As the increase of the testing temperature to 64°C from 50°C, rut depth slightly increased. The minimum rut depth was 1.76 mm, and the maximum was 4.24 mm. At 70°C, rut depth increases a little more; the minimum was 2.2 mm, and the maximum was 5.87 mm. It is noted that the maximum rut depths were from the A2 mixtures. The reason for this phenomenon may be the high asphalt content in the RAP and the overall asphalt content in the mixtures.

The modified 4.75 mm Superpave mixtures had an average rut depth of 1.47 mm with a standard deviation of 0.24 mm. At 64°C, the modified 4.75 mm mixtures had an average rut depth of 2.31 mm with a standard deviation of 0.67 mm. At 70°C, the deepest rut was 5.2 mm in A2 mixtures. Again, the high asphalt content in the mixtures including RAP may be one of the reasons to cause the high rutting.

Modified 12.5 mm SMA mixtures had deeper ruts than the modified 12.5 mm Superpave and 4.75 mm dense-graded mixtures, regardless of source. Rut depths averaged 2.36, 5.04, and 6.81 mm at 50, 64, and 70°C, respectively, with standard deviations of 0.16, 0.36, and 0.68 mm, respectively. The standard deviation of rut depth for all mixtures consistently increased up to 70°C, and between Superpave and SMA, and a greater variance was found in the SMA tests.

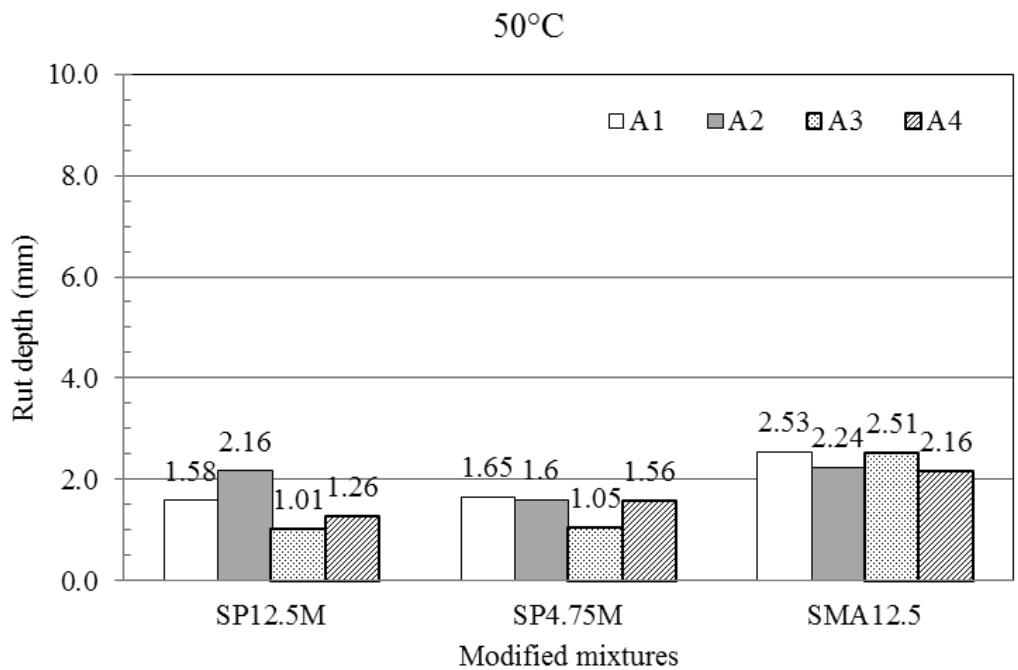


Figure 3-81 Rut depth of modified mixtures at 50°C

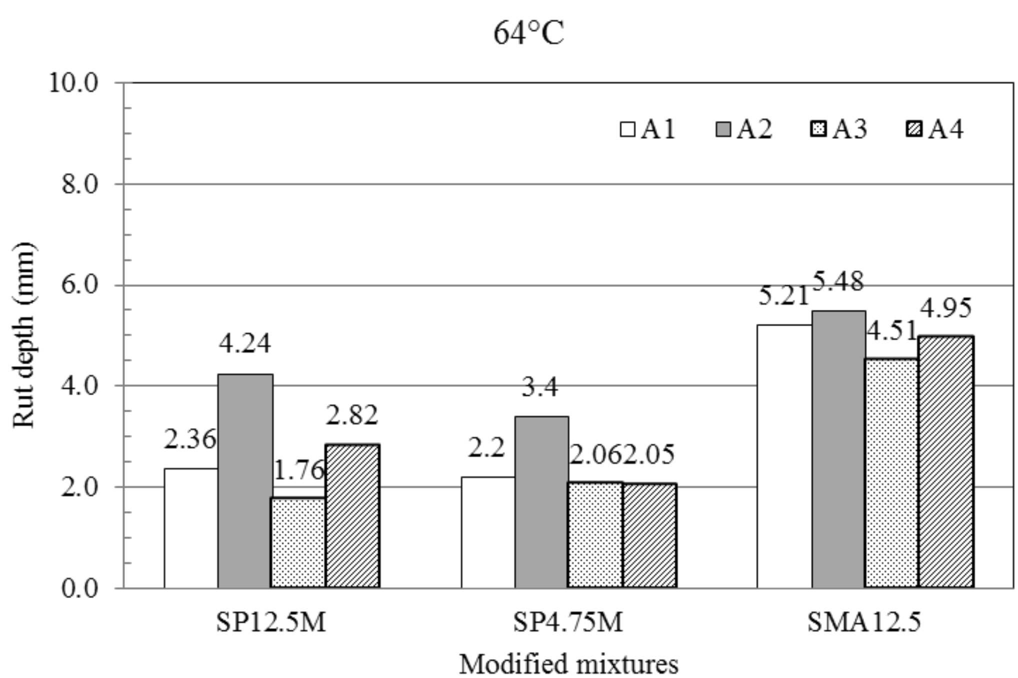


Figure 3-82 Rut depth of modified mixtures at 64°C

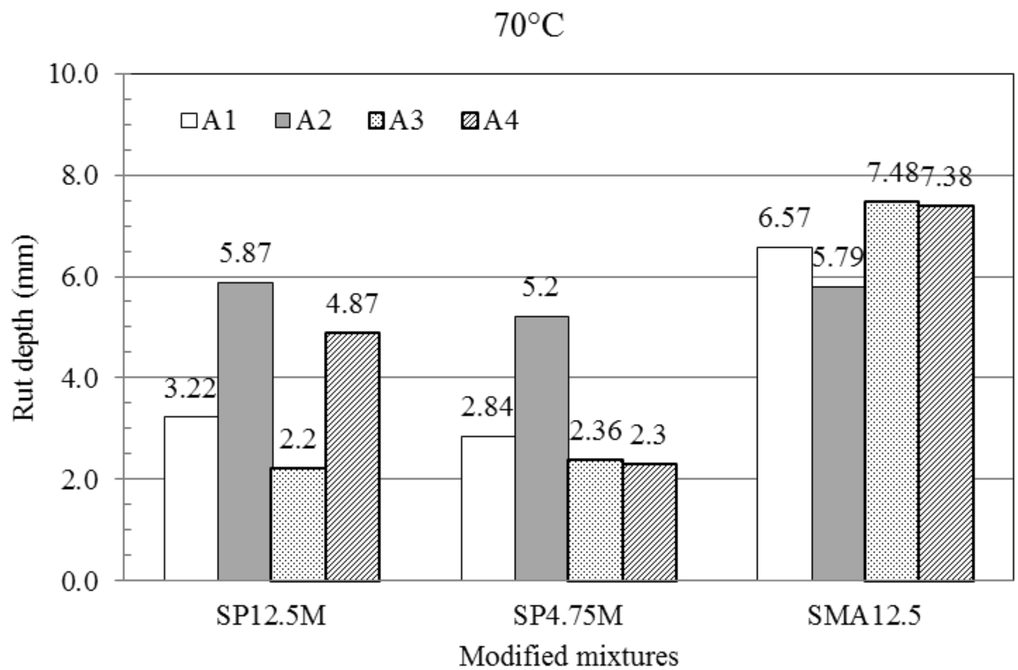


Figure 3-83 Rut depth of modified mixtures at 70°C

3.2.3 SIP

Table 3-32 shows the SIPs of modified asphalt mixtures. The SIP “>20,000” indicates that SIP did not occur on the profiles with 20,000 wheel passes. SIP could not be found for any of the modified asphalt mixtures because it did not occur within 20,000 passes. No further analysis was conducted.

Table 3-32 SIP test results of at 50, 64 and 70°C

Mixtures \ Sources		SIP			
		A1 (30R)	A2 (30R)	A3 (25R)	A4 (25R)
12.5M	50°C	>20,000	>20,000	>20,000	>20,000
	64°C	>20,000	>20,000	>20,000	>20,000
	70°C	>20,000	>20,000	>20,000	>20,000
4.75M	50°C	>20,000	>20,000	>20,000	>20,000
	64°C	>20,000	>20,000	>20,000	>20,000
	70°C	>20,000	>20,000	>20,000	>20,000
12.5SMA15R	50°C	>20,000	>20,000	>20,000	>20,000
	64°C	>20,000	>20,000	>20,000	>20,000
	70°C	>20,000	>20,000	>20,000	>20,000

3.2.4 HWTD test criteria for modified asphalt mixtures

As indicated in Table 1-1, several other DOTs adopted 12.5 mm as the maximum allowable rut depth when HWTD tests were used to evaluate rutting resistance and anti-stripping properties for both unmodified and modified mixtures. Based on the test results for modified mixtures containing RAP shown above, the recommendations are as follows:

1) A test temperature of 64°C and 20,000 wheel passes are recommended for achieving no more than a 6.0 mm rut depth for modified 12.5 mm SMA, 12.5 mm Superpave, and 4.75 mm dense-graded mixtures.
2) The criterion for minimum allowable the SIP is more than 20,000 passes at 64°C, i.e., no SIP is allowed to appear with 20,000 passes.

Chapter 4 Modification of the HWTD test criteria of Asphalt Mixtures Containing RAP with Preheating

Virgin aggregates, asphalt binders and RAP mixtures without drying and preheating are mixed together in a drum in mix plants everywhere in the USA. In the laboratory, several referred studies suggest that RAP mixtures be oven-dried at 60°C for 12 hours before mixing to remove any moisture, and then oven-heated at 110°C for less than two hours to improve the mixing with new aggregates (35, 36, 37).

This chapter has two aims: 1) to modify the results of previous chapter that the testing samples were made with a preheating process for RAP after examining the effect difference between asphalt plant practice and the RAP heating; and 2) to offer some insight into how inappropriate it is to preheat the RAP in the laboratory given that this is not what happens in the real world, i.e., the preheating effect on the selected properties of asphalt mixtures tested by HWTD.

To this end, recovered RAP binders from the RAP mixtures with and without preheating were evaluated by DSR. In addition, the asphalt mixtures containing RAP with and without preheating were tested by HWTD at three different temperatures of 50, 64 and 70°C.

4.1 Effects of Preprocessing on the Recovered RAP Binder

RAP binders from A2 and A3 were extracted by the Abson method after the RAPs were subjected to two different processes: air dried at ambient temperature in the lab without preheating, and oven dried at 60°C for 12 hours and preheating at 110°C for 2 hours. The extracted RAP binders were tested by DSR. Tables 4-1 and Figure 4-1 show the results.

$G^*/\sin\delta$ of the recovered binder using preheating process of RAP was higher than that from no heating. The difference of the values of $G^*/\sin\delta$ from the RAP binders between using the preheating and no heating process got smaller as the testing temperature was raised to 76°C. The values of the G*/sin δ using preheating process were 20, 13 and 12% higher than that using no preheating process at 58, 64 and 70°C, respectively.

Table 4-1 DSR results (G*/sin δ) using recovered binder

Test temp. (°C)	RAP, dried in laboratory at room temperature but no preheating		RAP, heated @ 110°C for 2 hrs after drying at 60°C for 12 Hrs.	
	A2	A3	A2	A3
58	3.76	4.52	5.35	4.75
64	2.64	3.01	3.19	3.22
70	1.56	1.86	1.85	1.98
76	0.98	1.12	1.08	1.24

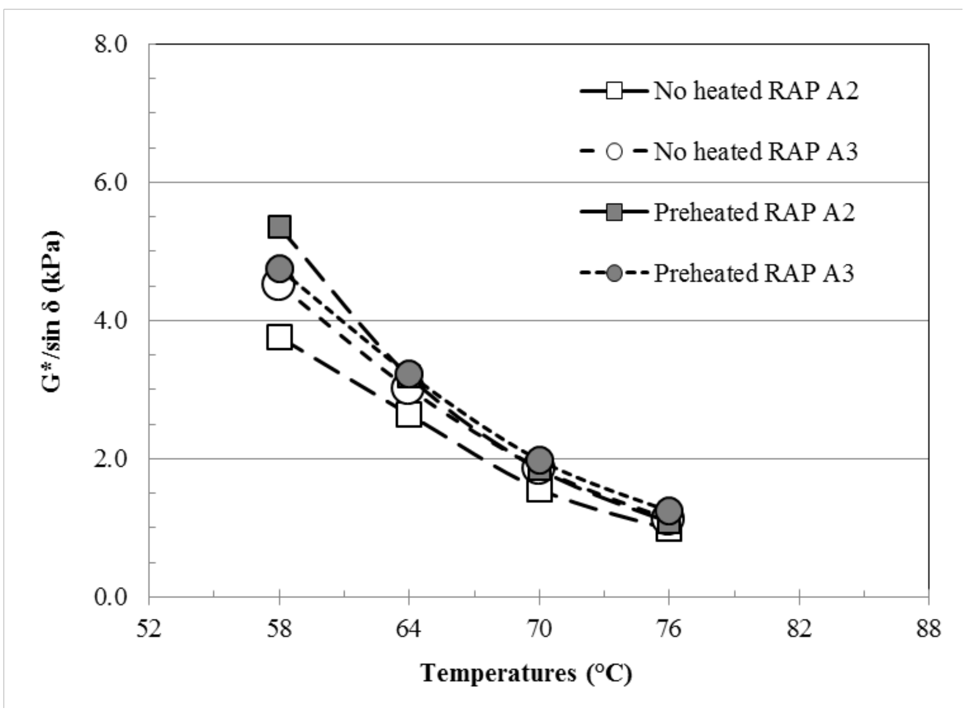


Figure 4-1 G*/sin δ of recovered binder with pre-process

4.2 Effects of Preprocessing on Asphalt Mixtures Containing RAP

The asphalt mixtures were manufactured following the process shown in Figure 2-9. Tests were conducted at 50, 64, and 70°C.

4.2.1 Test results at 50°C

4.2.1.1 Profiles of rut depth vs. wheel passes at 50°C

Figures 4-2 to 4-3 showed the rut depth profile with and without preheating process for unmodified asphalt mixtures at test temperature of 50°C. The mixture with both aggregate source of A2 and A3 presented low rut depth with preheating process. The mixtures of aggregate source for A3 showed lower rut depth than aggregate source of A2 both with and without preheating process. The mixtures of NMAS 19 mm showed lower rut depth than the mixtures of NMAS 4.75 mm under both conditions with and without preheating process.

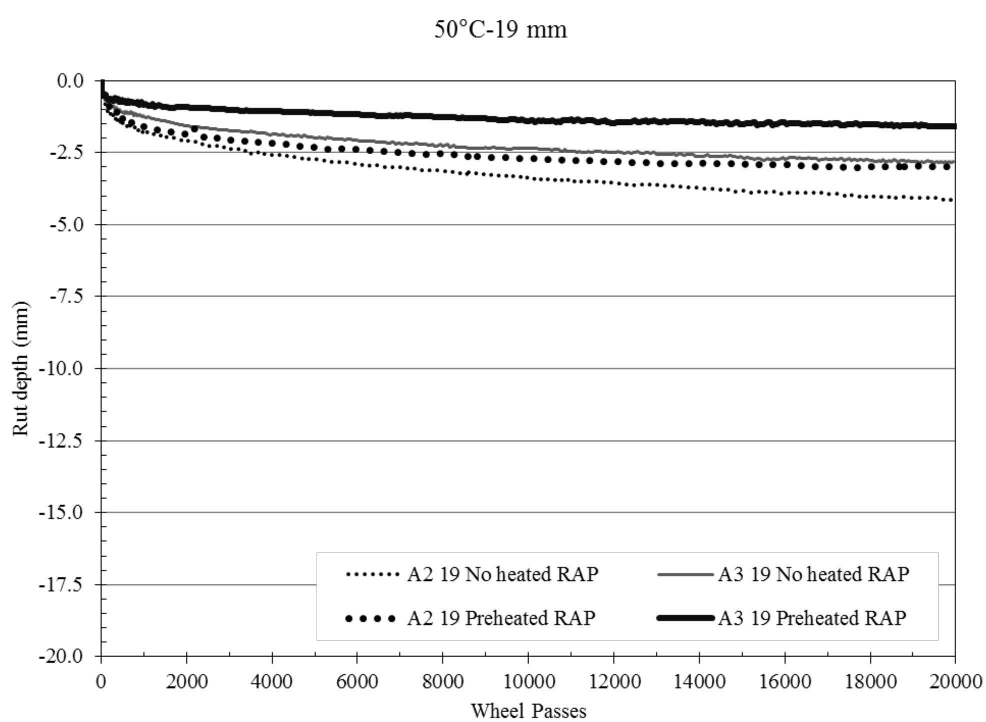


Figure 4-2 Profiles of 19 mm mixtures at 50°C with and without preheating RAP

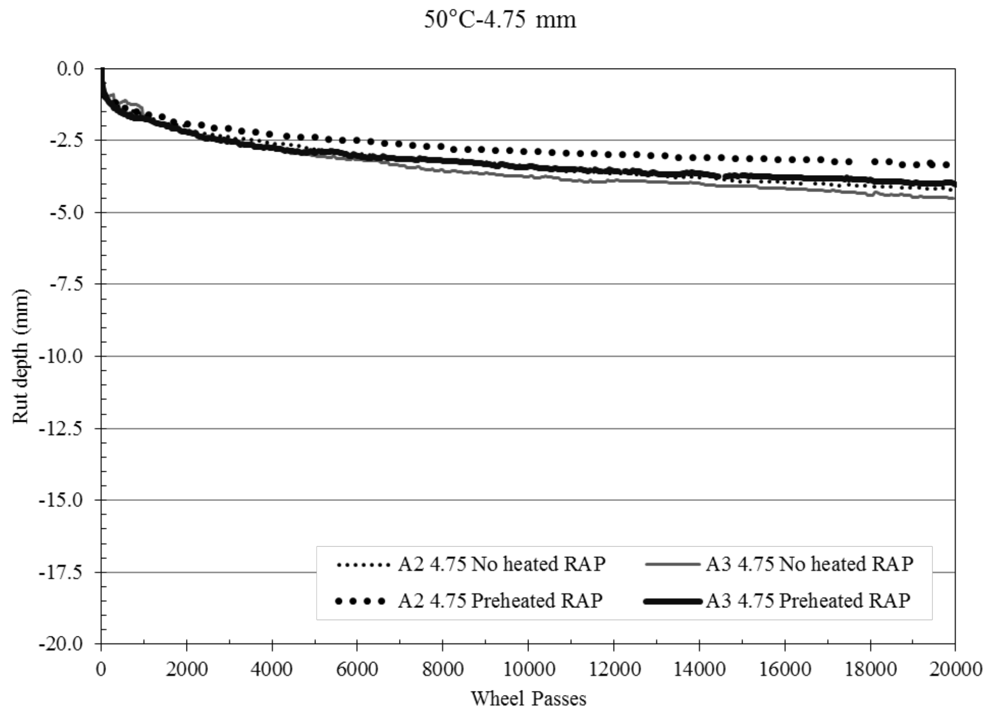


Figure 4-3 Profiles of 4.75 mm mixtures at 50°C before and after preheating RAP

4.2.1.2 Rut depth and SIP

Table 4-2 and Figures 4-4 to 4-5 list the testing results of all the mixtures discussed at 50°C. A general finding is that the preheating process of RAP makes for lower rut depths than those of the RAP without preheating. The rate, in Table 4-3, was defined by the rut depth for the mixtures with preheating RAP to that of no heating. The wheel passes are all exceeding the limit set for this test, i.e., 20,000 for any specified rut depth; consequently, there is no SIP within the 20,000 load passes, Figure 4-6. In other words, the SIP was at least higher than 20,000 wheel passes.

Table 4-2 Rut depth and SIP at 50°C before and after preheating

Mix Type		19 mm Superpave						4.75 mm Dense-graded					
Sources		A2			A3			A2			A3		
Pre-process		No heated RAP	Preheated RAP	Rate	No heated RAP	Preheated RAP	Rate	No heated RAP	Preheated RAP	Rate	No heated RAP	Preheated RAP	Rate
Rut depth @ wheel passes	20000	4.22	3.17	0.75	3.58	1.58	0.44	4.20	3.33	0.79	4.50	4.02	0.89
	18000	4.04	3.12	0.77	3.32	1.46	0.44	3.89	3.17	0.81	4.32	3.86	0.89
	15000	3.81	3.02	0.79	3.12	1.33	0.43	3.85	3.11	0.81	4.00	3.72	0.93
	12000	3.54	2.97	0.84	3.05	1.30	0.43	3.33	2.98	0.89	3.90	3.56	0.91
	10000	3.39	2.89	0.85	2.93	1.20	0.41	3.19	2.90	0.91	3.76	3.38	0.90
Wheel pass No. @ selected rut depth (mm)	5.0	>20000	>20000	-	>20000	>20000	-	>20000	>20000	-	>20000	>20000	-
	10.0	>20000	>20000	-	>20000	>20000	-	>20000	>20000	-	>20000	>20000	-
	12.5	>20000	>20000	-	>20000	>20000	-	>20000	>20000	-	>20000	>20000	-
	15.0	>20000	>20000	-	>20000	>20000	-	>20000	>20000	-	>20000	>20000	-
	20.0	>20000	>20000	-	>20000	>20000	-	>20000	>20000	-	>20000	>20000	-
SIP		>20000	>20000	-	>20000	>20000	-	>20000	>20000	-	>20000	>20000	-
Rut depth at SIP		-	-	-	-	-	-	-	-	-	-	-	-

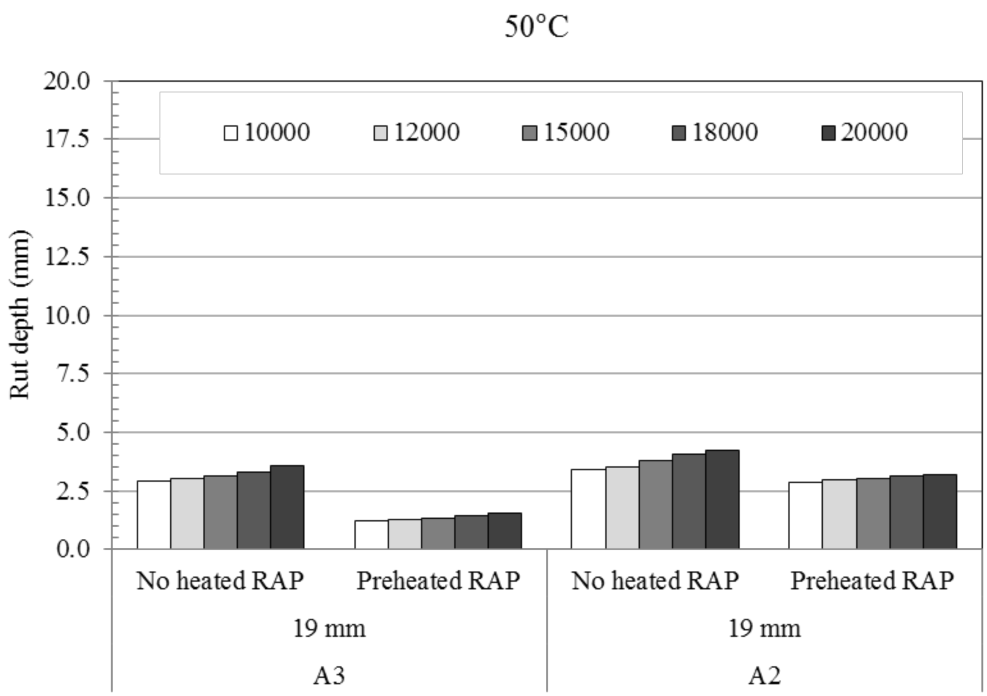


Figure 4-4 Rut depth of 19 mm mixtures at 50°C before and after preheating RAP

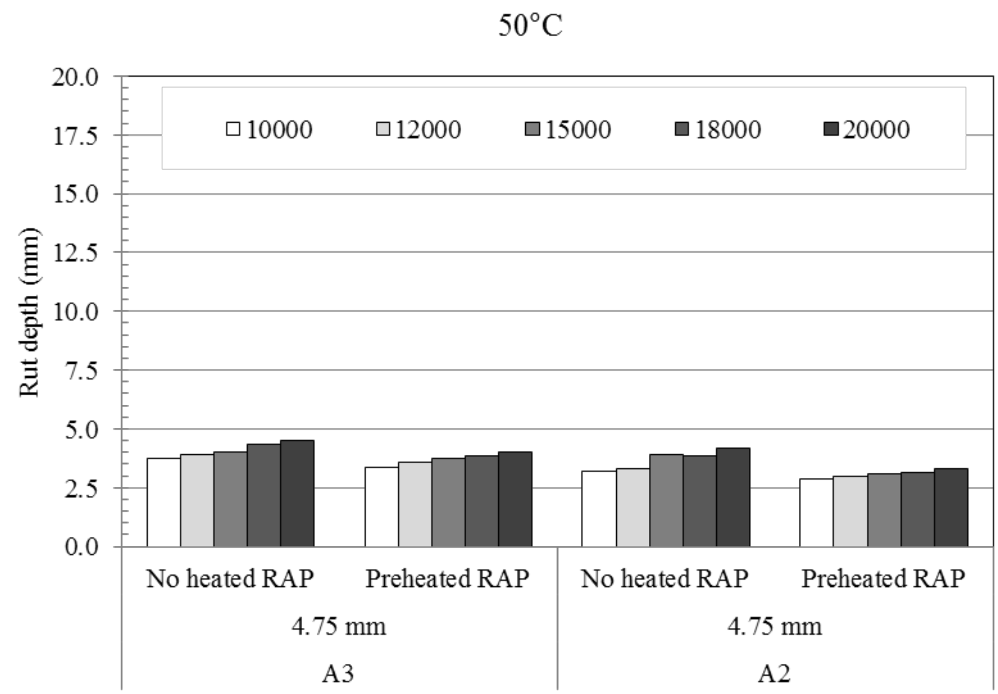


Figure 4-5 Rut depths of 4.75 mm mixtures at 50°C before and after preheating RAP

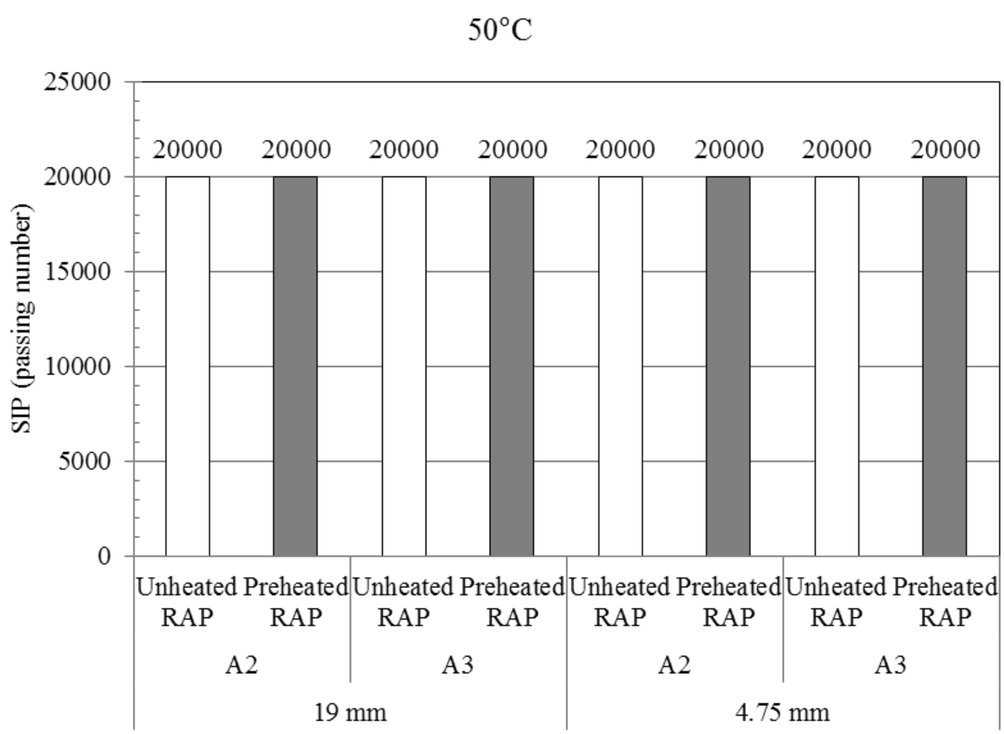


Figure 4-6 SIP at 50°C with/without preheating RAP

4.2.2 Test results at 64°C

4.2.2.1 Profiles of rut depth vs. wheel pass at 64°C

Figures 4-7 to 4-8 show the rut depth profile with and without preheating process at 64°C. The mixtures for both aggregate sources of A2 and A3 presented lower rut depths with preheating process than no preheating. The mixtures for aggregate source of A3 showed lower rut depths than those of aggregate source of A2 both with and without preheating process. The mixtures of NMAS 4.75 mm showed higher rut depth than those of NMAS 19 mm under both conditions with and without preheating process.

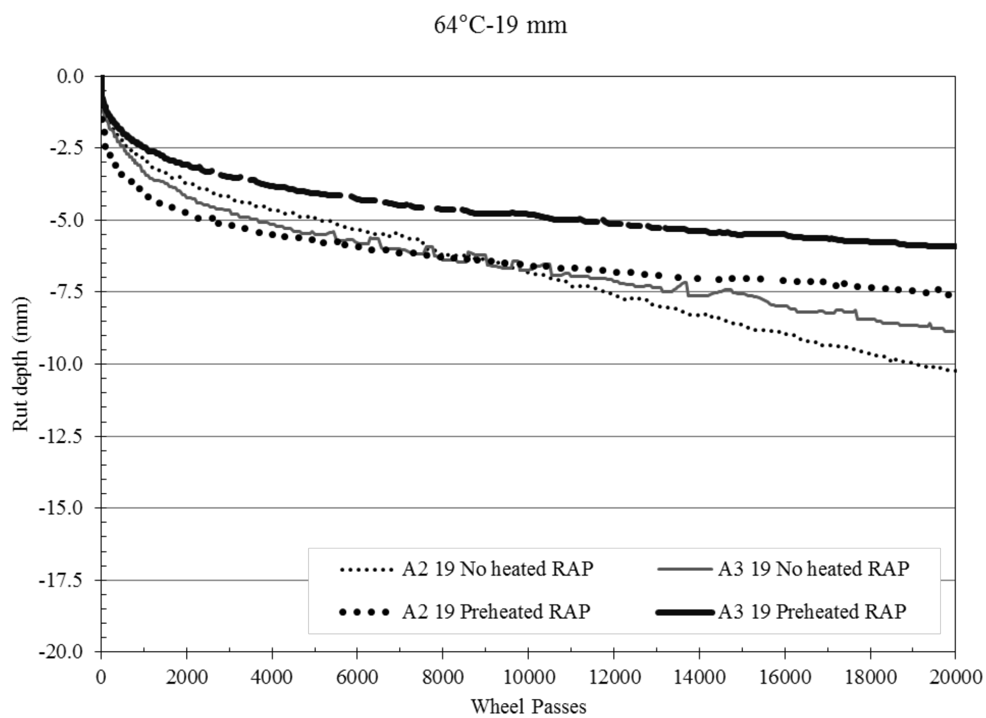


Figure 4-7 Profiles of 19 mm mixtures at 64°C with and without preheating RAP

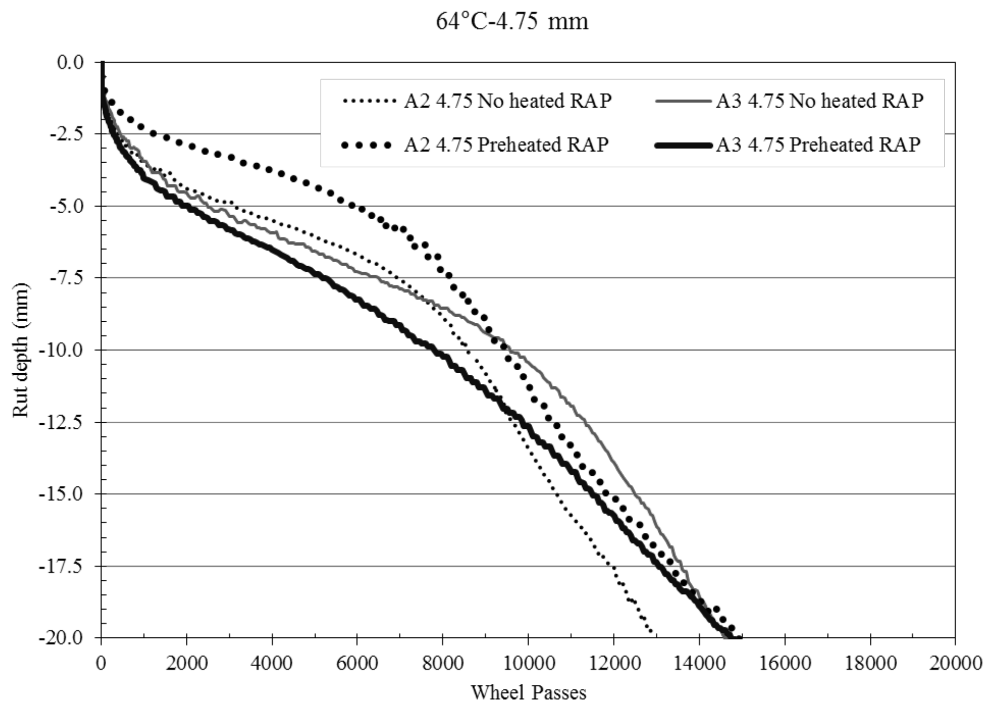


Figure 4-8 Profiles of 4.75 mm mixtures at 64°C with and without preheating RAP

4.2.2.2 Rut depth and SIP

Table 4-3 and Figures 4-9 to 4-10 list the test results of all the mixtures at 64°C. A general finding again is that the preheating process of RAP makes for lower rut depths than those of the RAP without preheating.

The 19 mm mixture, regardless of the pre-process, required more than 20,000 wheel passes to cause 10.0 mm rut depths, but the mixtures that used the preheated RAP showed a lower rut depth than those that used un-preheated RAP at the same wheel pass condition. The 4.75 mm mixture, regardless of the pre-process, reached 20.0 mm rut depth before 15,000 wheel passes. The SIP of 19.0 mm mixture did not appear even at 64°C regardless of whether or not the RAP was preheated. However, the 4.75 mm mixture showed SIP and the values of the SIP were slightly different, depending on whether the RAP was preheated.

Table 4-3 Rut depth and SIP at 64°C with and without preheating process

Mix Type		19 mm Superpave						4.75 mm Dense-graded					
Sources		A2			A3			A2			A3		
Pre-process		No heated RAP	Preheated RAP	Rate	No heated RAP	Preheated RAP	Rate	No heated RAP	Preheated RAP	Rate	No heated RAP	Preheated RAP	Rate
Rut depth @ wheel passes	20000	10.24	7.57	0.74	9.33	5.92	0.63	>20	>20	-	>20	>20	-
	18000	9.45	7.35	0.78	8.24	5.72	0.69	>20	>20	-	>20	>20	-
	15000	8.60	6.64	0.77	7.50	5.50	0.73	>20	>20	-	>20	>20	-
	12000	7.44	6.59	0.89	6.75	5.13	0.76	17.56	14.68	0.84	13.67	15.66	1.15
	10000	6.70	6.54	0.98	6.35	4.78	0.75	13.44	10.33	0.77	10.21	12.64	1.24
Wheel pass No. @ selected rut depth (mm)	5.0	5200	3850	0.74	3900	11400	2.92	3150	6000	1.90	2600	2200	0.85
	10.0	>20000	19250	-	>20000	>20000	-	8600	9550	1.11	9700	7950	0.82
	12.5	>20000	>20000	-	>20000	>20000	-	9650	10600	1.10	11400	10000	0.88
	15.0	>20000	>20000	-	>20000	>20000	-	10700	12100	1.13	12600	11600	0.92
	20.0	>20000	>20000	-	>20000	>20000	-	12800	14950	1.17	14700	14850	1.01
SIP		>20000	>20000	-	>20000	>20000	-	7520	7225	0.96	8399	8450	1.01
Rut depth at SIP		-	-	-	-	-	-	8.20	6.04	0.74	8.78	6.56	0.75

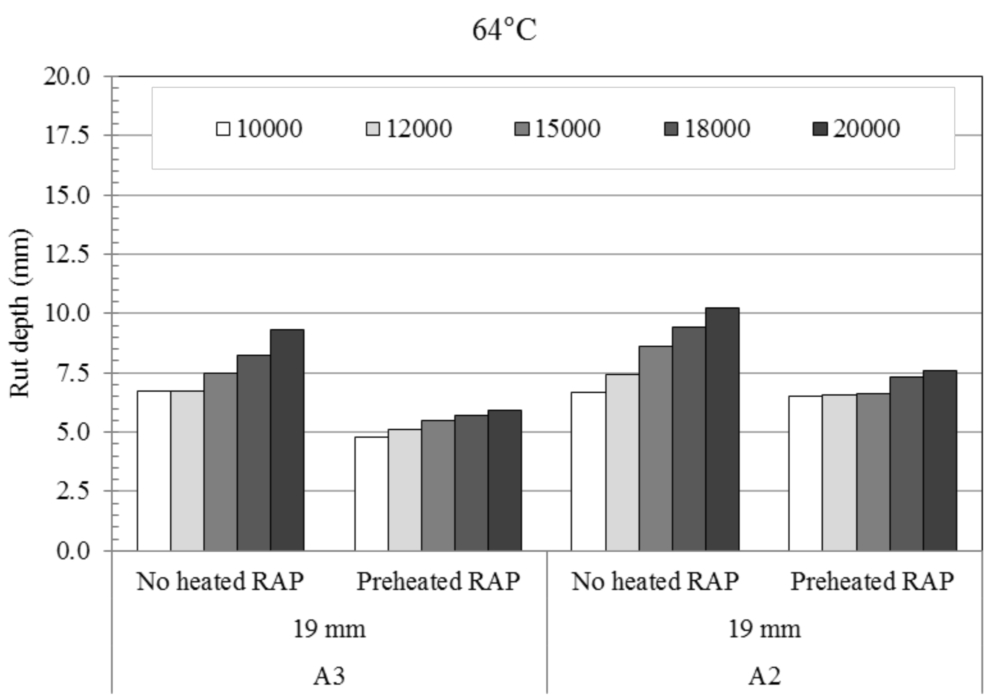


Figure 4-9 Rut depth of 19 mm mixtures at 64°C with and without preheating RAP

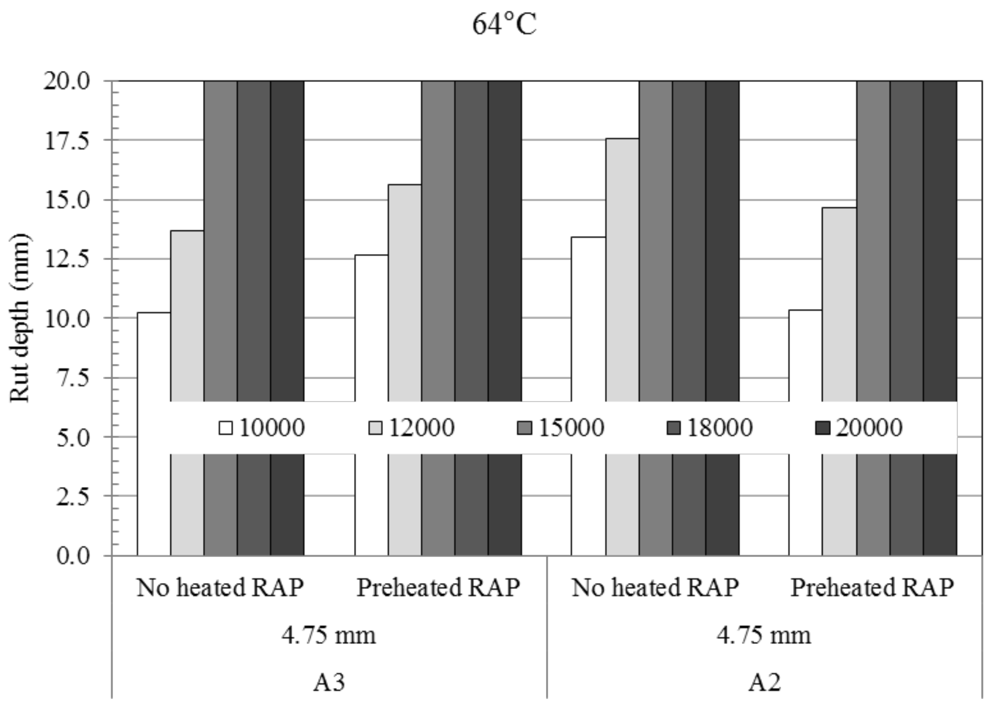


Figure 4-10 Rut depths of 4.75 mm mixtures at 64°C with and without preheating RAP

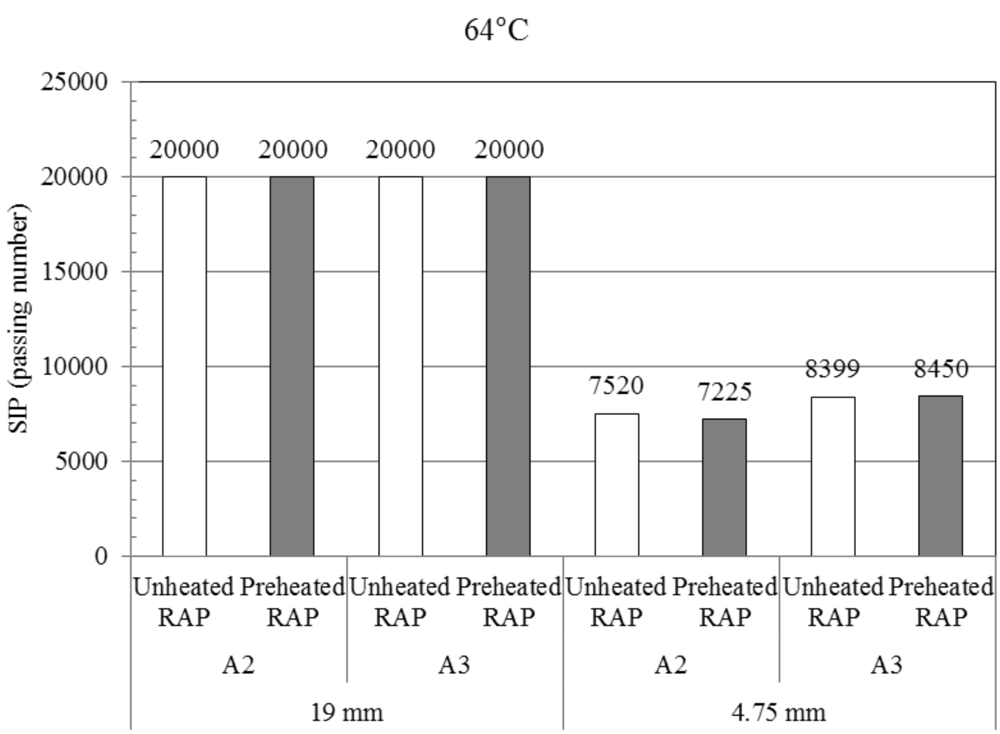


Figure 4-11 SIP at 64°C with and without preheating RAP

4.2.3 Test results at 70°C

4.2.3.1 Profiles of rut depth vs. wheel pass at 70°C

Figures 4-12 to 4-13 show the rut depth profile with and without preheating process at 70°C. The mixtures for both aggregate sources of A2 and A3 showed low rut depths with preheating process than no preheating. The 19 mm mixtures for aggregate source of A3 showed lower final rut depths than those for the aggregate source of A2 both with and without preheating process. The mixtures of NMAS 4.75 mm showed very low profiles to reach 20.0 mm rut depth and showed higher rut depths than those of NMAS 19 mm under both conditions with and without preheating process. This trend of showing the increase of rut depth without preheating process presented similarly at three test temperatures of 50, 64, and 70°C.

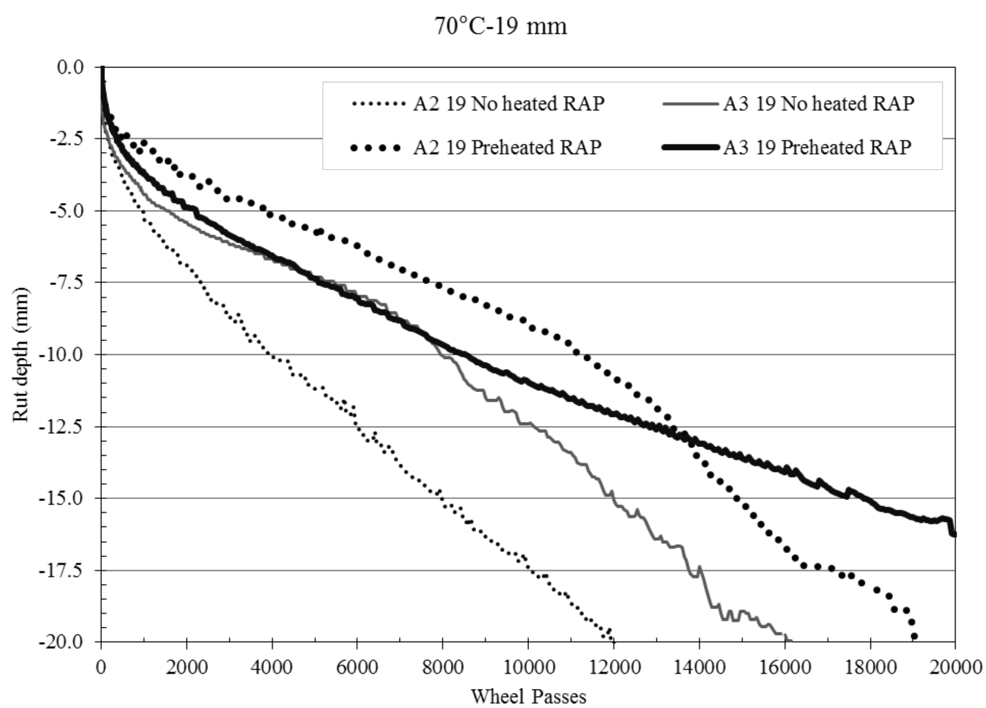


Figure 4-12 Profiles of 19 mm mixtures at 70°C with and without preheating RAP

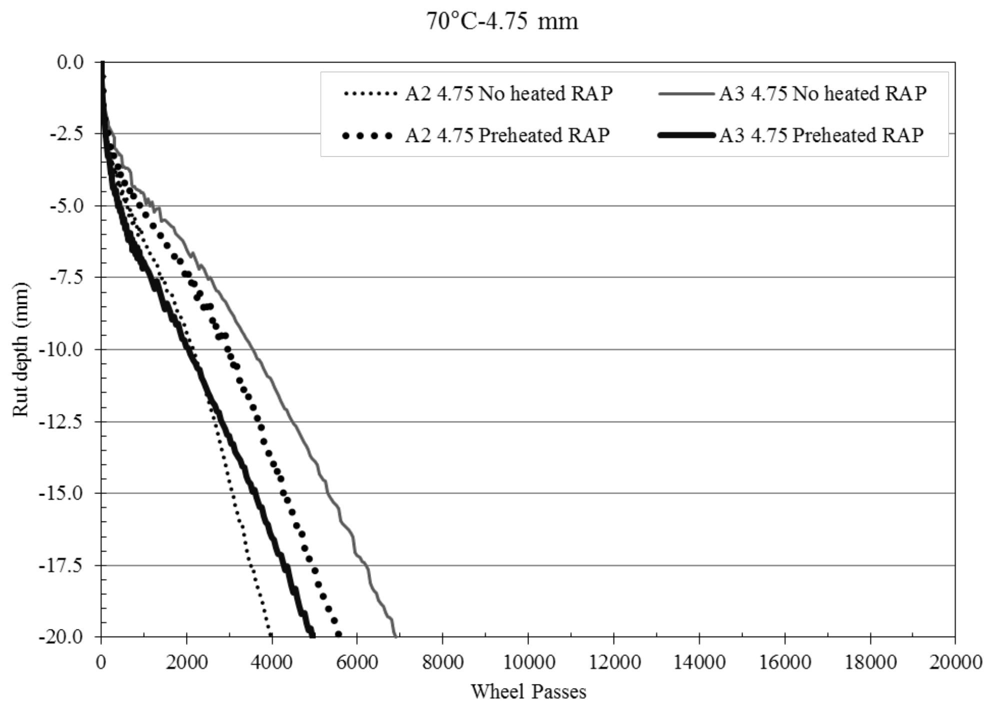


Figure 4-13 Profiles of 4.75 mm mixtures at 70°C with and without preheating RAP

4.2.3.2 Rut depth and SIP

Table 4-4 and Figures 4-14 to 4-16 list the results of all the mixtures tested at 70°C. A general finding again is that the preheating process of RAP makes for lower rut depths than those of the RAP without preheating. A higher wheel pass number was required to reach a specific rut depth, and SIP for the 19 mm type of mix using preheated RAP.

Table 4-4 Rut depth and SIP at 70°C before and after RAP preheating

Mix Type		19 mm Superpave						4.75 mm Dense-graded					
Sources		A2 (with 30% RAP)			A3 (with 25% RAP)			A2 (with 30% RAP)			A3 (with 25% RAP)		
Pre-process		No heated RAP	Preheated RAP	Rate	No heated RAP	Preheated RAP	Rate	No heated RAP	Preheated RAP	Rate	No heated RAP	Preheated RAP	Rate
Rut depth @ wheel pass No. (passes) of	20000	>20	>20	-	>20	16.26	-	>20	>20	-	>20	>20	-
	18000	>20	17.32	-	>20	15.07	-	>20	>20	-	>20	>20	-
	15000	>20	15.08	-	18.55	13.59	0.73	>20	>20	-	>20	>20	-
	12000	19.46	10.58	0.54	14.75	12.08	0.82	>20	>20	-	>20	>20	-
	10000	16.92	8.71	0.51	12.41	10.96	0.88	>20	>20	-	>20	>20	-
Wheel pass No. @ specific rut depth (mm) of	5.0	1050	4050	3.86	1800	2250	1.25	620	880	1.42	1150	400	0.35
	10.0	4100	11400	2.78	8200	8550	1.04	2200	3100	1.41	3600	2100	0.58
	12.5	6150	13500	2.20	10250	12850	1.25	2650	4000	1.51	4500	2800	0.62
	15.0	8100	15000	1.85	12100	17850	1.48	3100	4650	1.50	5350	3650	0.68
	20.0	12050	18000	1.49	16400	>20000	-	4000	5550	1.39	6900	4950	0.72
SIP		7000	12500	1.79	7000	>20000	-	2348	3000	1.28	3369	3108	0.92
Rut depth at SIP		13.66	11.07	0.81	8.55	-	-	10.88	10.36	0.95	9.77	13.27	1.36

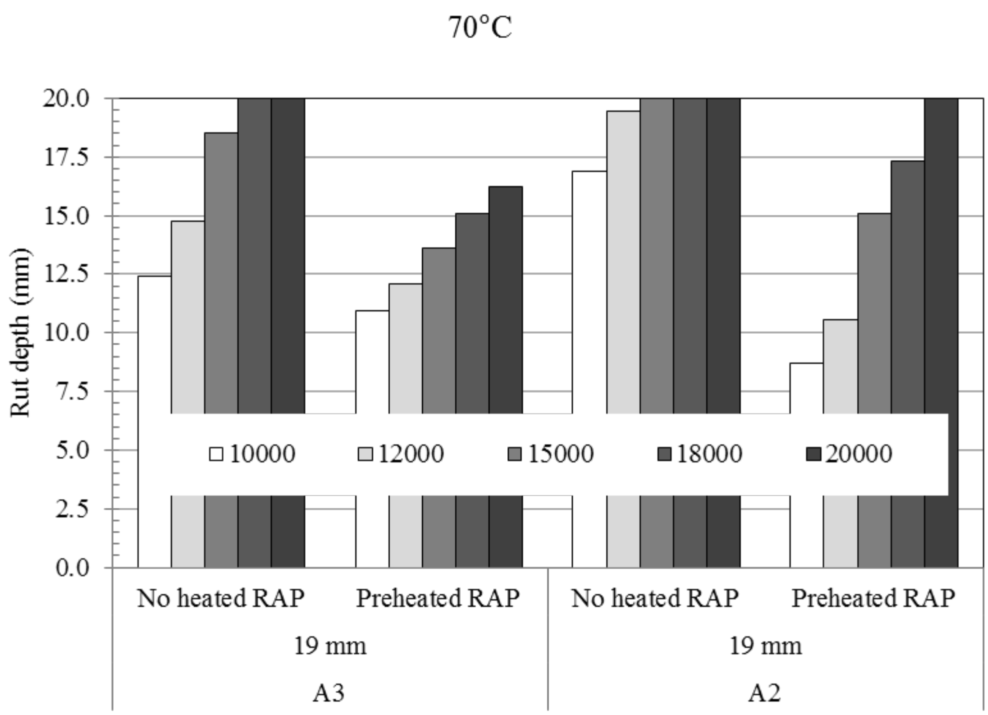


Figure 4-14 Rut depth of 19 mm mixtures at 70°C with and without RAP preheating

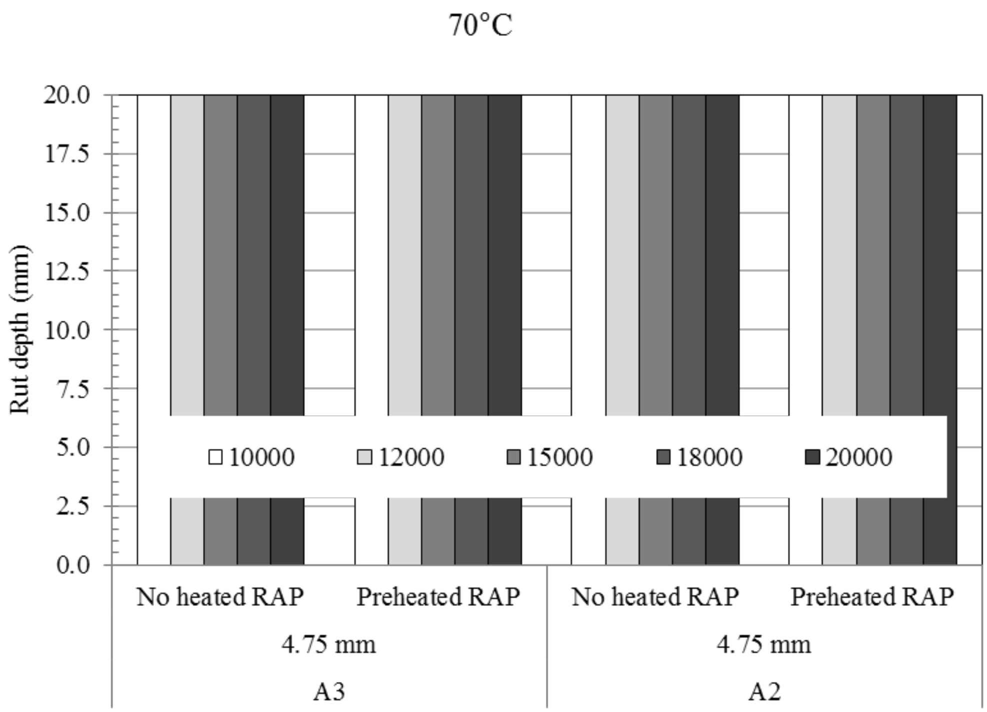


Figure 4-15 Rut depth of 4.75 mm mixtures at 70°C with and without RAP preheating

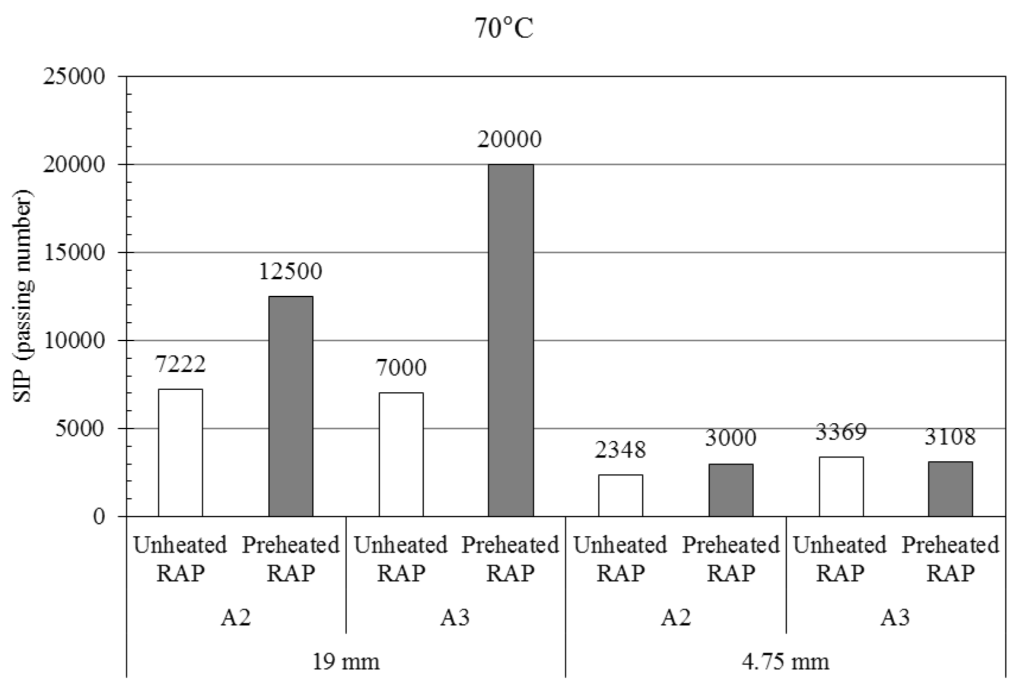


Figure 4-16 SIP at 70°C with and without RAP preheating

4.3 Effect of RAP Preheating on Rut Depth and SIP

As shown in Table 4-5 and Figures 4-17 and 4-18, for the 19 mm mixtures tested at 50 and 64°C, wheel pass numbers of 20,000 to reach a 12.5 mm rut depth were required for using both preheated and un-preheated RAP. When the test temperatures were raised to 70°C, a higher wheel pass number was required for the mixtures using preheated RAP.

For the 4.75 mm mixtures tested at 50°C, a wheel pass number of more than 20,000 were required to reach a 12.5 mm rut depth for both the mixtures with preheated and un-preheated RAP. At 64 and 70°C, the mixtures exhibited a mixed tendency depending on the materials sources.

Table 4-5 Wheel pass number at 12.5 mm rut depth

Mix Type		19 mm Superpave						4.75 mm Dense-graded					
Sources		A2 (with 30% RAP)			A3 (with 25% RAP)			A2 (with 30% RAP)			A3 (with 25% RAP)		
Pre-process		No heated RAP	Preheated RAP	Rate	No heated RAP	Preheated RAP	Rate	No heated RAP	Preheated RAP	Rate	No heated RAP	Preheated RAP	Rate
Test Temp	50°C	>20,000	>20,000	-	>20,000	>20,000	-	>20,000	>20,000	-	>20,000	>20,000	-
	64°C	>20,000	>20,000	-	>20,000	>20,000	-	9,650	10,600	1.10	11,400	10,000	0.88
	70°C	6,150	13,500	2.19	10,250	12,850	1.25	2,650	4,000	1.51	4,500	2,850	0.63

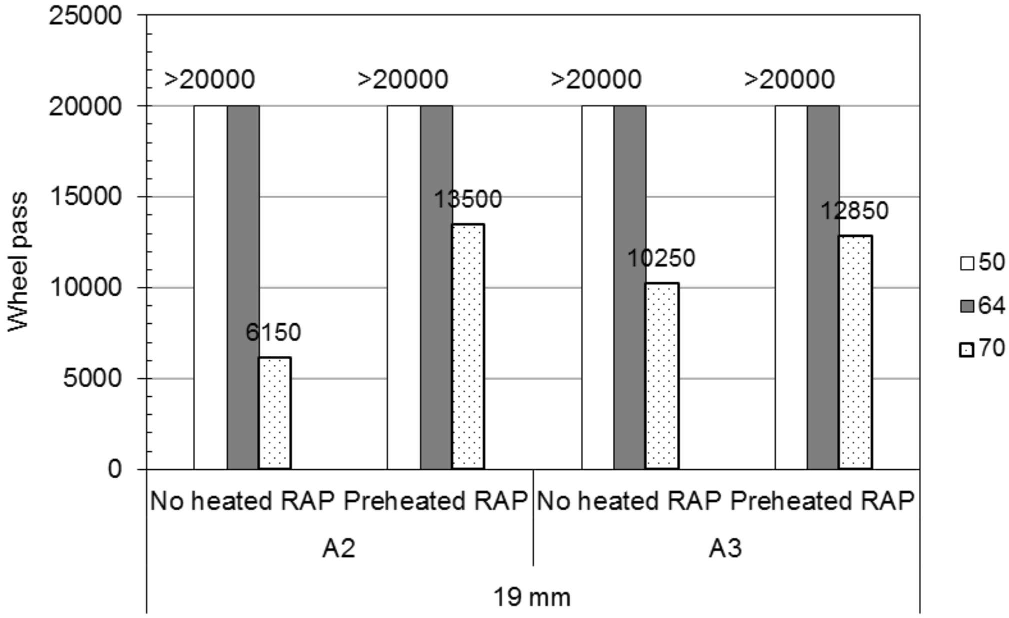


Figure 4-17 Wheel pass number at 12.5 mm rut depth for 19 mm mixtures at different temperatures

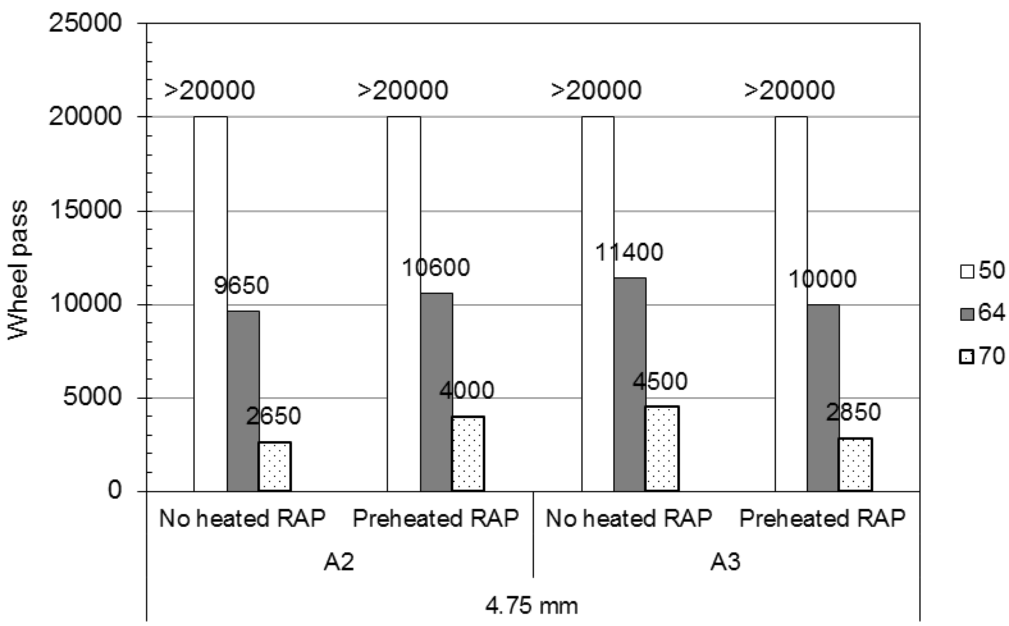


Figure 4-18 Wheel pass number at 12.5 mm rut depth for 4.75 mm mixtures at different temperatures

4.4 Modifications of the Recommendations

Table 4-6 shows the wheel pass number when the rut depth reached 12.5 mm at the three different test temperatures. Based on the values in Table 4-6, regression equations for determining the wheel pass were calculated as shown in Figures 4-19 and 4-20, and the predicted wheel pass number for the occurrence of 12.5 mm rut depth is presented in Table 4-7.

Table 4-6 Wheel pass number at 12.5 mm rut depth and SIP by the different pre-process

Temp. (°C)	19 mm Superpave				4.75 mm Dense-graded			
	No heated RAP		Preheated RAP		No heated RAP		Preheated RAP	
	Rut depth	SIP	Rut depth	SIP	Rut depth	SIP	Rut depth	SIP
50	>20,000	>20,000	>20,000	>20,000	>20,000	>20,000	>20,000	>20,000
64	>20,000	>20,000	19,404	19,332	10,525	14,331	10,300	10,747
70	8,200	7,111	13,582	12,994	3,575	4,915	3,400	4,172

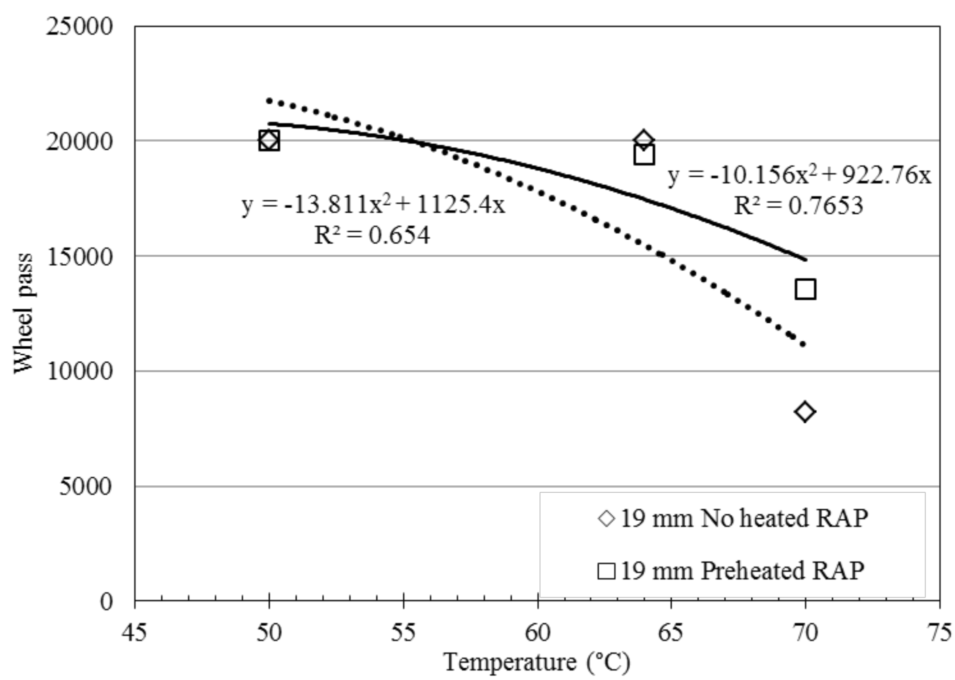


Figure 4-19 Combination of temperature and wheel pass number to reach 12.5 mm rut depth by the different pre-process for 19 mm mixtures

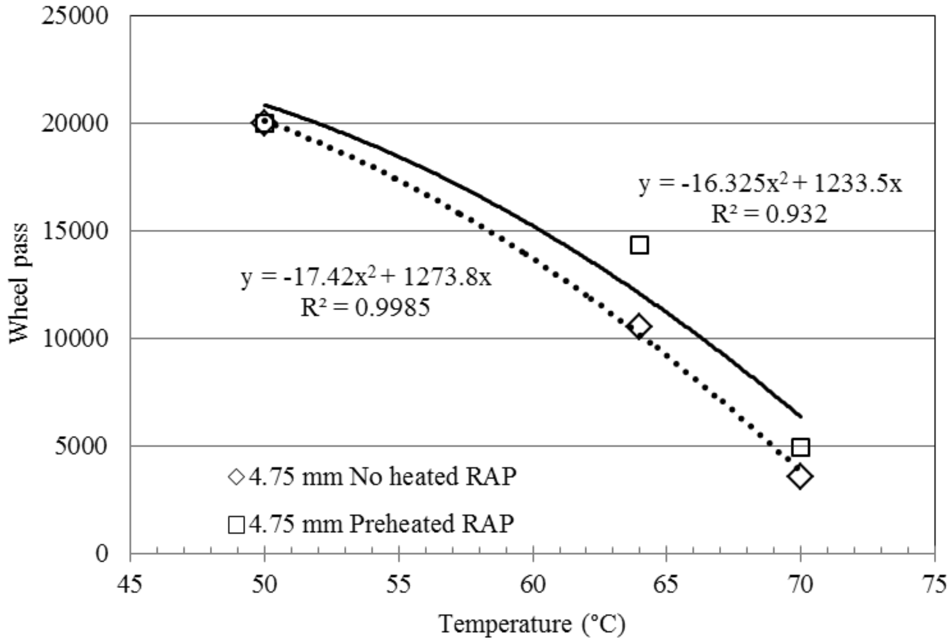


Figure 4-20 Combination of temperature and wheel pass number to reach 12.5 mm rut depth by the different pre-process for 4.75 mm mixtures

Table 4-7 Regression equations between test temperature (X, °C) and wheel pass at 12.5 mm rut depth (Y, pass)

Mixtures		Pre-process	Regression equations			R^2
25-19	Equations	No heated RAP	$Y = -13.811 X^2 + 1125.4X$			0.654
		Preheated RAP	$Y = -10.561 X^2 + 947.92X$			0.765
	Prediction	Temp.	58°C	60°C	62°C	64°C
		No heated RAP	18,813	17,804	16,685	15,456
		Preheated RAP	19,452	18,856	18,175	17,409
		Ratio	0.967	0.944	0.918	0.888
12.5-4.75	Equations	No heated RAP	$Y = -17.42 X^2 + 1273.8X$			0.998
		Preheated RAP	$Y = -16.537 X^2 + 1238.7X$			0.932
	Prediction	Temp.	58°C	60°C	62°C	64°C
		No heated RAP	15,280	13,716	12,013	10,171
		Preheated RAP	16,214	14,789	13,231	11,541
		Ratio	0.942	0.927	0.908	0.881

Based on the values in Table 4-7, regression equations for criteria of SIP were calculated as shown in Figures 4-21 and 4-22, and the predicted SIP with test temperature presented in Table 4-8.

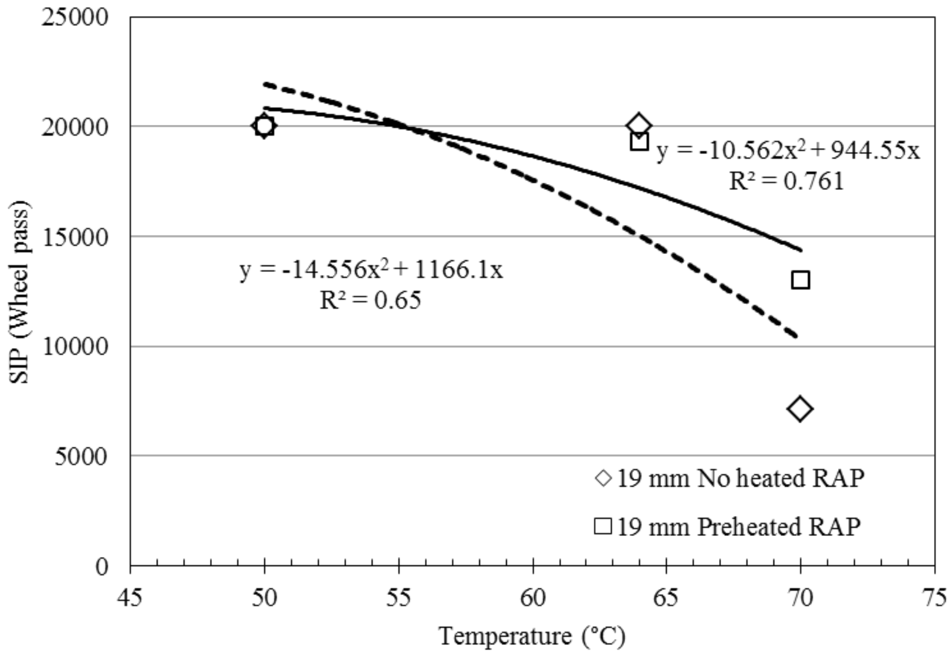


Figure 4-21 Combination of temperature and SIP by the different pre-process for 19 mm mixtures

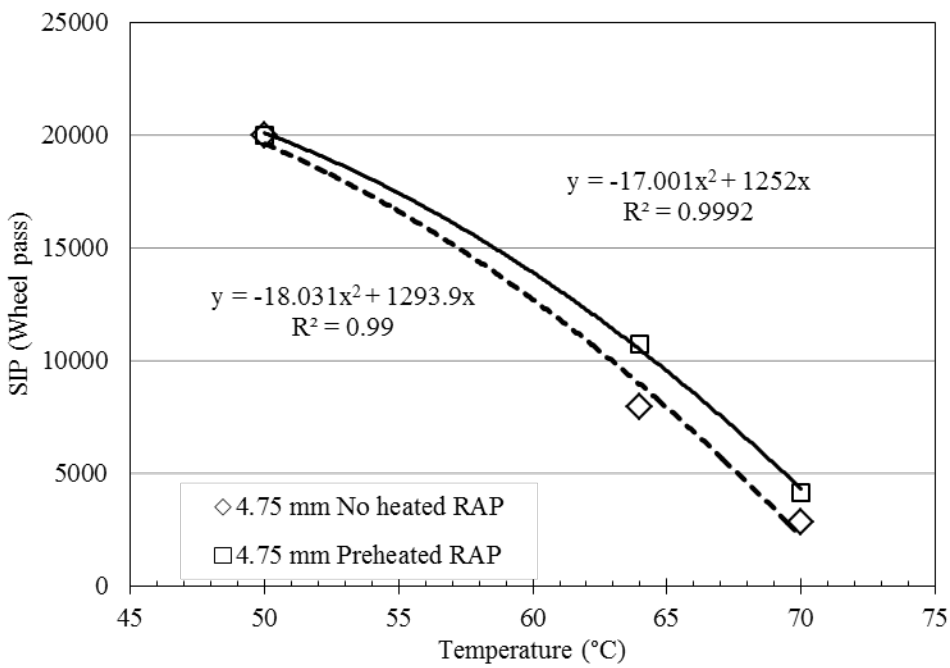


Figure 4-22 Combination of temperature and SIP by the different pre-process for 4.75 mm mixtures

Table 4-8 Regression equations between test temperature (X, °C) and SIP (Y, pass)

Mixtures		Pre-process	Regression equations			R^2
25-19	Equations	No heated RAP	$Y = -14.556 X^2 + 1166.1X$			0.650
		Preheated RAP	$Y = -10.562 X^2 + 944.55X$			0.761
	Prediction	Temp.	58°C	60°C	62°C	64°C
		No heated RAP	18,867	17,654	16,345	15,009
		Preheated RAP	19,253	18,650	17,962	17,189
		Ratio	0.980	0.947	0.910	0.873
12.5-4.75	Equations	No heated RAP	$Y = -18.031 X^2 + 1293.9X$			0.998
		Preheated RAP	$Y = -17.002 X^2 + 1252X$			0.999
	Prediction	Temp.	58°C	60°C	62°C	64°C
		No heated RAP	18,867	17,654	16,345	15,009
		Preheated RAP	19,253	18,650	17,962	17,189
		Ratio	0.980	0.947	0.910	0.873

For NMAS of 25 and 19 mm, at a test temperature of 58°C, asphalt mixtures with preheating RAP need about 98.0% in wheel pass number to reach a 12.5 mm rut depth as compared to the asphalt mixtures using the un-preheating process. For NMAS of 12.5, 9.5T1, 9.5T2, and 4.75 mm, at a test temperature of 58°C, asphalt mixtures with preheating RAP need about 94.2% in the wheel pass number to reach a 12.5 mm rut depth as compared to the asphalt mixtures using the no-preheating process.

Based on the test results of the chapter, the following revisions were recommended for the test process and criteria of HWTD test:

1) The combination of 18,500 wheel pass number at 58°C is recommended for the NMAS of 25 and 19 mm mixtures. The number for the SIP is recommended to be at least 18,500.

2) The combination of 15,000 wheel pass number at 58°C is recommended for the NMAS of 12.5, 9.5T1, 9.5T2 and 4.75 mm mixtures. The number for the SIP is recommended to be at least 15,000.

Chapter 5 Conclusions and Recommendations

5.1 Summary and Conclusions

In this study, Hamburg Wheel-Tracking Device tests were conducted to evaluate the rutting resistance and anti-stripping properties of asphalt mixtures containing RAP. The tests were performed at three testing temperatures, 50, 64, and 70°C. A total of 432 specimens were tested. The specimens consist of aggregates from four sources with RAP at six aggregate gradations and two grades of asphalt binder. Main conclusions are as follows:

1) When the test temperature increased from 50 to 70°C, the rut depth of the asphalt mixtures containing RAP increased and SIP decreased, regardless of the source of the aggregates used. At 50°C, rut depths were very small, less than 5 mm, even at the wheel pass limit of 20,000, regardless of mix type, binder type, size and type of gradation, or RAP content.
2) When the test temperature was 64°C, rut depths were deeper than at 50°C and, most importantly, the values were influenced by the mix type and size of the aggregates and the binder type. The rut depths for the mixtures with large aggregates of Nominal Maximum Aggregate Size (NMAS) 25 and 19 mm were obviously lower than those with smaller aggregates of NMAS 12.5, 9.5, and 4.75 mm.
3) When the test temperature was 70°C, rut depths were severe for unmodified asphalt mixtures; most exceeded the 20.0 mm limit set for the test. The rut depths for modified binder mixtures were lower than 8.0 mm, even at 20,000 wheel passes, regardless of the size and type of gradation or RAP content.
4) Aggregate size had an obvious effect on the asphalt mixtures' performance. Rut depth and SIP increased as NMAS decreased, especially for mixtures tested at 64°C and 70°C.

5) When modified binders (PG 76-22) were used for 12.5 mm SMA and 12.5 mm Superpave and 4.75 mm dense-graded mixtures, rut depth was generally very low and considerably lower than that of 12.5 SMA and 12.5 Superpave and 4.75 with unmodified binders (PG 64-22), even at 70°C. SIPs were generally very high, mostly at over 20,000 passes, for all aggregate sources and sizes used in the project. The 12.5 mm SMA showed higher rut depths than that of 12.5 mm Superpave and 4.75 mm dense-graded mixtures, regardless of the test temperatures.
6) Material sources had a readily apparent effect on rutting and stripping performance. Generally, the mixtures using A1 and A3 aggregates had shallower rut depths than A2 and A4 mixtures, regardless of the test temperatures and type of binder.
7) RAP preprocessing methods (i.e., preheating RAP at 110°C for 2 hours in an oven or no preheating) before mixing the RAP with the virgin aggregate and binder significantly affected rutting performance at test temperatures of 64 and 70°C. This impact was not significant at 50°C.
8) Since rut depth and SIP were significantly affected by the test temperatures and wheel passes, correlations were well established between rut depth, SIP, temperature, and wheel pass number.

5.2 Recommendations

For asphalt mixtures using asphalt binder of PG 64-22 and containing RAP:

1) The combination of 18,500 wheel pass number at 58°C is recommended for the NMAS of 25 and 19 mm mixtures for an allowable maximum rut depth of 12.5 mm. The number for the SIP is recommended to be at least 18,500.

2) The combination of 15,000 wheel pass number at 58°C is recommended for the NMAS of 12.5, 9.5T1, 9.5T2 and 4.75 mm mixtures for an allowable maximum rut depth of 12.5 mm. The number for the SIP is recommended to be at least 15,000.

For asphalt mixtures using asphalt binder of PG 76-22 and containing RAP:

1) A test temperature of 64°C and 20,000 wheel passes are recommended to achieve a rut depth of not more than 6.0 mm in modified SMA and Super 12.5 and Super 4.75.
2) The criterion for allowable minimum SIP is more than 20,000 passes at 64°C.

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