Evaluation of Mix Composition and Compactability on Rutting Performance of Asphalt Mixtures

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Authorization to Submit Thesis

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Abstract

The asphalt industry continues to be the country's most consistent recycler of highway pavement materials with more than 99% being used as Reclaimed Asphalt Pavement (RAP) in the construction and rehabilitation of pavements. The average RAP percentage utilized in asphalt mixes has increased from 15.6% in 2009, to 21.1% in 2018. The increase of RAP content in asphalt mixtures may result in stiffer mixtures, which are more prone to cracking. The use of softer asphalt binder or increased binder content can improve the cracking performance but may compromise the rutting resistance of the asphalt mixtures. This study examined the sensitivity of rutting performance and compactability to mix composition including RAP content and source, binder content and grade, mix design, and aggregate type. In addition, this study evaluated the moisture susceptibility of asphalt mixtures prepared with different percentages of RAP and the use of anti-stripping agents to improve the resistance of these mixtures to moisture damage.

The results of this study demonstrated that mixtures with RAP within a range of ± 0.75% of optimum binder content had good resistance to cracking. Increasing the binder content and using softer binders at various RAP contents resulted in higher rutting, but this increase was less than the maximum threshold for various rut tests. This means using softer binders or increasing binder content to improve the cracking resistance should not significantly affect the rutting performance for the mixtures evaluated in this study. The results also showed that the rutting was less sensitive to RAP content and binder grade. The stiffening effect of RAP materials in asphalt mixtures was not significant on rutting performance.

Furthermore, the results showed that the inclusion of RAP had a negative effect on moisture susceptibility and resulted in a lower tensile strength ratio (TSR). In addition, the use anti-stripping agents was found to improve resistance to moisture damage.

This study developed a correlation between rutting and compactability of asphalt mixtures. Mixtures with less resistance to densification during laboratory compaction were found to experience higher rutting than those with higher resistance to densification. Such correlation may be used to evaluate the rutting resistance from the compaction data during the mix design or mix production. It can also be used during project construction to assess significant variations in mix composition.

Key Words: Hamburg, APA, Rutting, Laboratory Compaction Index, RAP, Binder Grade, Binder Content, Aggregate Type, Moisture Susceptibility

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Dedication

In Dedication to my family and Mohammed Abu-Saq who supported me and kept me more positive through my master’s program.

Table of Contents

List of Tables

List of Figures

CHAPTER 1 INTRODUCTION

1.1 Background and Problem Statement

The Federal Highway Administration (FHWA) and National Asphalt Pavement Association (NAPA) have been collecting data over the years to track the current practice of RAP usage by each state (NAPA 2018). In the United States, the asphalt industry continues to be the country's most consistent recycler of highway pavement materials with more than 99% being used as Reclaimed Asphalt Pavement (RAP) in the construction and rehabilitation of pavements. The average RAP percentage utilized in asphalt mixes has increased from 15.6% in 2009 to 21.1% in 2018. The estimated RAP used in asphalt mixtures was 82.2 million tons in 2018. The RAP materials are often stiffer due to aging and thus may result in stiffer mixtures when blended with virgin materials (e.g., asphalt binders and aggregates). In designing asphalt mixtures with RAP, the stiffness may be reduced by using softer binders or increasing binder content to improve the cracking performance; however, this could compromise the resistance to rutting.

The use of RAP in asphalt mixtures may also affect the moisture susceptibility and compactability of the mixtures. This study investigated the effect of mix composition including RAP content and source, binder content and grade, mix design, and aggregate type on mix performance including rutting, compactability, and moisture damage.

Rutting is a common pavement distress found in asphalt pavements caused by repeated and heavy traffic loading. The permanent deformation, or rutting, is a further densification of the asphalt mixtures. Moisture damage can also accelerate pavement distresses, which refers to the stripping of asphalt from the aggregates leading to raveling. This occur if aggregates have a greater affinity to water than the asphalt binders. Water gets in between the asphalt binders and aggregates, reducing the adhesion between the particles. Anti-stripping additives are often added to the mix to improve the adhesion between the asphalt binder and aggregates which improve the resistance to moisture damage.

Standard tests are used to evaluate the resistance of asphalt mixtures to rutting and moisture damage. The Asphalt Pavement Analyzer Jr. device is used to conduct two standard rutting tests: APA rut depth test in accordance with AASHTO T340 and the Hamburg Wheel Tracking Test (HWTT) in accordance with AASHTO T324. The APA rut depth is performed in dry conditions at a temperature equivalent to the higher Performance Grade (PG) temperature of the asphalt binder used in the test mix. While the HWTT is performed in wet conditions where the test samples are submerged in a water bath at a constant temperature of 50^{o}C. Therefore, the HWTT is used to evaluate the moisture susceptibility in addition to rutting resistance. Also, the resistance of asphalt mixtures can be evaluated using the Lottman protocol in accordance with AASHTO T283 (AASHTO, 2014).

1.2 Research Objectives

This study had the following five main objectives:

- Evaluate the effect of mix composition on the rutting performance of asphalt mixtures. The examined variables included RAP content and source, binder content and grade, mix design, and aggregate type.
- Examine the effect of mix composition with above-mentioned variables on the compactability of asphalt mixtures in the laboratory.
- Evaluate the correlation between rutting performance and compactability of asphalt mixtures.
- Study the rutting performance of field projects and the variability in mix performance during production.
- Evaluate the resistance of asphalt mixtures with RAP to moisture damage and the use of anti-stripping agents to improve the adhesion between asphalt binders and aggregates.

1.3 Research Tasks

Several tasks were performed to achieve the listed research objectives. These are described below:

1.3.1 Task 1: Literature Review

The objective of this task was to conduct a comprehensive literature review on the effects of RAP content, binder content, aggregate type, and anti-strip agents on rutting characteristics. The literature review also covers various testing procedures used to evaluate the rutting performance and moisture susceptibility of test mixtures. The main subjects of the literature review include the following:

- Standard test methods used to measure the rut depth. These methods include the APA rut depth test and HWTT. Also, the review covered the test methods used to examine the moisture damage using the Lottman protocol.
- Characterization of reclaimed asphalt pavement (RAP) in the laboratory and its use in asphalt pavements.
- Assessment of the compactability of asphalt mixtures in the laboratory.
- Effect of different test parameters and mix variables on rutting performance of asphalt mixtures both in the laboratory and field.

1.3.2 Task 2: Obtain Virgin Materials and loose Mixtures and Prepare Test Specimens

The purpose of this task was to obtain virgin materials including aggregates, asphalt binders, anti-stripping agents. The aggregates were procured from asphalt plants in Pullman, WA and Lewiston, ID. The asphalt binders were acquired from asphalt producers in Spokane, WA. In addition, RAP materials were sampled from two sources. Two aggregate types, three different binder contents, three binder types, and two RAP sources were considered in preparing laboratory-mixed laboratory-compacted (LMLC) test specimens. In addition, this study also included Plant-Mixed Laboratory-Compacted (PMLC). The PMLC mixes were samples from new field paving projects. The PMLC had different mix designs and mix composition. Three batches were obtained from each project.

1.3.3 Task 3: Rutting Analysis using APA and Hamburg

The Pine Superpave gyratory compactor was used to compact cylindrical samples for testing which included both APA and HWTT for rutting. Each rut depth using APA or HWTT requires four samples. The test samples were compacted to have 7 ± 0.5% air voids. The APA rut depth and HWTT are conducted in accordance with AASHTO T340 and AASHTO T324, respectively. The HWTT was also used to evaluate the moisture susceptibility in addition to rutting resistance as the test is conducted in wet conditions. The APA rut test was used to evaluate the rutting resistance of LMLC samples, while HWTT was used to evaluate both LMLC and PMLC samples. The HWTT was selected to study the rutting performance of PMLC as the Idaho Transportation Department (ITD) is implementing HWTT for measuring rutting resistance in the state.

1.3.4 Task 4: Moisture Susceptibility using Lottman Procedure

Under this task, the moisture susceptibility of selected test mixtures prepared at different binder and RAP contents was evaluated. The test is performed in accordance with AASHTO T283 where the test samples are tested in both dry and wet conditions. Three replicates are conditioned where they are subjected a freeze and thaw cycle and then submerged in a water bath at 135 ± 1°F (57 ± 0.5°C). After conditioning, the specimens are placed in another water bath at 77 ± 1°F (25 ± 0.5°C) for two hours before testing. Another group of samples from the same test mixture is tested at 77 ± 1°F (25 ± 0.5°C) in dry conditions. The Tensile Strength Ratio (TSR) (wet to dry) is calculated to evaluate the loss of strength due to conditioning. In this study, the TSR results were also compared to those of HWTT.

1.3.5 Task 5: Laboratory Compaction Index Calculations

Under this task the author used the compaction curves of APA and HWTT to determine the change in percent air voids versus the number of gyrations. The slope and intercept of the compaction curves were used to calculate the Laboratory Compaction Index (LCI). The LCI will be used to evaluate the compactability of asphalt mixtures. Higher LCI values indicate that less compaction effort is needed as the resistance to densification is lower. This study examined the correlation between the rut depth measured using both APA and HWTT and the LCI. The assumption is that if mixtures are easy to compact, they may experience higher rutting due to densification under loading.

1.3.6 Task 6: Performing Statistical Analyses

Under this task the author performed statistical analyses to study the results of various laboratory tests to evaluate whether there is a statistically, significant difference in the results among various testing groups. The Minitab 19 software (Arend, 1993) was used to conduct all statistical analyses for this study. ANOVA and Tukey's Honestly Significant Difference (Tukey HSD) were performed at 95 percent confidence interval (i.e., $\alpha = 0.05$). The results of the statistical analyses are presented in form of statistical groups or Tukey HSD groups in the form of letters. The statistical groups that do not share the same letters are significantly different in terms of comparison parameters (e.g., rut depth).

1.4 Thesis Organization

This thesis consists of five chapters and three appendices. Chapter 1 includes introduction, background, problem statement, research objectives, research tasks, and thesis organization.

Chapter 2 provides the main findings of the literature review on factors that affect rutting resistance and moisture susceptibility. The literature review also explains the testing procedures and guidelines used in this study.

Chapter 3 provides information about the materials and equipment used in testing asphalt specimens. This involves the gradations and properties of aggregates and RAP materials. The testing program is also discussed alongside the field projects.

Chapter 4 presents the results and discussion of all performed tests. It covers the analysis of rutting performance and moisture susceptibility of the laboratory-mixed laboratory-compacted samples. In addition, field projects were tested using HWTT to assess the change in rut depth at during the project construction as well as the change among different projects. Chapter 4 also includes the results of Tukey statistical analysis. The correlation between LCI and rutting data as well as the results of the moisture damage were also presented and discussed.

Chapter 5 discusses the conclusions and outcomes based on the analysis of Chapter 4. Further research and recommendations are also provided in Chapter 5.

The appendices provide additional information and figures that were cited and discussed in the thesis. These provide a summary of the data measured using APA and HWTT tests, as well as examples of compaction data. Different job mix formulas used in this study are also included in the appendices. The last appendix supplies the permission approvals for figures found in the literature review.

CHAPTER 2 LITERATURE REVIEW

2.1 Introduction

The literature review presents the key findings of previous research on various topics including characterization of Reclaimed Asphalt Pavement (RAP), test methods used to measure rutting and moisture susceptibility, APA and HWTT thresholds used by various transportation agencies, effect of mix composition RAP content and aggregate type on the rutting performance, the use of anti-stripping agents to improve the resistance to moisture damage, and evaluation of compactability of asphalt mixtures.

2.2 Reclaimed Asphalt Pavement (RAP)

When asphalt pavement roadways approach the end of their service life, a new pavement is constructed, or asphalt overlays are often added to extend the service life of pavements. Reclaimed Asphalt Pavement (RAP) materials can be used in the construction of new pavement or overlays. RAP materials include aggregates and asphalt binder that can be incorporated in new mixtures. The cost of the asphalt mixtures that include RAP materials is often cost less since they require a less amount of virgin binder. Meanwhile, RAP materials are often aged, and stiffer and RAP characterization is needed before it can be incorporated in new mixtures. The bulk specific gravity (G_{sb}) of RAP aggregate, percentage of RAP binder and its grade, RAP aggregate gradation should be measured. To determine these parameters, different AASHTO procedures are conducted (Kassem et al., 2019).

The bulk specific gravity of RAP aggregates is an important parameter since it affects the percent air voids of the mix and air voids have significant effect on pavement performance. RAP aggregates can be extracted using the ignition oven (AASHTO T308) or using solvents (AASHTO T164) (AASHTO, 2015) and RAP coarse aggregates are then separated from the RAP fine aggregates. The specific gravity or coarse aggregates and fine aggregates can be measured using AASHTO T85 and AASHTO T84, respectively. The solvent extraction method was found to have less effect on the specific gravities compared to the ignition oven (Hajj et al., 2012; Prowell and Carter, 2000). The other method is an indirect approach that uses the effective specific gravity (G_{se}) instead of the G_{sb} to calculate the voids in the mineral aggregates (VMA). This method was found to be less accurate, and not recommended for VMA calculation (Hajj et al., 2012; Prowell and Carter, 2000).

The binder content can also be determined using the ignition oven (AASHTO T308) by acquiring the weight of the RAP materials before and after the ignition oven test in accordance with AASHTO T308. In addition, the sieve analysis is conducted on the aggregates after the ignition oven to determine the RAP aggregate gradation. The RAP PG binder can be determined by testing the extracted RAP binder in accordance with AASHTO M323. The RAP PG binder is only needed if RAP materials exceed 25% according AASHTO M323. Detailed procedures for determining the performance grade of recovered RAP binder were proposed in NCHRP 9-12 project. The recommended procedure was rolling thin-film oven (RTFO) aging (McDaniel and Anderson, 2001).

After calculating RAP materials characterization, the new mix is designed in accordance with Superpave mix design system (SHRP-A-407) (Cominsky et al., 1994). There are no limitations on the amount of RAP materials that can be included in the mix as long as the Superpave criteria are met. When adding RAP to asphalt mixtures, there are two methods to meet the specifications of Superpave. The first is to determine the RAP content to meet the specified weight. The other method is to determine the contribution of RAP binder toward the total amount of binder needed in the mixture (Cominsky et al., 1994).

2.3 Test Methods

This section reviews the test methods used to evaluate the resistance of asphalt mixtures to rutting and moisture damage. The test methods include Asphalt Pavement Analyzer (APA), Hamburg Wheel Tracking Device HWTD, dynamic modulus and Lottman moisture sensitivity protocol. In addition, this section reviews the laboratory compaction index that was found to correlate well with the densification of asphalt mixtures in the field.

2.3.1 Asphalt Pavement Analyzer (APA)

The APA device is used to evaluate the rutting resistance of asphalt mixtures by measuring the permanent deformation or rut depth of cylindrical test samples subjected to accelerated loading. The samples can be hot mix or cold mix asphalt, and the test can be conducted in a dry or wet state, to analyze the moisture susceptibility of the mix composition. Using concave wheels, a pressured hose, and a conditioning cabin, the APA test can be conducted different climates, and applied loads (Figure 2.1). Testing asphalt mixtures with different characteristics (e.g., different aggregates gradations, different materials, RAP content, and binder grade and content), gives more insight to transportation agencies to select the appropriate mix design for different sites (Skok et al., 2002).

Figure 2.1: APA setup for Rutting Analysis (Asphalt Testing Solutions, 2021)

The APA test samples are 150 mm (5.91 in) in diameter and 75 ± 2 mm (3.0 ± 0.1 in) in height. A total number of four or six cylindrical samples are tested in the APA depending on the size and model of the APA device. Some devices can only accommodate four samples, while others can test six replicates at a time. A Superpave gyratory compactor (SGC) is used to prepare a test sample with 7.0 ± 0.5% air voids.

Before running the test, the APA machine must be calibrated to ensure proper loading and positioning. The APA software automatically calibrates the vertical distance of each wheel. Next, the software adjusts the load cylinder pressure for each wheel to achieve a load of 100 ± 5 lbf. The test temperature during the test depends on the higher Performance Grade (PG) of the binder used in the mix. The test samples are placed in the test molds and tightened in place using spacers. The test specimens are conditioned at the test temperature for a minimum of 6 hours, but no more than 24 hours, before testing. A standard test runs for 8,000 cycles, and automatically starts taking rut depth measurements at different points after 25 cycles. When the test is complete, the wheels automatically retract, and the data can be extracted for analysis. The APA rut depth is conducted in accordance with AASHTO T340. Table 2.1 summarizes the rutting test parameters for APA testing (Kassem et al. 2019). The APA test pass or fail criteria depend on several factors including rut depth, mix design, binder grade, etc. Table 2.2 illustrates the pass or fail criteria for some transportation agencies (Kassem et. al., 2019).

Table 2.1 APA and HWTT Rutting Testing Parameters (Kassem et al., 2019)

Test	HWTT	HWTT	APA rut test
Testing Standards	AASHTO T 324	AASHTO T 324	AASHTO T 340
Specimen shape	Cylindrical or	slabs	Cylindrical
Specimen replicates	4 or 6	2	4 or 6
Specimen diameter (mm)	150	150	150
Specimen thickness (mm) for lab prepared	60	38-100	75
Specimen thickness (mm) for field Projects	38 - 60	NA	38 -75
Test temperature (°C)	Specified by the agency	Specified by the agency	High binder PG
Specimen conditioning	Water bath	Water bath	Air bath
Conditioning time (hour)	1	1	6 – 24
Testing time (hour)	≈10	≈10	≈ 2
Wheel type	Solid steel	Solid steel	Concave wheel
Wheel speed (Pass/minute)	52	52	50 ± 5
Load (N)	705 ± 4.5	705 ± 4.5	578
Number of data collection locations	11 locations	11 locations	5 locations
Test output	passes-deformation curve	passes-deformation curve	Cycle-deformation curve
Distress assessed	Rutting and moisture susceptibility	Rutting and moisture susceptibility	Rutting

Table 2.2. APA Rutting Criteria (Kassem et al., 2019)

DOT	Test procedure	Performance threshold (maximum rut depth @ 8,000 loading cycles)
ITD	AASHTO T340	5.0 mm
GDOT	GDT 115	7.0 mm for mix design level A
GDOT	GDT 115	6.0 mm for mix design level B
GDOT	GDT 115	5.0 mm for mix design level C and D
ALDOT	ALDOT -401	4.5 mm For ESAL range "E" mixes (($1E10^7$ < ESALs < $3E10^7$)
NJDOT	AASHTO T340	7.0 mm for high RAP, PG 64-22, surface and intermediate course,
NJDOT	AASHTO T340	6.0 mm for binder-rich intermediate course
NJDOT	AASHTO T340	5.0 mm for bottom-rich base course
NJDOT	AASHTO T340	4.0 mm for high RAP, PG 76-22, surface and intermediate course,
NJDOT	AASHTO T340	3.0 mm for bridge deck waterproofing surface course
VDOT	VTM-110	7.0 mm for mix designation A
VDOT	VTM-110	5.5 mm for mix designation D
VDOT	VTM-110	3.5 mm for mix designation E

2.3.2 Hamburg Wheel Tracking Device (HWTD)

The Hamburg Wheel Tracking Device also known as HWTD evaluates the rutting resistance and moisture susceptibility of asphalt mixtures. The Hamburg test can be performed in the APA Jr. device by replacing the wheels and removing the pressurized hoses as shown in Figure 2.2. The HWTD test evaluates different mix compositions of asphalt mixtures that are susceptible to premature failure due to weak aggregate structure, moisture damage, incorrect binder, and adhesion between the binder and aggregates. The rutting results using the HWTD test are controlled by the aggregate quality, binder choice, aging of material, binder source and anti-stripping treatments (Rahman and Hossain, 2014). Similar to the APA test, the test specimens are subjected to accelerated reciprocating wheel loading. The test specimens, either cylindrical samples or slabs, are submerged in water to evaluate the moisture susceptibility in addition to rutting resistance.

Figure 2.2: Hamburg setup inside the Asphalt Pavement Analyzer Jr.

Preparation of the asphalt specimens follow the SuperPave guidelines. The APA Jr. allows a maximum of four cylindrical samples to be tested at a time. The dimensions of the cylindrical samples are 150 mm in diameter and the thickness must be twice the value of the nominal aggregate size, ranging from 38 to 100 mm. If using slab specimens, the dimensions must be 320 mm long by 260 mm wide with the thickness twice the nominal aggregate size. If using field cores, and not enough material is available to meet the thickness requirement to fit the mold, plaster may be used to fill the gap for appropriate testing. A target air void value of 7.0 ± 0.5% is required for cylindrical samples and 7.0 ± 1.0% for slab specimens for testing. With specimens at the correct air void, they must be cut to the correct size for testing. Slab specimens must be cut to 320 mm long by 260 mm wide with the thickness of 60 ± 1.0 mm thick. Cylindrical specimens are cut to fit the molds described by Figure 2.3 below where the gap between the two specimens must not exceed 7.5 mm. The dimensions of where to cut the specimens can be used by putting the specimens in the mold and drawing line for it to fit. The Hamburg rutting test is conducted in accordance with AASHTO T324.

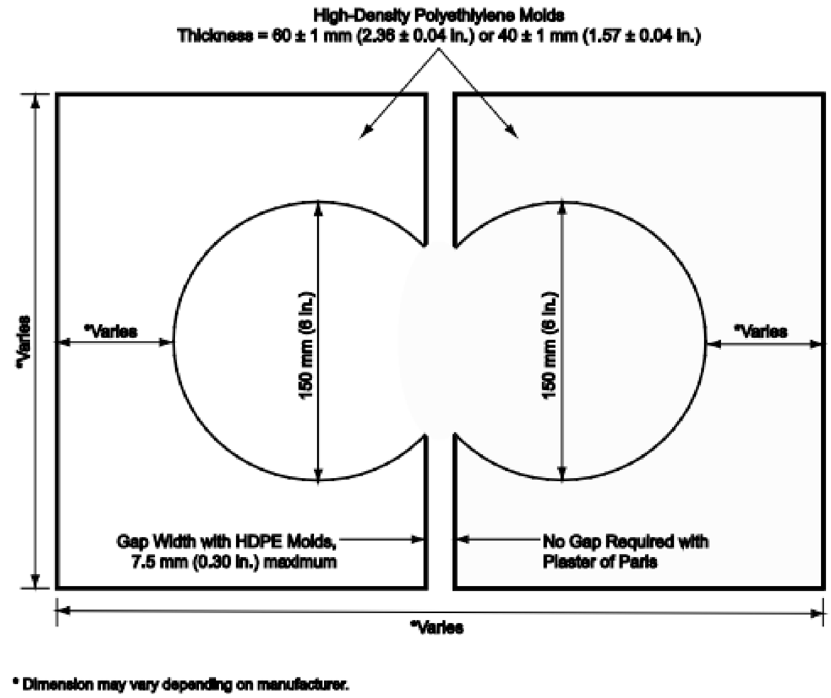


Figure 2.3: Dimensions of Hamburg Samples (AASHTO T324-16, 2016)

After the specimens are fully prepared and ready for testing, the APA software is calibrated for the Hamburg test. The concave wheels are replaced with flat steel wheels for Hamburg testing. The system must be calibrated for vertical distancing and each wheel load must be calibrated to 158 lbf for wheel. Next the specimens are put into the machine and locked into place using spacers. Before testing, the samples must be conditioned in the water bath for a minimum time of 30 min. at a temperature of 50 degrees Celsius, but no longer than 60 ± 5 minutes including the conditioning time. After sample conditioning, the test runs for 20,000 passes or until the maximum rutting depth is achieved. Once the test is completed, the wheels will retract, and the data can be downloaded for analysis (AASHTO, 2016). The HWTT test pass or fail criteria depend on several factors including rut depth, mix design, binder grade, etc. Table 2.3 illustrates the pass or fail criteria of HWTT for some transportation agencies (Kassem et. al., 2019).

Table 2.3. HWTT Rutting Criteria (Kassem et al., 2019)

DOT	Test Procedure	Rutting limits for various PG grading or mixture type
TXDOT	Tex-242-F	<=PG 64; 10,000 passes @12.5mm rut depth tested at 50 °C
TXDOT	Tex-242-F	PG 70; 15,000 passes @12.5mm rut depth tested at 50 °C
TXDOT	Tex-242-F	=>PG 76; 20,000 passes @12.5mm rut depth tested at 50 °C
WSDOT	AASHTO T 324	15,000 passes @10 mm rut depth tested at 50 °C
CODOT	CP-L 5112	10,000 passes @ 4 mm rut depth tested at 50 °C
MTDOT	MT 334-14	Minimum of 10,000 passes @13 mm rut depth for mix design (for PG 58-28,64-22,64-28 and 70-28)
MTDOT	MT 334-14	Minimum of 10,000 passes @13 mm rut depth for mix design (for PG 58-28,64-22,64-28 and 70-28)
LADOT	AASHTO T 324	Incidental Paving and ATB; Design Level 1; Max rut depth at 50 °C: 10 mm @ 10,000 passes
LADOT	AASHTO T 324	Wearing and Binder Course; Design Level 1; Max rut depth at 50 °C: 10 mm @ 20,000 passes
LADOT	AASHTO T 324	Wearing and Binder Course; Design Level 2; Max rut depth at 50 °C: 6 mm @ 20,000 passes

2.3.3 Lottman Moisture Susceptibility Testing Protocol

Asphalt mixtures are susceptible to water, as water strips the binder away from the aggregates further weakening pavements. This is referred to as stripping and can be prevented by using better aggregate-binder combinations, or additives such as hydrated lime and liquid anti-stripping chemicals. The Lottman test procedure, conducted in accordance with AASHTO T 283, is used to determine the susceptibility of asphalt mixtures to moisture damage and evaluate the use of additives (e.g., anti-stripping chemicals) to improve the resistance to stripping. The test is performed on three samples in dry conditions with no moisture conditioning and three samples tested after moisture conditioning. The indirect tensile strength test is conducted on the specimens to determine the indirect tensile strength. The indirect tensile strength ratio is calculated using the division between the wet and dry samples. The closer the ratio is to 1, the better the samples are to resist stripping, and/or the additives are effective.

The preparation of the specimens follows the same guidelines as Superpave with dimensions of 150 mm in diameter and 63.5 mm in height. After compaction, samples are kept at room temperature for 24 ± 3 hrs. before measuring percent air voids. The test samples should have a target air voids of 7.0 ± 0.5% in accordance with AASHTO T269. The test specimens are split into two different groups, three samples each. One group is tested in dry conditions and the other group is tested after moisture conditioning where it is subjected to a freeze-thaw cycle.

The group of specimens that are undergoing the freeze-thaw cycle are placed in a water container and subjected to a vacuum of 13 to 67 kPa absolute pressure (10 to 26 in Hg) for 5 to 10 min until a saturation level between 70 and 80 percent is achieved. The degree of saturation is calculated following Method A of AASHTO T 166. The volume of absorbed water is calculated using Equation 2.1

$$J^1 = B^1 - A \qquad \text{Eqn. 2.1}$$

where:

J^1 = volume of absorbed water (cm^3)

B^1 = weight of the saturated, surface-dry specimen after partial vacuum saturation (g)

A = weight of the dry specimen in air (g)

The degree of saturation (S^1) is found next using the volume of absorbed water using Equation 2.2.

$$S^1 = \frac{100J^1}{V_a} \qquad \text{Eqn. 2.2}$$

where:

S^1 = degree of saturation (%)

V_a = Volume of air voids (cm^3)

If the degree of saturation is less than 70%, the partial vacuum procedure must be repeated. If the values are between 70% to 80%, the conditioning of the freeze-thaw cycle may continue. Specimen saturation values greater than 80% saturation are considered damaged and discarded. Extra specimens are made in precaution if specimens do not meet the correct degree of saturation.

For the specimens, that met the required degree of saturation, are wrapped wet in plastic wrap, placed in a plastic bag with 10 ± 0.5 mL of water, and sealed. These samples are placed in a freezer to a temperature of 0 ± 5°F (-18 ± 3°C) for 24 ± 1 hr. Then, the test specimen is moved to a water bath set to 135 ± 1°F (57 ± 0.5°C) with at least an inch of water above the samples for another 24 ± 1 hr. When the specimens are placed in the water bath, the plastic film and wrap are removed. When conditioning is complete, the specimens are placed in a water bath set to 77 ± 1°F (25 ± 0.5°C) for two hours before testing. The dry samples are also placed in an environmental chamber at 77 ± 1°F (25 ± 0.5°C) before testing.

Before testing is performed, the thickness and diameter of the test specimens are measured and recorded. The test specimen is then placed on its side between the two bearing plates for the IDT test using the Material Testing System (MTS) as shown in Figures 2.4 and 2.5. Steel loading strips are placed between the bearing plates and the sample for good contact. The load is applied at a constant rate of 2 in (50 mm) per minute until failure. Figure 2.6 shows the samples after testing while the specimen is split along the direction of the applied load. The maximum applied load is recorded. The moisture susceptibility is quantified by measuring the tensile strength ratio (TSR) (Equation 2.3) in accordance with AASHTO T 283.

$$TSR = \frac{S_2}{S_1} \qquad \text{Eqn. 2.3}$$

where:

S_1 = average tensile strength of the dry subset, psi (kPa)

S_2 = average tensile strength of the conditioned subset, psi (kPa)

The closer the TSR is to 1, the less susceptible of asphalt mixtures to moisture damage. An asphalt mixture with a minimum value of 0.80 for TSR is expected to have good resistance to moisture damage (AASHTO 2014).

Figure 2.4: The Material Testing System

Figure 2.5: Sample Setup inside the MTS

Figure 2.6: IDT Test Sample after Testing

2.3.4 Dynamic Modulus

The dynamic modulus test is conducted in accordance with AASHTO T 342. The test is conducted at various temperatures (−10, 4.4, 21.1, 37.8, and 54.4°C) and frequencies (0.1, 0.5, 1.0, 5, 10, and 25 Hz). It applies sinusoidal loading and measures the axial strain. The load is adjusted to maintain the axial strain between 50 and 150 microstrain. Three axial linear variable differential transformers (LVDTs) are used to measure the axial deformation during the test. Figure 2.7 shows an example of the dynamic modulus setup.

The Mechanistic-Empirical Pavement Design Guide (MEPDG) is used to find the physical causes of stresses in pavement structure and correlate them with observed pavement performance. The pavement design industry has recently been moving towards more of mechanistic-based methodologies to improve pavement design in a more cost-effective manner. The Dynamic modulus is an important material characterization property that is used to correlate material properties to field fatigue cracking and rutting performance. In the MEPDG, for asphalt pavements, the dynamic modulus |E*| is the most important property and is an input to the pavement response model to determine the stress/strain responses. The responses from this test are used to further determine the pavement performance through its pavement's life. The dynamic modulus test is primarily used to predict the top-down and bottom-up fatigue cracking and rutting (Dougan et al., 2003).

Figure 2.7: Dynamic Modulus Test Setup (Masad et al., 2011)

2.3.5 Laboratory Compaction Index (LCI)

Compaction of asphalt mixtures is the process of decreasing the volume and increasing the unit weight by the interlocking of aggregates and binder. The level of compaction is affected by many factors including binder content, angularity of aggregates, method of compaction, etc.. The binder grade can take effect as different binder grades have different viscosities and affect the interlocking process of aggregates and binder. The compaction process is important to the performance of laboratory and field asphalt mixtures, as bad compaction can lead to premature distresses on the pavement. With the importance of asphalt compaction to the overall performance of asphalt specimens, research studies were conducted to investigate the correlation between laboratory compaction methods and mechanical properties (Kassem et al., 2012). The researchers evaluated the compactability of 20 different asphalt mixtures. Table 2.4 shows the compiled projects and mixture type for all mixes used in the study. Several compaction indices including Laboratory Compaction Index (LCI), Workability Energy Index (WEI), and Porosity Index (PI), were calculated to evaluate the compactability of the asphalt mixtures and correlate the laboratory compaction to the field compaction.

Table 2.4: Summary of the Asphalt Mixtures (Kassem et al., 2012)

Mixture #	Project ID	Mixture Type	Compaction Index	LCI	WEI	PI
1	Riverside 1	HMA Type C	5.45	24.21	4.93	5.34
2	Riverside 2	HMA Type D	7.4	23.85	3.19	4.69
3	Riverside 3	WMA Type D	4	25.98	6.87	5.59
4	SL 111	HMA Type C	4	27.14	5.40	5.32
5	SH 31	HMA Type B	5.5	24.75	3.90	4.54
6	Loop 340	HMA Type C	4.8	22.03	4.28	4.54
7	FM 2854	HMA Type D	1	29.69	7.53	6.22
8	US 87	HMA CMHB-F	*	18.90	1.18	3.61
9	US 290	WMA Type C	3.6	21.90	2.57	4.68
10	US 159	HMA Type D	1	28.21	7.01	6.87
11	LAREDO	HMA Type C	5	20.13	3.36	4.61
12	LA-modified	HMA Type C	2.5	24.09	7.29	6.14
13	LA-control	HMA Type C	3.5	23.12	6.14	5.53
14	IH 35	HMA SMA	1.4	27.92	5.32	4.16
15	HW 6	HMA SMA	2	26.24	4.44	4.12
16	SH 44	HMA Type B	3	25.19	5.13	5.89
17	SH 36	HMA Type D	2.1	24.83	4.21	5.05
18	US 259	HMA Type C	3.8	27.13	5.79	5.46
19	SH 21	HMA Type C	4.4	21.59	2.72	4.89
20	US 87	HMA Type C	6.1	22.74	3.65	5.44

* Could not achieve 8 percent air voids in the field

The researchers prepared two samples from each mixture to approximately 2.5-in in height and 6-in diameter and compacted at a 1.25° gyration angle. The compaction data/curves were recorded which show the number of gyrations and %G_{mm}. Converting the %G_{mm} to percent air void, Figure 2.8 can be developed, which shows the number of gyrations (in logarithmic scale) on the x-axis versus the percent air void on the y-axis. Then, the slope (b) and intercept (a), of the laboratory compaction curve were determined (Figure 2.8) and used in Equation 2.4. The researchers developed the Laboratory Compaction Index (LCI) as a function of the intercept (a) and slope (b) of the compaction data. The LCI quantifies the laboratory compaction effort needed to achieve the target air void and was correlated to the field compaction index. The LCI was calculated using Equation 2.4.

$$LCI = 100 * \frac{b^{1.2}}{a} \qquad \text{Eqn. 2.4}$$

where:

b = the absolute value of the slope

a= the intercept

The steeper the slope, the larger reduction in percent air void for each gyration which results in a larger LCI value. The opposite shows with a steadier slope have low percent air voids after the first gyration (Kassem et al., 2012).

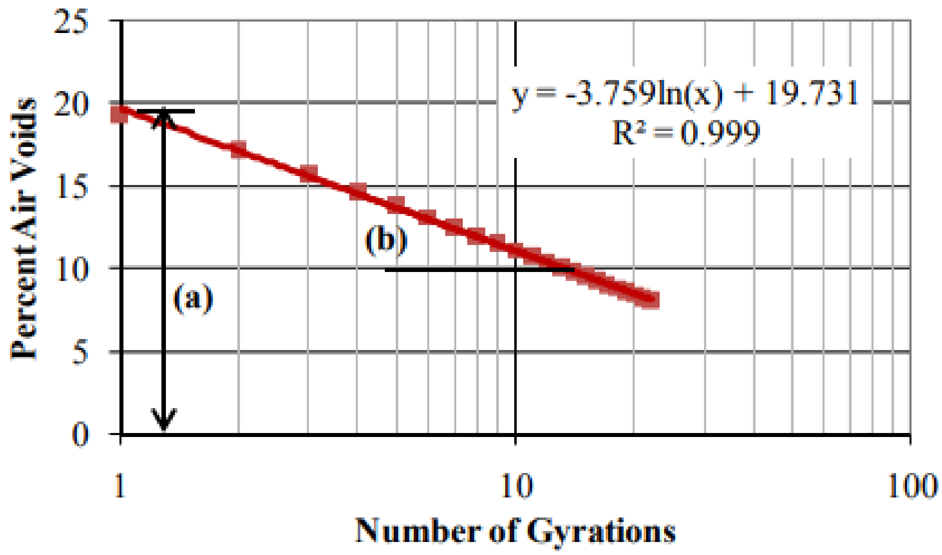


Figure 2.8: Example of SGC Compaction Curves (Kassem et al., 2012)

The LCI index was found to have a fair correlation with field compaction (number of passes to achieve a certain density) as presented in Figure 2.9. The correlation coefficient (R^2) of this relationship is considered acceptable since field compaction is affected by several factors including mix temperature, air temperature, wind speed, and roller speed and weight. The LCI can be used to assess the compactability level (easy, moderate, or difficult) of asphalt mixtures during the mix design stage. Asphalt mixtures with high LCI values are easier to compact compared to those with low LCI values.

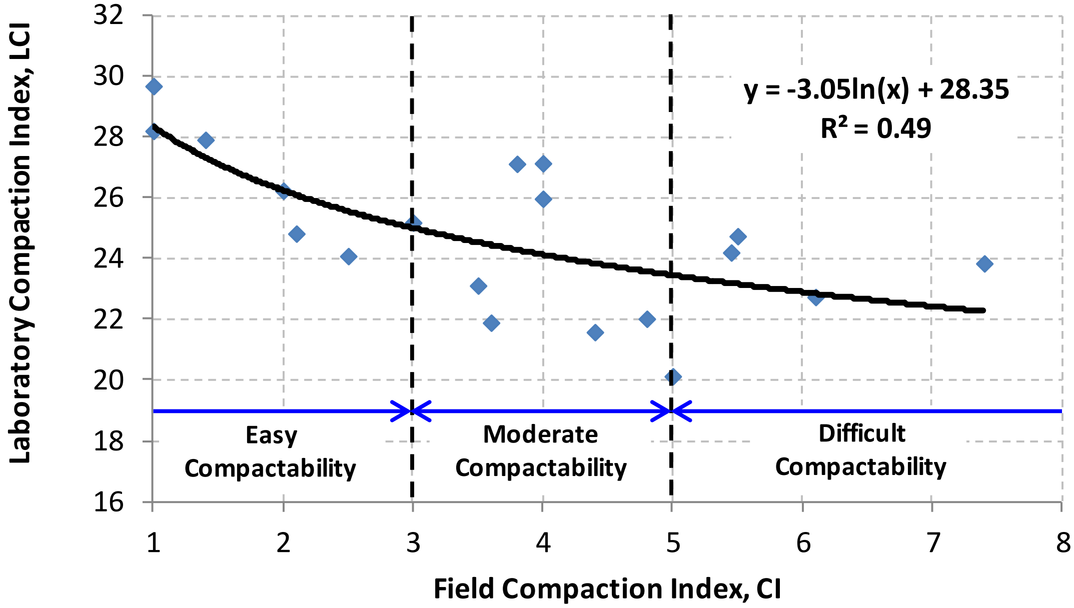


Figure 2.9. Relationship between laboratory and field HMA compaction as proposed by Kassem et al. (2012)

2.4 Performance Graded (PG) Asphalt Binder Modification – Lessons Learned with the Hamburg and MSCR

The Washington State Department of Transportation (WSDOT) manages 18,500 lane miles of roadways. This includes construction, maintenance, and repairs to ensure smooth, safe, and economic pavements. In 2016, WSDOT forecasted 1,043,000 tons of unmodified HMA, and 586,555 tons of modified asphalt would be used. To extend the service life of pavements, WSDOT conducted a study to investigate the use of anti-strip agents in asphalt mixtures and its effect on Hamburg test results. WSDOT discovered the compatibility between asphalt and anti-strip agents, as well as the products and procedures of asphalt modification (DeVol, 2016).

WSDOT compared the HWTT rutting results of the test samples prepared with 0.50% anti-strip agent to the HWTT rutting results of mixtures without anti-strip agents. PG 64-28 asphalt binders was used in the study. Figures 2.10 and 2.11 show the test samples after testing and the change in rut depth with number of passes, respectively. The resulted demonstrated that test samples with no anti-strip had significantly less rutting compared to the ones with anti-strip agent.

Figure 2.10: Hamburg Samples with PG 64-28 “Original Formulation” (DeVol, 2016)

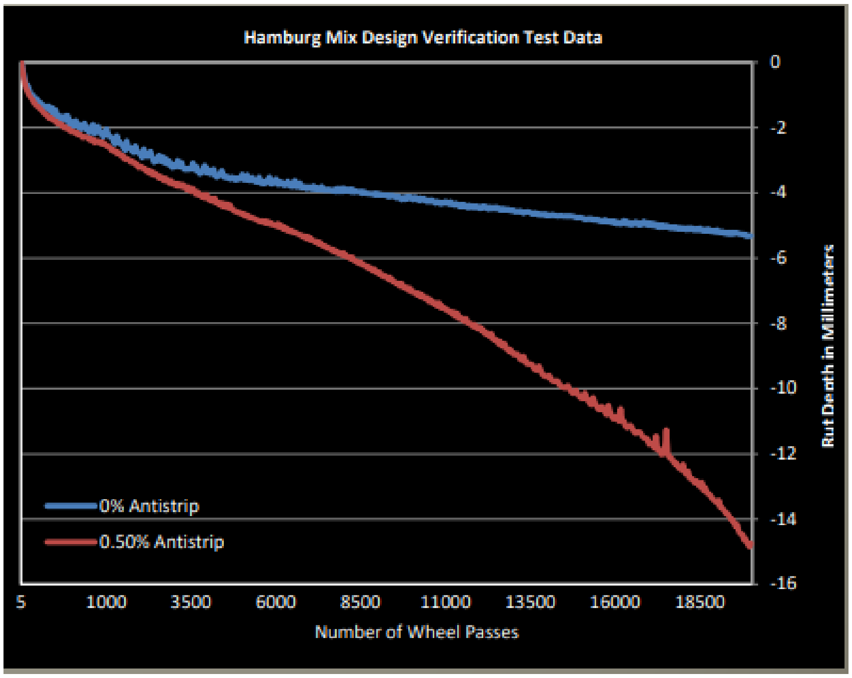


Figure 2.11: Graph of Rutting Depth for PG 64-28 Hamburg Samples (DeVol, 2016)

Then, the researchers evaluated the use of PG 64-28 polymer-modified binder, and the results demonstrated significant improvement in the rutting resistance as shown in Figures 2.12 and 2.13. In addition, the results show an improved tensile strength ratio when anti-strip agents was used (DeVol, 2016).

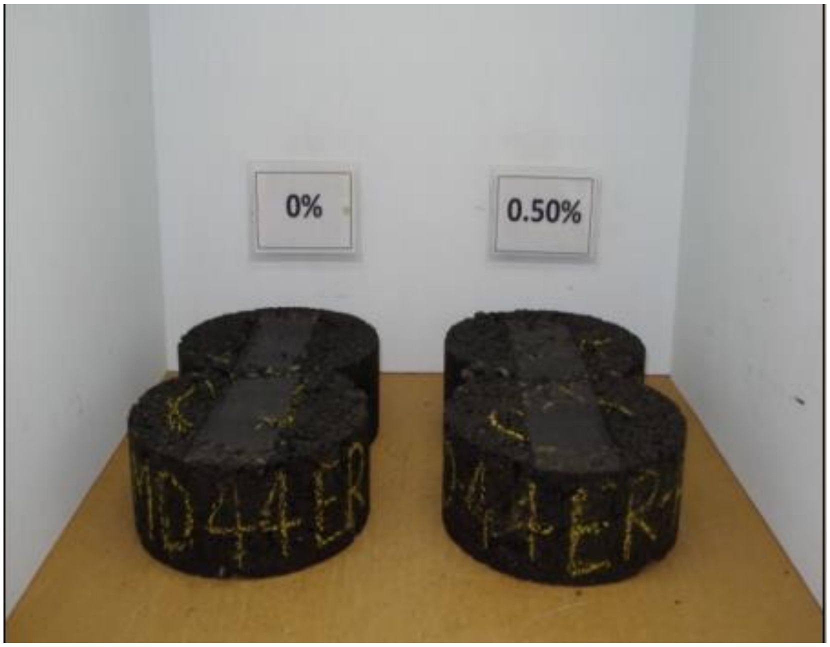


Figure 2.12: Hamburg Samples with PG 64-28 "Polymer Modified" (DeVol, 2016)

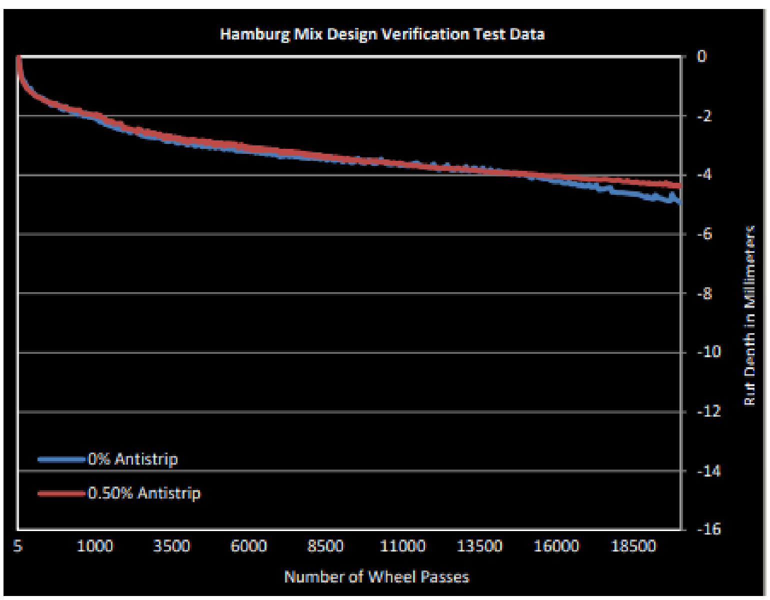


Figure 2.13: Hamburg Rutting Depth using Polymer Modified Binder (DeVol, 2016)

2.5 Effect of RAP Content on Rutting Performance of Asphalt Mixtures

Rahman and Hossain (2014) evaluated the effect of RAP content (up to 50%) on the HWTT rutting results. Historically the Kansas Department of Transportation (KDOT) has used up to 15% RAP content, but since 2008, Superpave mixtures have increased the percentage to around 25%. Figure 2.14 shows the number of HWTT passes before reaching a rut depth of 20 mm. The results demonstrated a significant increase in number of passes for mixtures containing higher percentages of RAP (>35%) compared to the moderate and low RAP contents. This was true for the creep slope, stripping slope and stripping inflection points for higher percentages of RAP. All evaluated mixtures used the same soft binder grade of PG 58-28 due to the aged RAP binder.

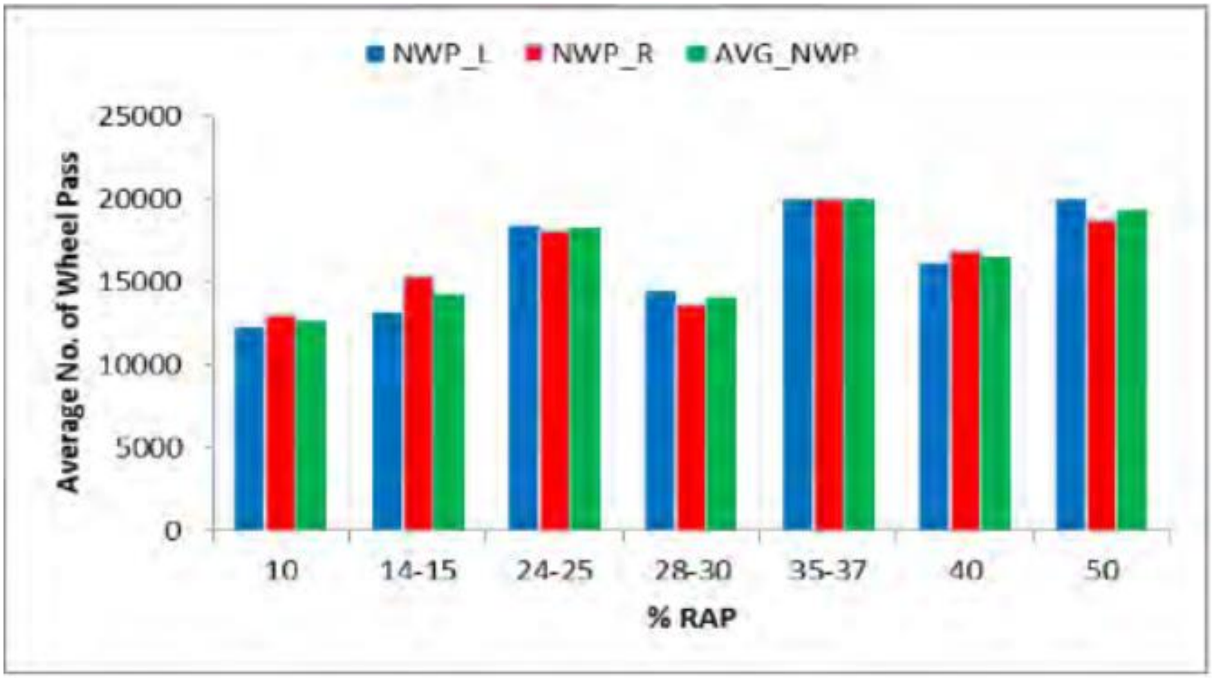


Figure 2.14: Hamburg Results for Different Percentages of RAP (Rahman and Hossain, 2014)

Re-using existing asphalt pavements to produce new asphalt pavements saves money on energy, materials, and money. Though these pavements have reached the end of their service life, the aggregates and binder are still useful in new designs. New pavements incorporating recycled asphalt pavements have proven to be both economically feasible and effective in protecting the environment. RAP mixed with virgin aggregates for the most part has performed well in respect to rutting performance (Xiao et al., 2009).

Alireza et al. (2016) evaluated the effect of RAP content on the rutting performance of asphalt mixtures. In this study, three different percentages of crumb rubber (0%, 10%, and 20% by weight of bitumen) were added to the binder. It was mixed (wet process) and reacted for 30 minutes at a temperature of 350°F (177°C). In addition, four different percentages of RAP (0%, 20%, 40%, and 60% by weight of mixture) were used in the mixtures. Figure 2.15 shows the gradations used for each percentage of RAP.

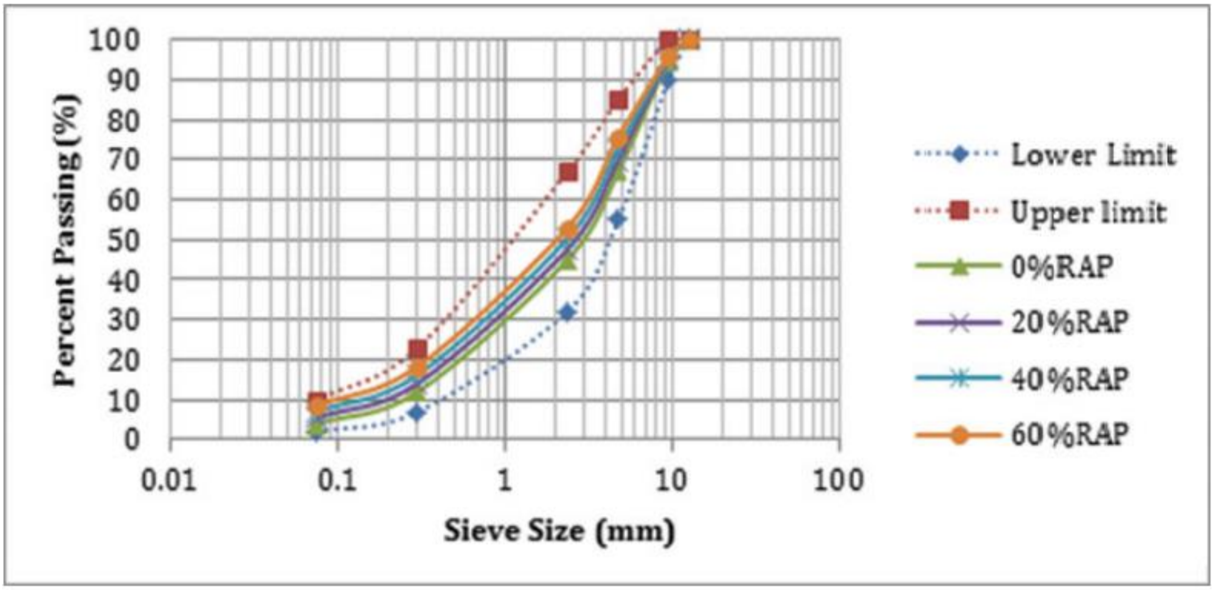


Figure 2.15: Gradations of Designated Aggregate and RAP sources (Alireza et al., 2016)

Three different test methods were used to analyze the effects of crumb rubber and RAP: Marshall Stability and Flow Tests, Dynamic Creep Test, and Wheel Tracking Test. Table 2.5 shows the results of the wheel-tacking test and flow number, the table is split into the percentage of rubber and RAP. The results show a decrease in rut depth as the percentage of crumb rubber and RAP content increase. Thus, the rutting resistance increased as the percentage of rubber and RAP increased in the mixture. The addition of high percentage of RAP, greater than 40%, increased rutting resistance as well (Alireza et al., 2016).

Table 2.5: Rutting Test Results (Alireza et al., 2016)

	Flow Number CR				**Rut Depth CR**		
RAP	0	10	20		0	10	20
0	2100				4.61		
20	3500	3980	4500		3.05	2.80	2.40
40	4900	5040	5500		2.15	2.10	2.00
60	5950	6100	6580		1.75	1.40	1.10

Hajj et al. (2007) evaluated the rutting resistance of asphalt mixtures prepared with RAP using the APA following AASHTO TP63-03. Table 2.6 provides different mixtures evaluated in their study. The factors included two different binder grades, three sources of RAP and three percentages of RAP. The APA was conducted at 140°F for 8,000 cycles or until the maximum criterion of 8-mm rut depth is achieved and used by Nevada DOT. Table 2.7 shows the results for different mixture types, where all samples met the maximum rut depth of 8 mm. The PG 64-28 samples had a rut depth close to the failure criterion (Hajj et al., 2007). Comparing the percentages of RAP from each source for PG 64-22, the rut depth increased with the increase in RAP percentage. The PG 64-28 samples showed the same effect, but at less increments at each stage. The outcome of adding RAP to asphalt mixtures resulted in reduced rutting resistance.

Table 2.6: Type of Mixtures and Nomenclatures (Hajj et al., 2007)

Target Binder Grade	Source	RAP Percentage	Sample ID
PG64-22	Virgin Aggregates	0%	C-22*
	RAP Source I	15%	SI-22-15+
		30%	SI-22-30
	RAP Source II	15%	SII-22-15
		30%	SII-22-30
	RAP Source III	15%	SIII-22-15
		30%	SIII-22-30
PG64-28NV	Virgin Aggregates	0%	C-28*
	RAP Source I	15%	SI-28-15+
		30%	SI-28-30
	RAP Source II	15%	SII-28-15
		30%	SII-28-30
	RAP Source III	15%	SIII-28-15
		30%	SIII-28-30

Table 2.7: Rutting Resistance of the Various Mixtures (Hajj et al., 2007)

Target Binder Grade	Mix	Mix Proportions	APA Rut Depth under 8,000 Cycles @ 140°F	
			mm	inch
PG64-22	C-22	0% RAP	4.6	0.18
	SI-22-15	15% RAP	5.9	0.23
	SI-22-30	30% RAP	6.0	0.24
	SII-22-15	15% RAP	2.2	0.09
	SII-22-30	30% RAP	7.3*	0.29
	SIII-22-15	15% RAP	1.4	0.06
	SIII-22-30	30% RAP	2.1	0.08
PG64-28NV	C-28	0% RAP	2.1	0.08
	SI-28-15	15% RAP	2.1	0.08
	SI-28-30	30% RAP	3.1	0.12
	SII-28-15	15% RAP	2.1	0.08
	SII-28-30	30% RAP	2.4	0.09
	SIII-28-15	15% RAP	2.1	0.08
	SIII-28-30	30% RAP	2.2	0.08

2.6 Effect of Aggregate Type in the Blend on Rutting Performance

Rahman and Hossain (2014) evaluated the effect of aggregate type on the HWTT rutting test results. Different combinations of aggregate sources were evaluated. The aggregate types include crushed gravel (CG), crushed limestone (CS), natural sand (RS), and manufactured sand (MS) sand. Some mixtures contained a combination of different aggregate types of crushed gravel with sand or crushed limestone with sand. Figures 2.16 and 2.17 show the effect of aggregate type on Hamburg wheel passes, and Hamburg rutting depth, respectively. None of the mixtures exceeded 20,000 passes. Figure 2.16 shows the rutting depth after 10,000- and 15,000-wheel passes. The results demonstrated that mixtures containing crushed gravel showed increased rutting resistance with lower rutting depth compared to the other mixtures. The rut depth at 15,000 passes was about 73% higher resistance when the mix contained crushed stone in the aggregate blend. The same trend was observed for the stripping point. Asphalt mixtures containing crushed gravel (CG) had lower rutting than crushed limestone mixtures (Rahman and Hossain, 2014).

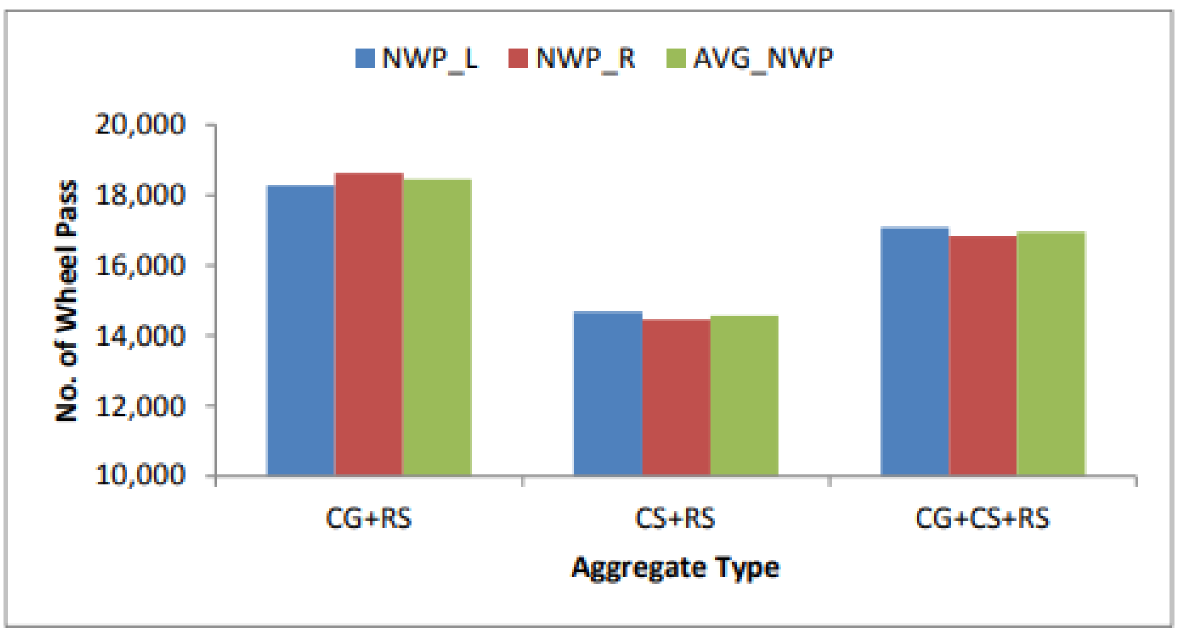


Figure 2.16: Effect of Aggregate Type on Hamburg wheel passes (Rahman and Hossain, 2014)

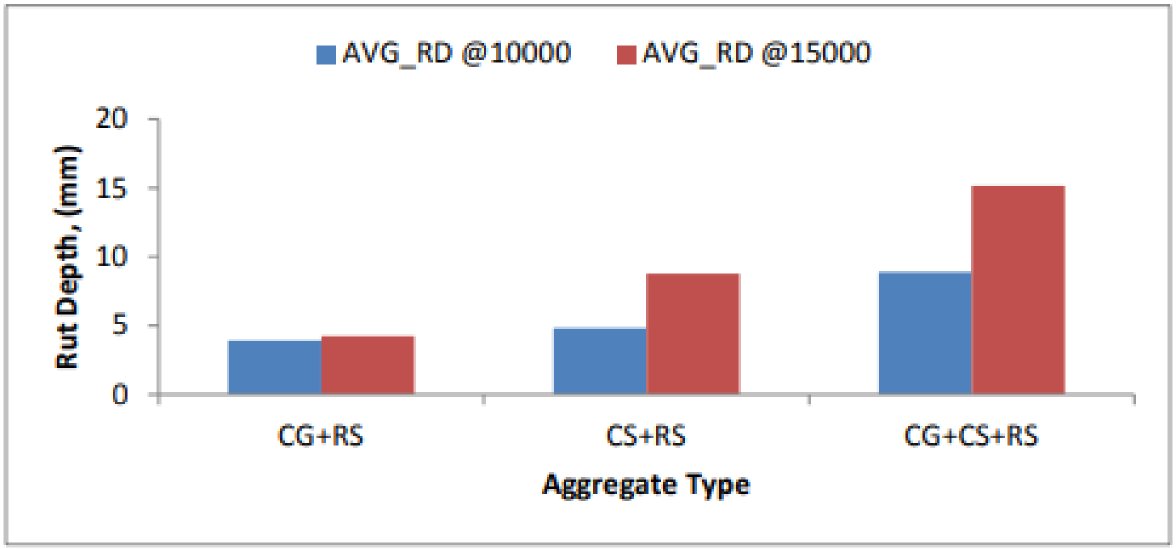


Figure 2.17: Effect of Aggregate Type on Hamburg Rutting Depth (Rahman and Hossain, 2014)

Sabahat et al. (2019) evaluated the rutting performance of two different aggregate types (i.e., dolomite and limestone). The dolomite rock was obtained from Ubhan Shah quarry, while the limestone was acquired from two different sources: Margallah and Sargodha quarries. Three different tests were performed to examine the rutting resistance of different asphalt mixtures that included the Cooper Wheel Tracking Test (CWTT), Asphalt Pavement Analyzer (APA) and Repeated Load Axial Test (RLAT). Table 2.8 shows the results for the tested aggregates. The average rut depths were 2.663-mm, 1.818-mm, and 2.094-mm for Ubhan Shah, Margallah, and Sargodha aggregates, respectively. The dolomite rock from Ubhan had the worst rutting resistance compared to limestone. The difference in rut depth between Margallah and Sargodha was small.

Table 2.8: Test Results for CWTT, APA and RLAT for Selected Mixtures at Temperature Condition of 50°C (Sabahat et al., 2019)

Sr No.	Aggregate	Bitumen	Gradation	CWTT Rut depth (mm)	APA Rut depth (mm)	RLAT	
						Strain (%)	Terminal Cycles
1	Ubhan Shah	NRL 60/70	NHA-A	4.880	1.824	3.003	467
2	Ubhan Shah	NRL 60/70	NHA-B	11.774	4.085	3.004	151
3	Ubhan Shah	NRL 60/70	SP-A	11.891	4.452	3.001	140
4	Ubhan Shah	NRL 60/70	SP-B	8.310	2.845	3.005	203
5	Ubhan Shah	NRL 60/70	MS-II	5.979	2.685	3.001	417
6	Ubhan Shah	NRL 40/50	NHA-A	3.533	1.757	3.002	970
7	Ubhan Shah	NRL 40/50	NHA-B	6.677	2.237	3.000	164
8	Ubhan Shah	NRL 40/50	SP-A	7.637	2.483	3.000	152
9	Ubhan Shah	NRL 40/50	SP-B	5.841	2.039	3.005	548
10	Ubhan Shah	NRL 40/50	MS-II	3.866	1.923	3.000	453
11	Margallah	ARL 60/70	NHA-A	3.131	1.837	3.001	1320
12	Margallah	ARL 60/70	NHA-B	4.472	1.889	3.000	938
13	Margallah	ARL 60/70	SP-A	4.953	2.274	3.001	526
14	Margallah	ARL 60/70	SP-B	3.902	1.748	3.003	856
15	Margallah	ARL 60/70	MS-II	3.161	2.121	3.000	1340
16	Margallah	NRL 40/50	NHA-A	1.540	1.356	3.001	1435
17	Margallah	NRL 40/50	NHA-B	2.371	1.740	3.003	1464
18	Margallah	NRL 40/50	SP-A	2.678	2.109	3.001	642
19	Margallah	NRL 40/50	SP-B	1.820	1.583	3.005	930
20	Margallah	NRL 40/50	MS-II	1.694	1.523	3.006	1920
21	Sargodha	ARL 60/70	NHA-A	3.664	2.092	3.001	1195
22	Sargodha	ARL 60/70	NHA-B	4.839	2.169	3.012	849
23	Sargodha	ARL 60/70	SP-A	5.158	2.640	3.000	476
24	Sargodha	ARL 60/70	SP-B	4.572	1.991	3.001	775
25	Sargodha	ARL 60/70	MS-II	4.525	2.446	3.003	1213
26	Sargodha	NRL 40/50	NHA-A	3.335	1.562	3.001	1299
27	Sargodha	NRL 40/50	NHA-B	3.880	2.020	3.002	923
28	Sargodha	NRL 40/50	SP-A	4.236	2.442	3.004	517
29	Sargodha	NRL 40/50	SP-B	3.566	1.832	3.000	842
30	Sargodha	NRL 40/50	MS-II	3.513	1.750	3.003	1318
31	Ubhan Shah	NRL 60/70	NHA-A (BC)	4.853	1.478	3.005	1198
32	Ubhan Shah	NRL 60/70	NHA-B (BC)	5.453	1.917	2.906	470
33	Ubhan Shah	NRL 60/70	SP-B (BC)	6.245	2.576	3.001	427
34	Ubhan Shah	NRL 60/70	DBM (BC)	4.041	2.331	3.000	616
35	Margallah	ARL 60/70	NHA-A (BC)	3.299	1.578	3.000	3204
36	Margallah	ARL 60/70	NHA-B (BC)	3.253	1.550	3.002	831
37	Margallah	ARL 60/70	SP-B (BC)	4.335	1.604	3.001	611
38	Margallah	ARL 60/70	DBM (BC)	2.403	1.210	2.477	3600

Ahmed and Attia (2013) evaluated the effect of aggregate gradation and type, on rutting resistance of asphalt samples. Crushed basalt, crushed dolomite and crushed limestone were included in the testing matrix for rutting resistance evaluation using the wheel tracking test. The wheel tracking machine consists of a rubber-tired wheel with a diameter of 20-cm and 5-cm height. A load of 53.5-kg was applied to the specimens for a total of 60 minutes which presented 2520 passes. Figure 2.18 represents the rutting deformation for each aggregate type and gradation. For 2C open gradation, the final rut depth was over 6-mm for basalt, just over 5-mm for dolomite, and under 6-mm for limestone. The 3A coarse gradation had 4.5-mm for basalt, 2.1-mm for dolomite, and 4-mm for limestone. The difference in rut depth was larger for this gradation (i.e., 3A Coarse) compared to 2C open gradation. The dolomite had the best rutting resistance followed by limestone and basalt.

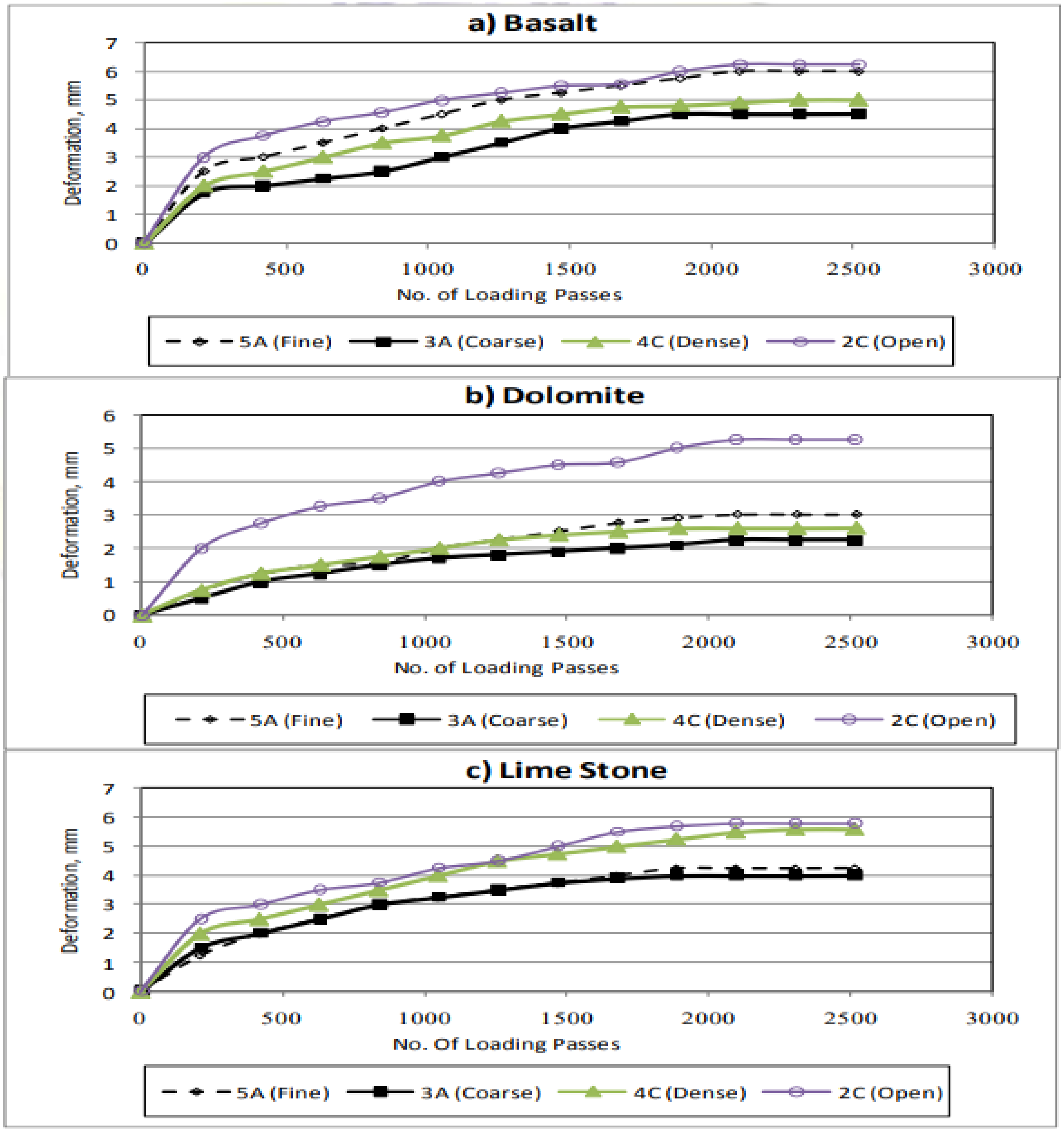


Figure 2.18: Effect of Aggregate Gradation on Rutting Resistance (Ahmed and Attia, 2013)

2.7 Effect of Binder Grade on Rutting Performance of Asphalt Mixtures

Rahman and Hossain (2014) evaluated the effect of binder grade on rutting performance of asphalt mixtures. KDOT primarily uses two binder grades for recycled Superpave mixtures: PG 64-22 and PG 58-28. An additional binder PG 70-28 was evaluated in the study for comparison between different binder grades. Over 90% of crushed gravel mixtures prepared with PG 64-22 and PG 70-28 binder completed 20,000-wheel passes, and 56% of mixtures prepared with PG 58-28 completed 20,000 passes (Rahman and Hossain, 2014). Mixtures prepared with stiffer binders had higher resistance to rutting compared those with softer binders.

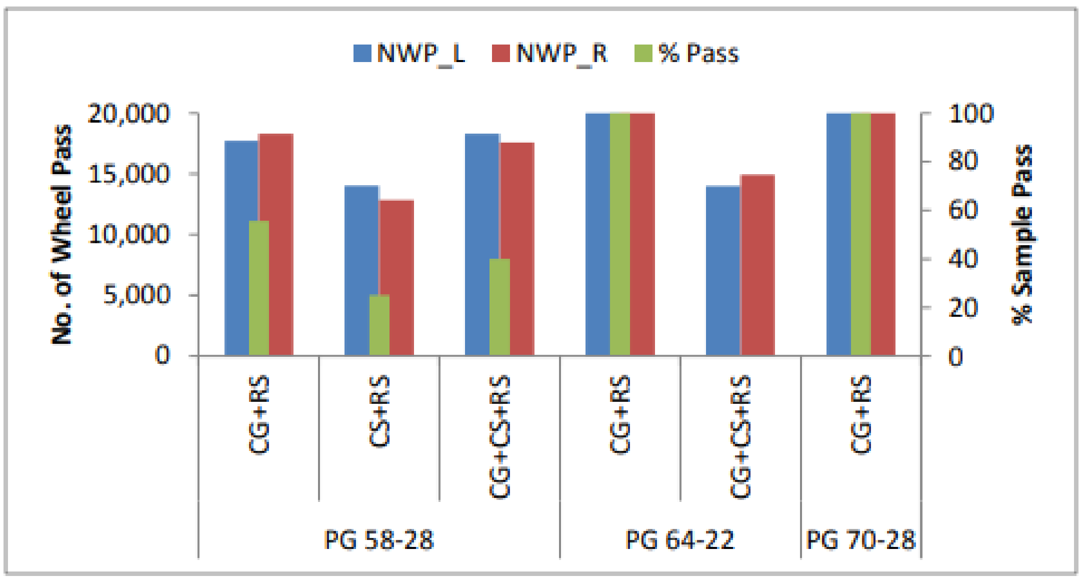


Figure 2.19: Effect of Binder Grade on HWTT Results (Rahman and Hossain, 2014)

Kassem et al. (2019) investigated the sensitivity of mix properties to binder grades. Two different rutting analysis tests were conducted, to analyze the rutting between different binder grades: APA (dry) and HWTT (wet) test. Two binders: PG 70-28 and PG 58-34 at three binder contents of 4.25%, 5.0% and 5.75% were evaluated. Figures 2.20 and 2.21 present the results of HWTT and APA rut depths for the test mixtures. For HWTT results, PG 70-28 resulted in less rutting compared to PG 58-34 at the corresponding binder content. The difference in rut depth between the binder grades was statistically significant ($p<0.05$). The APA results (Figure 2.21) showed different results due to the varying testing temperature. The test was conducted at 70°C for PG 70-28 and 58°C for PG 58-38 according to AASHTO T340. APA results showed an increase in rut depth for PG 70-28 than PG 58-34 and was statistically significant. Mixtures with stiffer binder grades are expected to have more resistance to rutting than softer binders if the test is conducted at the same temperature.

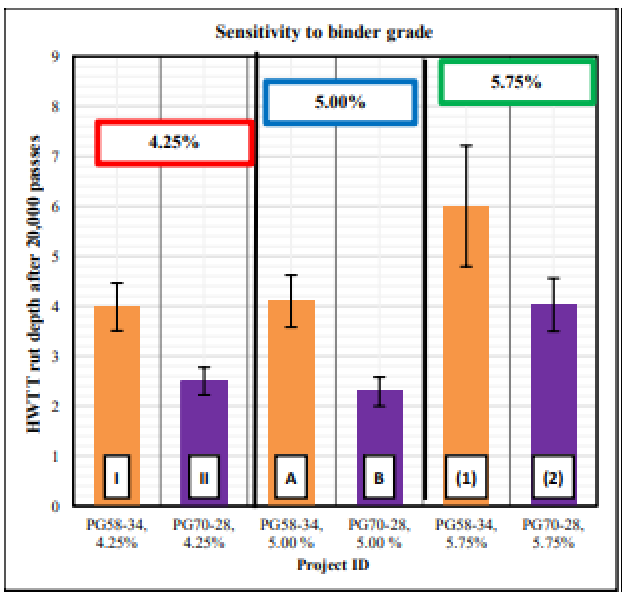


Figure 2.20: Sensitivity of HWTT Rut Depth after 20,000 Passes to PG Grade (Kassem et al., 2019)

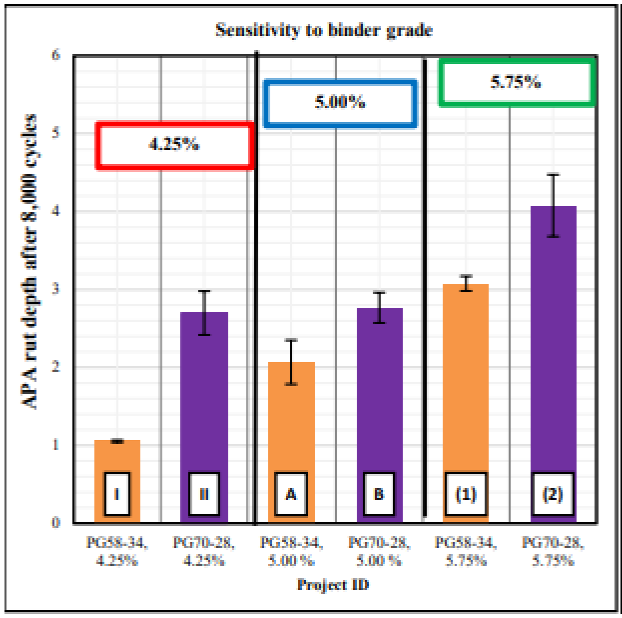


Figure 2.21: Sensitivity of APA Rut Depth at 8,000 Cycles to PG Grade (Kassem et al., 2019)

Baoshan et al. (2009) used the APA rut test to examine the rutting resistance of dense-graded surface HMA mixtures. Coarse aggregate with different angularities (100, 85, 70, 50, and 35% of aggregate with two or more fractured surfaces) were used to produce mixes in their study. In addition, three different binder grades (PG 64-22, PG 76-22, PG 82-22) were also included. They conducted the APA test in accordance with AASHTO TP63-03 but at a set testing temperature of 64°C. Figure 2.22 represents the APA rut depths in millimeters for each gradation and binder grade. In this study, the softer binders produced higher rut depth compared to the stiffer binders. Since the testing temperature was fixed in this study, the stiffer binders (PG 76-22 and PG 82-22) were more resistant to rutting.

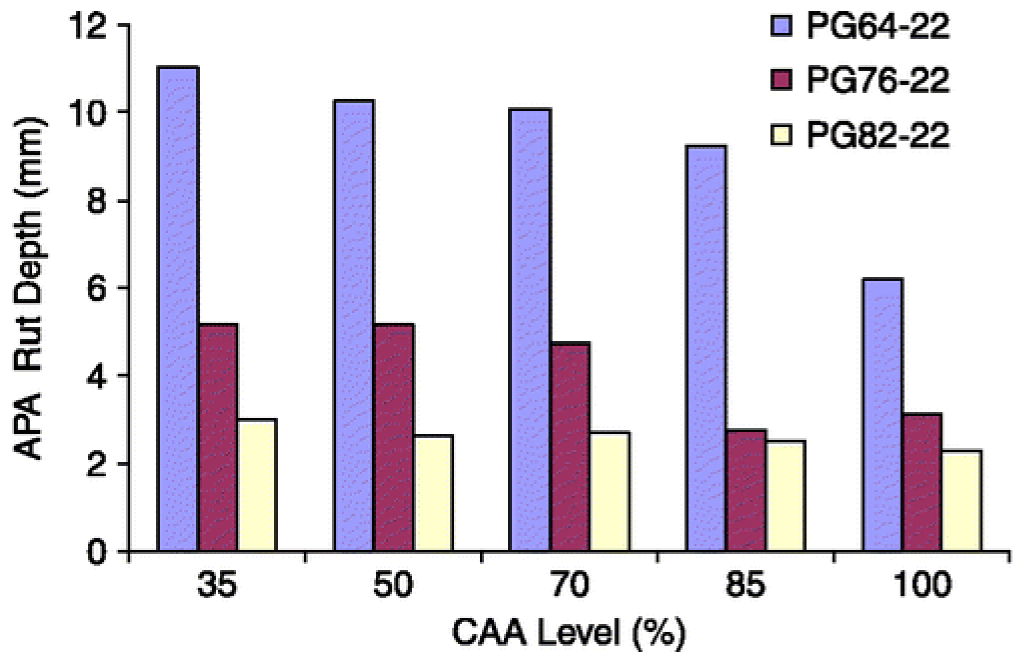


Figure 2.22: APA Rut Depths of HMA Mixtures (Baoshan et al., 2009)

2.8 Effect of Binder Source and Content on Rutting Performance of Asphalt Mixtures

Rahman and Hossain (2014) evaluated the effect of binder source on HWTT rutting performance of asphalt mixtures. They used the same binder grade (i.e., PG 58-28) from different sources or refineries. They also used 25% RAP content in the evaluated mixtures. Figure 2.23 shows the percentage of mixtures passing 20,000 passes. The results demonstrated that binders from different sources had different rutting performance. The asphalt binder from at Sinclair, Phillipsburg outperformed the other sources with 75% passing 20,000 passes (Figure 2.23).

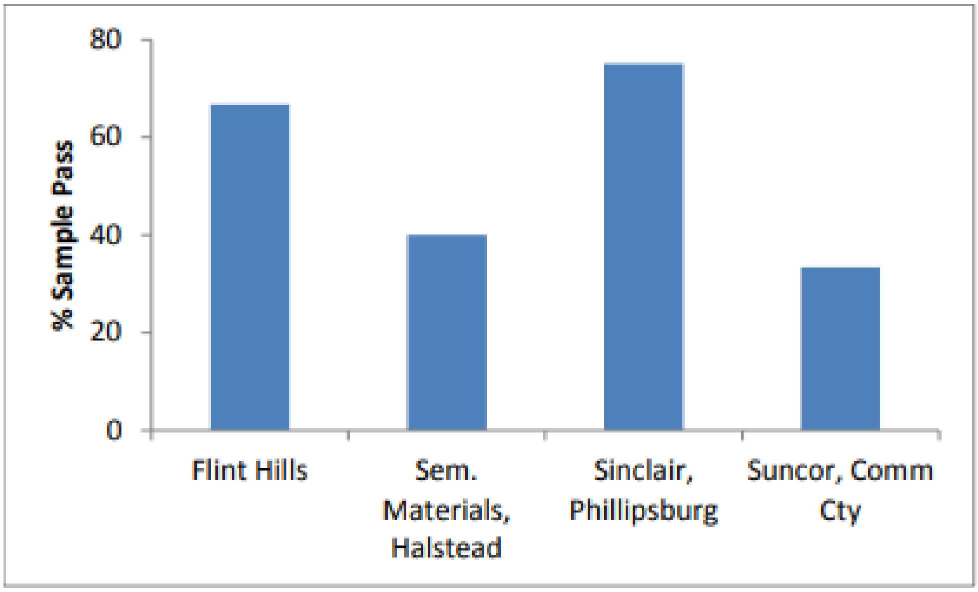


Figure 2.23: Effect of Binder Source on HWTT Test Results (Rahman and Hossain, 2014)

Kassem et al. (2019) analyzed the rutting characteristics of asphalt specimens at different binder contents. The analysis includes two different binder grades for further comparison of the effect of binder content on asphalt specimens. The two binder grades used were PG 70-28 and PG 58-34 with three binder contents: 4.25%, 5.0%, 5.75%. Two rutting tests were performed: the APA rut test in dry conditions and HWTT test in wet conditions. Figures 2.24 and 2.25 show the results of HWTT testing after 20,000 passes and APA test after 8,000 cycles, respectively. The results exhibited an increase in rut depth with the increase in binder content. For PG 70-28, the rut depth decreased from 4.25% to 5.0% binder content. For PG 58-34, the rut depth slightly increased between 4.25% B.C. and 5.0% B.C. The statistical analysis showed significance difference between 5.75% binder content and both 4.25% and 5.0% binder content; however, there was no significance between 4.25% and 5.0% binder content. The APA results showed higher rutting for PG 70-28 compared to PG 58-34. The difference in rut depth for PG 70-28 was statistically significant between 5.75% to both 4.25% and 5.0% binder content. For PG 58-34, the difference in rut depth was significant between each binder content.

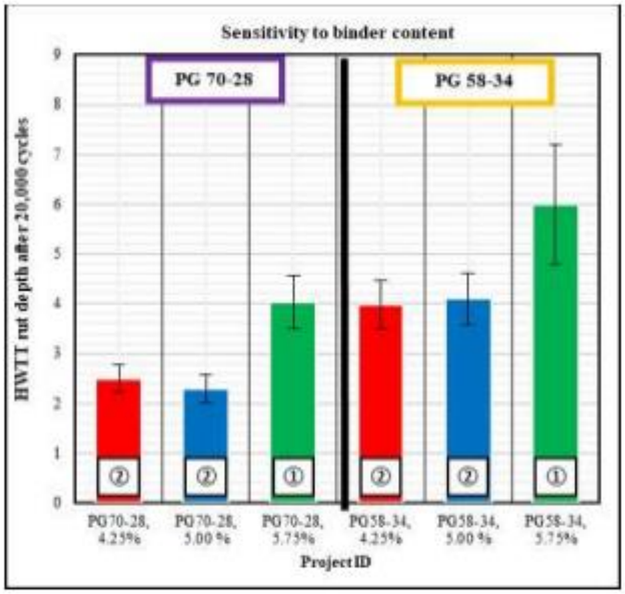


Figure 2.24: Sensitivity of HWTT Rut Depth after 20,000 passes to Binder Content (Kassem et al., 2019)

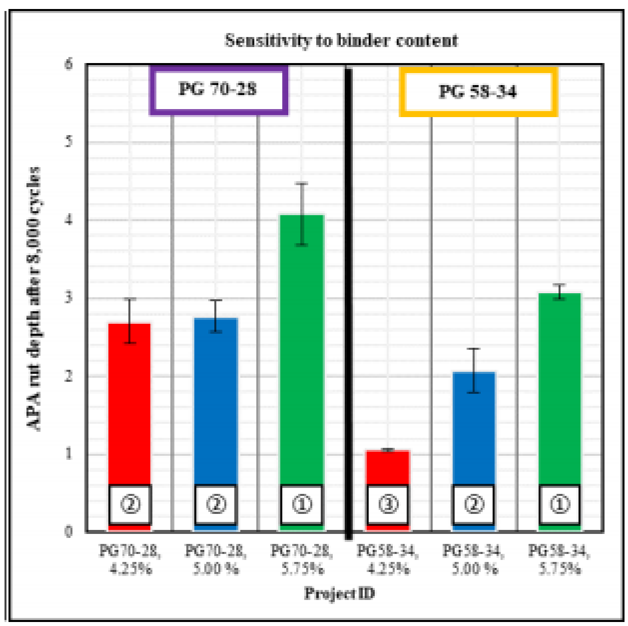


Figure 2.25: Sensitivity of APA Rut Depth at 8,000 Cycle to Binder Content (Kassem et al., 2019)

Zhao et al. (2012) examined the rutting characteristics of asphalt mixtures prepared using different binder grades and sources. Three different binder grades were used as presented in Table 2.9. They conducted the APA test in accordance with AASHTO TP63-03. The test was run for 8,000 cycles at the testing temperature specific to the binder grade. Figure 2.26 represents the average rut depth for each binder after 8,000 cycles. The binder source played a big role in rutting performance, binder (C) PG 64-22 and binder (I) PG 64-22 were the same binder grade but there was a 0.7-mm difference in overall rutting depth. Binder (I) PG 64-22 and binder (N) PG 58-28 come from the same source and show the same trend as APA testing with less rut depth coming from softer binders.

Table 2.9: Superpave Binder Properties for the Virgin Binders (Zhao et al., 2012)

Parameters		Binder source		
		C (PG64-22)	I (PG64-22)	N (PG58-28)
Original				
Viscosity, Ps-s	(135 °C)	0.626	0.405	0.31
$G^*/\sin\delta$, (Pa)	(64/58 °C)	1801	1207	1378
RTFO residue				
Mass change, (%)	(165 °C)	−0.24	−0.02	–
$G^*/\sin\delta$, (Pa)	(64/58 °C)	4608	2815	3875
PAV residue				
$G^*\sin\delta$, (kPa)	(25/19 °C)	2420	2970	4064
Stiffness (60 s), (MPa)	(−12/−18 °C)	129	183	249
m-value (60 s)	(−12/−18 °C)	0.354	0.311	0.281

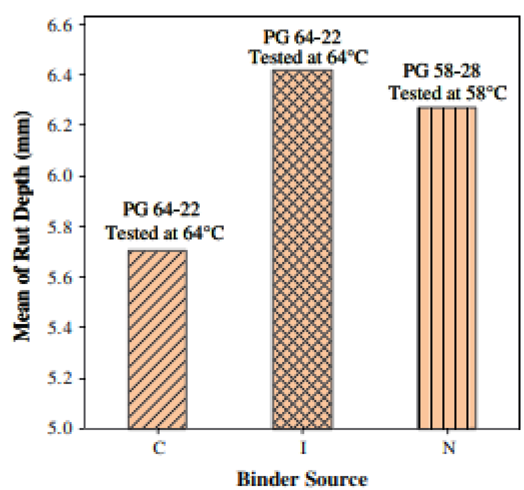


Figure 2.26: Binder Source Effects on Rutting Performance (Zhao et al., 2012)

2.9 The Use of Anti-Strip Additives on the Moisture Susceptibility of Asphalt Mixtures

Gu et al. (2020) examined the influence of anti-strip additives on the moisture susceptibility and durability on granite-based asphalt mixtures. The mixtures were comprised of granite from two different sources and were open-graded friction course, referred to as FC-5 asphalt mixtures. Four groups were tested using the modified Lottman procedure and HWTT. The four groups were comprised of 1% of hydrated lime by aggregate weight, 1% hydrated lime with 0.5% anti-strip (LAS) additive by binder weight, 1.5% hydrated lime, and 1.5% hydrated lime with 0.5% LAS. Table 2.10 presents to testing matrix of all the different samples.

Table 2.10: Summary of FC-5 Specimen Replicates for Performance Tests (Gu et al., 2020)

Aggregate Type	Additive Type	Test Method	Number of Specimens			
			Unconditioned	1 F-T Cycle*	1000-hr APWS	2000-hr APWS
Junction City Granite	1% HL**	Cantabro	3	NA	3	3
		IDT***	3	3	3	3
		HWTT	4	NA	4	4
	1% HL + LAS_1	Cantabro	3	NA	3	3
		IDT	3	3	3	3
		HWTT	4	NA	4	4
	1.5% HL	Cantabro	3	NA	3	3
		IDT	3	3	3	3
		HWTT	4	NA	4	4
	1.5% HL + LAS_1	Cantabro	3	NA	3	3
		IDT	3	3	3	3
		HWTT	4	NA	4	4
Nova Scotia Granite	1% HL	Cantabro	3	NA	3	3
		IDT	3	3	3	3
		HWTT	4	NA	4	4
	1% HL + LAS_2	Cantabro	3	NA	3	3
		IDT	3	3	3	3
		HWTT	4	NA	4	4
	1.5% HL	Cantabro	3	NA	3	3
		IDT	3	3	3	3
		HWTT	4	NA	4	4
	1.5% HL + LAS_2	Cantabro	3	NA	3	3
		IDT	3	3	3	3
		HWTT	4	NA	4	4

Note: * F-T = Freeze-Thaw; ** HL = Hydrated Lime; ***IDT = Indirect Tension.

IDT tests were conducted for both Junction City granite and Nova Scotia granite for each set of samples. Figure 2.27 shows the results of the tensile strength ratio (TSR) for each mixture for the Junction city granite. The TSR is defined as a ratio of the tensile strength of the conditioned samples by the tensile strength of the dry samples. In this figure, the blue column represents the dry tensile strength in psi, and the orange dots show the TSR for each set of samples. All values were above 80% TSR which means good resistance to moisture damage. The results of this group of asphalt mixtures showed that mixtures with 1% hydrated lime to have the highest TSR value. This means that adding LAS or the additional 0.5% hydrated lime did not improve the moisture resistance of these samples. An explanation could be the control mix of 1% hydrated lime already had excellence resistance to moisture damage, so additional additives diminished such effect (Gu et al., 2020).

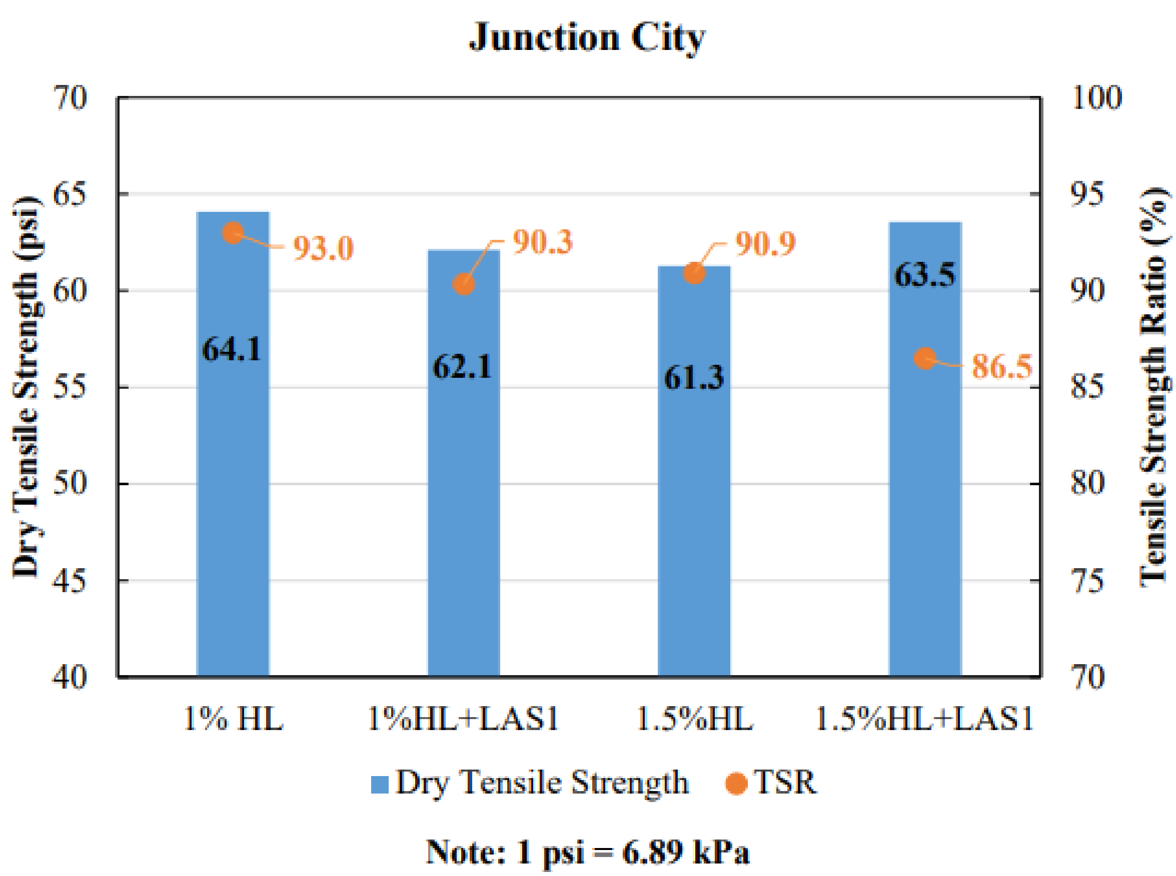


Figure 2.27: TSR Test Results for Junction City FC-5 Asphalt Mixtures (Gu et al., 2020)

Figure 2.28 shows the same results as Figure 2.27 but for granite from Nova Scotia. The results from the Nova Scotia aggregate showed similar findings of the Junction City where the additional hydrated lime and LAS had little effect on moisture resistance. Meanwhile, there was slight improvement to the control mixture from that of Junction City but not significant. This could be due to the fact that the control mixture had good resistance to the moisture damage. Comparing the mixtures with hydrated lime and liquid anti-strip, they do not improve the TSR compared to the controlled mixture. Comparing the mixtures from the two sources, the Nova Scotia TSR values are overall larger, which is better compared to Junction City Granite.

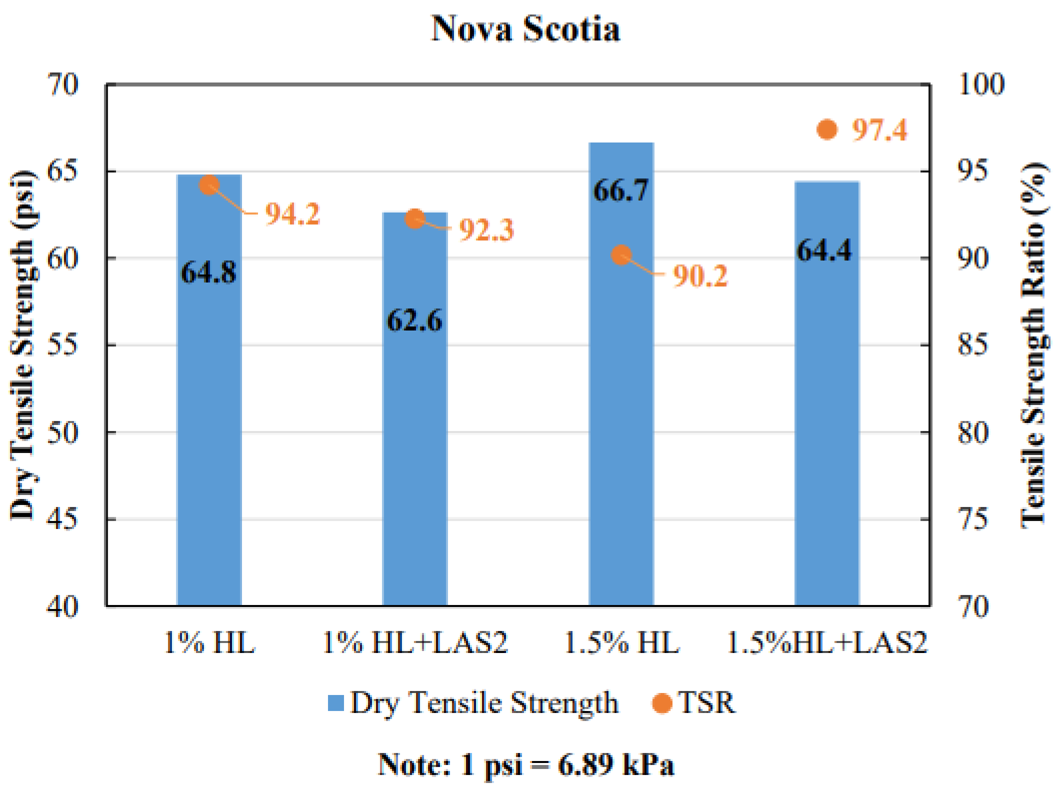


Figure 2.28: TSR Test Results for Nova Scotia FC-5 Asphalt Mixtures (Gu et al., 2020)

Figures 2.29 and 2.30 show the HWTT rut depth of the Junction City and Nova Scotia asphalt samples, respectively. Each bar represents an asphalt mixture prepared with different percentages of hydrated lime and LAS additives at different conditioning times. The rut depth for all test mixtures was below 12-mm, which is the failure rut criterion, after 20,000 passes. After 20,000 passes, the Junction City mixtures showed no signs of stripping and provided satisfactory durability and resistance to moisture damage. In addition, the values of TSR from Junction City aggregate are above 0.80, therefore not susceptible to moisture damage.

The results of the Nova Scotia samples demonstrated similar findings from the Junction City materials. the rut depths were well below the 12-mm max which indicates good resistance to moisture damage. The addition of LAS to the samples showed little favorable effects on the moisture resistance, and sometimes had adverse effects, especially after 2,000-hr conditioning time.

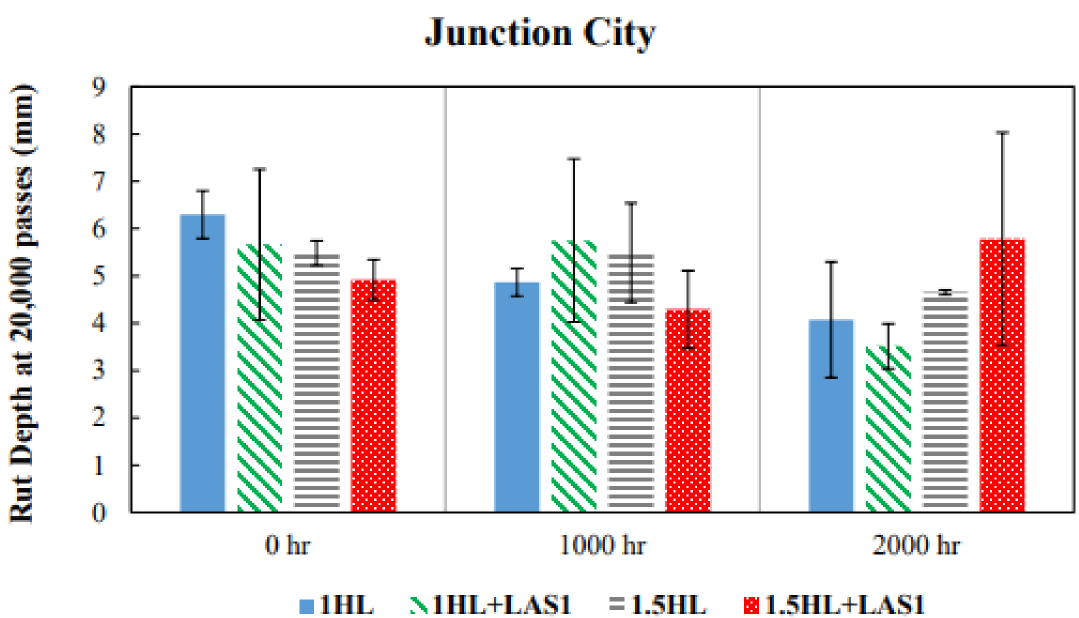


Figure 2.29: Rut Depth of Junction City FC-5 Asphalt Mixtures after 20,000 Passes (Gu et al., 2020)

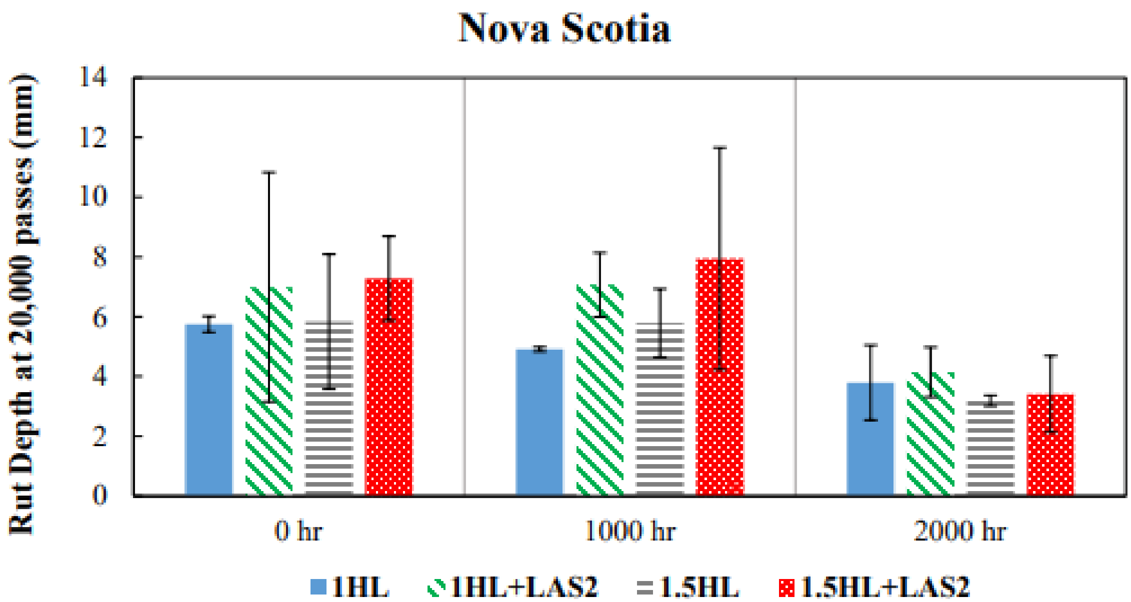


Figure 2.30: Rut Depth of Nova Scotia FC-5 Asphalt Mixtures after 20,000 Passes (Gu et al., 2020)

Shidhore (2005) used a modified AASHTO T283 (TSR) test to assess the moisture susceptibility of asphalt mixtures. The modified procedure does not require a freeze-thaw cycle, but only conditioned (saturated) and dry samples. Each TSR test was performed using two dry and two conditioned specimens that are 150 mm in diameter and 95 mm in height at 7.0 ± 1% air voids. Six sets of specimens, prepared with different percentages of fines and anti-strip additives, were tested (Table 2.11). Tables 2.12 to 2.14 show the wet and dry tensile strength values for all test samples containing Boone fines. The results demonstrated that better strength was achieved at 1.5% over 6.5% of fines. Comparing Boone fines of 0% Lime to 1%, the addition of lime to the mix improved the TSR value from 74.8% to 85.7%. The results from Enka fines showed an improvement from 70.1% to 93.8%. The overall results demonstrated significant improvement to moisture damage when adding 1% lime to asphalt mixtures.

Table 2.11: Rice Specific Gravity (G_{mm}) (Shidhore, 2005)

Description	Nomenclature	G_{mm}
1.5% Boone BHF, 0% Lime	BF1.5L0	2.517
1.5% Enka BHF, 0% Lime	EF1.5L0	2.514
6.5% Boone BHF, 0% Lime	BF6.5L0	2.516
6.5% Enka BHF, 0% Lime	EF6.5L0	2.517
5.5% Boone BHF, 1% Lime	BF5.5L1	2.510
5.5% Enka BHF, 1% Lime	EF5.5L1	2.511

Table 2.12: TSR Results: 1.5% Boone Fines with 0% Lime (Shidhore, 2005)

Unconditioned Specimens			Conditioned Specimens			
Specimen no.	**Air Voids (%)**	**Dry TS (psi)**	**Specimen no.**	**Saturation (%)**	**Air Voids (%)**	**Wet TS (psi)**
BF1.5L0-1	6.6	1157	BF1.5L0-5	75.3	6.6	859
BF1.5L0-2	6.7	1127	BF1.5L0-6	74.9	6.9	840
BF1.5L0-3	6.6	1139	BF1.5L0-7	74.2	6.6	859
BF1.5L0-4	6.7	1209	BF1.5L0-8	72.1	6.7	921
Average =	6.7	1158			6.7	870
		TSR =	**74.8**			

Table 2.13: TSR Results: 6.5% Boone Fines with 0% Lime (Shidhore, 2005)

Unconditioned Specimens			Conditioned Specimens			
Specimen no.	**Air Voids (%)**	**Dry TS (psi)**	**Specimen no.**	**Saturation (%)**	**Air Voids (%)**	**Wet TS (psi)**
BF6.5L0-1	6.7	992	BF6.5L0-5	70.5	6.6	676
BF6.5L0-2	6.4	1081	BF6.5L0-6	68.9	6.6	712
BF6.5L0-3	6.7	1068	BF6.5L0-7	72.3	6.6	677
BF6.5L0-4	6.4	1069	BF6.5L0-8	76.1	6.5	676
Average =	6.6	1052			6.6	685
		TSR =	**63.3**			

Table 2.14: TSR Results: 5.5% Boone Fines with 1% Lime (Shidhore, 2005)

Unconditioned Specimens			Conditioned Specimens			
Specimen no.	**Air Voids (%)**	**Dry TS (psi)**	**Specimen no.**	**Saturation (%)**	**Air Voids (%)**	**Wet TS (psi)**
BF5.5L1-1	6.4	1153	BF5.5L1-5	66.3	6.5	1040
BF5.5L1-2	6.6	1210	BF5.5L1-6	63.4	6.3	997
BF5.5L1-3	6.3	1201	BF5.5L1-7	60.5	6.6	1032
BF5.5L1-4	6.4	1228	BF5.5L1-8	58.0	6.3	1033
Average =	6.4	1198			6.4	1025
		TSR =	**85.7**			

Watson et al. (2012) evaluated the use of three different anti-stripping agents on the moisture susceptibility of asphalt mixtures. They used the modified Lottman procedure where the samples went through a freeze-thaw cycle before testing. The three different anti-stripping agents used in this study included 1) hydrated lime at 1% of dry weight; 2) one liquid anti-stripping agent, and 3) warm mix asphalt additive (WMX). The results of the TSR are shown in Figure 2.31. The results demonstrated that the hydrated lime provided higher TSR values which indicates better resistance to moisture damage compared to the other additives. The average TSR values for limestone mixtures containing hydrated lime ranged from 93.1 to 104.3%. Mixtures with the WMX additive resulted in 79.5 to 83.4% TSR and the liquid anti-stripping agent (LAS) ranged from 77.7 to 77.8%. The ranking of worst to best anti-stripping agents starts with LAS, WMX to Hydrated lime. The results also showed that the number of conditioning cycles was not significant in TSR values.

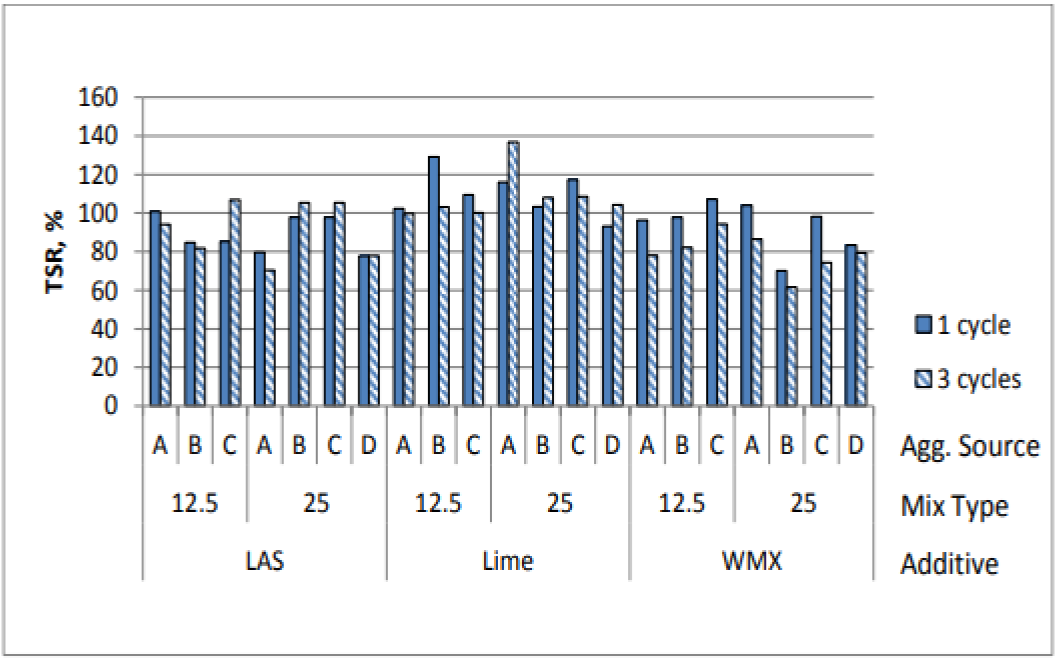


Figure 2.31: TSR Results by Aggregate Source, Mix Type, and Additive Type (Watson et al., 2012)

CHAPTER 3 Materials Description and Experimental Design

3.1 Introduction

Chapter 3 discusses different asphalt mixtures and field projects used in this study. In addition to information about testing matrices and protocols used to test the laboratory and field projects.. The laboratory experiments included rutting resistance tests using the APA and HWTT testing protocols, moisture susceptibility, and compactability of asphalt mixtures.

3.2 Materials Description

3.2.1 RAP and Aggregates Characterization

Two different sources of RAP materials were used in this study. The first source (i.e., RAP No. 1) was obtained from an asphalt plant in Pullman, WA, while the second source of RAP (RAP No. 2) was acquired from an asphalt plant in Lewiston, ID. To control the variability of the RAP materials, the RAP materials were fractionated into coarse (retained on Sieve No. 4) and fine (passing Sieve No. 4) sizes. Both coarse and fine materials were incorporated in the mix in accordance with the job mix formula. Figure 3.1 shows the RAP binder content for the two sources of RAP. RAP No. 2 had higher binder content (i.e., 5.7%) compared to RAP No. 1, which had 4.3% binder content. Figure 3.2 shows the gradation of RAP materials from the two sources. More information about the RAP materials is provided in Appendix A. In addition to the RAP materials, two types of virgin aggregates (i.e., basalt and river gravel) were obtained and used in this study. The basalt rock was acquired from an asphalt plant in Pullman, WA, while the river gravel was obtained from asphalt plant in Lewiston, ID.

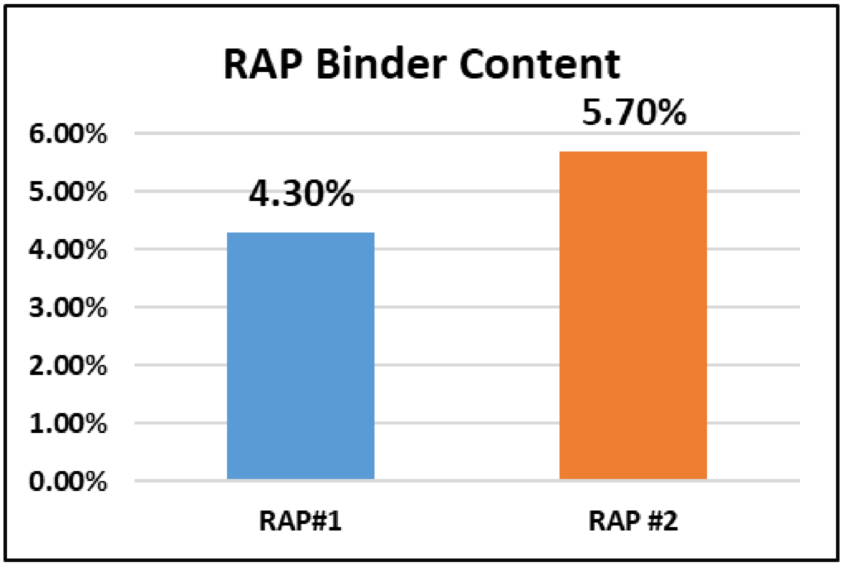


Figure 3.1: Binder Content of RAP #1 & #2

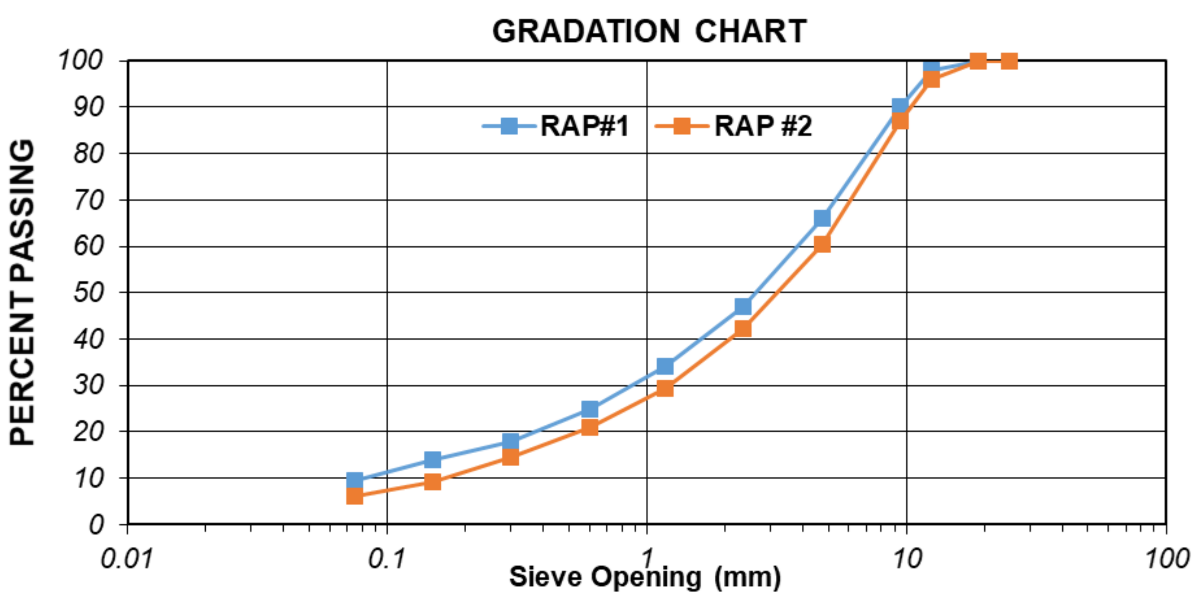


Figure 3.2: Aggregate Gradation of RAP #1 and RAP #2

3.2.2 Laboratory Mixed-Laboratory Compacted (LMLC) Mixes

Laboratory Mixed-Laboratory Compacted (LMLC) asphalt mixes were prepared. The LMLC included several variables including aggregate type, binder grade and content, RAP content, percent air voids and mix design. All the LMLC were tested to evaluate the mix performance in terms of mix compactability, rutting resistance, and moisture damage. In addition, the author assessed the applicability and sensitivity of Laboratory Compaction Index (LCI) to capture the change in mix compositions (e.g., RAP content, percent binder, aggregate structure) during the laboratory compaction of the LMLC. The LMLC mixes included different variable such as aggregate source, RAP source, RAP content, binder content and binder grade. All mixes meeting the acceptable air void (7.0 ± 0.5%) were tested to evaluate the rutting resistance, moisture damage, and mix compactability. Table 3.1 summarizes different factors and their levels included in the LMLC. The LMLC included SP5 mix design (Figure 3.3), two different RAP sources (RAP no. 1 and RAP No. 2), two rock types (basalt and river gravel); RAP contents (0%, 25%, 50%), three binder grades (PG 58-34, PG 64-28, PG 76-22), and three binder contents (4.25%, 5.0%, 5.75%). In addition, test mixtures prepared with and without antistrip agents (0% and 1.5%) to evaluate the effect of the anti-stripping agent on moisture damage.

Table 3.1: Testing Matrix of LMLC Asphalt Mixtures

Mix Type	SP5		
RAP	0%	25%	50%
RAP Source	1	2	
Air Void	7%		
Aggregate Type	Basalt	River Gravel	
Binder Grade	PG 58-34	PG 64-28	PG 76-22
Binder Content	5.00%	4.25%	5.75%
Anti-Stripping Agent	0%	1.50%	

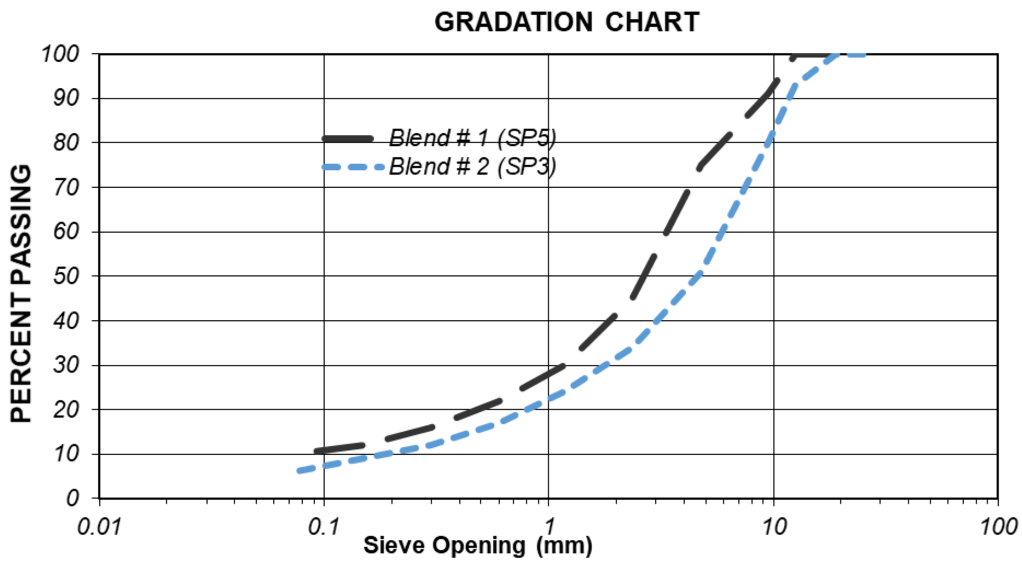


Figure 3.3: LMLC Aggregate Gradation (SP3 & SP5)

3.2.3 Plant Mixed-Laboratory Compacted (PMLC) Mixes

In addition to the LMLC mixes, the author evaluated Plant Mixed-Laboratory Compacted (PMLC) mixes that were obtained from new ITD paving projects. The main objective of testing PMLC was to evaluate mix compactability as well as resistance to rutting, and moisture damage of asphalt mixtures currently produced in the state, and to assess the change in mix characteristics throughout the course of project construction. Loose mixtures were collected from six paving projects distributed across the state of Idaho. Table 3.2 provides information about the PMLC mixes. Three batches were sampled from each project. Each batch represented a different time in the paving process, the first batch represents the beginning period of paving, second batch for the middle and third batch for the end. Each batch was received in a 50-lb box from the field labeled with the mixture type, key number, mileposts, binder content, and other information found in the job mix formula (JMF). The JMF for the field projects are provided in Appendix A. Each project came with the JMF that has all information pertaining to the asphalt mixture volumetrics. Table 3.3 summarizes different mixture parameters for the PMLC mixes. The PMLC included two mix designs (SP3 and SP5), two nominal maximum aggregate size (NMAS) of 12.5 mm and 19.5 mm; three different binder grades (PG 64-28, PG 70-28, PG 64-34), six binder contents ranging from 5.1% to 6.2%, and three RAP contents (0%, 17%, and 30%).

Table 3.2: PMLC Project Information

#	District Number	Project ID	Construction Year	Project Key Number	Location
1	1	D1-P1-b1	2020	20794	US-95, JCT SH-53 OIC, UPRP BR Kootenai Co.
2		D1-P1-b2			
3		D1-P1-b3			
4	3	D3-P5-b1	2020	21858	US 20/26, SH-16 to Linder Rd, SH-55 Marsing to SR
5		D3-P5-b2			
6		D3-P5-b3			
7	6	D6-P1-b1	2019	19711	US-Ashton Bridge to Dump ground Rd
8		D6-P1-b2			
9		D6-P1-b3			
10	1	D1-P2-b1	2020	20795 & 19794	US-95, Garwood Rd GS 4 Frontage Rds. & SH-57, Priest River Boat Access
11		D1-P2-b2			
12		D1-P2-b3			
13	4	D4-P1-b1	2020	18881	I-84/I-86 Interchange System
14		D4-P1-b2			
15		D4-P1-b3			
16	4	D4-P2-b1	2020	20170	SH-81, Decio to Burley
17		D4-P2-b2			
18		D4-P2-b3			

Table 3.3: PMLC Mix Properties

#	District	Project ID	Mix Type	Specified Binder PG	Virgin Binder PG	Binder Content	RAP (%)	NMAS	Theoretical Max Specific Gravity, G_{mm}	Bulk Specific Gravity, G_{sb}
1	D1	D1-P1	SP3	PG 64-28	PG 58-34	5.20%	30	1/2"	2.473	2.646
2	D3	D3-P5	SP3	PG 64-34	NA	5.40%	0	1/2"	2.43	2.571
3	D6	D6-P1	SP5	PG 64-34	PG 64-34	5.90%	16	3/4"	2.382	2.481
4	D1	D1-P2	SP3	PG 64-28	PG 58-34	5.30%	30	1/2"	2.476	2.654
5	D4	D4-P1	SP5	PG 70-28	NA	5.10%	17	3/4"	2.414	2.559
6	D4	D4-P2	SP3	PG 64-28	NA	6.20%	17	1/2"	2.293	2.417

3.3 Testing Protocols

3.3.1 Rutting Resistance

Evaluation of rutting resistance of test mixtures was performed using two different testing procedures: Asphalt Pavement Analyzer (APA) rut test and Hamburg Wheel Tracking Test (HWTT). The APA dry rut test was conducted in accordance with the American Association of State Highways and Traffic Officials (AASHTO T340), and Hamburg was conducted following AASHTO T 324. Both tests required four asphalt samples or replicates subjected to reciprocating wheel loading to simulate traffic in the field. Table 3.4 summarizes the testing parameters for each test. Both tests utilized cylindrical test specimens, though the Hamburg test can test both cylindrical samples and slabs. Cylindrical samples were used due to quicker preparation and able to compare to field cores. Both specimens are 150-mm in diameter, the height is 75-mm for APA and 60-mm for Hamburg. All samples were compacted to 7.0 ± 0.5% air voids. The test specimens were conditioned at a given temperature before testing. The conditioning temperature for APA was set at the higher binder performance grade. For example, the testing temperature for mixes prepared with PG 64-28 asphalt binder would be 64°C and the test samples were conditioned dry at this temperature for 7 hours to achieve a minimum of 6 hours at conditioned temperature. Hamburg samples were conditioned in a water bath at a temperature of 50°C and the test samples were conditioned for one hour. Since the HWTT tests are conducted in wet conditions, the HWTT is used to evaluate the rutting resistance as well as moisture damage of asphalt mixtures. The APA test applies a load of 578 N on rubber hoses that are pressurized to 690 kPa. This pressure is loaded on the samples at constant rate of 60 cycles per minute. Hamburg applies a load of 705 N directly to the samples at a rate of 52 passes per minute.

In this study, the Asphalt Pavement Analyzer Jr. (APA) was used to conduct both the dry APA and wet HWTT tests. This machine is an accelerated laboratory loading equipment that can simulate years of traffic loading on asphalt samples using steel wheels as shown in Figure 3.4. The rut depth is measured at five different points on the left side and another five points on the right for APA. The same applies to the HWTT but the rut depth is measured at 11 points on each side. The average rut depth is taken from both sides, then averaged for a total rut depth which is recommended in accordance with AASHTO T340 & T324 for APA and

Hamburg, respectively. The APA test is terminated after 8,000 cycles, while the HWTT is terminated after 20,000 passes or after a rut depth of 20-mm is achieved.

Table 3.4: Selected Testing Protocols for Rutting Assessments (Kassem et al., 2019)

Test	APA, Dry Rut Test	HWTT
Testing Standards	AASHTO T340	AASHTO T324
Specimen Shape	Cylindrical	Cylindrical or Beam
Specimen Replicates	4 or 6	4 or 6
Specimen Diameter (mm)	150	150
Specimen Thickness for LMLC (mm)	75	60
Specimen Thickness for FMLC (mm)	38-75	38-60
Test Temperature (°C)	High Binder PG	Specified by the Agency
Specimen Conditioning	Air Bath	Water Bath
Conditioning Time (hours)	6-24	1
Testing Time (hours)	≈ 2	≈ 10
Wheel Type	Concave Wheel	Solid Steel
Wheel Speed (Pass/Minute)	50 ± 5	52
Load (N)	578	705 ± 4.5
Number of Data Collection Locations	5	11
Test Output	Cycle-Deformation Curve	Passes-Deformation Curve
Distress Assessed	Rutting	Rutting & Moisture Susceptibility

B. HWTT testing set up

A. Asphalt Pavement Analyzer (APA)

C. APA rut testing set up

Figure 3.4: APA and HWTT Rutting Test in the Asphalt Pavement Analyzer (APA)

The data output from both tests produce different curves and phases as the test starts and finishes. The APA test has only two phases shown by Figure 3.5 of a primary (pre-consolidation) phase and a secondary phase. The primary phase is the initial compaction and deformation at the very beginning of testing, usually within the first 1,000 cycles. The secondary phase is a more gradual slope of consistent deformation over time, also known as the creep slope. The deformation in the secondary phase comes from the plastic flow. The Hamburg test has three main phases since this test is conducted in wet conditions producing an S-curve shape shown in Figure 3.6. The phases are primary, secondary, and tertiary where the deformation accelerates due to stripping of the binder also called the stripping slope. This phase can be the result of water stripping the binder away from the aggregates and/or rutting from plastic flow.

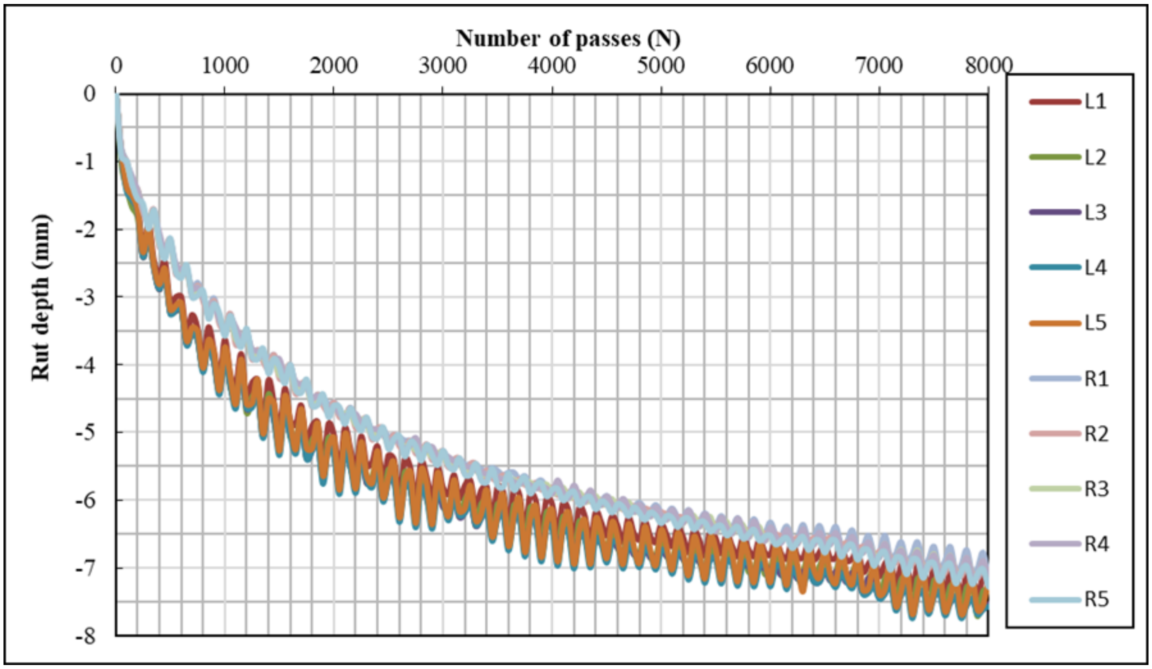


Figure 3.5: APA Rut Test, Left & Right (L1-L5, R1-R5) Wheel Deformation Measurement

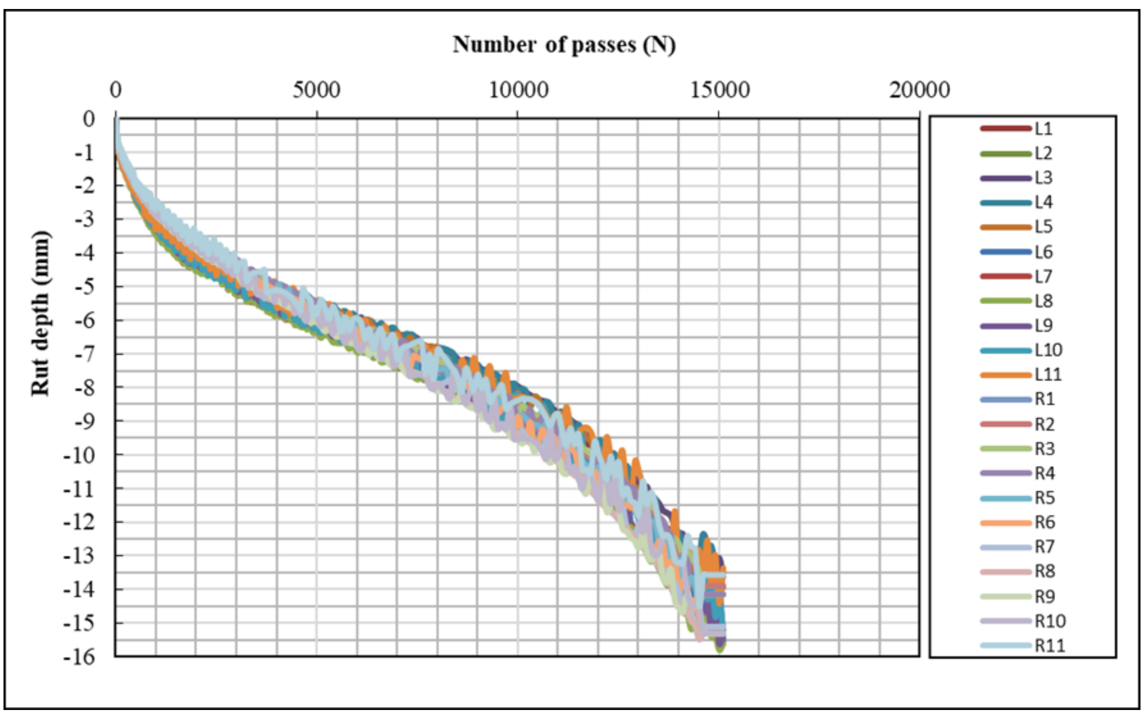


Figure 3.6: HWTT Left and Right (L1-L11, R1-R11) Wheel Data Points

3.3.2 Evaluation of Moisture Damage using Lottman Protocol

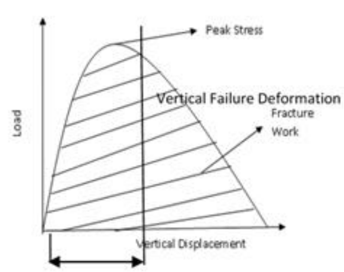
In this study, a modified Lottman test according to AASHTO T283, “Resistance of Compacted bituminous Mixture to Moisture-Induced Damage”, and ASTM D6931, “Standard Test Method for Indirect Tensile (IDT) Strength of Asphalt Mixtures” were used to evaluate the moisture damage susceptibility of asphalt samples. Table 3.5 summarizes the key elements of the test protocols. In this test, six samples were prepared to the dimensions of 150-mm diameter and 63.5-mm in height at 7.0 ± 0.5% air voids. The test samples were split into two groups, three samples each. One group was tested in a dry state “unconditioned” and the other in a wet state “conditioned.” The conditioned samples were first saturated with water to a degree of saturation between 70% to 80% percent. To achieve this, the test sample was placed in a partial vacuum with water covering at least an inch over the sample and pressured at 10 to 26 in. Hg (13 to 67 kPa) for 5 to 10 minutes. If the test sample had a saturation level less than 70%, a partial vacuum was applied again until the target degree of saturation is achieved (i.e., 70 to 80%). If the test sample had a saturation over 80%, the sample was discarded. After achieving the target saturation level, the samples are then wrapped in plastic wrap and placed in a heavy-duty plastic bag with 10 ± 0.5 milliliters (mL) of water. The conditioned samples were subjected to a freeze-thaw cycle by placing them in a freezer at 0 ± 5°F (-18°C) for 24 ± 2 hours. Then the plastic bag and wrap were removed, and the samples were placed in a water bath of at least of inch of water covering above the samples at 140 ± 5°F for 24 ± 2 hours. During this time, the unconditioned samples were placed at room temperature until the conditioned samples were prepared for testing. After 24 hours in the water bath, the conditioned samples were moved to another water bath at 77°F (25°C) for 2 hours and the dry samples were placed in dry conditions at the same temperature (77°F). All six samples are tested were the indirect tensile test at a constant rate of 2 in/min (55-mm/min) as shown in Figure 3.6 until failure. The tensile strength values were obtained from the results and average for the dry and wet samples were calculated. The tensile strength ratio (TSR) from the conditioned and unconditioned samples was calculated by dividing the conditioned tensile strength by the unconditioned tensile strength. Typical TSR values range from 0.70 to 0.90 where greater than 0.80 is known to have good water-resistant characteristics. Values below the 0.80 mark are indicate poor resistance to moisture damage and the addition of anti-stripping agents help improve the performance of these samples. In this study, untreated aggregates were tested to find the moisture damage and benefit of not adding and adding anti-strip agents to mixtures.

Table 3.5: Testing Protocols for Lottman Moisture Damage Testing

Test	**Moisture Damage (Lottman)**
Testing Standards	AASHTO T283 & ASTM D6931
Diameter (mm)	150
Specimen Thickness (mm) for LMLC Samples	63.5
Test Temperature (°C)	25
Loading Rate (mm/min)	50 ±5
Air Void	7 ± 0.5%
Test Output	Peak Load

a. MTS 810 Frame with the Environmental Chamber

b. IDT testing Set up



c. Load-Displacement Curve

Figure 3.7: Indirect Tensile Test Set-up and Load-Displacement Curve

3.3.3 Evaluation of Asphalt Mix Compactability

The authors evaluated the test mixture compactability and related the results to the rutting performance. Rutting is a further densification of the mix under traffic. In this study, the Laboratory Compaction Index (LCI) was calculated from the compaction data. The compaction machine used was the PINE Superpave AFG2 gyratory compactor (SGC) as shown by Figure 3.8. The SGC applies a constant pressure of 600 kPa at a gyration angle of 1.16 degrees and a rate of 30 rpm. Each sample was compacted to a targeted air void of 7.0 ± 0.5%. The compaction data were recovered from the PINE compactor and include number of gyrations, specimen height, gyration angle, and moment (Figure 3.9). The Compaction Index (LCI) is a function of the intercept (a) and slope (b) of the compaction data. The LCI quantifies the laboratory compaction effort needed to achieve the target air void and it is calculated using Equation 2.4. Chapter 2 provides detailed overview of the LCI.

Example: Pine AFG2A Data File Format

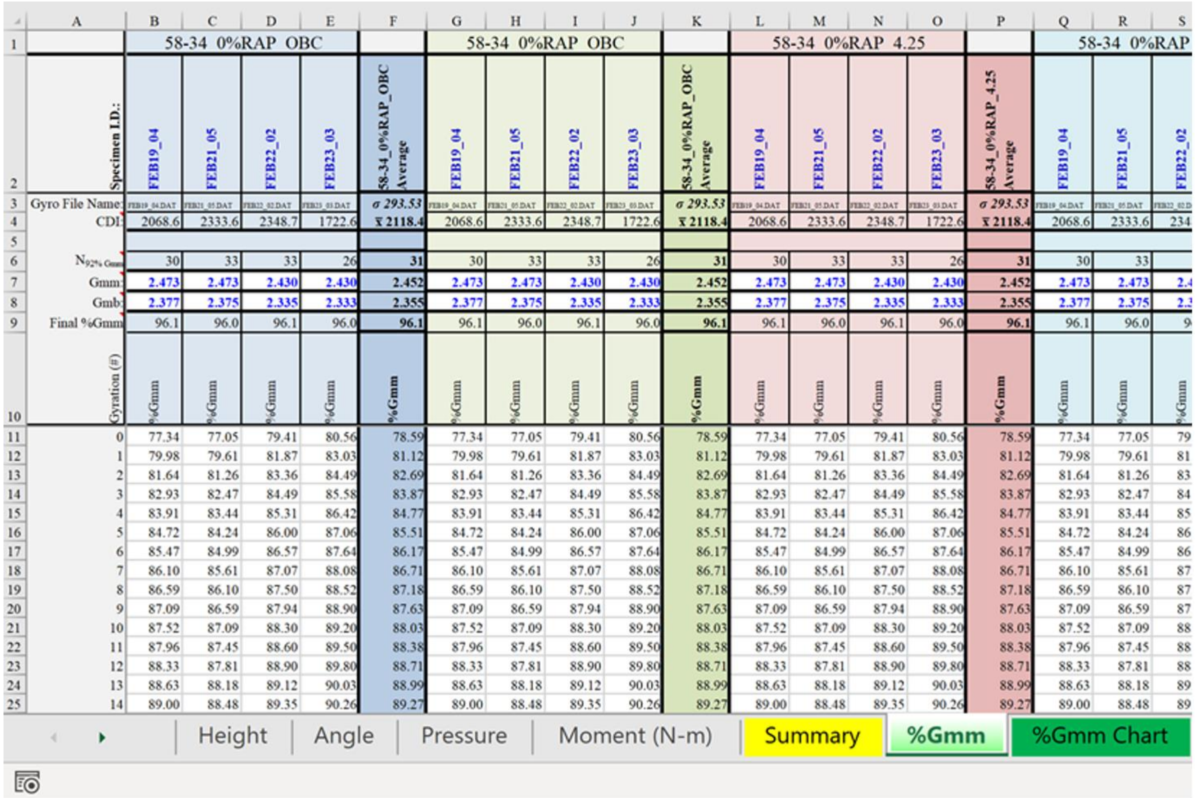
```
File Name: SEP14_04.DAT
     Time: 14:36
     Date: 04/14/07
 Diameter: 150 mm
      S/N: 8001
```

Gyration (#)	Height (mm)	Angle (deg Int)	Pressure (kPa)	Moment (N-m)
0	144.2	----	576	653.6
1	140.7	1.16	576	516.8
2	137.0	1.16	587	665.4
3	134.6	1.16	589	710.9
4	132.8	1.16	590	742.7
5	131.4	1.16	590	766.5
6	130.2	1.16	593	777.1
7	129.3	1.16	593	786.9
8	128.4	1.16	592	792.1
9	127.7	1.16	593	799.4
10	127.0	1.16	591	804.0
11	126.4	1.16	593	809.0
12	125.9	1.16	594	812.4
13	125.4	1.16	595	812.8
14	124.9	1.16	596	817.7
15	124.5	1.16	595	818.6
16	124.1	1.16	595	821.9
17	123.7	1.16	596	826.3
18	123.3	1.16	592	813.5
19	123.0	1.16	599	843.0
20	122.8	1.16	597	831.1
21	122.5	1.16	595	821.6
22	122.2	1.16	598	834.9
23	121.9	1.16	597	831.3
24	121.7	1.16	598	836.3
25	121.5	1.16	598	837.4
26	121.2	1.16	599	840.8
27	121.0	1.16	599	845.3
28	120.8	1.16	599	847.9
29	120.6	1.16	600	840.7
30	120.4	1.16	600	846.5
31	120.3	1.16	600	845.1
32	120.1	1.16	600	846.9

a. Pine AFG2 Compactor

b. Compaction Data File Formats

Figure 3.8: The Pine Superpave AFG2 Gyratory Compactor (SGC)



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
1		58-34 0%RAP OBC					58-34 0%RAP OBC					58-34 0%RAP 4.25					58-34 0%RAP		
2	Specimen I.D.:	FEB19_04	FEB21_05	FEB22_02	FEB23_03	58-34_0%RAP_OBC Average	FEB19_04	FEB21_05	FEB22_02	FEB23_03	58-34_0%RAP_OBC Average	FEB19_04	FEB21_05	FEB22_02	FEB23_03	58-34_0%RAP_4.25 Average	FEB19_04	FEB21_05	FEB22_02
3	Gyro File Name:	FEB19_04.DAT	FEB21_05.DAT	FEB22_02.DAT	FEB23_03.DAT	σ 293.53	FEB19_04.DAT	FEB21_05.DAT	FEB22_02.DAT	FEB23_03.DAT	σ 293.53	FEB19_04.DAT	FEB21_05.DAT	FEB22_02.DAT	FEB23_03.DAT	σ 293.53	FEB19_04.DAT	FEB21_05.DAT	FEB22_02.D
4	CDI:	2068.6	2333.6	2348.7	1722.6	x̄ 2118.4	2068.6	2333.6	2348.7	1722.6	x̄ 2118.4	2068.6	2333.6	2348.7	1722.6	x̄ 2118.4	2068.6	2333.6	234
5																			
6	$N_{92\% Gmm}$	30	33	33	26	31	30	33	33	26	31	30	33	33	26	31	30	33	
7	Gmm:	2.473	2.473	2.430	2.430	2.452	2.473	2.473	2.430	2.430	2.452	2.473	2.473	2.430	2.430	2.452	2.473	2.473	2.4
8	Gmb:	2.377	2.375	2.335	2.333	2.355	2.377	2.375	2.335	2.333	2.355	2.377	2.375	2.335	2.333	2.355	2.377	2.375	2.3
9	Final %Gmm	96.1	96.0	96.1	96.0	96.1	96.1	96.0	96.1	96.0	96.1	96.1	96.0	96.1	96.0	96.1	96.1	96.0	9
10	Gyration (#)	%Gmm	%Gmm	%Gmm	%Gmm	%Gmm	%Gmm	%Gmm	%Gmm	%Gmm	%Gmm	%Gmm	%Gmm	%Gmm	%Gmm	%Gmm	%Gmm	%Gmm	%Gmm
11	0	77.34	77.05	79.41	80.56	78.59	77.34	77.05	79.41	80.56	78.59	77.34	77.05	79.41	80.56	78.59	77.34	77.05	79
12	1	79.98	79.61	81.87	83.03	81.12	79.98	79.61	81.87	83.03	81.12	79.98	79.61	81.87	83.03	81.12	79.98	79.61	81
13	2	81.64	81.26	83.36	84.49	82.69	81.64	81.26	83.36	84.49	82.69	81.64	81.26	83.36	84.49	82.69	81.64	81.26	83
14	3	82.93	82.47	84.49	85.58	83.87	82.93	82.47	84.49	85.58	83.87	82.93	82.47	84.49	85.58	83.87	82.93	82.47	84
15	4	83.91	83.44	85.31	86.42	84.77	83.91	83.44	85.31	86.42	84.77	83.91	83.44	85.31	86.42	84.77	83.91	83.44	85
16	5	84.72	84.24	86.00	87.06	85.51	84.72	84.24	86.00	87.06	85.51	84.72	84.24	86.00	87.06	85.51	84.72	84.24	86
17	6	85.47	84.99	86.57	87.64	86.17	85.47	84.99	86.57	87.64	86.17	85.47	84.99	86.57	87.64	86.17	85.47	84.99	86
18	7	86.10	85.61	87.07	88.08	86.71	86.10	85.61	87.07	88.08	86.71	86.10	85.61	87.07	88.08	86.71	86.10	85.61	87
19	8	86.59	86.10	87.50	88.52	87.18	86.59	86.10	87.50	88.52	87.18	86.59	86.10	87.50	88.52	87.18	86.59	86.10	87
20	9	87.09	86.59	87.94	88.90	87.63	87.09	86.59	87.94	88.90	87.63	87.09	86.59	87.94	88.90	87.63	87.09	86.59	87
21	10	87.52	87.09	88.30	89.20	88.03	87.52	87.09	88.30	89.20	88.03	87.52	87.09	88.30	89.20	88.03	87.52	87.09	88
22	11	87.96	87.45	88.60	89.50	88.38	87.96	87.45	88.60	89.50	88.38	87.96	87.45	88.60	89.50	88.38	87.96	87.45	88
23	12	88.33	87.81	88.90	89.80	88.71	88.33	87.81	88.90	89.80	88.71	88.33	87.81	88.90	89.80	88.71	88.33	87.81	88
24	13	88.63	88.18	89.12	90.03	88.99	88.63	88.18	89.12	90.03	88.99	88.63	88.18	89.12	90.03	88.99	88.63	88.18	89
25	14	89.00	88.48	89.35	90.26	89.27	89.00	88.48	89.35	90.26	89.27	89.00	88.48	89.35	90.26	89.27	89.00	88.48	89

Figure 3.9: Compaction Data Imported to PineShear + (V15.6)

CHAPTER 4 RESULTS AND DISCUSSION

4.1 Introduction

Chapter 4 discusses the results and analysis of various laboratory tests conducted in this study. The tests included rutting assessment using APA and HWTT, which conduct in dry and wet conditions, respectively, and moisture susceptibility of asphalt mixtures in accordance with Lottman protocols. In addition, the compaction data were analyzed to calculate the laboratory compaction index (LCI) for the test samples. Chapter 4 presents comprehensive analysis of the test results to examine the factors that affect the resistance of asphalt mixtures to rutting and moisture damage. ANOVA statistical analysis was conducted to study the statistical significance between different mixes and test variables.

4.2 Effect of Mix Composition on Rutting Characteristics

4.2.1 Effect of Binder Content

Figure 4.1 represents the average APA rut depth at different binder and RAP contents. The error bars represent ± one standard deviation. The sensitivity of APA rut depth to the binder content was examined using ANOVA and Tukey's Honestly Significant Difference (Tukey HSD). Both tests were performed at 95% confidence interval (i.e., $\alpha = 0.05$). The statistical analysis results (Tukey HSD groups) are included in the form of letters (a, ab, b, c) on each bar. The mixes that do not share the same letters in each group (e.g., 0% RAP 1, 0% RAP 2, etc.) are significantly different in terms of their rut depth values. The Minitab 19 software was used to conduct the statistical analysis of this study. Figure 4.1 shows the statistical analysis within each group at the same RAP content (i.e., 0% RAP 1, 25% RAP 1, 50% RAP 1, etc.). Figure 4.1 demonstrated a general trend of increased rut depth as the binder content increases at different RAP contents. There was a statistically significant difference between mixtures prepared with 5.75% and 4.25% binder contents. There was no statistically significant difference between 4.25% and 5% binder content at different RAP contents. Regardless, all samples with different RAP and binder contents had a rut depth less than 5-mm (maximum APA threshold after 8,000 cycles). Results from Kassem et al. (2019), show similar results on effect of binder content to rutting depth.

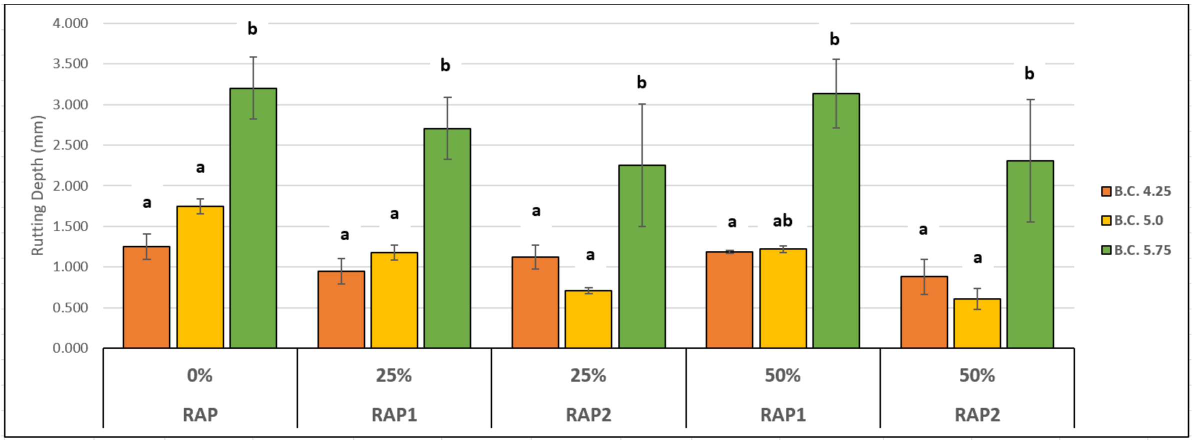


Figure 4.1: APA Rut Depth at Different Binder Contents for PG 58-34 Mixtures

Figure 4.2 shows the HWTT rut depth at different binder and RAP contents. The HWTT is conducted in wet conditions, where the test samples are submerged in water at 50^{o}C. Here, the HWTT can be used to assess the rutting as well as the moisture damage, due to stripping of binders from the aggregates. Comparing the APA and HWTT rut depth presented in Figures 4.1 and 4.2, respectively, HWTT resulted in more rutting than APA. Like APA testing, HWTT results showed increased rut depth with the increase in binder contents regardless the RAP content (i.e., 0%, 25%, and 50%); however, unlike the APA results, there was no statistically significant difference in the HWTT results in many cases (e.g., 0% RAP, 25% RAP 2, 50% RAP 1, 50% RAP 2).

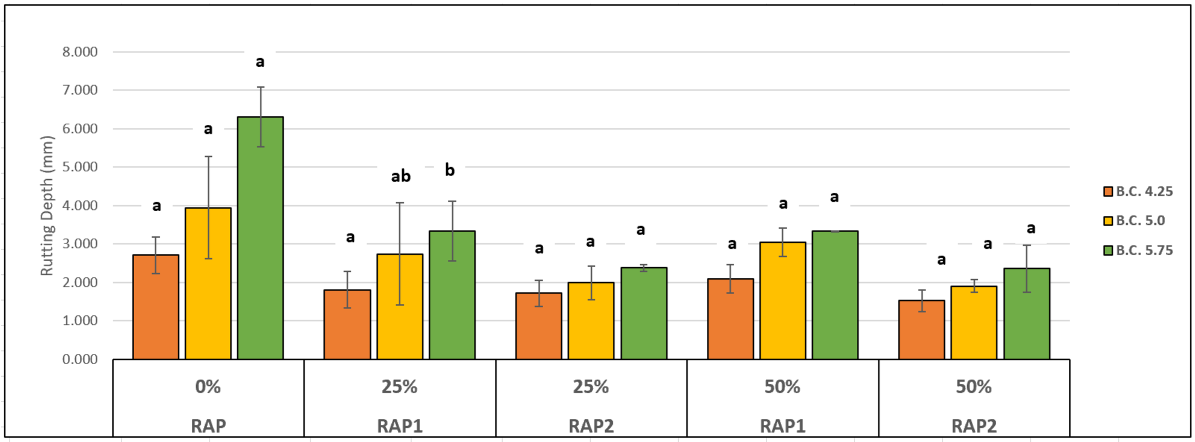


Figure 4.2: HWTT Rut Depth at Different Binder and RAP Contents

4.2.2 Effect of RAP Content

Figure 4.3 represents comprehensive analysis of APA rut depth results at different RAP contents, binder contents, binder grades, and RAP sources (i.e., RAP 1 and RAP 2). As the RAP content increases in the mix, the mix becomes drier and more brittle, due to less virgin binder in the mix. The expected results are to have less rut depth or permanent deformation in asphalt samples when using more percentages of RAP. All mixes using APA, had a rut depth less than 5-mm after 8,000 cycles which is the maximum rut depth per ITD current specifications. Based on the results, it is expected that all mixes to have good resistance to rutting. For mixes prepared with RAP 1 at 5.0% binder content, the rutting decreased as we move from 0% RAP to 25% RAP. When RAP content increased to 50%, the rutting increased slightly instead of following the trend. This same trend of an increase in rutting at 50% RAP than 25% was found at the other binder contents; however, the difference is small and not statistically significant in many cases (e.g., PG 58-34 5% binder content, PG 64-28 5% binder content, etc.).

Comparing RAP 2 to RAP 1 mixes, the rut depth at 25% RAP was slightly lower in RAP 2 compared to RAP 1 at 5% and 5.75% binder content but was slightly higher at 4.25%. At 50% RAP, the rutting for RAP 2 mixes was slightly lower than for RAP #1 at the corresponding binder contents. The results demonstrated that RAP 2 could be more aged and stiffer compared to RAP 1 materials which resulted in slightly less rutting as RAP content increased. Overall, the statistical analysis for all APA tests varying the percentage of RAP showed little significance. The only three sets with a statistically significant difference included: PG 58-34 at 5.0% binder content, where there was a significant change between 0%, 25% and 50% RAP; PG 76-22 at 5.0% binder content, where there was a significance between 0% and 50% RAP. RAP 2 mixes had consistent results pertaining to RAP 1 for the 5.0% binder content significance.

Results from literature reviews (Alireza et al., 2016) and (Hajj et al., 2007) show different results. The effect of RAP content in asphalt mixtures show a steady decrease in rut depth while this study shows a slight increase at 50% RAP.

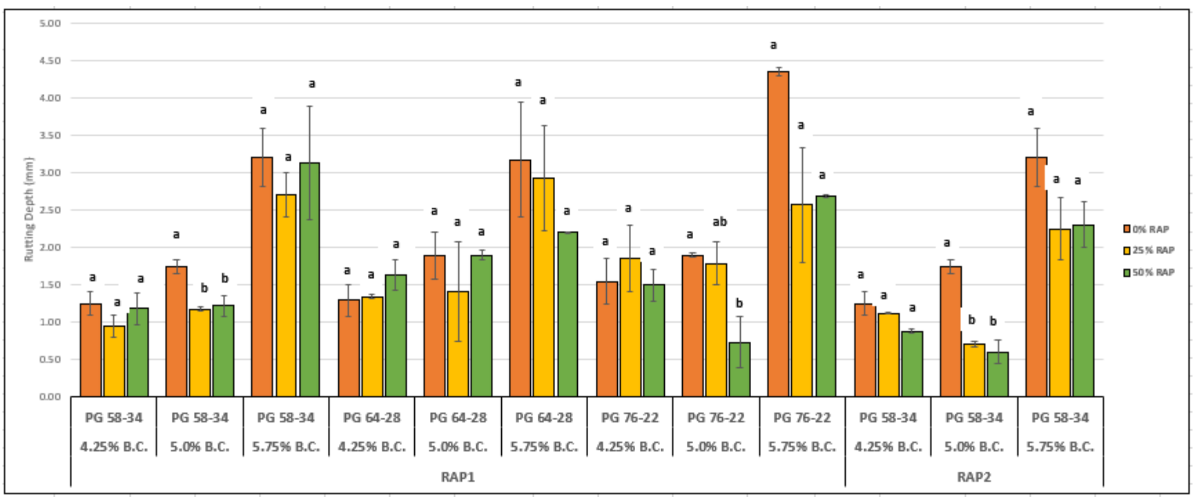


Figure 4.3: APA Rut Depth of LMLC Mixes

Figure 4.4 shows the HWTT rut depth for the test mixtures. All mixtures are expected to provide good rutting resistance since the rut depth was less than 12.5 mm after 20,000 cycles of HWTT. These results are in good agreement with the rutting resistance evaluation using APA where the mixture showed good rutting resistance too. In addition, the HWTT results exhibited the same trend as the APA results where the rutting depth decreased from 0% to 25% RAP, then increased at 50% RAP. Meanwhile, mixes with RAP 2 had less rut depth at

50% RAP compared to 0% RAP. The difference of RAP source on the HWTT rut depth showed similar to those of APA results, where RAP 2 mixes had slightly less rutting than RAP 1. The rutting deformation of RAP #2 show less overall rutting depth compared to RAP #1 especially at 4.25% B.C. The difference in rut depth between binder contents is around 1-mm, which is minor.

The HWTT results showed little to no significance of the effect of RAP content on rutting. The only two sets with significant changes to rutting depth results were RAP 1 mix with PG 64-28 at 5.0% binder content where 0% and 25% RAP are significant to 50% RAP. In addition, RAP 2 mix where 25% RAP and 50% RAP are significantly different than 0% RAP.

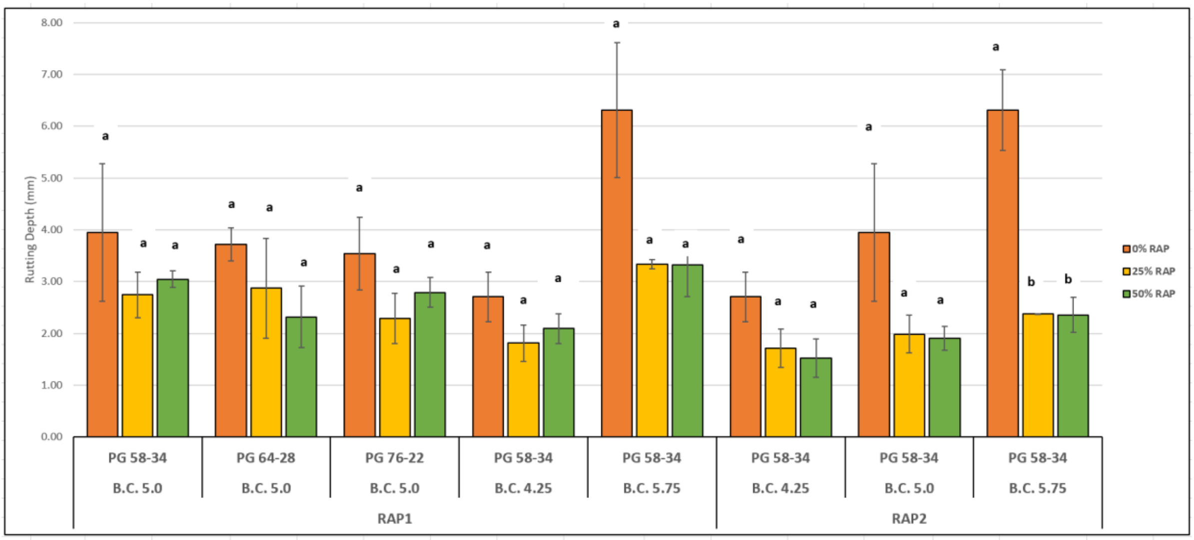


Figure 4.4: HWTT Rut Depth of LMLC Mixes

4.2.3 Effect Different Binder Grades on Rut Depth at Various Binder Grades

The author also evaluated the effect of binder grades at various RAP contents on rutting resistance using APA and HWTT. Different binders are used country-wide for different climates for improved performance. Softer binders are often used in hot climates and stiffer binders in cold climates. In this study, three different binder grades were tested from softest to hardest are PG 58-34, PG 64-28, and PG 76-22. Both APA and HWTT are conducted to compare the different effects of binder grade on the rutting characteristics. Asphalt mixtures were prepared using basalt aggregates and RAP No. 1 using various binder grades (i.e., PG 58-34, PG 64-28, and PG 76-22) at different binder contents (4.25%, 5.0%, and 5.75%). Figures 4.5 through 4.8 show the rutting deformation at 4.25%, 5.0%, and 5.75% binder content, respectively. Figure 4.5 shows that the stiffer binder (i.e., PG 76-22) experienced higher rutting depth compared to softer binders (i.e., PG 58-34). This can be explained by the testing procedures of APA, where the test is conducted at the higher performance grade temperature. For example, PG 76-22 samples were tested at 76°C compared to 64°C, and 58°C for PG 64-28 and PG 58-34, respectively. Samples get softer at a higher temperature which could affect the expect trend. Also, the results showed that there was a small increase in rutting as stiffer binders are used at 0% RAP. Mixes with 25% RAP showed a larger increase in rutting depth with the use of stiffer binders, and mixes with 50% RAP increased from PG 58-34 to PG 64-28, but slightly decreased from PG 64-28 to PG 76-22. The trend between different percentages of RAP for PG 58-34 showed a decrease in rutting from 0% to 25% RAP, then a small increase of rutting from 25% to 50% RAP. Meanwhile, there was a different trend for PG 64-28 and PG 76-22; PG 64-28 showed an increase in rutting as the percentage of RAP increased. PG 76-22 showed the opposite of PG 58-34 as the rutting increases from 0% to 25% RAP and decreased from 25% to 50% RAP. The Tukey analysis results clearly showed there is a statistically significant difference in rut depth results at different binder content for different binder grades.

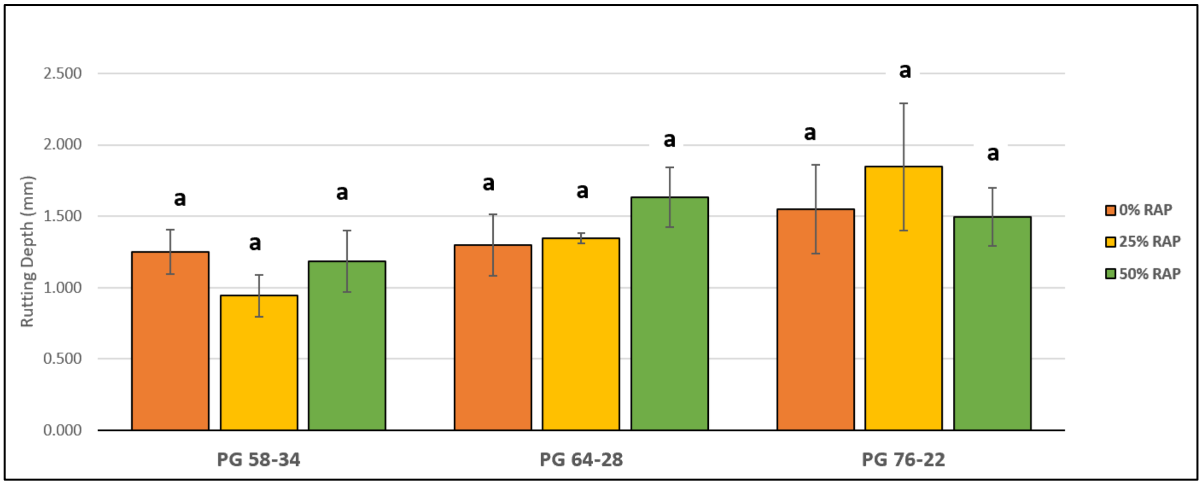


Figure 4.5: Comparison of APA Rutting with Different Binder Grades at 4.25% Binder Content

Figure 4.6 shows the APA rut depth at 5.0% binder content for various binder grades. The results showed a small increase in overall rutting depth compared to rutting at 4.25% (Figure 4.5). This is expected as the samples get softer as the binder content increases. Mixes with PG 64-28 at 5.0% binder content showed a different trend for the effect of RAP content than that of PG 64-28 at 4.25% binder content (Figure 4.5) but shows the same trend seen as PG 58-34 of a decrease in rutting at 25% RAP and a small increase at 50% RAP. Mixes with PG 76-22 showed a decrease in rutting at 25% RAP, then a significant drop in rutting at 50% RAP. There was a statistically significant difference in rut depth for PG 76-22 between 50% RAP and both 0% RAP and 25% RAP. Also, there was a statistically significant difference in rut depth for PG 58-34 between 0% RAP and both 25% RAP and 50% RAP.

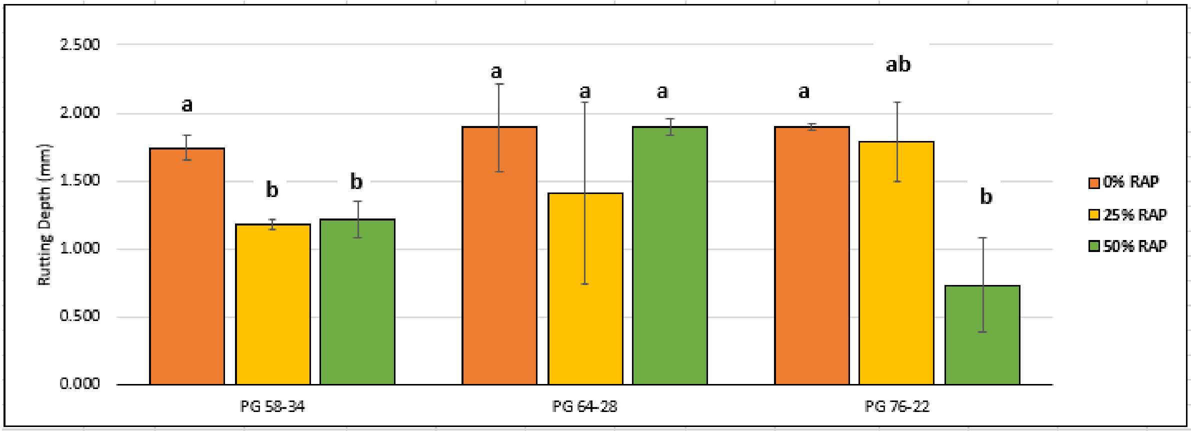


Figure 4.6: Comparison of APA Rutting with Different Binder Grades at 5.00% Binder Content

Figure 4.7 shows the APA rut depth at 5.75% binder content for various binder grades. Overall, there was an increase in rut depth compared to 4.25% and 5.0% at the corresponding binder contents. This is expected since the mix gets softer with binder content. PG 64-28 showed an opposite trend of that of 4.25% binder content where the rutting depth decreased with the increase in RAP content. PG 76-22 showed the same trend at 5.0% binder content where the rut depth decreased with RAP content. PG 58-34 showed the same trend between rut depth and RAP content, at all three different binder contents (4.25%, 5.0% and 5.75%). PG 64-28 and PG 76-22 showed three different trends at each different binder contents.

Overall, there was no statistically significant difference in rut depth at different RAP content for all binder grades at 5.75% binder content.

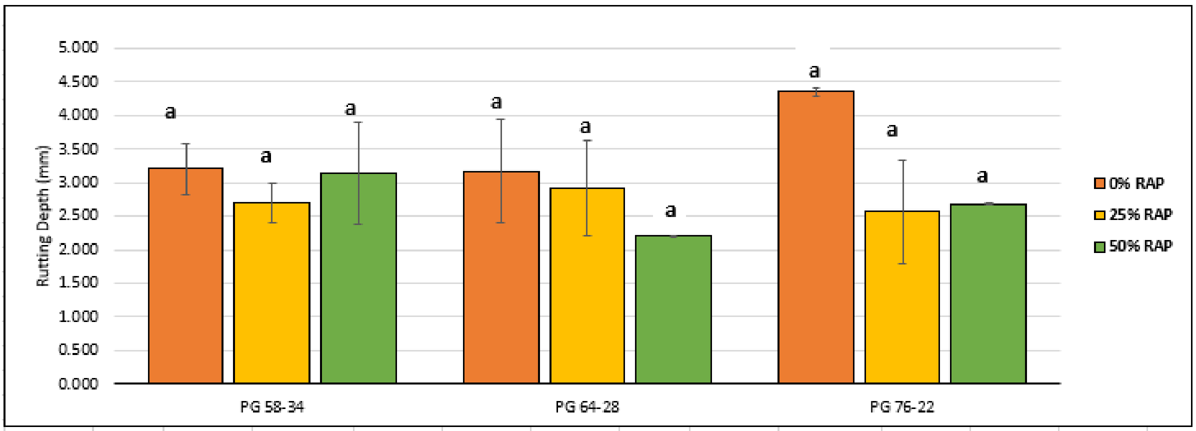


Figure 4.7: Comparison of APA Rutting with Different Binder Grades at 5.75% Binder Content

Figure 4.8 shows the HWTT rut depth at the optimum binder content of 5.0% for various binder grades. The HWTT rut depths at different RAP contents, at each binder grades were withing one half of a millimeter. The results showed that HWTT rut depth at 50% RAP was lower compared to 0% RAP for all binder grades. Unlike APA, PG 76-22 had lower HWTT rut depth compared to PG 58-34 at the corresponding binder content. The HWTT is conducted at a fixed temperature of 50^{o}C in wet conditions where stiffer binder is expected to experience less rutting compared to sifter binder, since stiffer binders have higher viscosity, and stiffer compared to softer binders. It is interesting to notice that PG 58-34 showed the same trend between rut depth and RAP content as found using the APA test where rut depth decreased at 25% RAP compared to 0% RAP and then slightly increased at 50% RAP. The Tukey analysis showed that there was no significant difference in the rut depth results at different RAP content for different binder grades.

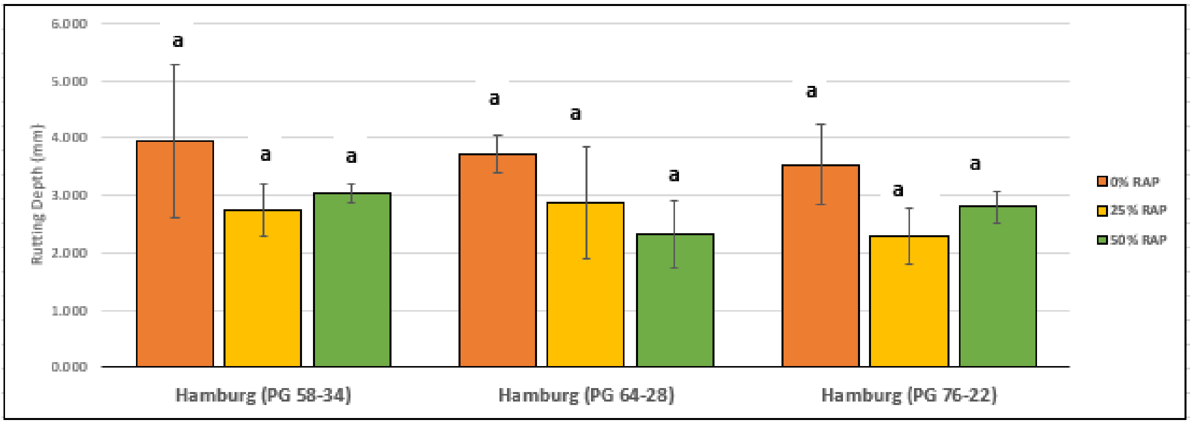


Figure 4.8: Comparison of Hamburg Rutting with Different Binder Grades at 5.0% Binder Content

4.2.4 Effect of Binder Grades on Rut Depth at Various RAP Contents

Figures 4.9 through 4.11 examine the significance of effect of binder grade on APA rut depth at various RAP contents at 4.25%, 5.0%, and 5.75% binder contents, respectively. The rut depth results in Figure 4.9 demonstrated PG 76-22 mixes had higher rut depth than PG 64-28 and PG 58-34 at 0% RAP and 25% RAP, while PG 76-22 mixes had slightly less rut depth compared to PG 64-28, but still higher than 0% RAP. Again, this could be due to the change in APA testing temperature as discussed earlier. The results showed that overall, the rutting depths were exceptionally low, and there was no statistically significant difference in rut depth results at various RAP contents for various binder grades.

Figure 4.10 shows the same trends as Figure 4.9, but with a small increase in rut depth with the increase in binder content. Mixes with 0% RAP showed similar results as 25% RAP as there was an increase in rut depth as the binder grade became stiffer. Mixes with 50% RAP showed a significant drop in rut depth from PG 64-28 to PG 76-22 proven to be statistically significant and a difference of 1.163-mm.

Figure 4.11 produced different trends compared to Figures 4.9 and 4.10, with a larger increase of rut depth for PG 76-22 at 0% RAP. Mixes with 25% RAP showed very consistent values of rutting depth, but a different trend than the last two binder contents (e.g., 4.25% and 5.0%). Looking at PG 64-28 on Figure 4.11, the trend does not continue at PG 64-28 where the rut depth slightly increases, instead it continues to decrease. This demonstrated that there was no statistically significant difference in rut depth at various binder grades at the corresponding RAP content.

Figure 4.12 examines the effect of binder grade on HWTT rut depth at various RAP contents at optimum binder content of 5.0%. The results show very consistent rutting depth between the binder grades at each RAP percentage. Also, the results showed there was no statistically significant difference in HWTT rut depth results for various binder grades at the corresponding binder content.

These results follow Kassem et al., (2019) as the rutting is larger for Stiffer binders in APA testing. The result is from the testing temperature changes for each binder grade in APA testing and is constant for Hamburg testing. The results show small changes in rut depth using different binder grades in Hamburg testing because the temperature is set to 50°C.

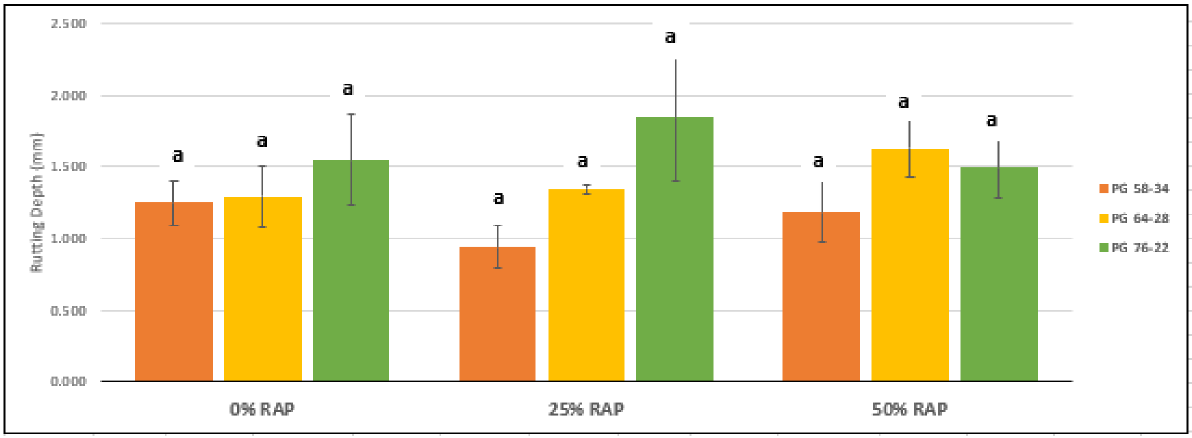


Figure 4.9: APA Comparison RAP Percentages at Different Binder Grades at 4.25% Binder Content

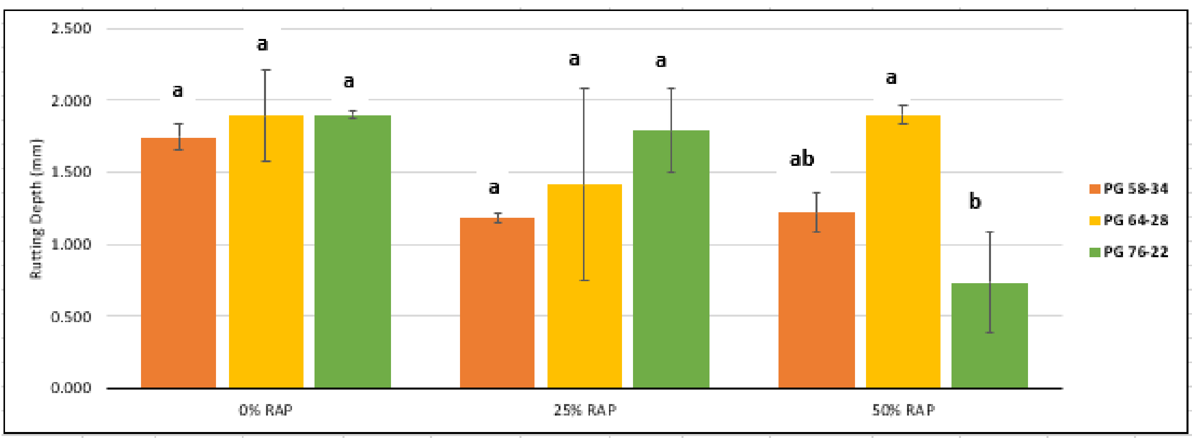


Figure 4.10: APA Comparison of RAP Percentage at Different Binder Grades at 5.0% Binder Content

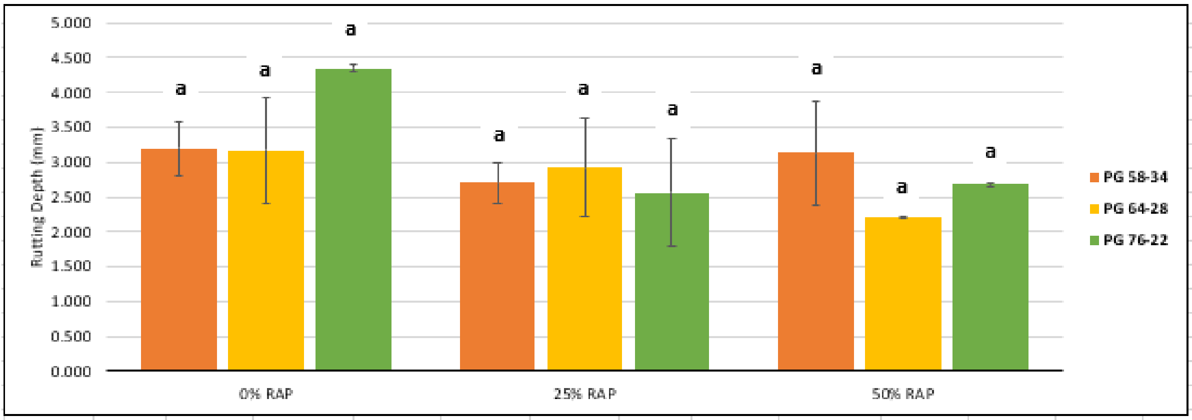


Figure 4.11: APA Comparison of RAP Percentage at Different Binder Grades at 5.75% Binder Content

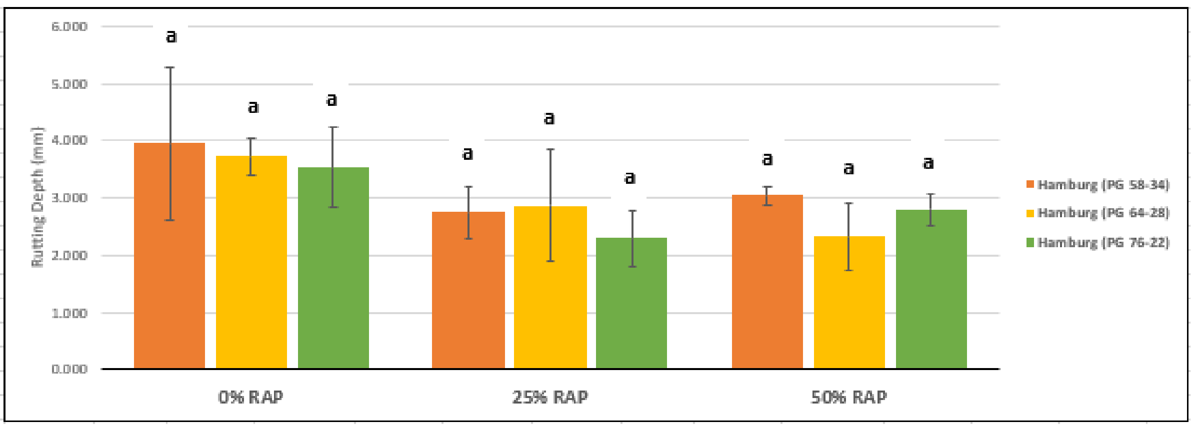


Figure 4.12: Hamburg Comparison of RAP Percentage at Different Binder Grades at 5.0% Binder Content

4.3 Correlation between HWTT and APA Rut Depth for LMLC Mixes

The author investigated the relationship between APA and HWTT rut depth for the LMLC mixes. It should be noted that the HWTT was used to assess the PMLC mixes. Figure 4.13 shows the rut depth measured using APA against HWTT. Poor correlation was found between APA and HWTT rut depth. Such relationship is expected since both APA and HWTT test asphalt mixtures under different conditions (Table 2.1). The APA is performed at different temperatures based on the binder grade, while the HWTT is conducted at a constant temperature of 50^{o}C. The testing temperature has a significant effect on rutting since the viscosity of asphalt binder decreases with the increase in temperature. Also, the HWTT is conducted in wet conditions, while the APA is performed in dry conditions. These results are consistent with the findings by Kassem et al. (2019).

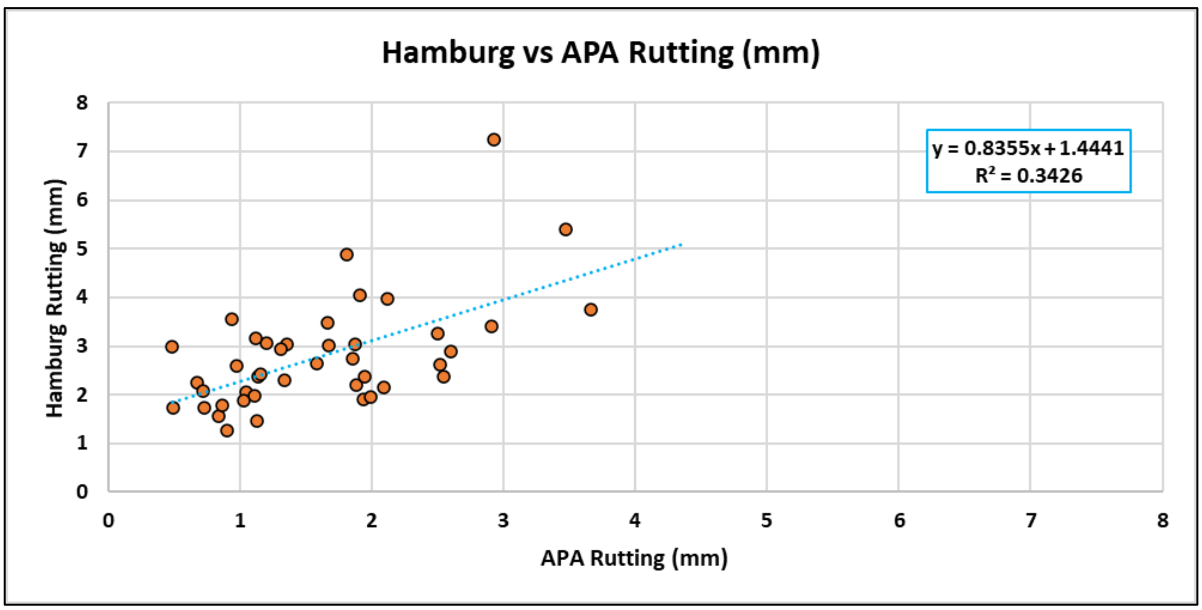


Figure 4.13. Correlation between APA and HWTT for LMLC Mixes

4.4 Rutting Characteristics of PMLC Mixes

The rutting performance of Plant-Mixed Laboratory-Compacted (PMLC) mixes collected from the field, as discussed in Chapter 3, were examined using HWTT. Six projects in different districts in the state of Idaho were examined, and three batches of loose mixtures were collected from each project. A total of 18 different mixes (6 projects and 3 batches of each project) were evaluated. These batches were samples throughout the course of construction to study the variation in mix performance.

Figure 4.14 shows the HWTT for all PMLC mixes for each project and each batch. The identification of each project is shown first by the district number, and second by the project number. The results clearly showed that all mixes and batches are expected to have good resistance to rutting in the field since the HWTT rut depth measurements were less than 12.5-mm after 20,000 passes of HWTT.

Th results also demonstrated that there are variations in HWTT rut depth among various batches of the same project; however, such difference is not statistically significant for the all the projects. Meanwhile, there was a statistically significant difference in HWTT rut depth among projects. For example, there is a statistically significant difference between D1-P1 and D3-P5, D4-P1, D4-P2. Also, there was a statistically significant difference between D4-P1 and D3-P5, D1-P2, and D1-P1.

For project D3-P5, there was a significant drop in rut depth from Batch 1 to Batch 2 and 3 from approximately 3.3-mm to less than 2-mm which may indicate change in mix characteristics (e.g., segregation or change in mix composition). Project D1-P1 showed a steady decrease in rut depth, but in small increments as also shown by D1-P2 and D4-P2 which is not significant. D6-P1 and D4-P1 showed the same trend; however, such change is not statistically significant as discussed earlier.

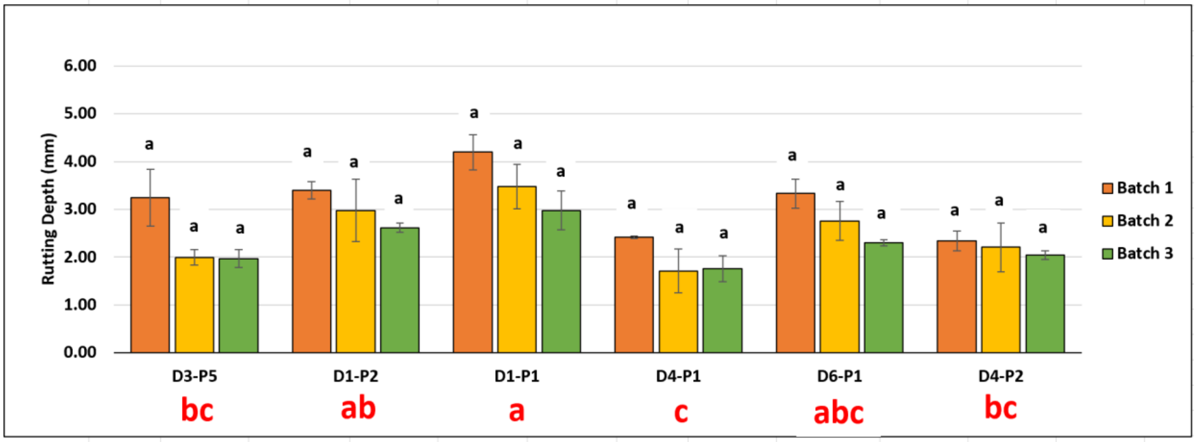


Figure 4.14: Hamburg Testing of Field Prepared Mixes

4.5 Results of Laboratory Compaction Index

4.5.1 Laboratory Compaction Index of LMLC

Figures 4.15 through 4.18 represent the LCI values for the test mixtures with different testing parameters. Similar to the rutting results, these figures demonstrated the effect of various variables including binder content, binder grade, RAP content, RAP source, etc., on the compactability of test mixtures. Figure 4.15 illustrates the effect of binder grade on LCI values. Tukey analysis showed little to no significant change in LCI values from different binder grades. The only significant change was for 5.0% binder content at 50% RAP, and 5.75% B.C. at 25% RAP. The significance is shown between PG 58-34 and PG 76-22 which is the softest and stiffest binders used in this study. Overall, there was no consistent and statistically significant trend for the effect of binder grade on LCI results. The binder grade generally does not have a significant effect on laboratory compaction data since the compaction is conducted at different temperatures depending on the PG grading, where different asphalt binders are expected to achieve the same viscosity (0.28 ± 0.30 Pa.s.). At typical compaction temperatures, different binders have comparable viscosities; therefore, the binder grade does not affect the resistance of the mix to the applied forces.

Figure 4.16 represents the change in RAP content and how it effects the compaction data of asphalt samples. Statistical analysis shows some significance in RAP percentage, but not the majority. Most significance came from the first change in RAP percentage of 0% RAP to 25% RAP. One set of asphalt specimens resulted in significance between each RAP percentage but was only seen for PG 76-22 at 5.75% B.C., where most significant change at this binder grade was found. Generally, there was no clear trend for the effect of RAP content on LCI values. A Possible explanation is the LCI is calculated at the compaction temperature, which is relatively high, the effect of higher binder stiffness due to higher RAP content might be minor.

Figure 4.17 represents the significance of binder content on LCI. This parameter resulted to be the most significant factor, as the Tukey analysis shows different letters (i.e., a, b, and c) on each column. If data sets do not share the same letter, then there is a statistically significant difference. The results clearly demonstrated that the binder content had a significant effect on the compactability of asphalt mixtures. Drier mixtures with lower binder contents had higher LCI values which indicate more compaction energy is needed, while softer mixtures with higher binder contents had lower LCI values which indicates that these mixtures are easier to compact. Such trend for the effect of binder content on LCI was consistent for different binder grades and RAP Percentage.

Figure 4.18 shows the effect of RAP source on the LCI. In this case, only PG 58-34 was used for both sources of RAP. Three out of five different mix groups showed that there was a significant effect on the LCI. Mixture prepared with RAP 2 had lower LCI compared to RAP 1 which indicates that these mixtures need more energy for compaction. Based on the results RAP 2 resulted in stiffer mixtures compared to RAP 1 at the corresponding binder content and grade.

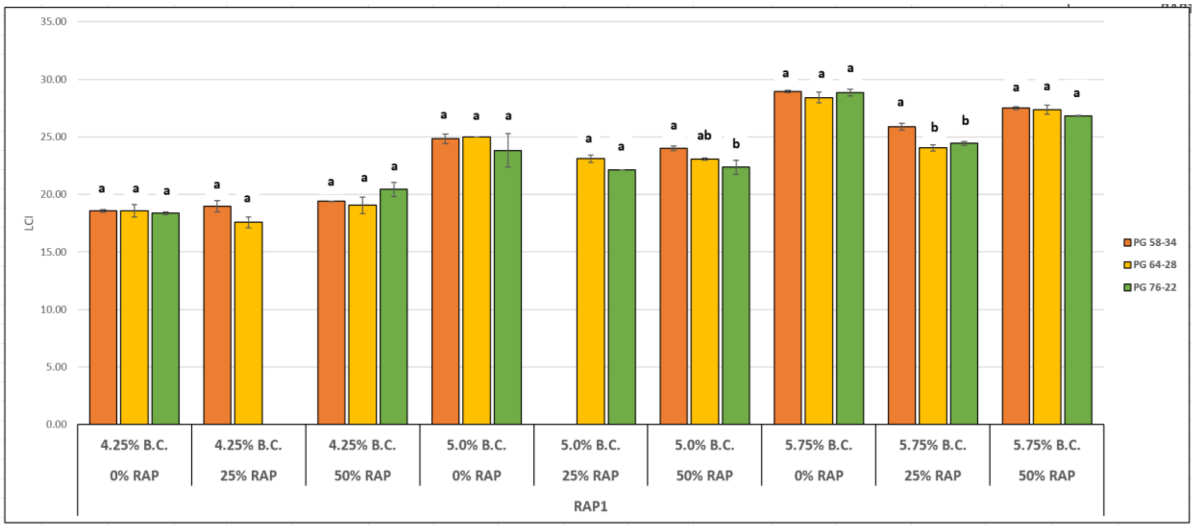


Figure 4.15: Effect of Binder Grade on LCI Values

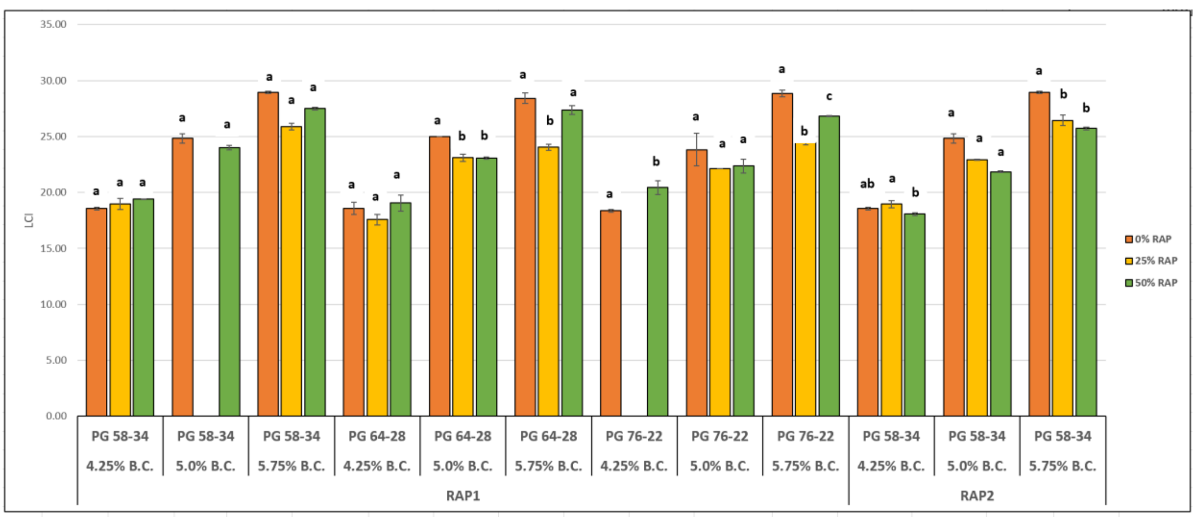


Figure 4.16: Effect of RAP Percentage on LCI Values

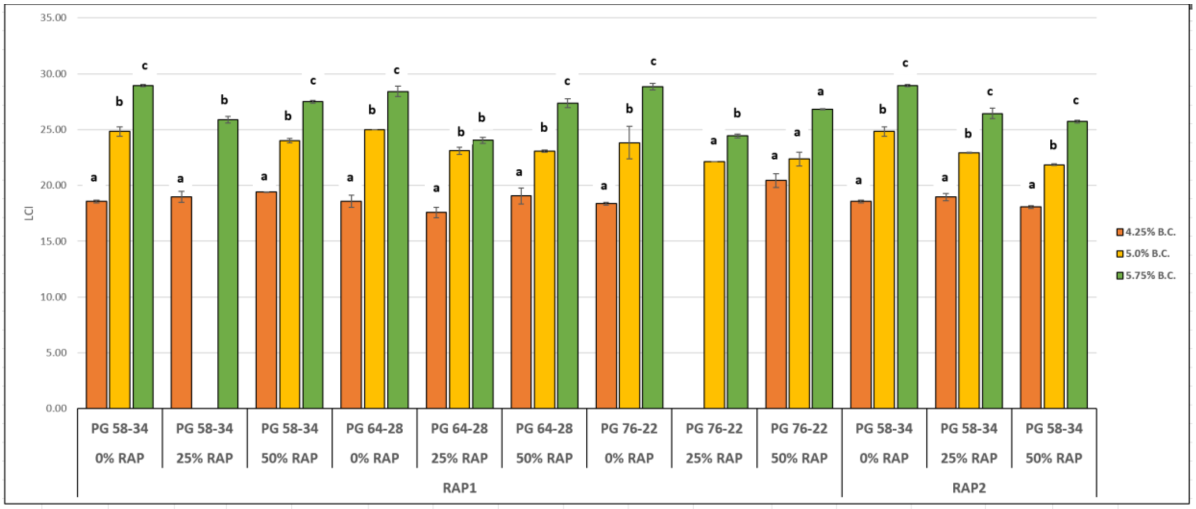


Figure 4.17: Effect of Binder Content on LCI Values

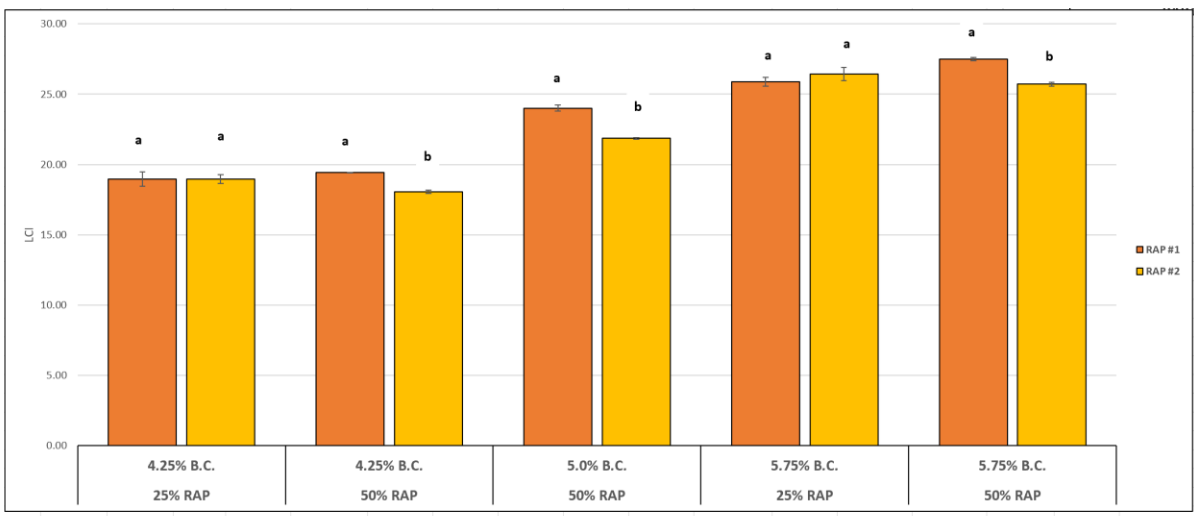


Figure 4.18: Effect of RAP Source on LCI Values

4.5.2 Laboratory Compaction Index of PMLC

Figure 4.19 represents the LCI values for each batch of PMLC mixes. The LCI results were similar to the rutting results. There were some variations in the LCI values between batches or the same PMLC mix; however, there was no significance difference in the results.

Meanwhile, the results showed that there was a statistically significance difference between some PMLC mix. For example, there was a significant difference between D3-P5 and both D1-P2 and D1-P1.

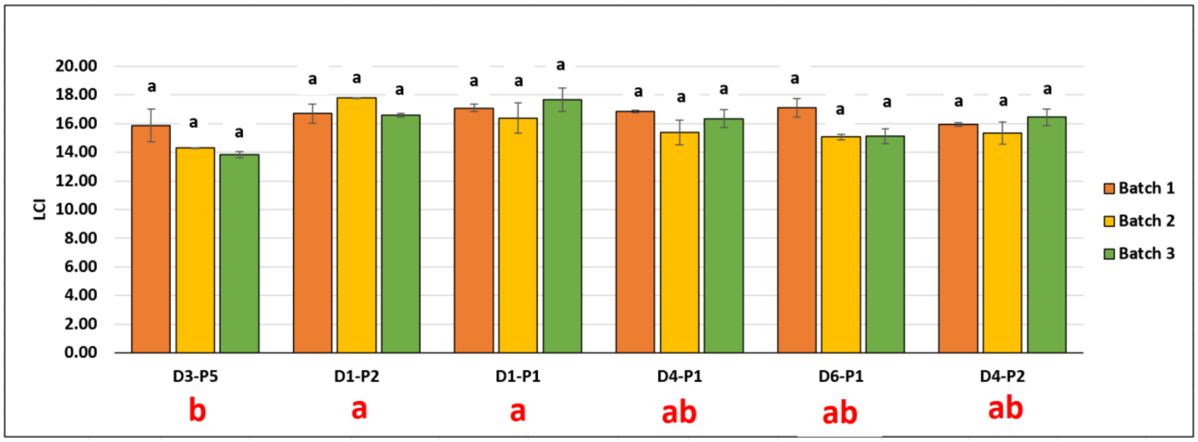


Figure 4.19: PMLC Batch effect on LCI Values

4.6 Correlation between Laboratory Compaction Index (LCI) and Rutting Characteristics

4.6.1 Correlation with APA Rut Depth

The researcher examined the correlation between the Laboratory Compaction Index (LCI) calculated from the compaction data using the PINE compactor as discussed earlier. Higher LCI values indicate that mixtures need less energy to compact (i.e., easy to compact) and vice versa. The assumption is, if mixtures are easy to compact, they may experience further densification or higher rutting under traffic loading. The researcher assessed the correlation between rut depth and LCI. The LCI is calculated using the slope and intercept of the compaction curves until 7.0% air voids using Equation 2.4. Figure 4.20 shows the correlation between LCI and APA rut depth for the LMLC mixes. The results demonstrated that there is a direct correlation between LCI and APA rut depth. The APA rut depth increased with the increase in LCI and vice versa. The R^2 for the correlation of 0.55 is considered particularly good given the inherent variability associated with the laboratory compaction and rutting test. This correlation can be used to predict rutting performance suing the laboratory compaction of asphalt mixtures during the mix design stage or during mix production. Also, the researcher examined such correlation for various conditions (e.g., binder grade, binder content, etc.).

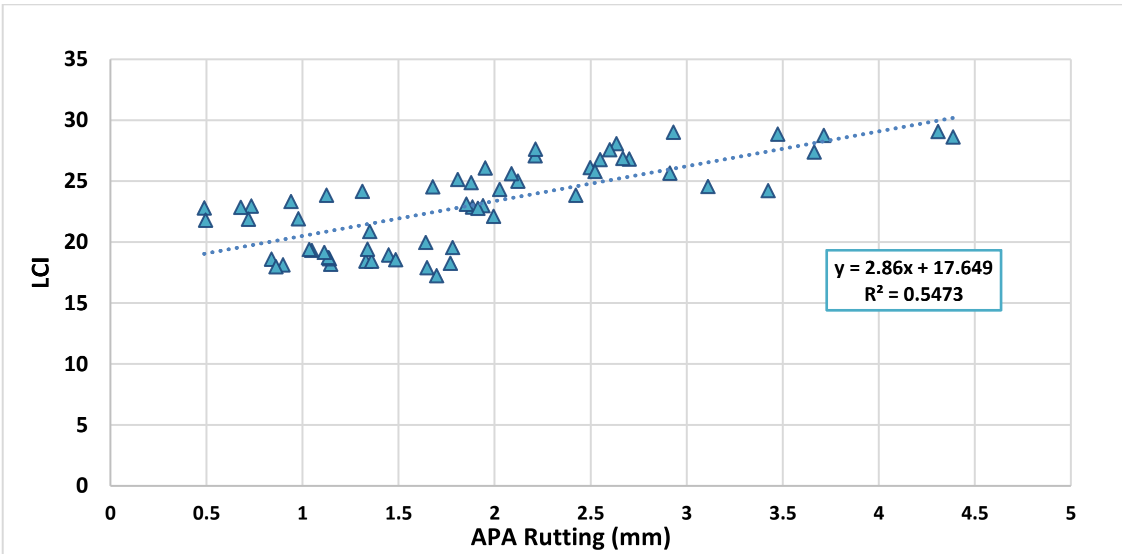


Figure 4.20: Correlation between LCI and APA Rut Depth for LMLC Mixes

Figure 4.21 represents the APA results from both sources of RAP (RAP 1 and RAP 2) at different binder grades. The blue data line and symbols represent PG 64-28, red for PG 76-22 and orange for PG 58-34. PG 64-28 had the lowest correlation (R^2 = 0.46) while PG 76-22 had R^2 of 0.61. PG 58-34 provided R^2 of 0.66 which was the highest correlation among different binder grades. Overall, the R^2 for the correlation was improved from 0.55 (all data points) to 0.61 for PG 76-22 and 0.66 for PG 58-34 but decreased to 0.46 for PG 64-28. These results demonstrated that there was no significant improved on R^2 when different binder grades were considered separately.

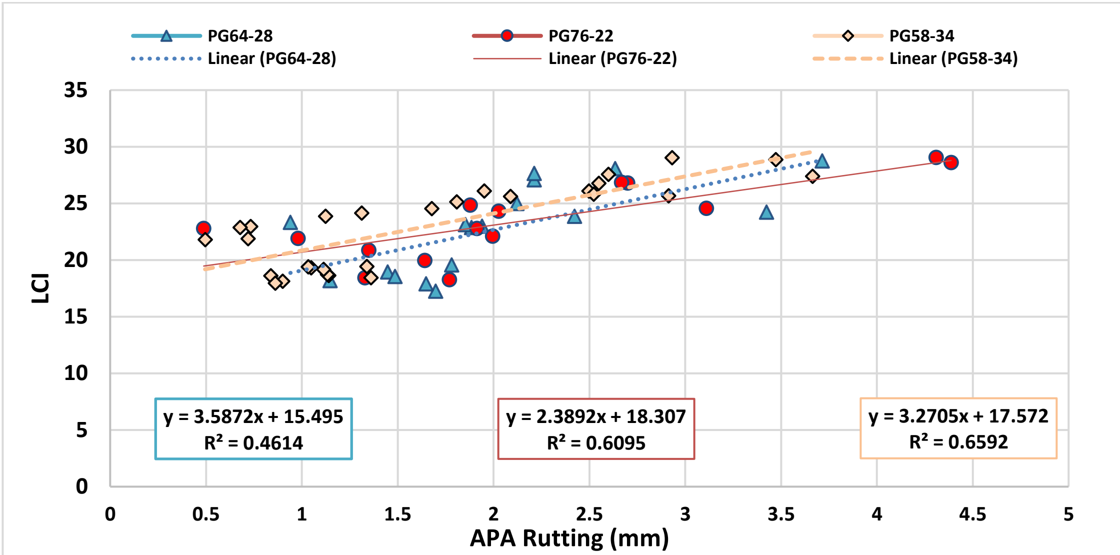


Figure 4.21: Correlation between LCI and APA Rut Depth at Different Binder Grades

The between the different source of RAP shown by Figure 4.15 did not demonstrate much change in the overall results. Also, Figure 4.16 shows the comparison between LCI and APA rut depth for PG 58-34 and RAP sources (RAP 1 and RAP 2). PG 58-34 was the only binder used with both RAP sources. The results showed that improved correlation for RAP 1 mixes (R^2 = 0.71) than RAP 2 mixes (R^2 = 0.53), but this could be due to the number of data points or mixes prepared and tested using RAP 1 materials.

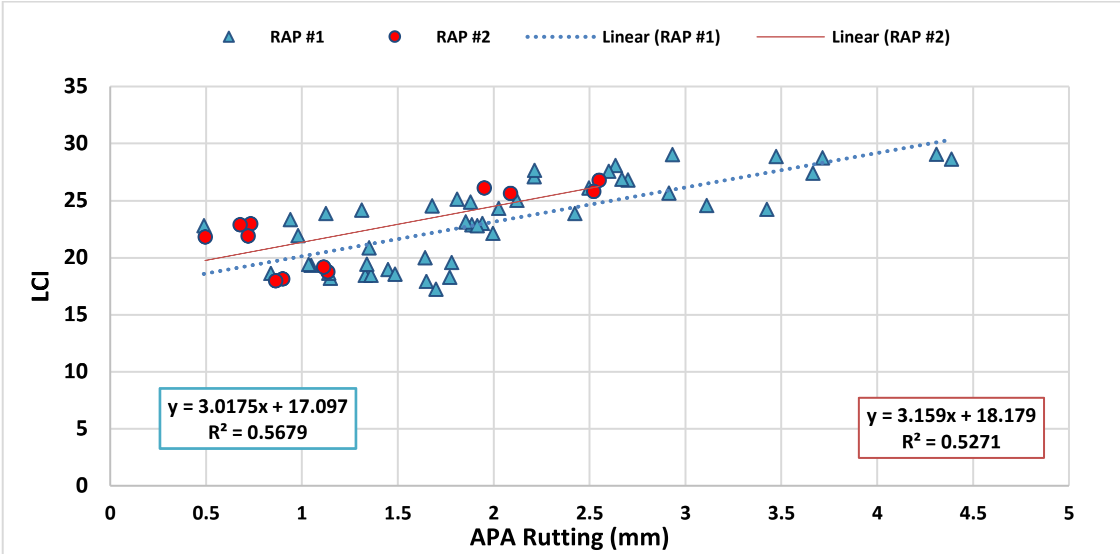


Figure 4.22: Correlation between LCI and APA Rut Depth at Different RAP Contents

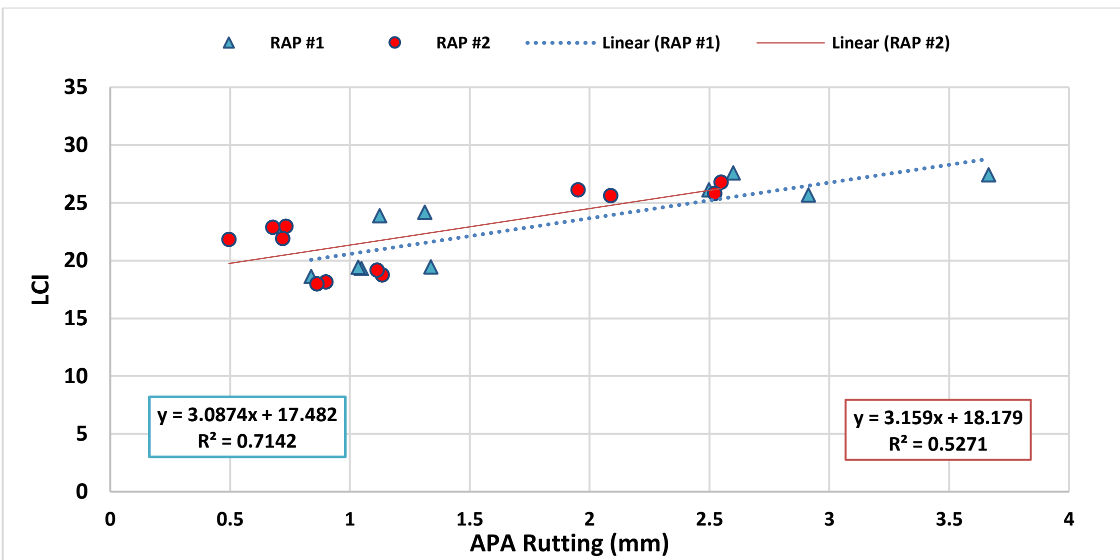


Figure 4.23: Correlation between LCI and APA Rut Depth at RAP Contents using PG 58-34

4.6.2 Correlation with HWTT Rut Depth

Figure 4.24 shows correlation between LCI and HWTT rut depth. This correlation had more of a cluster of points, with R^2 of 0.23 which is way less than the correlation of APA rut depth (R^2 = 0.55). One explanation is that the LCI is calculated from the compaction data which is conducted at different temperatures based on the binder grade where the compaction temperature increases with the stiffness of the binders to achieve optimum viscosity during compaction. The HWTT is conducted at a constant temperature of 50°C and in wet conditions, while the APA is performed at different temperatures based on the binder grade. Since the viscosity of asphalt binders change with temperature, the rutting performance also changes with temperature. Therefore, the comparison of LCI to APA rut depth is more appropriate compared to HWTT. Figure 4.24 includes all the LMLC and PMLC mixes, the author further examined the correlation between LCI and HWTT rut depth at various conditions as discussed next.

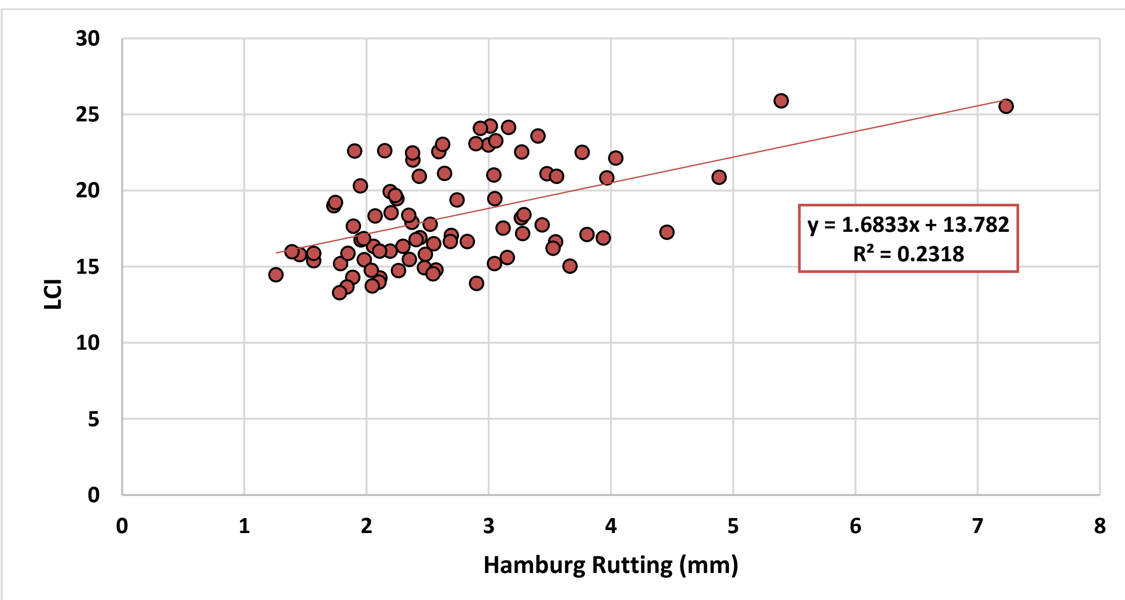


Figure 4.24: Correlation between LCI and HWTT Rut Depth

Figure 4.25 examines the correlation between LCI and HWTT rut depth at different binder grades. Binder PG 58-34 had the best correlation with R^2 of 0.48. The number of data points for PG 64-28 and PG 76-22 was low which might result in low R^2 compared to PG 58-34.

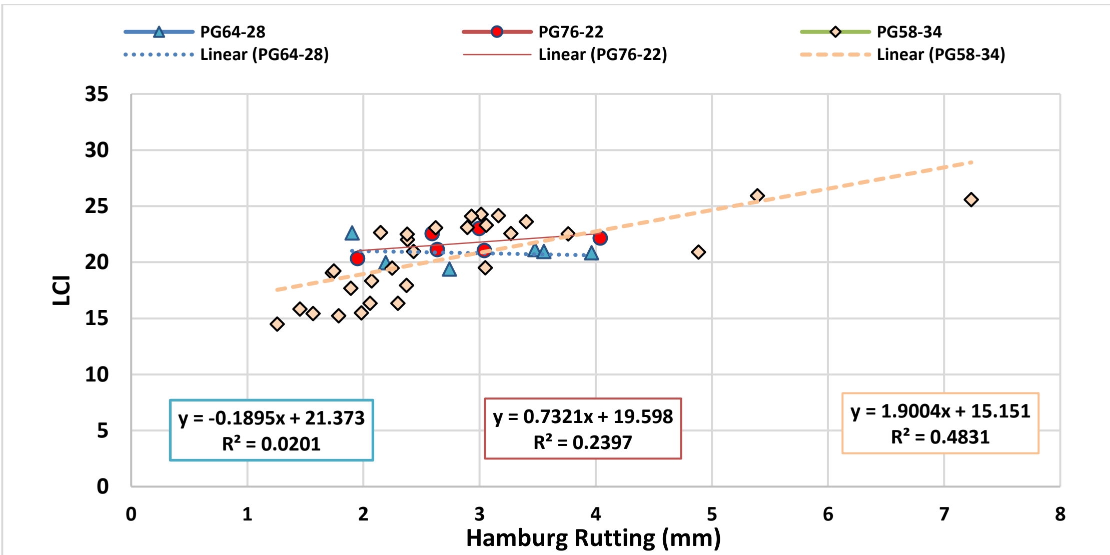


Figure 4.25: Correlation between LCI and HWTT Rut Depth at Different Binder Grades

Figure 4.26 shows the relationship between HWTT rutting results and LCI for mixes prepared with various RAP sources (RAP 1 and RAP 2) at 25% and 50% RAP contents. This provides equal comparison from the LCI values of samples containing virgin aggregates and RAP. Mixes with RAP 1 showed better correlation (R^2 = 0.75) that that of RAP 2 (R^2 = 0.49) and both are better than the general correlation including all data points (R^2 = 0.23); however, limited data points in Figure 4.19 may results in such improved correlation.

Figures 4.27 and 4.28 examine the correlation between LCI and HWTT rut depth for PMLC and LMLC mixes, separately. The results showed not much variation in LCI values for PMLC which resulted in poor correlation (R^2 = 0.22) with HWTT rutting, while the correlation was slightly improved (R^2 = 0.36) for LMLC mixes since we have wide range of LCI values. The LMLC mixes were prepared in the laboratory to have different characteristics (binder content, binder grade, RAP content, etc.). Overall, the results demonstrated that there was no good correlation between LCI and HWTT rut depth for all the data.

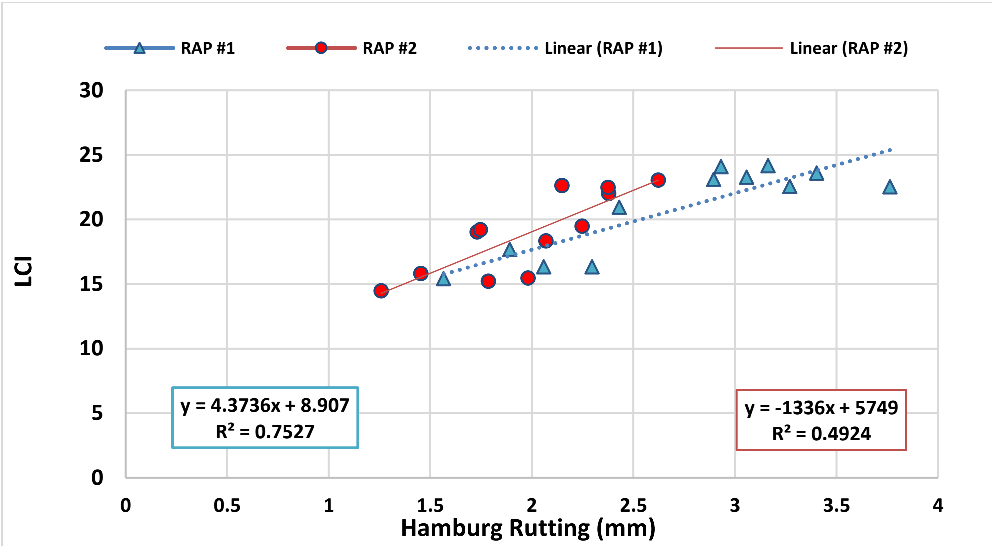


Figure 4.26: Correlation between LCI and HWTT Rut Depth at Different RAP Sources

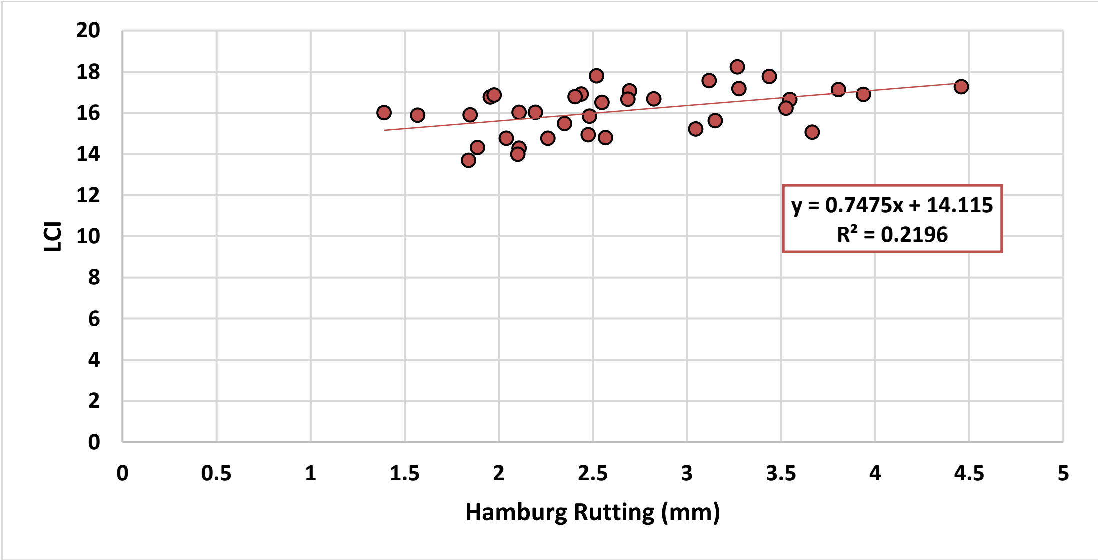


Figure 4.27: Correlation between LCI and HWTT Rut Depth for PMLC Mixes

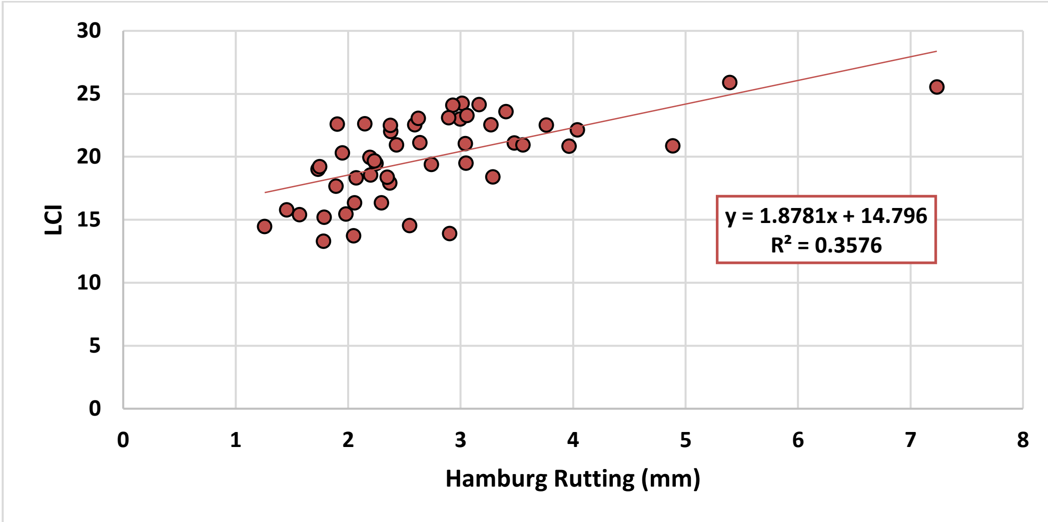


Figure 4.28: Correlation between LCI and HWTT Rut Depth for LMLC Mixes

4.7 Moisture Damage using Lottman Procedure and Anti-Strip Agents

The author evaluated the moisture susceptibility of selected asphalt mixtures using the Lottman protocol in accordance with AASHTO T 283 "Resistance of Compacted Bituminous Mixture to Moisture-Induced Damage" and ASTM D6931 "Standard Test Method for Indirect Tensile (IDT) Strength of Asphalt Mixtures" as discussed in Chapter 3. The test mixtures were prepared using river gravel rock, PG 58-34 at different binder contents (i.e., 4.25%, 5.0%, and 5.75%), three different RAP contents (0%, 25%, 50%) of RAP No. 2. These mixtures were prepared with 0% and 1.5% of liquid anti-stripping agent (ASA). Typically, a TSR value of 0.80 and greater indicates good resistance to water damage. ASA is often used to improve the resistance to moisture damage when the TSR is less than 0.8. Moisture damage refers to the stripping of asphalt binder from the aggregates leading to raveling and premature pavement failure.

Figure 4.29 shows the results of TSR of the test samples. The results demonstrated that the addition of the anti-strip agent improved the TSR in all samples except 0% RAP at 5.0% binder content; however, the TSR was still above 0.8. Mixes prepared with 0% RAP at 5.75%

binder content and 25% RAP at 5.0% binder content exhibited significant improvement in moisture damage resistance (i.e., higher TSR) with the addition of 1.5% anti-strip. Mixes with 0% RAP at 5.75% binder content and 1.5% anti-strip, had a TSR value of 0.99 which indicates that conditioned sample had almost the same maximum load compared to the dry specimens.

The results also demonstrated that the addition of RAP had negative effects on moisture susceptibility and resulted in lower TSR values. Mixtures with RAP had TSR lower than 0.8 (0.6 at 25% RAP, and 0.68 at 50% RAP) which are more susceptible to the water damage. The addition of ASA improved the performance at 25% RAP mixture where TSR increased from 0.6 to 0.82. However, the ASA did not enhance the resistance to moisture damage at 50% RAP (TSR = 0.69).

Statistical analysis shows significance between TSR values at 5.75% B.C. at 0% RAP and 5.0% B.C. at 25% RAP. This means there was significant effect from the anti-strip agents, significantly improving the moisture resistance of the aggregates. Comping the difference between different mixtures shows significant change between the first two sets of mixtures and the rest.

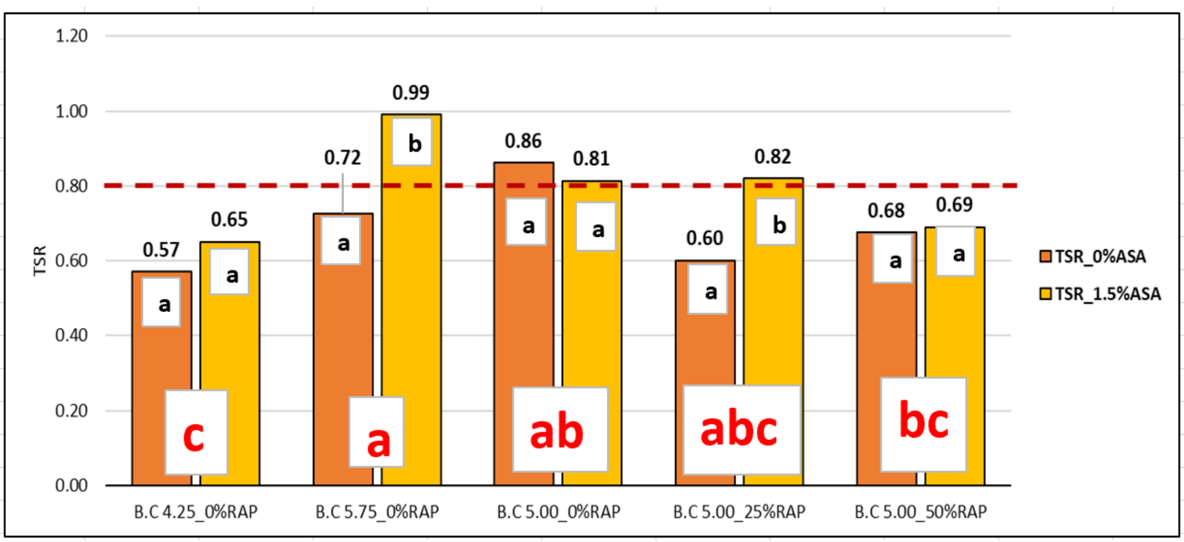


Figure 4.29: TSR Values of Test Samples

The author also evaluated the effect of use anti-strip on HWTT rut depth (Figure 4.30). Mixtures prepared without RAP at 4.25% and 5.75% binder contents. Also, these mixtures were prepared without anti-strip agent (0%) and 1.5% anti-strip agent. The results demonstrated that test samples with 1.5% anti-strip agent at 4.25% and 5.75% binder content had less rutting than without anti-strip. The addition of anti-strip agent slightly improved the resistance to rutting; however, there is no statistically significant difference between samples prepared with and without anti-strip agent. Test samples without ASA had good resistance to rutting and moisture damage based on the HWTT results, and this could reduce the effect of anti-strip agent on HWTT results. Overall, the HWTT did not provide comparable evaluation of the moisture susceptibility to that of TSR.

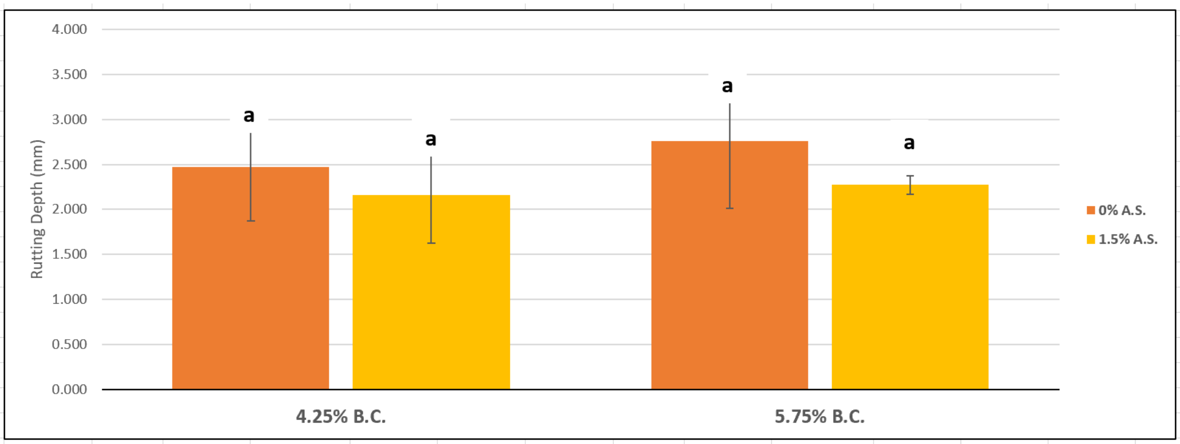


Figure 4.30: Effect of Anti-Strip Agent on HWTT Rutting

4.8 Effect of Aggregate Type on Rutting Characteristics

A limited comparison was performed to compare the rutting performance of mixtures prepared using different aggregate sources. The rutting performance of test mixtures prepared using basalt and river gravel at lower and higher binder contents (4.25% and 5.75%) was evaluated. Figure 4.31 shows the HWTT rutting depth of test samples. The results demonstrated that there was no statistically significant difference in rut depth between basalt and river gravel mixtures at low binder content of 4.25%; however, there was a statistically significant difference in rut depth at higher binder content. The river gravel mixtures experienced higher rutting compared to basalt mixtures. It should be noted that the basalt rock has crushed faces and high angularity which provides good aggregate interlock leading to better resistance to densification and rutting. while the river gravel has more round faces which makes hard to interlock aggregates in place. In addition, river gravel has less resistance to moisture damage compared to basalt. The river gravel was selected to study the effect of use of antistrip agents to improve the resistance of asphalt mixtures to stripping as discussed earlier in this chapter.

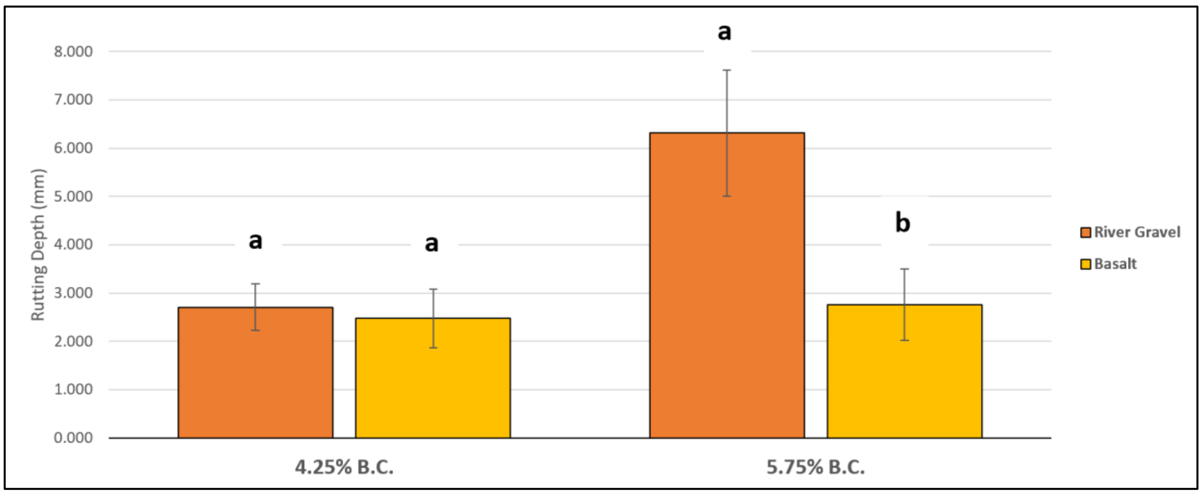


Figure 4.31: Effect of Aggregate Type on HWTT Results

CHAPTER 5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary

The asphalt industry continues to be the country's most consistent recycler of highway pavement materials with more than 99% being used as Reclaimed Asphalt Pavement (RAP) in the construction and rehabilitation of pavements. The average RAP percentage utilized in asphalt mixes has increased from 15.6% in 2009 to 21.1% in 2018 (NAPA 2018). The increase in RAP content in asphalt mixtures may result in stiffer mixtures which are more prone to cracking. Depending on the RAP content in the asphalt mixtures (e.g., RAP > 30%), the asphalt mix may require softer binders or an increase in the binder content to offset the negative impact of high RAP content on mix cracking performance.

This study examined the rutting characteristics of asphalt mixtures prepared at different RAP and binder contents with different binder grades. In addition, the compactability of the test mixtures was assessed by calculating the laboratory compaction index (LCI). Mixtures with higher LCI are found to be easy to compact compared to those with lower LCI. Furthermore, this study examined the moisture susceptibility of asphalt mixtures prepared with RAP and the use of anti-stripping agent to improve the resistance of these mixtures to moisture damage.

The author prepared and tested Laboratory-Mixed Laboratory-Compacted (LMLC) mixes. These mixes had different RAP contents (0%, 25%, and 50%), RAP sources (Source No. 1 and Source No. 2), binder contents (4.25%, 5%, and 5.75%), and binder grades (PG 58-34, PG 64-28, and PG 76-22). In addition, to the LMLC mixes, Plant Mixed-Laboratory Compacted (PMLC) mixes were obtained from new ITD paving projects. Similar to the LMLC, the PMLC had different mix constituents including RAP content, binder content, binder grade, mix design, Nominal Maximum Aggregate Size (NMAS), etc. Three batches were sampled from each project throughout the construction.

The rutting performance was evaluated using two rutting tests: APA rut test and HWTT. These tests are conducted at different conditions in accordance with AASHTO T340 and

AASHTO T 324, respectively, as discussed in Chapter 3. In addition, the compactability of asphalt mixtures was examined using the Superpave gyratory compaction curves which show the reduction in percent air voids versus number of gyrations. Finally, moisture damage was evaluated for selected asphalt mixtures following the Lottman protocol in accordance with AASHTO T283.

5.2 Main Findings of The Study

5.2.1 Evaluation of Rutting Performance

- The APA rut depth results showed an increased in rut depth with an increase in binder content. There was a statistically significant difference between mixtures prepared with 5.75% and 4.25% binder content. While there was no statistically significant difference between 4.25% and 5% binder content at different RAP contents. Also, all the LMLC mixes showed good resistance to rutting. The maximum rut depth was less than the than 5 mm, which corresponds to the failure threshold for APA rut depth after 8,000 cycles.
- The HWTT showed the same trend indicated by the APA tests with increased rut depth as the binder content increased. However, unlike the APA, the HWTT results were not statistically different at different binder contents. This could be due to the small HWTT rut depths measured for the LMLC mixes. All LMLC mixes had good resistance to rutting since the HWTT rut depth was less than 12.5 mm after 20,000 passes, which is the failure criteria for the HWTT.
- The results showed that there was no defined trend for the effect of RAP content on APA rut depth for mixtures prepared with RAP Source No. 1; however, the rut depth decreased at 25% and 50% RAP compared to 0% for RAP No. 2. Overall, the difference in the APA rut depth results was not statistically different at different RAP content. Similar results were also obtained from the HWTT.
- The HWTT results demonstrated that the PMLC mixes have good rutting resistance. However, there was significant difference in rutting among some projects which was probably due to differing mix compositions. Also, the results demonstrated that there was variation in rut depth among different batches for each individual field project.

5.2.2 Evaluation of Compactability of LMLC Mixtures

- The results clearly showed that the binder content had a significant effect on the compactability of asphalt mixtures. Mixtures with lower binder contents had lower LCI values which indicate more compaction energy is needed compared to mixture with higher binder contents. This trend was also observed for different binder grades and RAP Percentages.
- Generally, mixtures prepared with RAP 2 had lower LCI compared to RAP 1, which indicates that RAP 2 resulted in stiffer mixtures compared to RAP 1 at the corresponding binder content and grade.
- Overall, there was no consistent and statistically significant trend for the effect of binder grade on LCI results. The binder grade generally does not have a significant effect on laboratory compaction data since the compaction is conducted at different temperatures depending on the PG grading, where different asphalt binders are expected to achieve the same viscosity (0.28 ± 0.30 Pa.s.).
- There was no clear trend for the effect of RAP content on LCI. As the LCI is calculated at the compaction temperature, which is relatively high, the effect of higher binder stiffness due to higher RAP content might be minor.

5.2.3 Correlation between Rutting and Compactability

- There was a direct correlation between LCI and APA rut depth. The LCI is calculated using the slope and intercept of the compaction curves until 7% air voids. Higher LCI values indicate that mixtures need less energy for compaction (i.e., easy to compact) and vice versa. The assumption is that if mixtures are easy to compact, they may experience further densification or higher rutting under loading. The R^2 for the correlation of 0.55, which is considered good given the inherent variability associated with the laboratory compaction and rutting test.
- A poor correlation was found between the LCI and HWTT rut depth. The reason is that the LCI is calculated from the compaction data which is conducted at different temperatures based on the binder grade where the compaction temperature increases

with the stiffness of the binders to achieve optimum viscosity during compaction. While the HWTT is conducted at a constant temperature of 50°C and wet conditions.

5.2.4 Moisture Damage Assessment

- The tensile strength ratio (TSR) results demonstrated that the use of anti-stripping agents improved the resistance of asphalt mixtures to moisture damage. The anti-stripping agents enhance the adhesion between the asphalt binder and aggregates which makes it hard for water to strip the binder off the aggregates. In addition, the results showed that the addition of RAP had negative effects on moisture resistance and resulted in lower TSR values. However, the addition of anti-strip agents improved the performance at 25% RAP but did not enhance the resistance to moisture damage at 50% RAP.
- The HWTT results did not show any sign of moisture damage for the mixtures prepared at different RAP contents which were not consistent of TSR results. This could be due to the harsh Lottman conditioning protocol compared to HWTT conditions.

5.3 Recommendations for Future Research

Recommendations for further research are presented below.

- Investigate the correlation between the LCI and field rutting performance. Historical compaction data and field rutting performance observations should be examined and analyzed to achieve this objective.
- Evaluate additional mixtures prepared with different aggregate types used in Idaho using HWTT and Lottman testing protocols.
- Evaluate a balanced mix design approach to adjust the binder content in mixtures with RAP to provide adequate resistance to cracking and rutting.

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APPENDIX A MIX DESIGN SUMMARY

Design Specifications: Blend 3 / 100 Gyrations @ N Design (PG 70-34) Binder Bump PG 64-34

Gyratory Compactor: Model # AFGB1A Serial # 5443

		Job Mix Formula	Spec
1	Percent Asphalt by Weight of Total Mix	**5.0**	--
2	Percent Asphalt by Weight of Aggregate	5.3	--
3	Virgin Asphalt by Weight of Mix	3.72	--
4	Virgin Asphalt by Weight of Aggregate	3.92	--
5	Percent Air Voids (Pa)	4.0	4.0
6	Voids in Mineral Aggregate (VMA)	14.3	14min
7	Compacted Unit Weight Gmb, pcf	2.497 155.4	--
8	Theoretical Maximum Density Gmm, pcf	**2.602 162.0**	--
9	Percent Effective Asphalt Content (Pbe)	4.2	--
10	Percent Absorbed Asphalt (Pba)	0.83	--
11	Specific Gravity of Binder (Gb)	**1.028**	--
12	Percent Gmm @ N Initial (8 Gyrations)	85.5	≤ 89.0
13	Percent Gmm @ N Design (100 Gyrations)	96.0	96.0
14	Percent Gmm @ N Max (160 Gyrations)	97.4	≤ 98.0
15	Dust to Asphalt Ratio (DP)	1.4	0.8-1.5
16	Percent Passing #200 Sieve	6.0	2.0-10.0
17	Voids Filled w/ Asphalt (VFA)	72	65-75
18	Laboratory Mixing Temperature for Design (°F)	312	304-312
19	Laboratory Compaction Temperature for Design (°F)	**290**	283-291
20	Laboratory Sample Weight for Volumetric Testing (g)	**4950**	--
21	Ignition Oven (NCAT) Correction Factor @ 538 °F	**0.86**	--
22	Sand Equivalent	66	45 Min
23	Fracture Face Count (%)	99/98	98/98 Min
24	Fine Aggregate Angularity (%)	49.1	45 Min
25	Flat and Elongated Particles in Coarse Aggregates (%)	4.0	10 Max
	Recycled Asphalt Pavement (RAP) Properties		
26	Percentage of Asphalt in RAP (Wt. of Mix)	4.3	--
27	Percentage of RAP by Total Weight of Aggregate	30	--
28	Percent of RAP Binder by Weight of Total Binder	25.7	30 Max
29	RAP Contribution by Mix	1.28	--
30	RAP Contribution by Aggregate	1.34	--
31	RAP NCAT Correction Factor	1.57	--

Figure 1A: SP5 Mix Design for the First Source of RAP

Stockpile Gradation / Blend Percentages

Source	WCW-18							
Sieve Sizes	5/8-3/8	1/4-0	RAP				Combined Gradation	Specs.
Blend Ratio, %	42	28	30				100%	
1" (25mm)	100	100	100				100	100
3/4" (19mm)	100	100	100				100	100
1/2" (12.5mm)	81	100	98				91	90-100
3/8" (9.5mm)	47	100	90				75	90max
No. 4 (4.75mm)	4	83	66				45	
No. 8 (2.36mm)	3	53	47				30	28-58
No. 16 (1.18mm)	3	36	34				22	
No. 30 (600um)	3	26	25				16	
No. 50 (300um)	2	20	18				12	
No. 100 (150um)	2	16	14				10	
No. 200 (75um)	2.0	11.2	9.4				* 6.0	2.0-10.0

* #200 Controlled at plant mitigation process, minus 1.0% -#200

N-Cat Aggregate Correction Factors

Sieve Sizes	Target Gradation	N-Cat Ave.	N-Cat Ave. Corr.
(25mm)	100	100	--
3/4" (19mm)	100	100	--
1/2" (12.5mm)	91	91	--
3/8" (9.5mm)	75	75	--
No. 4 (4.75mm	45	45	--
No. 8 (2.36mm	30	32	--
No. 16 (1.18mr	22	23	--
No. 30 (600um	16	17	--
No. 50 (300um	12	13	--
No. 100 (150ur	10	11	--
No. 200 (75um	* 6.0	5.9	--

Specific Gravity & Absorption

	+4	-4	RAP	Avg.
Bulk Dry (Gsb)	2.792	2.739	2.752	2.767
SSD	2.858	2.805	n/a	n/a
Apparent	2.989	2.932	n/a	n/a
% Absorption	2.3	2.4	n/a	n/a
Effective (Gse)	2.830			

Saturation Pressure: 260mm HG
Saturation Time: 15-20min
Specimen Weight agg & rap (g): 3775
Specimen Weight with oil (g): 3920

Stripping Evaluation (TSR)

Type of Stripping Agent: AD-here LOF 65-00

% Anti-Strip	% Voids	Dry Strength, psi	Wet Strength, psi	Retained Strength	Spec.
0.50%	6.9	87	78	90%	80min

* Check saturation in 5 minute intervals to ensure it is not over saturated.

Figure 1A: SP5 Mix Design for the First Source of RAP (cont.)

Mix Design Summary

Project	Top of Bear Ridge Grade to Pine Cr., Latah Co
Mix Producer	Knife River
SPMDT (print)	Justin Drye
JMF Mix ID NO.	18020-19640-12.5mmSP3-R27

Mix Class	12.5mm SP3(1-<10 Design ESALs)
Specified Asphalt Grade	PG 64-28
*Adjusted Binder Grade	PG 58-34
Project Number	A019 (640)
Key Number	19640

Aggregate & (Gravel) Other Constituents (RAP, Blend Sand, Lime, ETC.)							
Stock Pile	B	C	C3	Basalt B	RAP		
Stock Pile Percentage (Psp)	22	26	10	15	27		
Stock Pile Source Number	NP168c	NP168c	NP168c	NP168c	NP168c		
Design developed with "dry back" Gmm			Yes		No	X	

Mixture at Design Asphalt Content	
Maximum Specific Gravity (Gmm)	**2.521**
Gyratory Bulk Specific Gravity (Gmb)	**2.420**
Combined Aggregate (Gsb)	**2.719**
Effective Specific Gravity (Gse)	2.762
Combined Apparent Gravity (Gsa)	2.802
Absorbtion	1.6
Bulk Specific Gravity Rap (Gsb)	2.799
Absorbed Asphalt, % (Pba)	0.59
Effective Asphalt Content, % (Pbe)	5.143
P200 / Pbe Ratio	1.19
Air Voids, % (Va)	4.0
VMA %	16.1
VFA %	75
Rap oil content	5.84
Percent Rap by Binder	**30**
Relative Density %gmm @ Nmax	**97.1**
Ncat Correlation Factor **@538C**	**0.51**
Laboratory Compaction Temp	**290**
Gmb sample weight @ JMF	**4750**
Number of Gyrations	**75**
Aggregate Properties	
Uncompacted Void Content Fines	60
Sand Equivalent	63
Fracture Face (1 Face / 2 Face)	100/100
Flat and Elongated Particles	1
Fine Aggregate Gsb	2.656

Job Mix Formula		
Aggregate Gradation Sieve	Blend	Spec. Limits
1" (25 mm)	**100**	100
3/4" (19 mm)	**100**	100
1/2" (12.5 mm)	**93**	90-100
3/8" (9.5 mm)	**80**	90max
No. 4 (4.75 mm)	**51**	
No. 8 (2.36 mm)	**34**	28-58
No. 16 (1.18 mm)	**24**	
No. 30 (0.60 mm)	**17**	
No. 50 (0.30 mm)	**12**	
No. 100 (0.150 mm)	**9**	
No. 200 (0.075 mm)	**6.1**	2-10

Asphalt content, % (Pb)	**5.7**
Rap % AC contributed	1.6
Asphalt content added	4.1
Asphalt content by weight of agg	6.0
Asphalt content by agg added	4.5
Antistrip, %	0.75%
Asphalt Brand	Idaho Asphalt
Asphalt Grade	PG 64-28
Mix temp. range	313-327
Compaction temp. range	282-298
Asphalt specific gravity (Gb) 77 F	1.029
Asphalt specific gravity (Gb) 60 F	**1.033**

Min/Max Properties	Min	Target	Max	Spec Limits
Asphalt content, % (Pb)	5.3	5.7	6.0	
Air Voids, % (Va)	5.0	4.0	3.0	3.0-5.0
VMA %	16.1	16.1	15.9	14 min.
Maximum Specific Gravity (Gmm)	2.536	2.521	2.510	
Bulk Specific Gravity (Gmb)	2.410	2.420	2.434	
P200 / Pbe Ratio	1.3	1.2	1.1	0.8-1.6

Breakdown will be controlled by means of our baghouse.

Figure 3A: SP3 Mix Design for the Second Source of RAP

Design Specifications: Blend 3 / 75 Gyrations @ N Design PG 64-28 (58-34 Adjusted Binder)

Gyratory Compactor: Model # AFG2AS Serial # 8732

		Job Mix Formula	Spec
1	Percent Asphalt by Weight of Total Mix	**5.2**	--
2	Percent Asphalt by Weight of Aggregate	5.5	--
3	Virgin Asphalt by Weight of Mix	3.87	--
4	Virgin Asphalt by Weight of Aggregate	4.09	--
5	Percent Air Voids (Pa)	4.0	4.0
6	Voids in Mineral Aggregate (VMA)	15.0	14 min
7	Compacted Unit Weight Gmb, pcf	2.374 147.8	--
8	Theoretical Maximum Density Gmm, pcf	**2.473 153.9**	--
9	Percent Effective Asphalt Content (Pbe)	4.77	--
10	Percent Absorbed Asphalt (Pba)	0.50	--
11	Specific Gravity of Binder (Gb)	**1.030**	--
12	Percent Gmm @ N Initial (7 Gyrations)	86.2	≤ 89.0
13	Percent Gmm @ N Design (75 Gyrations)	96.0	96.0
14	Percent Gmm @ N Max (115 Gyrations)	97.6	≤ 98.0
15	Dust to Asphalt Ratio (DP)	1.4	0.8-1.6
16	Percent Passing #200 Sieve	6.5	2.0-10.0
17	Voids Filled w/ Asphalt (VFA)	73	65-75
18	Laboratory Mixing Temperature for Design (°F)	324	316-324
19	Laboratory Compaction Temperature for Design (°F)	**302**	294-303
20	Laboratory Sample Weight for Volumetric Testing (g)	**4700**	--
21	Ignition Oven (NCAT) Correction Factor @ 538 °F	**0.31**	--
22	*Los Angeles Abrasion (LAR) (%)	**18**	30 max
23	*Idaho Degredation Δ % -200	**3.2**	5.0 max
24	Sand Equivalent	68	40 min
25	*Fracture Face Count (%)	99/98	75/60
26	Fine Aggregate Angularity (%)	47.3	40 min
27	*Flat and Elongated Particles in Coarse Aggregates (%)	2.8	10 Max
	Recycled Asphalt Pavement (RAP) Properties		
28	Percentage of Asphalt in RAP (Wt. of Mix)	4.58	
29	Percentage of RAP by Total Weight of Aggregate	30	--
30	Percent of RAP Binder by Weight of Total Binder	26	30 max
31	RAP Contribution by Mix	1.37	--
32	RAP Contribution by Aggregate	1.44	--
33	RAP NCAT Correction Factor	0.35	--

***Composite blend including RAP**

Figure 4A: District 1 – JMF P1

Design Specifications: Blend 1 / 75 Gyrations @ N Design PG 64-28 (58-34 Adjusted Binder)

Gyratory Compactor: Model # AFG2AS Serial # 8436

		Job Mix Formula	Spec
1	Percent Asphalt by Weight of Total Mix	**5.3**	--
2	Percent Asphalt by Weight of Aggregate	5.64	--
3	Virgin Asphalt by Weight of Mix	4.08	--
4	Virgin Asphalt by Weight of Aggregate	4.32	--
5	Percent Air Voids (Pa)	4.0	4.0
6	Voids in Mineral Aggregate (VMA)	15.6	14 min
7	Compacted Unit Weight Gmb, pcf	2.366 147.3	--
8	Theoretical Maximum Density Gmm, pcf	**2.465 153.4**	--
9	Percent Effective Asphalt Content (Pbe)	5.04	--
10	Percent Absorbed Asphalt (Pba)	0.32	--
11	Specific Gravity of Binder (Gb)	**1.028**	--
12	Percent Gmm @ N Initial (7 Gyrations)	86.8	≤ 89.0
13	Percent Gmm @ N Design (75 Gyrations)	96.0	96.0
14	Percent Gmm @ N Max (115 Gyrations)	97.3	≤ 98.0
15	Dust to Asphalt Ratio (DP)	1.1	0.6-1.4
16	Percent Passing #200 Sieve	5.6	2.0-10.0
17	Voids Filled w/ Asphalt (VFA)	74	65-75
18	Laboratory Mixing Temperature for Design (°F)	320	316-324
19	Laboratory Compaction Temperature for Design (°F)	**299**	295-303
20	Laboratory Sample Weight for Volumetric Testing (g)	**4720**	--
21	Ignition Oven (NCAT) Correction Factor @ 538 °F	**0.30**	--
22	*Los Angeles Abrasion (LAR) (%)	24	30 max
23	*Idaho Degradation Δ % -200	3.5	5.0 max
24	Sand Equivalent	66	40 min
25	*Fracture Face Count (%)	98/96	75/60
26	Fine Aggregate Angularity (%)	47.2	40 min
27	*Flat and Elongated Particles in Coarse Aggregates (%)	0.3	10 max
	Recycled Asphalt Pavement (RAP) Properties		
28	Percentage of Asphalt in RAP (Wt. of Mix)	4.20	
29	Percentage of RAP by Total Weight of Aggregate	30	--
30	Percent of RAP Binder by Weight of Total Binder	24	30 max
31	RAP Contribution by Mix	1.26	--
32	RAP Contribution by Aggregate	1.32	
33	RAP NCAT Correction Factor	0.36	--

***Composite blend including RAP**

Figure 5A: District 1- JMF P2

Report of Super Pave Mix Properties

ITD Mix Design Confirmation Report

ITD 0773 (Rev. 09-19)
itd.idaho.gov

Gradation Analysis, Asphalt Content, Volumetric, Rutting and Stripping Properties

Idaho Transportation Department

Key Number	Project Number	Project Name	District
58, 13387, 1	A021(858), A013(387), A013(932)	US20/26, SH-16 to Linder Road, SH55 Marsing to SR	3

Identification Number (Program/Task/Phase/Sample#)	Contract Item Number	Testing Laboratory Name & Location	Mix Design No.
P-193260 / T-193260	405	ITD Central Laboratory	GT0S644

Send Reports To (Resident Engineer's Name)	Sampled By	WAQTC Number	Date Sampled	Date Lab Received	Date Lab Tested
Shawna King, Jayme Coonce	Brian Arnold	22320	3/6/2020	3/30/2020	4/4/2020

Asphalt Binder Supplier	Asphalt Binder Grade	Sp. Gr. of Binder (from Mix Design)	JMF Intended Binder, % (by Wt of Mix)	Source Number
Western States Asphalt	PG 64-34	1.031	5.4	Cn-144c

Sample Location (Sta./offset, truck, plant, lab, etc.)	Mix Design Lab & Location	SPMDT	P.E. in Responsible Charge of Design
Stockpiles	Idaho Materials & Constr.	Brian Arnold	Bob J. Arnold, P.E.

ESALs	Nom. Max. Size Aggregate	Primary Control Sieve	Percent Passing Primary Control Sieve	Class of Mix
1 <10 (75 Gyrations)	1/2"	No. 8	39 %	SP3

Combined Aggregate Bulk SPG G_{sb} from ITD 0802 2.571

Test Results

Gradation Anayisis — **FOP for AASHTO T 30**

Sieve Size (mm)	(in.)	Lab No. 209MX 0016	Lab No.	Lab No.	Avg.	JMF
(50)	2	100			100	100
(37.5)	1/1/2	100			100	100
(25)	1	100			100	100
(19)	3/4	100			100	100
(12.5)	1/2	93			93	95
(9.5)	3/8	85			85	85
(4.75)	No. 4	64			64	61
(2.36)	No. 8	47			47	45
(1.18)	No. 16	36			36	34
(0.600)	No. 30	26			26	24
(0.300)	No. 50	15			15	14
(0.150)	No. 100	9			9	8
(0.075)	No. 200	5.9			5.9	5.6
Avg. Sample Height, mm		115.5				

Asphalt Binder Content (By Weight of Mix) — **FOP for AASHTO T 308**

	Lab No. 209MX 0016	Lab No.	Lab No.	Average
Total Asphalt Binder Content	5.67			
NCAT Correction Factor	0.05			
Moisture % (-)	0.09			
Act. Asph. Binder Content %	5.53			5.53

Compaction Temperature, °F 300

FOP for AASHTO T 312 / AASHTO M 323

	Lab No. 209MX 0016	Lab No.	Lab No.	Average
Lab Air Voids % at N_{Design}	4.6			4.6
G_{mb} (compacted mixture)	2.318			2.318
G_{mm} (max spec gravity)	2.430			2.430
VMA, %	14.8			14.8
VFA, %	69			69
Dust Proportion (DP)	1.3			1.3
G_{se} - Effective Sp. Gravity	2.640			
P_{be} - Eff. Binder Content, %	4.54			
P_{ba} - Binder Absorbed, %	1.05			

FOP for AASHTO T 209 result within 0.020 of JMF? Gmm from JMF= 2.412 Gmm from Sample Tested= 2.430 **Yes**

FOP for AASHTO T 166 result within 0.020 of JMF? Gmb from JMF= 2.314 Gmb from Sample Tested= 2.318 **Yes**

ASTM D1075 & AASHTO T 167

Sample # 1-4, 6

90 % @ 0.50 % Evotherm M1

PASS

AASHTO T 340

Sample # 209MX016

Rutting Depth, mm	3.9
Left Sample	4.27
Center Sample	4.77
Right Sample	2.669

Maximum Allowable Rut Depth 0.2 in. (5 mm) **PASS**

Mix Design Volumetrics Confirmation: ☒ **Pass** ☐ **Fail**

Remarks

Tested By	WAQTC Number
Jaime Conley, Armin Mirahcic, Dan Henscheid	24080, 24084, 24083

Date Mailed	Laboratory Manager's Signature	
4/8/2020		Chad Clawson, P.E.

Figure 6A: District 3 – Field JMF P5

Design Specifications: Blend 1 / 75 Gyrations @ N Design PG 64-34

Gyratory Compactor:	Model # AFG2AS Serial # 8436	Job Mix Formula	Spec
1	Percent Asphalt by Weight of Total Mix	6.2	--
2	Percent Asphalt by Weight of Aggregate	6.66	--
3	Virgin Asphalt by Weight of Mix	5.21	--
4	Virgin Asphalt by Weight of Aggregate	5.58	--
5	Percent Air Voids (Pa)	4.0	4.0
6	Voids in Mineral Aggregate (VMA)	14.5	14 min
7	Compacted Unit Weight Gmb, pcf	2.204 137.2	--
8	Theoretical Maximum Density Gmm, pcf	2.296 142.9	--
9	Percent Effective Asphalt Content (Pbe)	4.90	--
10	Percent Absorbed Asphalt (Pba)	1.43	--
11	Specific Gravity of Binder (Gb)	1.029	--
12	Percent Gmm @ N Initial (7 Gyrations)	86.7	≤ 89.0
13	Percent Gmm @ N Design (75 Gyrations)	96.0	96.0
14	Percent Gmm @ N Max (115 Gyrations)	97.2	≤ 98.0
15	Dust to Asphalt Ratio (DP)	1.3	0.6-1.4
16	Percent Passing #200 Sieve	6.5	2.0-10.0
17	Voids Filled w/ Asphalt (VFA)	72	65-75
18	Laboratory Mixing Temperature for Design (°F)	327	320-333
19	Laboratory Compaction Temperature for Design (°F)	299	291-306
20	Laboratory Sample Weight for Volumetric Testing (g)	4365	--
21	Ignition Oven (NCAT) Correction Factor @ 538 °F	0.38	--
22	Sand Equivalent	45	40 min
23	Fracture Face Count (%)	100/100	75/60
24	Fine Aggregate Angularity (%)	45.2	40 min
25	Flat and Elongated Particles in Coarse Aggregates (%)	0.0	10 Max
	Recycled Asphalt Pavement (RAP) Properties		
26	Percentage of Asphalt in RAP (Wt. of Mix)	5.40	--
27	Percentage of RAP by Total Weight of Aggregate	19	--
28	Percent of RAP Binder by Weight of Total Binder	17	17 max
29	RAP Contribution by Mix	1.03	--
30	RAP Contribution by Aggregate	1.08	--
31	RAP NCAT Correction Factor	0.47	--

Figure 7A: District 4 -Field JMF P2

MATERIALS & CONSTRUCTION

Proposed Job Mix Formula

Laboratory Values	Target			Spec.
Total Asphalt by Weight of Mix % (Pb)	5.1			
Total Aspalt by Weight of Aggregate	5.39			
Air Voids % (Va)	4.0			3.0-5.0
Voids in Mineral Aggregate (VMA)	13.9			13.3
Voids Filled with Asphalt (VFA)	71			65-75
Bulk Specific Gravity (Gmb)	2.323			
Unit Weight lb./cuft.	144.6			
Theo Max Spec Gravity (Gmm)	2.420			
Theo Max Spec Gravity lb./cuft.	150.6			
Effective Specific Gravity of Blend (Gse)	2.609			
Effect of Water on Compressive Strength *(AllWest)*	98			85 min
Ninitial (8 Gyrations)	86.6			≤ 89.0
Ndesign SP-5 (100 Gyrations)	96.0			= 96.0
Nmax (160 Gyrations)	97.4			≤ 98.0
NCAT Asphalt Correction Factor	0.21			
Dust to Asphalt	1.1			0.8-1.6
Laboratory Mixing Temperature(deg in F)	320			
Laboratory Compaction Temperature(deg in F)	300			
Plant Mixing Temperature(deg in F)**	316	-	324	
Field Compaction Temperature(deg in F)**	295	-	303	
Superpave Design Sample Wt. in grams	4575			

**Field mixing and compaction may be adjusted +/- 25 degrees per Viscosity Graph*

Aggregate Gradation Data

Sieve Size	Ln-80c A 18.0%	Ln-80c B 28.0%	Cs-201 C 20.5%	Ln-80c WC 12.0%	Md-101c Sand 4.0%	RAP 17.0%	Break down 0.5%	JMF Blended Gradation
1" / 25mm	100	100	100	100	100	100	100	100
3/4" / 19mm	92	100	100	100	100	100	100	99
1/2" / 12.5mm	16	88	100	100	100	95	100	81
3/8" / 9.5mm	5	46	100	100	100	86	100	65
No. 4 / 4.75mm	1	2	85	75	100	62	100	42
No. 8 / 2.36mm	1	2	58	43	85	45	100	29
No.16 / 1.18mm	1	1	41	26	66	34	100	21
No. 30 / 600um	1	1	30	16	54	26	100	16
No. 50 / 300um	1	1	22	9	20	20	100	11
No. 100 / 150um	1	1	15	4	4	14	100	7
No. 200 / 75um	0.5	0.7	9.9	1.4	1.4	9.5	90.0	4.6

** Aggregate breakdown will be controlled by the Hot Plant dust control system.*

Figure 8A: District 4 – Field JMF P5

Mix Design Test For Laboratory Produced Mix (Loose)

ITD 0733B (Rev. 05-19)
itd.idaho.gov

ITD Mix Design Confirmation Report

Idaho Transportation Department

Key Number	Project Number	Project Name	District
19711	A019(711)	US-20 Ashton Bridge to Dumpground Road	6

Identification Number (Program/Task/Phase/Sample#)	Contract Item Number	Lift Thickness (ft.)	Test Number	Lab Number	Mix Design No.
E166110	405-455A	N/A	0065	MX190	BL190457A

Send Reports To (Resident Engineer's Name)	Sampled By	WAQTC Number	Date Sampled	Date Lab Received	Date Lab Tested
Drew Meppen	David Miller	22647	4/24/2019	7/5/2019	7/10/2019

Asphalt Binder Supplier	Asphalt Binder Grade	Sp. Gr. of Binder(from Mix Design)	JMF Intended Binder, % by Wt of Mix	Source Number
Idaho Asphalt Supply	PG 64-34	1.029	5.9	FR-112c

Sample Location (Sta./offset, truck, plant, lab, etc.)	Mix Design Lab & Location	SPMDT	Testing Laboratory Name & Location
Stockpile	St. Anthony Id	David Miller	ITD Central Laboratory

ESALs	Nominal Max Aggregate Size	Primary Control Sieve	Percent Passing Primary Control Sieve	Class of Mix
>= 10 (100 Gyrations)	3/4"	No. 4	47 %	SP5

FOP for AASHTO T 209 Theoretical Max Specific Gravity (Bowl Method)

Sample	1A	1B	
Wt. Bowl and Sample	5225.1	5222.4	Within 50gm?
Wt. of Bowl	2728.5	2721.3	
Wt. of Sample (A)	2496.6	2501.1	
Wt. Bowl in Water with Sample	3168.0	3167.8	
Wt. of Bowl in Water	1717.9	1717.7	Average
Wt. of Sample in Water (B)	1450.1	1450.1	G_{mm}
G_{mm} (Maximum Specific Gravity)	2.386	2.380	2.383
G_{mm} Range 0.006	Acceptable? (Within d2s precision, 0.014)		YES

$$G_{mm} = \frac{A}{(A-B)}$$

Result within 0.020 of JMF Gmm? JMF Gmm = 2.378 Acceptable? YES

FOP for AASHTO T 312 SuperPave Gyratory Compactor

Sample	1A	1B	
Compaction Temp., °F	300	300	Spec Limits
Sample Height (mm)	115.2	115.7	110 to 120
Mass to Achieve Mix Design Specimen Height:			4550 g.

FOP for AASHTO T 166 Bulk SP. GR. of Compacted Mix (Method A)

Sample	1A	1B	
Specimen Surface Temperature	78.1	77	68°F to 80°F
Wt. of Specimen Dry (A)	4544.0	4559.9	Within ±15gm?
Wt of Specimen SSD (B)	4554.6	4571.2	YES
Wt. of Specimen in Water (C)	2564.8	2579.3	Avg. G_{mb}
Gmb (Bulk Specific Gravity)	2.284	2.289	2.286
G_{mb} Range 0.006	Acceptable? (Within 0.012)		YES

$$G_{mb} = \frac{A}{(B-C)}$$

Result within 0.020 of JMF Gmm? JMF Gmm = 2.283 Acceptable? YES

Volumetric Properties

	Value		Tolerance Limits	
P_a %- Lab Air Voids @ Ndesign	4.0		2.5	5.5
VMA, % - Voids in Mineral Aggregate	13.3	>		12.0
VFA, % - Voids Filled with Asphalt	70		65	75
DP - Dust Proportion	1.5		0.5	1.3

$$P_a = 100 - \left(\frac{100 \times G_{mb}}{G_{mm}}\right)$$

$$VMA = 100 - \left(\frac{G_{mb} \times P_s}{G_{sb}}\right)$$

$$VFA = 100 \times \left(\frac{VMA - P_a}{VMA}\right)$$

$$DP = \frac{P_{200}}{P_{be}}$$

G_{sb} - Aggregate Bulk SPG (from ITD 0802)	2.481
G_b - Specific Gravity of Binder (from Mix Design)	1.029
P_{200} - Percent Passing #200 (from ITD 0733A)	6.3
P_b - Binder Content, % (from ITD 0733A)	6.0
P_s - Percent of Aggregate (100 - Binder Content)	94.0
G_{se} - Effective Specific Gravity	2.600
P_{be} - Effective Binder Content, %	4.18
P_{ba} - Binder Absorbed, %	1.89
% Water Absorbed, (by volume)	0.55

$$G_{se} = \frac{P_s}{\left(\frac{100}{G_{mm}} - \frac{P_b}{G_b}\right)} \qquad G_{se} = 2.600$$

$$P_{be} = P_b - \frac{P_{ba}}{100} \times P_s \qquad P_{be} = 4.18$$

$$P_{ba} = 100 \times \frac{(G_{se} - G_{sb})}{(G_{se} \times G_{sb})} \times G_b \qquad P_{ba} = 1.89$$

$$\%\ Water\ Absorbed, = \left(\frac{B-A}{B-C}\right) \times 100 \qquad = 0.55$$

Remarks: See ITD spec 405.02 table 405.02-1 for dust proportion.

FOP for T 209 Tested By	WAQTC Number	Date Tested	FOP for T 166 Tested By	WAQTC Number	Date Tested	Checked By
Ed Horn GH	22615	7/10/2019	Ed Horn GH	22615	7/10/2019	Tracy McGillick, P.E.
FOP for T 312 Tested By	**WAQTC Number**	**Date Tested**	**AASHTO T 331 Tested By**	**WAQTC Number**	**Date Tested**	**WAQTC Num. / Date Checked**
Ed Horn GH	22615	7/10/2019	Ed Horn GH	22615	7/10/2019	07/11/19

Figure 9A: District 6 – Field JMF P1

Appendix B Rutting and Moisture Damage

==
File Name: FEB20_05.DAT
Time: 20:56 RP280_50%RAP PG58-34_5%BC Time:
Date: 02/19/2020 Axial Force Axial Displacement 11/30/2020 16:45
Diameter: 150 mm lbf in 35.97363 Sec
S/N: 8835
==

Gyration (#)	Height (mm)	Angle (Deg Int)	Pressure (kPa)	Moment (N-m)
0	140.1	----	597	0.0
1	135.3	1.17	575	654.0
2	132.4	1.16	575	759.9
3	130.3	1.15	580	813.6
4	128.7	1.15	594	844.8
5	127.4	1.16	599	862.8
6	126.3	1.16	601	871.8
7	125.4	1.16	601	877.6
8	124.6	1.15	601	881.4
9	123.9	1.15	601	885.3
10	123.3	1.16	601	890.2
11	122.7	1.16	601	893.6
12	122.2	1.16	601	894.4
13	121.7	1.16	601	894.6
14	121.3	1.16	601	896.5
15	120.9	1.16	601	896.2
16	120.5	1.16	601	896.4
17	120.2	1.16	601	896.2
18	119.9	1.16	601	896.3
19	119.6	1.16	601	897.9
20	119.3	1.16	601	900.7
21	119.0	1.16	601	900.9
22	118.8	1.16	601	901.8
23	118.5	1.16	600	901.2
24	118.3	1.16	600	900.0
25	118.1	1.16	600	899.3
26	117.9	1.16	600	897.5
27	117.7	1.16	600	896.5

Figure 1B: Sample of Compaction Data for PG 58-34 (50% RAP & 5.0% B.C.)

File Name: FEB20_05.DAT
RP280_50%RAP PG58-34_5%BC
Axial Displacement

S/N: 8835

==

Gyration (#)	Height (mm)	Angle (Deg Int)	Pressure (kPa)	Moment (N-m)
34	116.6	1.16	599	887.4
35	116.4	1.16	599	885.5
36	116.3	1.16	600	884.2
37	116.2	1.16	600	882.6
38	116.0	1.16	600	881.9
39	115.9	1.16	600	881.4
40	115.8	1.16	600	880.4
41	115.7	1.16	600	880.4
42	115.6	1.16	600	880.7
43	115.5	1.16	600	881.0
44	115.4	1.16	600	880.0
45	115.3	1.16	600	879.2
46	115.2	1.16	600	879.4
47	115.1	1.16	600	879.0
48	115.0	1.16	600	877.6
49	114.9	1.16	601	876.4
50	114.8	1.16	601	876.2
51	114.7	1.16	601	874.2
52	114.6	1.16	601	873.0
53	114.5	1.16	601	871.3
54	114.5	1.16	601	869.3
55	114.4	1.16	601	867.5
56	114.3	1.16	601	867.1
57	114.2	1.16	601	866.4
58	114.2	1.16	601	866.2
59	114.1	1.16	601	865.7
60	114.0	1.16	601	865.8
61	114.0	1.16	601	865.0
62	113.9	1.16	601	864.4
63	113.8	1.16	601	864.2

Figure 2B: Sample of Compaction Data for PG 58-34 (50% RAP & 5.0% B.C.) _Cont.

==
File Name: FEB20_05.DAT
RP280_50%RAP PG58-34_5%BC
Axial Displacement

S/N: 8835
==

Gyration	Height	Angle	Pressure	Moment
64	113.8	1.16	601	863.2
65	113.7	1.16	601	862.8
66	113.6	1.16	601	861.5
67	113.6	1.16	601	861.5
68	113.5	1.16	601	860.8
69	113.5	1.16	601	860.3
70	113.4	1.16	601	859.8
71	113.3	1.16	601	859.9
72	113.3	1.16	601	859.4
73	113.2	1.16	601	859.4
74	113.2	1.16	602	858.8
75	113.1	1.16	602	857.7
76	113.1	1.16	602	857.2
77	113.0	1.16	602	856.8
78	113.0	1.16	602	856.1
79	112.9	1.16	602	855.6
80	112.9	1.16	602	854.4
81	112.8	1.16	602	853.3
82	112.8	1.16	602	852.3
83	112.7	1.16	602	851.6
84	112.7	1.16	602	850.8
85	112.6	1.16	602	849.8
86	112.6	1.16	602	850.3
87	112.6	1.16	602	849.6
88	112.5	1.16	602	848.5
89	112.5	1.16	602	848.3
90	112.4	1.16	602	848.1
91	112.4	1.16	602	846.0

Figure 3B: Sample of Compaction Data for PG 58-34 (50% RAP & 5.0% B.C.) _Cont.

==

File Name: FEB20_05.DAT

RP280_50%RAP PG58-34_5%BC

Axial Displacement

S/N: 8835

==

Gyration	Height	Angle	Pressure	Moment
92	112.4	1.16	602	844.9
93	112.3	1.16	602	843.2
94	112.3	1.16	602	842.1
95	112.2	1.16	602	842.0
96	112.2	1.16	602	840.4
97	112.2	1.16	602	840.5
98	112.1	1.15	602	834.7
99	112.1	1.15	602	834.7
100	112.0	1.15	602	834.9
101	112.0	1.15	602	835.3
102	112.0	1.15	602	835.3
103	111.9	1.15	602	834.6
104	111.9	1.15	602	834.5
105	111.9	1.15	602	834.0
106	111.8	1.15	602	833.3
107	111.8	1.15	602	833.0
108	111.8	1.15	602	832.3
109	111.7	1.15	602	831.8
110	111.7	1.15	602	832.2
111	111.7	1.15	602	831.9
112	111.7	1.15	602	831.0
113	111.6	1.15	602	830.1
114	111.6	1.15	602	828.8
115	111.6	1.16	602	829.0
116	111.5	1.15	602	829.4
117	111.5	1.16	602	828.6
118	111.5	1.16	602	828.6

Figure 4B: Sample of Compaction Data for PG 58-34 (50% RAP & 5.0% B.C.) _Cont.

==

File Name: FEB20_05.DAT

RP280_50%RAP PG58-34_5%BC

Axial Displacement

S/N: 8835

==

Gyration (#)	Height (mm)	Angle (Deg Int)	Pressure (kPa)	Moment (N-m)
147	110.8	1.16	603	821.2
148	110.7	1.16	602	820.3
149	110.7	1.16	602	820.0
150	110.7	1.16	602	819.7
151	110.7	1.16	603	819.4
152	110.6	1.16	603	819.0
153	110.6	1.16	603	818.6
154	110.6	1.16	603	818.6
155	110.6	1.16	603	817.9
156	110.6	1.16	603	817.9
157	110.5	1.16	603	817.5
158	110.5	1.16	603	816.6
159	110.5	1.16	603	816.7
160	110.5	1.16	603	816.5
161	110.5	1.16	603	816.3
162	110.5	1.16	603	816.1
163	110.4	1.16	603	816.4
164	110.4	1.16	603	817.3
165	110.4	1.16	603	818.1
166	110.4	1.16	603	817.8
167	110.4	1.16	603	816.8
168	110.3	1.16	603	817.4
169	110.3	1.16	603	817.1
170	110.3	1.16	603	816.6
171	110.3	1.16	603	816.3
172	110.3	1.16	603	815.3
173	110.3	1.16	603	814.6
174	110.2	1.16	603	813.9
175	110.2	1.16	603	813.9
176	110.2	1.16	603	813.2
177	110.2	1.16	603	812.4
178	110.2	1.16	603	812.1

Figure 5B: Sample of Compaction Data for PG 58-34 (50% RAP & 5.0% B.C.) _Cont.

==
File Name: FEB20_05.DAT
RP280_50%RAP PG58-34_5%BC
Axial Displacement

S/N: 8835
==

Gyration	Height	Angle	Pressure	Moment
179	110.2	1.16	603	812.2
180	110.1	1.16	603	812.3
181	110.1	1.16	603	811.8
182	110.1	1.16	603	811.9
183	110.1	1.16	603	810.8
184	110.1	1.16	603	810.3
185	110.1	1.16	603	809.8
186	110.0	1.16	603	809.4
187	110.0	1.16	603	808.2
188	110.0	1.16	603	807.4
189	110.0	1.16	603	807.0

Figure 6B: Sample of Compaction Data for PG 58-34 (50% RAP & 5.0% B.C.) _Cont.

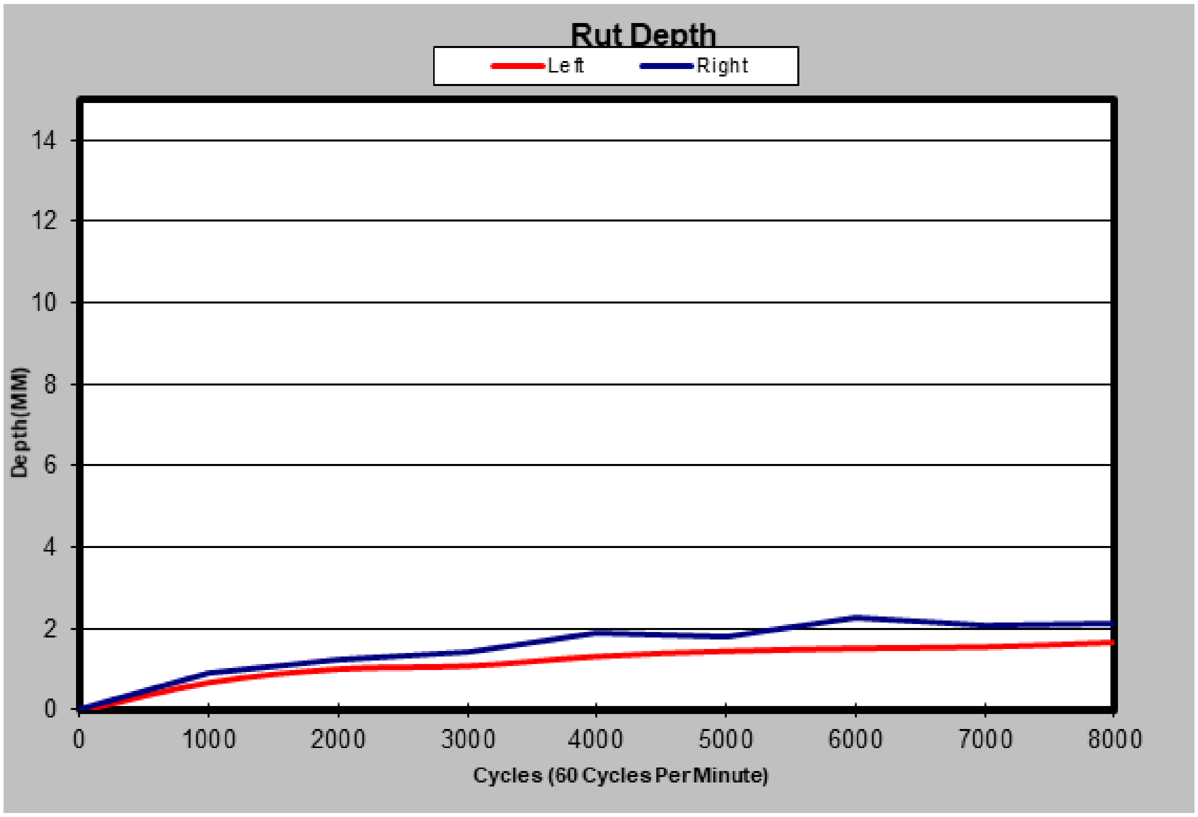

Figure 7B: APA Rutting Data Sample @ PG 64-28, 0% RAP and 5.0% B.C.

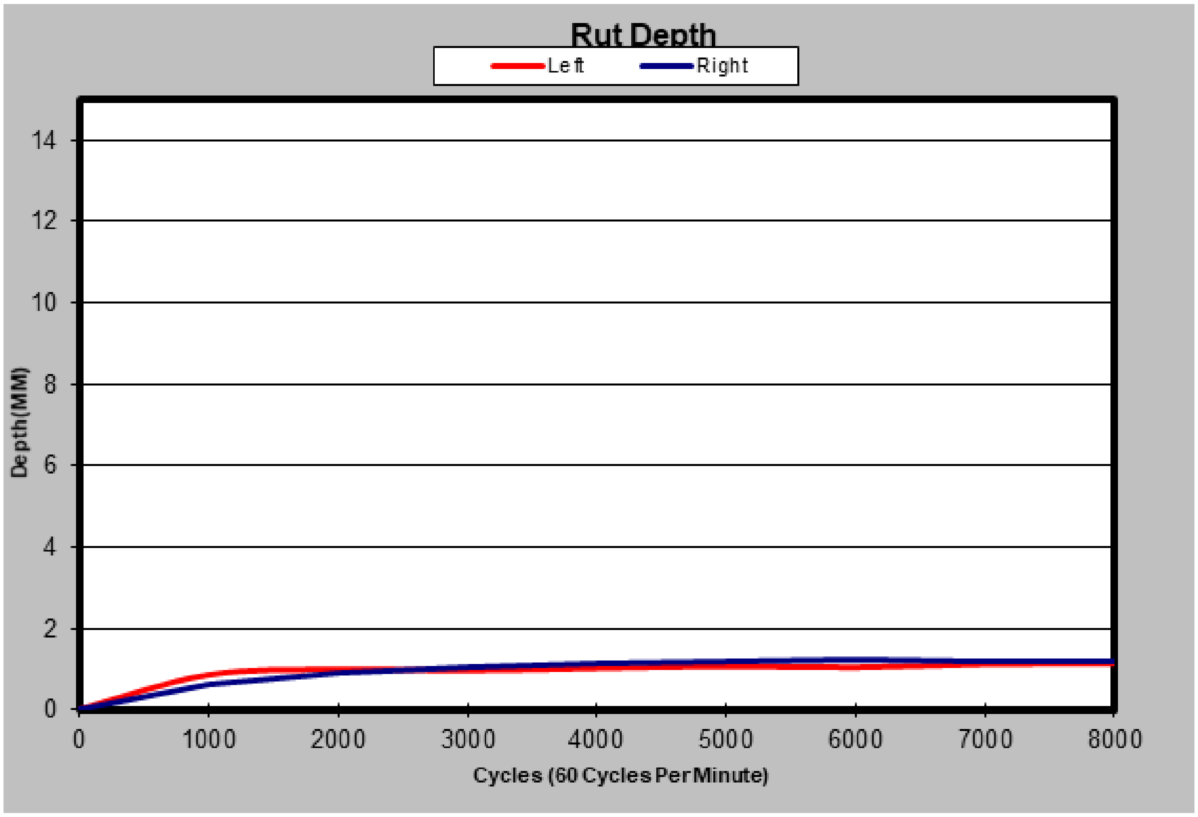

Figure 8B: APA Rutting Data Sample @ PG 58-34, 25% RAP and 5.0% B.C.

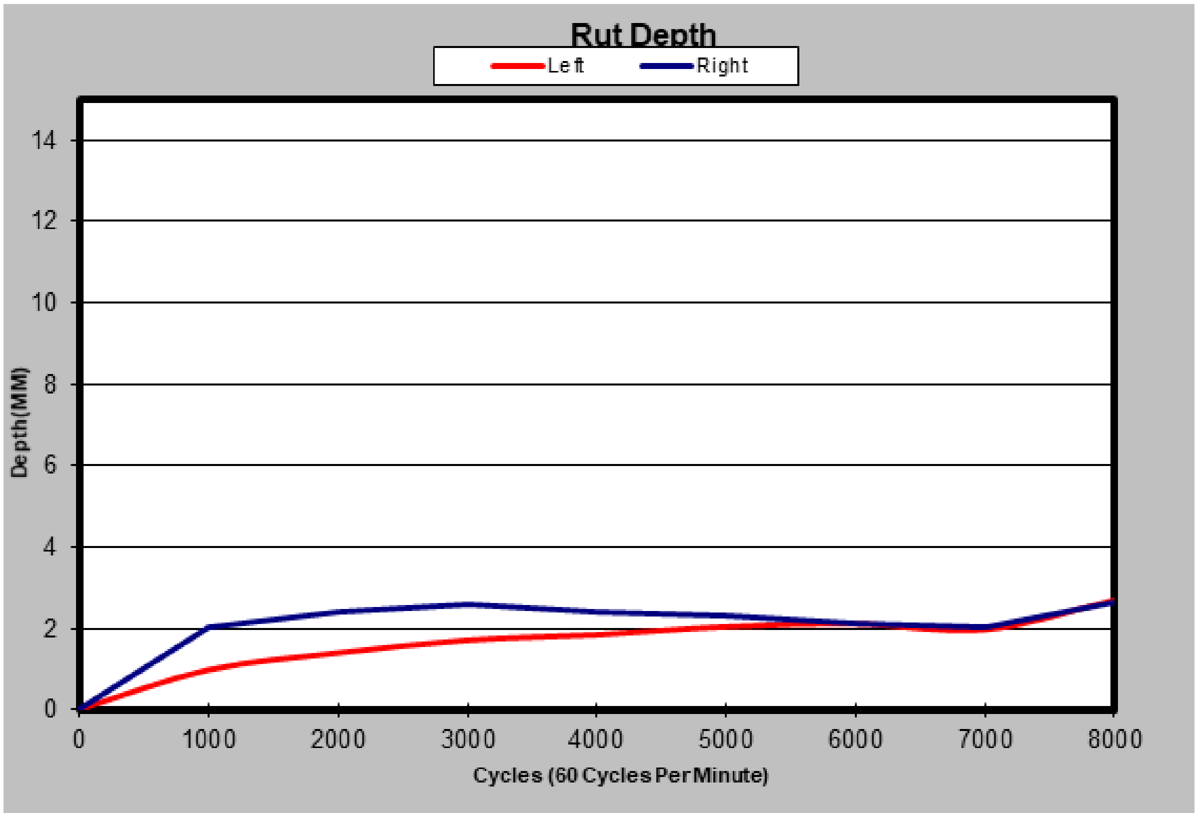

Figure 9B: APA Rutting Data Sample @ PG 76-22, 50% RAP and 5.75% B.C.

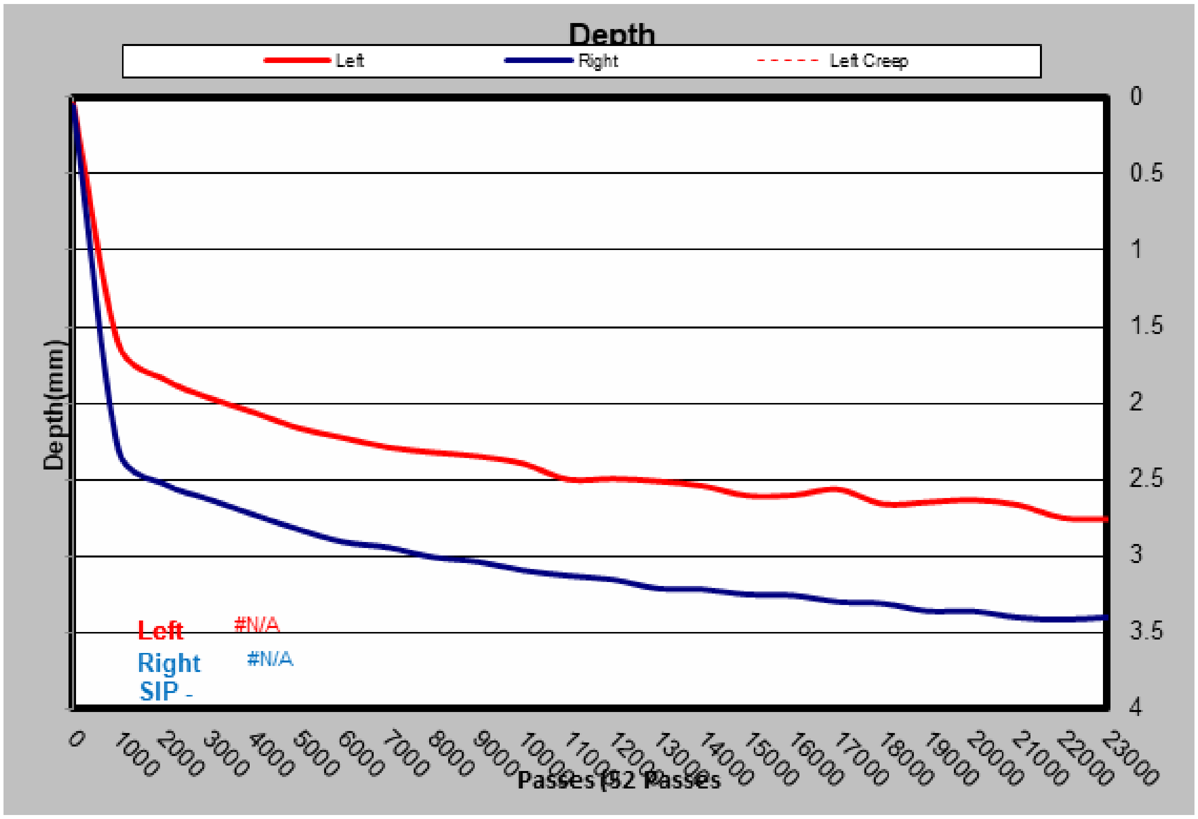

Figure 10B: Hamburg Rutting Data Sample @ PG 58-34, 0% RAP and 4.25% B.C.

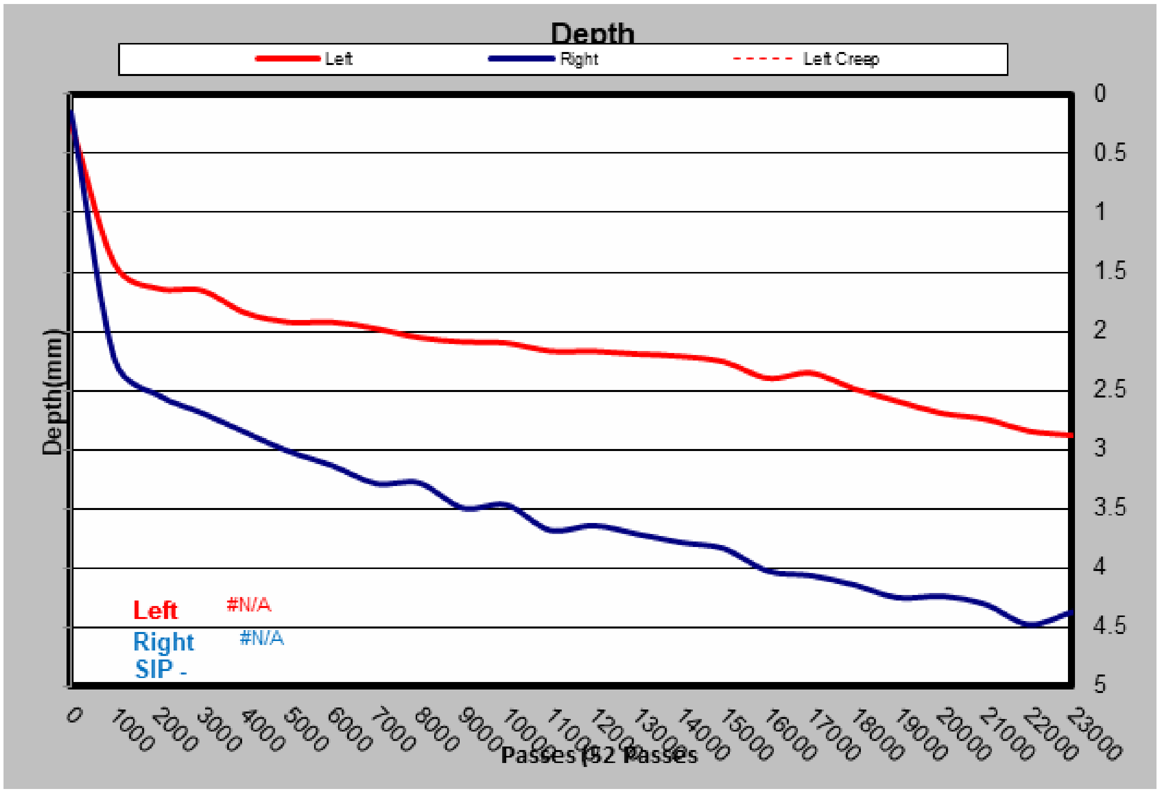

Figure 11B: Hamburg Rutting Data Sample @ PG 64-28, 25% RAP and 5.0% B.C.

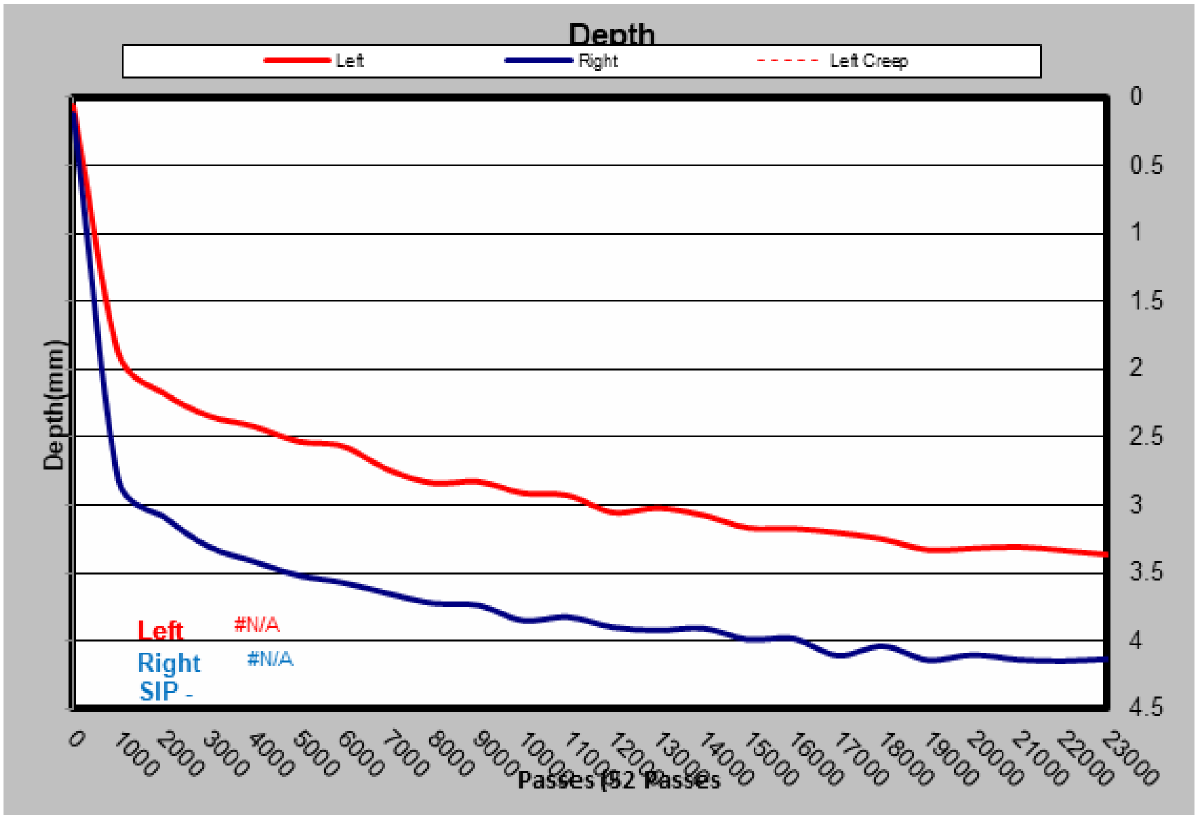

Figure 12B: Hamburg Rutting Data Sample @ PG 58-34, 50% RAP and 5.75% B.C.

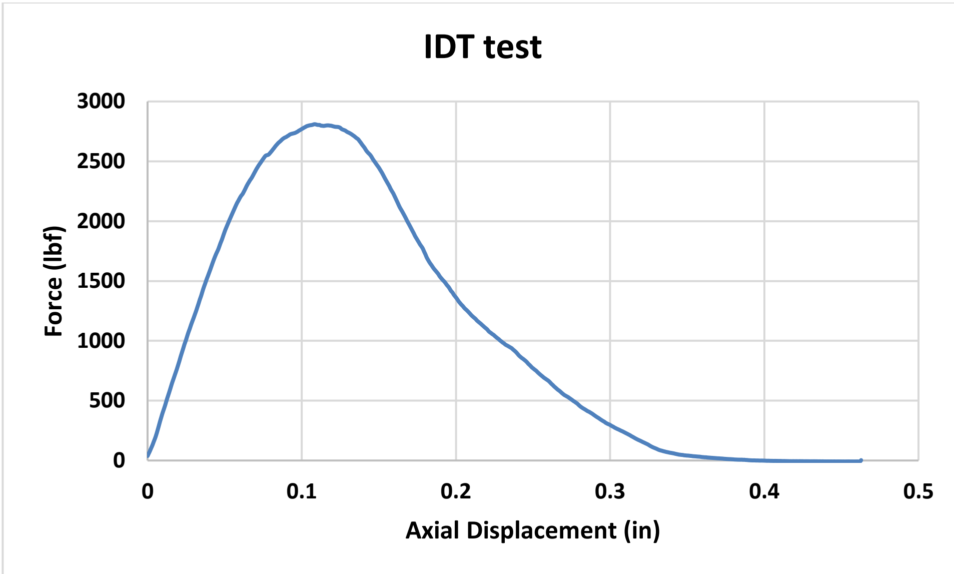

Figure 13B: Lottman Dry IDT Testing Sample 0% RAP, 0% ASA, 5.0% B.C.

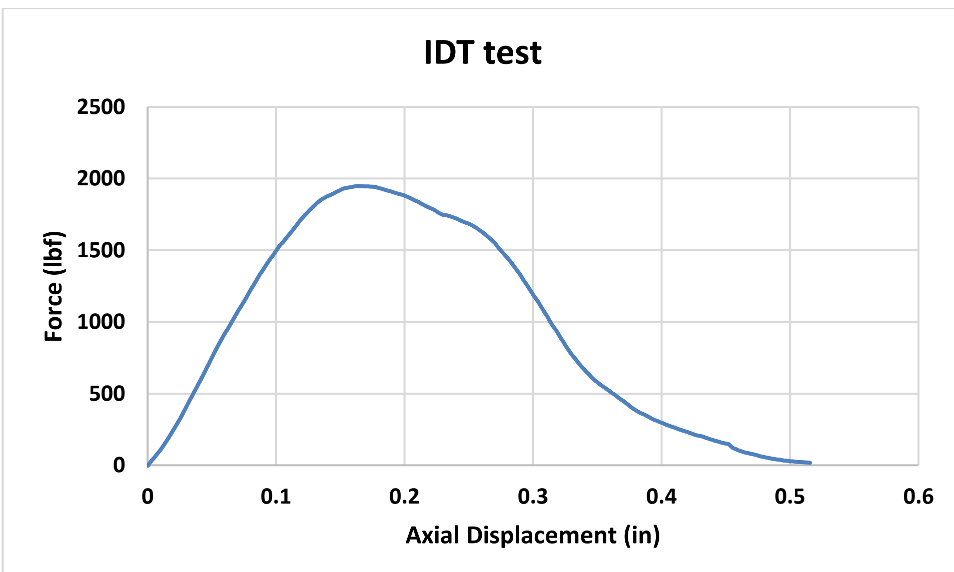

Figure 14B: Lottman Wet IDT Testing Sample 0% RAP, 0% ASA, 5.0% B.C.

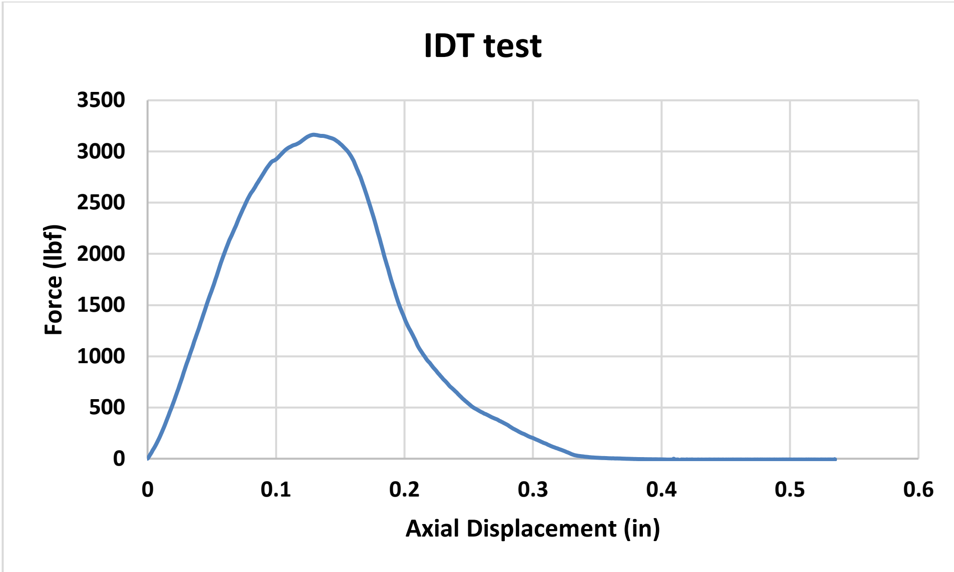

Figure 15B: Lottman Dry IDT Testing Sample 0% RAP, 0% ASA, 4.25% B.C.

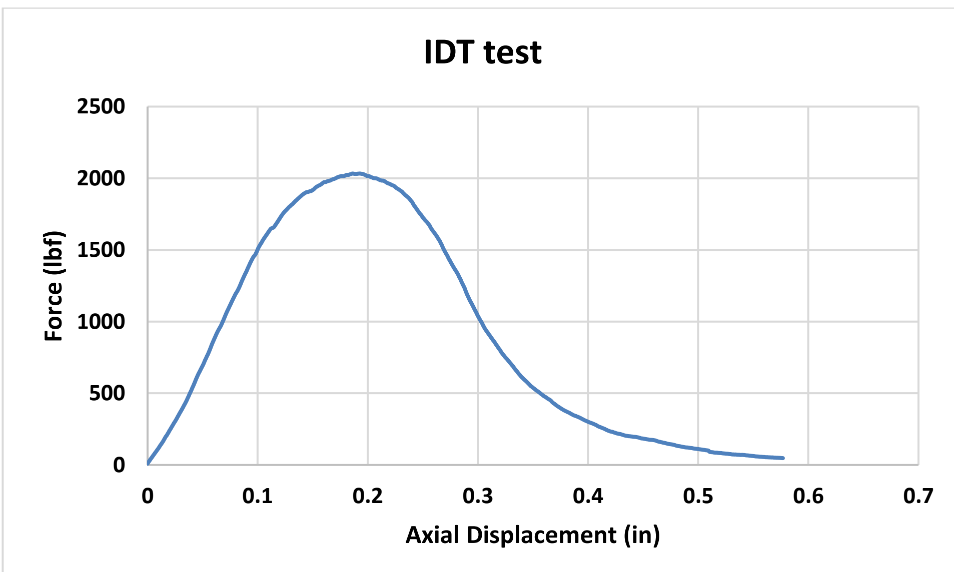

Figure 16B: Lottman Wet IDT Testing Sample 0% RAP, 0% ASA, 4.25% B.C.

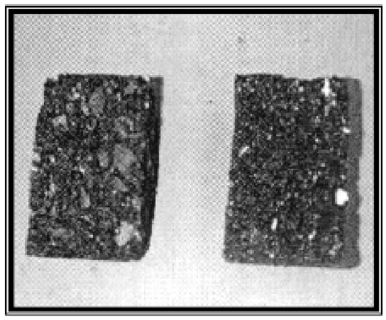

Figure 4
Specimen Broken for Observation

Calculations

The tensile strength is calculated using the following equation:

English units:

$$S_t = \frac{2P}{\pi\, t\, D}$$

where:

S_t = tensile strength, psi
P = maximum load, lbs
t = specimen thickness, in.
D = specimen diameter, in.

SI units:

$$S_t = \frac{2000P}{\pi\, t\, D}$$

where:

S_t = tensile strength, kPa
P = maximum load, Newtons
t = specimen thickness, mm
D = specimen diameter, mm

The tensile strength ratio is calculated as follows:

$$\text{Tensile Strength Ratio (TSR)} = \frac{S_2}{S_1}$$

where:

S_1 = average tensile strength of the dry subset, psi (kPa)
S_2 = average tensile strength of the conditioned subset, psi (kPa)

Figure 17B: TSR Calculations from AASHTO

Appendix C Permissions

Hi Austin, thank you so much for reaching out!

Are you referring to the images in our FAA Spec Update blog?

You can use this image provided you credit Asphalt Testing Solutions & Engineering.

Respectfully,

Molly (Soltis) Berry
ATS | Marketing & Business Development
904.349.9496

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Date: Monday, August 2, 2021 at 4:09 PM
To: Info <info@ats.consulting>
Subject: Permission to use Figure

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My name is Austin and I am a graduate student a the University of Idaho. I am asking permission to use the picture of the Asphalt Pavement Analyzer Jr. on your website in my thesis. Thank you

Austin P. Corley
Teaching Assistant/Graduate Student
University of Idaho
Bel 114

Figure 1C: Permission for Asphalt Testing Solutions, (2021)

To: Corley, Austin (corl2623@vandals.uidaho.edu)

Sure, Austin! Good luck in your research!! MH.

--
Mustaque Hossain, Ph.D., P.E., Fellow ASCE
Department Head, Munger Professor in Civil Engineering and Civil Engineering Alumni Professorship Honoring Dr. Robert Snell
Department of Civil Engineering
Kansas State University
2118 Fiedler Hall
Manhattan, KS 66506.

Tel: (785) 532-1576
Fax: (785) 532-7717
web: http://www.ce.ksu.edu/people/faculty/hossain/

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My name is Austin and I am a graduate student at the University of Idaho. I am asking permission to use information from

"Rahman, F., Hossain, M. (2014, February). *Review and Analysis of Hamburg Wheel Tracking Device Test Data* (KS-14-1). Kansas State University Transportation Center"

In my thesis. The information involves the effect of binder source, and content on the affect of rutting performance. My thesis and titled "Evaluation of mix composition and compactability on rutting performance of asphalt mixtures." Information from your report is very useful in the literature review of my thesis, thank you.

Regards,

Austin P. Corley
Teaching Assistant/Graduate Student
University of Idaho
Bel 114

Figure 2C: Permission for Rahman and Hossain, (2014)

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KW **Kelsh, William <bill.kelsh@vdot.virginia.gov>**
3:41 AM

To: Corley, Austin (corl2623@vandals.uidaho.edu)

Permission granted.

~~~~~~~~~~~~~~~~~~~~~~~~
Bill Kelsh
Virginia Transportation Research
434-293-1934 - but best to contact me via email
~~~~~~~~~~~~~~~~~~~~~~~~

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Figure 3C: Permission for Prowell and Carter, (2000)

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Figure 4C: Permission for Xiao et al., (2009)

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