Evaluation of the Rapid Rutting Test and High Temperature Indirect Tensile Test for Practical Use in Asphalt Mix Design, Quality Assurance, and Quality Control

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By

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The undersigned, appointed by the Dean of the Graduate School, have examined the thesis entitled:

Evaluation of the Rapid Rutting Test and High Temperature Indirect Tensile Test for Practical Use in Asphalt Mix Design, Quality Control, and Quality Assurance

Presented by Patrick Wayne Beckemeyer

a candidate for the degree of Master of Science,

and hereby certify that, in their opinion, it is worthy of acceptance.

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Professor Bill Buttlar

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Professor Giraldo-Londono Oliver

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Professor Brent Rosenblad

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Professor Yaw Adu-Gyamfi

To my parents Curt and Joan Beckemeyer

I would have never in a million years achieved what I have without you.

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Abstract

The asphalt industry has a large number of mixture performance tests available to evaluate a mix design's ability to withstand typical pavement distresses. Some of these tests are widely used whereas others tend to fall into the background for reasons such as cost, being time and labor intensive, and most importantly correlating poorly to field performance. This study focuses on the evaluation of two newly proposed asphalt rutting tests, specifically looking at their practicality in use for mix design, quality control, and quality assurance purposes. These tests are the Rapid Rutting Test (RRT) and the High temperature Indirect Tensile Test (HT-IDT). The various asphalt mixtures that were used in this study came from several different asphalt pavement design projects completed by the Missouri Asphalt Pavement Innovations Lab (MAPIL) here at the University of Missouri. These projects include both dense graded and stone matrix asphalt (SMA) mixture types for a total of 11 different asphalt mix designs. Within the 11 used asphalt mixtures, novel materials such as recycled rubber and recycled plastic were implemented as modifiers to the mix designs.

In this study, the evaluation of the RRT and HT-IDT was carried out through five individual areas of focus. The first focus area involved correlating the test results of the RRT and HT-IDT to the existing and commonly used Hamburg Wheel Track Test (HWTT). It was found that the RRT showed R^2 values ranging from 45% to 84% for dense graded mixtures and 69% to 82% for the HT-IDT. Correlations to the HWTT for the SMA mixes were below 30% for the RRT and HT-IDT. Next, the effects of reheating on the RRT and HT-IDT testing procedures was evaluated by comparing the results between lab and plant reheated forms of each mixture. It was found that dense grade mixes resulted in -6% to 30% percent difference and -22% to 26% when tested in the RRT and HT-IDT, respectively. The next area of focus involved analyzing the effects that the additives and modifiers (rubber, plastic, anti-strip) had on the testing results in the RRT and HT-IDT. These effects were able to be made due to the incorporation of unmodified “control” mixtures being compared to their counterparts who were modified with such materials. It was found that the addition of rubber and plastic had significant increases in performance for dense graded mixtures (RRT and HT-IDT) and the addition of rubber had a negligible effect on performance of SMA mixtures (RRT and HT-IDT). The last area of analysis in this study focused on statistical analysis of the data results for the RRT and HT-IDT. It was found that the RRT and HT-IDT tests showed low coefficient of variation for dense graded and SMA mixtures with COVs ranging from 1% to 7% and 4% to 7%, respectively.

From the obtained data results, each test shows merit in use for QA/QC purposes due to their very low variation and high repeatability. However, the other section’s data results indicate that these tests show promise in rut evaluation but must be further researched before any type of consideration for implementation is made.

Chapter 1. Introduction

1.1 Background

The performance of pavements in the transportation industry is of great importance and concern. Poor performing pavements lead to societal challenges both regarding economics as well as safety hazards experienced by drivers. Considering that in the United States, 94% of the 2.6 million miles of roads are paved with asphalt (1). The control and prevention of asphalt pavement distresses becomes extremely important to uphold. Although there are many different forms of distress in asphalt pavements, the two most prominent and fundamental forms of distress recognized by the asphalt industry are cracking and rutting. In this paper, the primary focus will be placed on rutting in asphalt and subsequently how the rut resistance of asphalt mixtures is evaluated via multiple testing procedures. The new testing procedures that were studied in this thesis are the Rapid Rutting Test (RRT) and the High Temperature Indirect Tensile Test (HT-IDT). These two tests are newly developed rutting tests that test asphalt specimens in a very quick manner compared to current test procedures that are preferred by the asphalt industry. Specifically, these two tests take less than 2 minutes to test a specimen compared to the several hours that other rutting tests require(2). A more in-depth discussion of these two tests will be found in the literature review.

The exact definition of rutting and its causes varies slightly within the asphalt community (e.g., researchers, DOTs, contractors). However, when reading through published literature, there seems to be a general agreement in the community on what asphalt pavement rutting is characterized as in addition to the factors leading to rutting. The physical appearance of rutting is described as a longitudinal depression in the wheel path of roadways along with slight upheavals of the pavement near the edges of the wheel path (3-5). A more technical term for describing rutting is “permanent deformation”. As the term implies, the alteration of an asphalt pavement’s surface structure in the form of rutting results in permanent damage that will require rehabilitation or reconstruction to alleviate. Figure 1 shows an image of what asphalt rutting typically looks like in the field. This image represents an extremely severe case of rutting. This image serves to clearly depict what asphalt rutting looks like. Permanent deformation is caused by a combination of two physical properties, densification (volume change) and shear deformation (no volume change) (6). When it comes to the factors that cause rutting, there are many different considerations to be made. Firstly, rutting in asphalt can by structural failure of any of the material layers (subgrade, subbase, base, pavement surface) that are consistent with typical roadway design. However, in this paper the primary focus is on evaluating the rut resistance of asphalt mixtures and not the sub surface layers below the asphalt pavement. Therefore, proceeding discussion will pertain only to the causes of rutting regarding asphalt mixtures themselves. Considering only the asphalt layer itself, literature suggests that the most

Figure 1. Image of Severe in Field Asphalt Pavement Rutting

prominent factors that affect the permanent deformations in asphalt pavements are the quality of materials in asphalt mixtures (aggregates, binders, modifiers), severity of loading due to automobile wheel contact, and environmental factors such as moisture and temperature (3).

The evaluation of an asphalt pavement's rutting resistance can be achieved through several different forms of laboratory testing procedures. In the United States there are approximately five methods of testing that are prominently used to evaluate how resistant an asphalt mix design is to rutting. The most commonly used rutting tests are as follows in no specific order: Hamburg Wheel Track Test (HWTT), Asphalt Pavement Analyzer (APA), Superpave Shear Tester (SST), Flow Number (FN), and Hveem Stabilometer. The preference on which of these tests are most reliable varies among state DOT's and contractors across the country. A survey implemented by the National Cooperative Highway Research Program (NCHRP) was conducted to illustrate a clear picture of typical practices for asphalt mix design testing for all types of pavement distresses. Specifically, on July 17, 2017, a survey was sent out to all 50 state DOTs' as well as numerous contractors across the country (7). As a result, the NCHRP received a total of 50 responses from 47 state DOTs in addition to 51 responses from contractors in 34 US states and 2 Canadian provinces (7). The proceeding discussion will go into detail about the responses received in relation to rutting tests. Of the previously mentioned rutting tests, it was found that twenty-four state DOTs utilize a rutting test in their mix design specifications. Furthermore, it was found that eleven states use the APA test, ten states use the HWTT, two states use the Hveem Stabilometer, and one state used the FN test (7). Figure 2 illustrates the use of each test in their respective states. Additionally, state DOT's and contractors were asked which of the rutting tests they believe had to most potential to address rutting. Figure 3 illustrates the responses to this question. Two of the rutting tests (HWTT & APA) are far more used than the rest, as shown in figure 3. Here at the University of Missouri in the MAPIL laboratory, the HWTT is the rutting test that is routinely used to evaluate rutting resistance of asphalt mix designs. For this reason, this study focused partly on the correlations between the HWTT and the two newly proposed RRT and the HT-IDT because of the preexisting rut depth data obtained via the HWTT for asphalt mix design projects completed in the MAPIL laboratory.

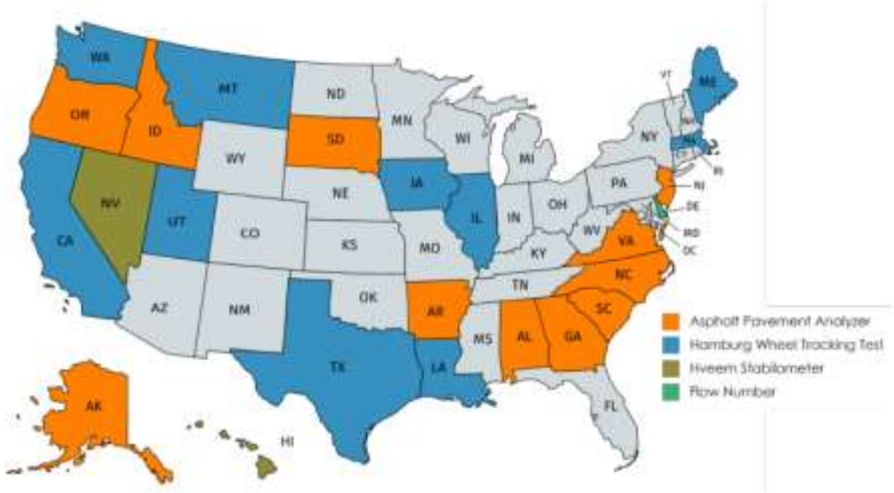
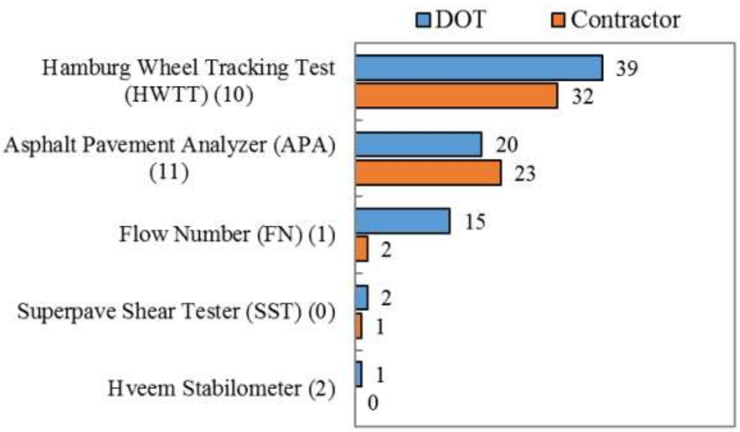


Figure 2. Different Rutting Tests Used by Each State in the U.S. (7)



Note: Number in a parenthesis indicates the number of states using that particular test

Figure 3. DOT & Contractor Selection of Best Practical Asphalt Rutting Test (7)

Although the previously mentioned rutting tests have been routinely used by a large percentage of the asphalt community for many years, that does not indicate whether these tests should be improved or replaced by newly developed methods. The most important criteria when determining the practicality of a mixture performance test is how well the tests results compare to field performance.

Beyond the goal of using a mixture performance test that accurately correlates to field performance, there are many other factors that should be considered when choosing a mixture performance test. One of the most important factors that DOT's and contractors are interested in improving across the board for all type of asphalt mixture performance tests pertains to the time needed to run a test as well as the associated cost of running the test. More specifically, it is the motivation of contractors to decrease the time and cost of such tests. For this reason, there is a major motivation to evaluate the RRT and HT-IDT testing procedures so that they may be used in a practical manner when it comes to the process of quality control and quality assurance. Considering the requirements for a suitable test for QC/QA, the important aspects that a performance test must encompass involves the test being adequately sensitive to mixture characteristics such as material properties, volumetric properties, and aging conditions (2), Additionally, there is a large motivation by DOT's and researchers to evaluate the practicality of these two new rutting tests so that the question of whether to or not to implement them in balanced mix design (BMD) procedures can be answered. BMD is a new method of design that has been continuing to be adopted by more agencies across the country. In essence, BMD is a method of design meant to balance the performance of asphalt mixtures for the two primary pavement distresses (7). These two distresses being cracking and rutting. Therefore, the objective of balanced mix design is to provide proper resistance to these two forms of distress by meeting thresholds for cracking and rutting tests (7). Ultimately, there is a want among the entire industry to better understand the practicality of the RRT and HT-IDT rutting tests because these two tests provide a much cheaper and quicker form of rut resistance evaluation compared to already commonly used rutting tests like the HWTT. A more in-depth discussion of the pros of these two tests from their developers will be discussed in the proceeding literature review.

1.2 Project Objectives

The primary objective of this research project is to evaluate new testing procedures which specifically serve to determine the rutting resistance of various asphalt mixtures that have been recently placed in part with pavement projects in Missouri. The two new testing procedures examined in this project include Rapid Rutting Test (RRT) and the High Temperature Indirect Tensile Test (HT-IDT). The primary unique and desirable feature of these two rutting tests is their ability to be performed in a very quick manner, especially when compared to current commonly used rutting tests like the Hamburg Wheel Track Test (HWTT) and the Asphalt Pavement Analyzer (APA), which are much more time consuming. The RRT and HT-IDT testing procedures were developed with the intention of providing laboratories and contractors additional means of evaluating an asphalt mixture’s resistance to rutting in mix design as well as for quality control and quality assurance protocols. To properly evaluate these two new rutting tests, subsequent investigations were performed to provide a better understanding about the data obtained from the RRT and HT-IDT. The investigations that were implemented to help satisfy the overall objective of assessing the practicality of the RRT and HT-IDT can be summarized as below:

1. As the Balanced Mix Design (BMD) continues to become a more commonly used method of asphalt pavement design grows in popularity, this study serves to aid in the implementation of BMD by benchmarking existing mix designs used in Missouri projects in the RRT and HT-IDT
2. As previously discussed, the HWTT and APA are among the most used rutting performance tests used by DOT's and Contractors. Therefore, the second primary objective of this study is to draw comparisons between these already well accepted in practice rutting tests and the newly proposed tests. Specifically, this study will investigate how strongly the data results of the RRT and HT-IDT correlate to existing rutting performance data obtained via the HWTT.
3. Quality control and quality assurance protocols are important aspects of asphalt mix design because they provide verification that the quality of asphalt mixtures designed in labs are maintained when produced in asphalt plants. Therefore, the third primary objective of this study is to investigate the effects to RRT and HT-IDT data results when testing lab produced and reheated plant produced asphalt mixtures.
4. The last subsequent objective of this study pertains to the evaluation of how asphalt additives/modifiers (anti-stripping agents, rubber, plastic) used in the existing Missouri projects affect the RRT and HT-IDT test results. Therefore, this study investigated these effects by drawing comparisons between unmodified virgin mixes and their corresponding modified mix designs.

Chapter 2. Literature Review

The Rapid Rutting Test (RRT) was originally developed by Dr. Fujie Zhou and colleagues at the Texas Transportation Institute(TTI) (2). According to the authors, the need for a test such as the RRT stems from a general need to provide a testing procedure in the asphalt industry that can evaluate the rutting resistance of various asphalt mixtures in a timely manner. Currently most DOT's and contractors use tests like the Hamburg Wheel Track Test (HWTT) and the Asphalt Pavement Analyzer (APA) to evaluate the rutting performance of tested asphalt mixtures (7). Furthermore, these two tests are very applicable in their usage, but one key problem faced by the usage of these two rutting tests pertains to the amount of time it requires to implement and obtain data. The time needed to run the HWTT is approximately 6-8 hours (8) and the time needed for the APA is approximately 8 hours (9). Due to the time-consuming nature of these tests, the HWTT and APA tests have been hardly used for quality control and quality assurance purposes during plant production and field placement of asphalt. Therefore, Dr. Zhou and colleagues sought out to develop such a test that would address this problem and allow for a better way to ensure that what has been designed in the lab, produced at the plant, and placed in the field yield similar rutting performance. What they came up with was the Rapid Rutting Test which utilizes the apparatus used for the IDEAL-CT test with a slight modification in the way that specimens are held in the testing fixture (2). The IDEAL-CT test is an asphalt cracking test that was also developed by Dr. Fujie Zhou in 2017 (7). In this test, asphalt specimens are subjected to indirect tension at a temperature of 25°C. The IDEAL-CT test has become more popular among industry for its rapid testing time of less than 2 minutes per specimen like the RRT.

Dr. Zhou proposed eight desirable features that an ideal rutting test should have. These features will be described one-by-one, below. First, an ideal rutting test should be simple. According to Dr. Zhou, simplicity is achieved in the RRT because the testing procedure requires no instrumentation, coring, cutting, gluing, or notching of samples as compared to other rutting tests. Next, an ideal rutting test should be efficient. The RRT provides a high level of efficiency because of the very short testing time of 2 minutes. Practicality is the third desirable feature of an ideal rutting test and can be attributed to the RRT because there is very minimal training needed to operate the test. Additionally, the RRT is practical because it can be used for both laboratory molded specimens and field cores. Economics is another desirable feature according to Dr. Zhou. Furthermore, the RRT is a low-cost test because it utilizes testing equipment already found in most laboratories and asphalt plants, with one minimal piece of additional equipment. The one piece of additional equipment is a cradle that holds the specimen in place. In terms of data acquisition, the next desirable feature of an ideal rutting test pertains to the overall repeatability of the testing procedure. The RRT satisfies this feature because it has been shown to have a low coefficient of variation (COV), specifically being less than 10% with 3 specimen replicates. As previously discussed, the asphalt industry is continuously becoming more complex in terms of the composition of asphalt mix designs (aggregate type, air voids, binder type, recycled materials, binder modifiers, etc.). Therefore, it is necessary for an ideal rutting test to be sensitive to these characteristics and additions to mix designs. Dr. Zhou proved that the RRT is sensitive to these components through various tests that localize the effect of each variable component within mixtures. The next desirable feature involves the manifestation of a rutting mechanism. Rutting is mainly caused by shear stress as well as slight volumetric effects.

Furthermore, the RRT cradle which holds the specimen in place was specifically designed to induce a shearing type of failure within the specimen. A further illustration of this failure mechanism will be discussed later. The last desirable feature described by Dr. Zhou pertains to the correlation between the data results of the test and the actual performance of the asphalt in the field. He states that the new rutting parameter based on the shear rutting mechanism exhibits strong correlations with the measured field rutting performance.

Regarding the eight features measured above, the TTI study noted (2) that all of the existing rutting tests incorporate some of the features. However, there are currently no rutting tests that incorporate all eight. Therefore, his goal as well as the goal of this study, is to validate that these eight features are satisfied when implementing the Rapid Rutting Test.

The High Temperature Indirect Tensile Test is very similar to the RRT test. The key similarities between these tests include the rapid testing time and use of pre-existing equipment. The key difference between these tests is the manner in which the asphalt specimen is placed into the testing apparatus. The difference in placement will become clearer in the methods section. The HT-IDT test was originally developed by Christensen, Bonaquist, and Jack in the year 2000 (10). A study conducted by these researchers found that cohesion in an asphalt mixture correlated well to its rutting resistance. More specifically, the shear resistance in the asphalt mixtures is comprised of cohesive forces provided by an asphalt binder and frictional resistance provided by the aggregate interlock (11). Thus, they concluded that the cohesion parameter could be accurately estimated from the indirect tensile strength test (11). Much like the RRT, an elevated testing temperature of 50°C was selected so that the cohesion parameter could be captured while the asphalt specimen was under rutting prone conditions.

Chapter 3. Mixture types and Material Characteristics

3.1 Dense Graded Mixtures

According to Pavement Interactive, a website with general pavement information (9), a dense graded mixture can be described as well-graded, relatively impermeable HMA mixture to be used for general purposes. Furthermore, it is stated that dense graded mixtures can be classified by their nominal aggregate size, which can either be “fine-graded” or “coarse-graded” depending on the amounts of fine and coarse sized aggregates in the overall gradation of the mix. Dense graded mixtures are suitable for all pavement layers and for all traffic conditions. Additionally, they work well for structural, friction, and patching needs (7,12).

3.2 Stone Matrix Asphalt (SMA) Mixtures

The second type of mixture that was used in this study is Stone Mastic Asphalt (SMA) or Stone Matrix Asphalt. SMA mixtures were originally developed in Germany in the late 1960’s (12), specifically to serve the purpose of creating mix designs that were more resistant to studded tires in high traffic volume roads (13). By the 1990’s, SMA’s were adopted by the asphalt community here in the United States as a premium mixture type to enhance cracking and rut-resistance in asphalt pavements. SMA mixtures are asphalt mixtures that can be characterized by a large number of coarse aggregates, a high proportion of binder and mineral powder, a low amount of intermediate -size aggregates, and a small amount of stabilizing additive (14). These proportions generate a good mineral structure and a high proportion of filler-based mastic, which allows for the mixture to have a high carrying capacity without affecting the flexibility of the mixture (14). A key distinction between dense graded and SMA mixtures is the difference in binder content. Specifically, SMA mixtures tend to use a higher binder content which results in a lower air void content than dense graded mixtures. Although there are many pros to the use of SMA mixes, the inclusion of high-quality aggregates, modifiers, fibers, and elevated binder content tend to make this mixture type much more expensive. For this reason, many states in the U.S are unwilling to implement the use of SMA mixtures. Figure 4 illustrates the usage of SMA mixtures across the country.

Figure 2. Usage of Stone Matrix Asphalt Mixture Type Across the United States (12)

3.3 Ground Tire Rubber (GTR)

In the 1960's Charles H. McDonald developed a new technique to obtain rubber from recycled scrap tires in the state of Arizona (15). After the development of this technique, he demonstrated that when rubber was mixed with asphalt binder during the heating process the "modified" asphalt binder became more flexible. This discovery resulted in two potential solutions. By adding recycled rubber to asphalt binders, the environmental dangers of scrap tire disposal could be reduced while also providing the possibility of increased pavement performance due to the asphalt binder’s increased flexibility. Following McDonald’s discovery and further research by industry, the Federal Highway Administration (FHWA) mandated the use of ground tire rubber (GTR) in pavement construction in 1991 (15,16). Fast forward to 2003, the use of rubber in asphalt had grown from 11% to 80% between 1991 and 2003 (17). Figure 5 illustrates the usage of GTR in asphalt pavement design across the United States in 2014.

More recent research (2003-2016) has indicated that addition of GTR into asphalt mixtures leads to an increase in the rutting resistance of pavements and mitigated the cracking potential of the mixtures (18). The primary mechanism of increased rut resistance that GTR provides is via the increase in overall stiffness of asphalt mixtures (18).

Figure 3. State DOTs that use GTR in Asphalt Mixtures (19)

3.4 Polyethylen Plastic (PE)

In more recent years, the asphalt industry has begun to look to plastic as another recycled material to improve both the sustainability and performance of asphalt mixtures. Following China's shift away from importing plastics in 2018, a global interest in the usage of plastics in asphalt mixtures had begun (1). A major challenge in the implementation of plastic usage for asphalt mixtures pertains to the high variation of different types of plastics found in recycling streams. Research has found that not all types of plastics are compatible with asphalt binders. However, after several research studies, it was found that polyethylene (PE) plastics are suitable because of their similar melting point to typical asphalt compaction temperatures (1). Furthermore, it is estimated that 29.2% of the total plastics in the municipal solid waste stream is PE (1). Much of the current research into PE modified asphalt mixtures has indicated that plastic modification leads to increased rut resistance and lower moisture damage (20).

3.5 In Study Mixture Summaries

In this study there were a total of 11 different asphalt mixtures that were tested in the Rapid Rutting Test, High Temperature Indirect Tensile Test, and Hamburg Wheel Track Test. Furthermore, these mixes were comprised of both dense graded and stone matrix asphalt (SMA) mixes. There was a total of 8 different dense graded mix designs and a total 3 SMA mix designs. All of these mixtures were designed in the Missouri Asphalt Pavement Innovation Lab (MAPIL) for various projects throughout the state of Missouri. All of the mixtures used in this study incorporated both laboratory compacted, and plant reheated compacted specimens to be tested in the three rutting tests. However, two mixtures (CTL2 and CTL3) only incorporated lab compacted specimens due to the fact that these mixtures were never created in an asphalt plant. The characteristics of these two mixtures will be discussed below.

The first batch of dense graded mixtures used for this study came from a field demonstration project on the campus of the University of Missouri. This mix design phase for this project was carried out through the Missouri Asphalt Pavements Innovation Lab (MAPIL) and resulted in five different mix designs being placed in a 1.5” overlay for a 7.2-mile-long stretch of roadway. The roadway for the project is “a heavily traveled arterial connecting Interstate 70 to the Mizzou campus” (1). The primary objective of this project was to demonstrate the implementation of recycltes in asphalt mix designs and demonstrate the implementation of Balanced Mix Design (BMD). Furthermore, of the three methods for BMD, this project utilized the second method being Performance-Modified Volumetric Design(7). In this sub choice of BMD, this approach begins with the Superpave mix design method to establish a preliminary aggregate structure and binder content. The performance test results are then used to adjust either the binder content or mix component properties and proportions (e.g., aggregates, asphalt binders, recycled materials, and additives) until the performance criteria are satisfied. For this approach, the final design is primarily focused on meeting performance test criteria and may not be required to meet all the Superpave volumetric criteria (7). The type of recycltes used and studied in the project were engineered crumb rubber (ECR) as well as plastics in the form of polyethylene (PE). Of the five different mix designs in this project, there was one control mix (no modifiers), one rubber mix, and three plastic mixes. A brief description of each of the mixes will be discussed below, however for a more in-depth discussion of the mix design phase for this project please reference (1). As stated, there were five different mixes in total for this specific project, however there were underlying similarities for each of the mixes. Specifically, each of the five mixes utilized the same aggregates and gradation. The gradations and job mix formulas for each mixture can be seen in Appendix A. The next similarity among all the mix designs was the percentage of recycled asphalt pavement (RAP) used. RAP is old asphalt pavements that have been removed and can be used as an aggregate source for new pavements. For each mix design, there was an inclusion of 30% RAP in the gradation where the binder content of the RAP was found to be 4.9%.

Next the differences between each mix design will be described. First, the control mix for this project “used a PG64-22V binder and was designed based on standard MoDOT Superpave mix design methodology, where a target of 4.0% air voids was followed, at 80 gyrations for moderate traffic, urban arterial, which resulted in a virgin binder content of 4.0%” (1). Next, three plastic modified mixes were designed. For these mix designs, plastic pellets were added during bucket mixing, which can be considered a form of “dry modification” because the pellets were added to the aggregates and not blended in with the binder. Furthermore, for these three mixes designs a varying amount of plastic was used as well as one of the mixes incorporating a RET compatibilizer. This compatibilizer helps with the compatibility and bonding of the plastic with the asphalt. Specifically, the amounts of plastic used by weight of the mix was 0.25%, 0.5%, and 0.5% again with the addition of the compatibilizer. Also, for these three mixtures a binder grade of PG 59-28 was used. A more novel discussion of the process of including the new technology of dry plastic modification can be seen in (1). Finally, a rubber modified mix design was produced. For the rubber modified mixture, a total of 10% ECR by weight of binder was added to the PG 58-28 binder grade along with an amount of 0.2% (by weight of mix) unmodified supplemental PG 58-28 binder. Contrary to the plastic mixes, the rubber was blended directly with binder (wet-process) rather than being directly added to the aggregates (dry-process) when mixing.

After completion of testing of the above mix designs, it was decided by the author to incorporate two alterations to the control mix. Furthermore, the above control mix could be viewed as a mix that is comparing apples to oranges because although the gradation and materials used are the same, the difference in binder grades does not allow for a direct comparison to evaluate the effects of modifiers like the rubber, plastics, and anti-strips. Therefore, it was decided to make two new "control" (CTL2 and CTL3) mixtures utilizing the same PG 58-28 binder grade (one with and one without addition of a liquid anti-strip) so that when tested in the HWTT, RRT, and HT-IDT a better comparison of the effects of these modifiers can be illustrated.

Lastly for the dense graded mixtures, the final mix design that was included in this study was a less complex design used for a low volume roadway that ultimately was very poor in performance for rut resistance. This mix design did not incorporate the use of RAP or any other modifier such as recycltes or anti-strips.

Mixture Summaries:

1. **CTL1:** This mixture is the control mix from the Stadium Blvd Project. This mixture is unmodified (no rubber or plastic). The binder grade used was a PG 64-22V with an addition of 1.0% LOF anti-strip by weight of binder. The binder content is 4.0% by weight of the entire mix. There was 30% RAP used in the gradation.

2. **CTL2:** This mixture is a variation of the CTL1 mixture. This mixture is unmodified (no rubber or plastic). The binder grade used was a PG 58-28. The binder content was 4.8% by weight of the entire mix. There was 30% RAP used in the gradation.
3. **CTL3:** This mixture is a variation of the CTL1 mixture. This mixture is unmodified (no rubber or plastic). The binder grade used was a PG 58-28 with an addition of 1.0% LOF anti-strip by weight of binder. The binder content is 4.8% by weight of the entire mix. There was 30% RAP used in the gradation.
4. **10ECR**: This mixture was modified with engineered crumb rubber (ECR). The binder grade used was a PG 58-28 with an addition of 10% ECR by weight of the binder. The binder content is 4.6% by weight of the entire mix. There was 30% RAP used in the gradation.
5. **50PE:** This mixture was modified with polyethylene (PE) plastic. The binder grade used was a PG 58-28 with an addition of 3.0% CA4 anti-strip by weight of binder. The binder content is 4.7% by weight of the entire mix. There was 30% RAP used in the gradation. The amount of plastic used in the mix was 0.5% by weight of the mix.
6. **25PE:** This mixture was modified with polyethylene (PE) plastic. The binder grade used was a PG 58-28 with an addition of 3.0% CA4 anti-strip by weight of binder. The binder content is 4.7% by weight of the entire mix. There was 30% RAP used in the gradation. The amount of plastic used in the mix was 0.25% by weight of the mix.
7. **50PEL:** This mixture was modified with polyethylene (PE) plastic. The binder grade used was a PG 58-28 with an addition of 1.0% Elvaloy compatiblizer by weight of binder. The

binder content is 4.7% by weight of the entire mix. There was 30% RAP used in the gradation. The amount of plastic used in the mix was 0.5% by weight of the mix.

8. **IKT3:** This mixture was an unmodified (no rubber or plastic) low volume road mix design that had poor rutting performance. The binder grade used was a PG 64-22. The binder content is 4.7% by weight of the entire mix. There was no RAP used in this mixture.
9. **SMA(U1):** This SMA mixture was unmodified (no rubber or plastic). The binder grade used was a PG 64-22V with an addition of 0.5% LAS anti-strip by weight of binder. The binder content is 6.2% by weight of the entire mix. There was no RAP used in this mixture.
10. **SMA(U2):** This SMA mixture was unmodified (no rubber or plastic). The binder grade used was a PG 64-22V with an addition of 0.5% P14 anti-strip by weight of binder. The binder content is 6.0% by weight of the entire mix. There was no RAP used in this mixture.
11. **SMA(R1):** This SMA mixture is a modified variation of the SMA(U2) mixture. This mix incorporated engineered crumb rubber (ECR). This binder grade used was a PG 64-22 with an addition of 0.5% P14 anti-strip and 10% ECR by weight of binder. The binder content is 6.0% by weight of the entire mix. There was no RAP used in this mixture.

Chapter 4. Methodology

4.1 Compaction & Aging Protocols

For this study, all the mixtures (dense graded & SMA) followed similar protocols when it came to the compaction and aging of the specimens. Where there was variation in the procedure was when it came to whether the mixture was laboratory compacted or plant reheated specimens. For the lab compacted and plant reheated specimens, all mixtures were compacted using a gyratory compactor in accordance with AASHTO T 312 to a height of 62 mm and a diameter of 150 mm. When aging all the lab compacted mixtures, each was aged at the specified temperature by each mix's JMF for a total of two hours. After the two-hour aging, the mixtures were then compacted in the gyratory compactor. For plant reheated specimens, there was no designated amount of time for aging before compaction. Rather these specimens were aged for time that it took for the loose mix to reach the specified compaction temperature.

4.2 Hamburg Wheel Track Test (AASHTO T324-19)

The Hamburg Wheel-Track Test (HWTT) is a commonly used testing method used to determine the rutting resistance and moisture-susceptibility of asphalt mixtures. The testing procedure is used to determine the premature failure susceptibility of asphalt mixtures due to weakness in the aggregate structure, inadequate binder stiffness, or moisture damage. The HWTT is performed in accordance with AASHTO T324-19 Standard. It should be noted that almost all the HWTT rut depth data results were tested and obtained prior to the author's arrival at the University of Missouri. However, the rut depth data results for the two additional dense graded control mixes created were completed by the author.

The HWTT is conducted at 50°C with the specimens of equal air voids being submerged in a water-bath and subjected to repeated passes of a steel wheel back and forth across the specimens. The steel wheel used in this testing procedure weighs approximately 71.7 kg. Figure 6 illustrates the apparatus of the HWTT. Specimens used for this test were compacted with a

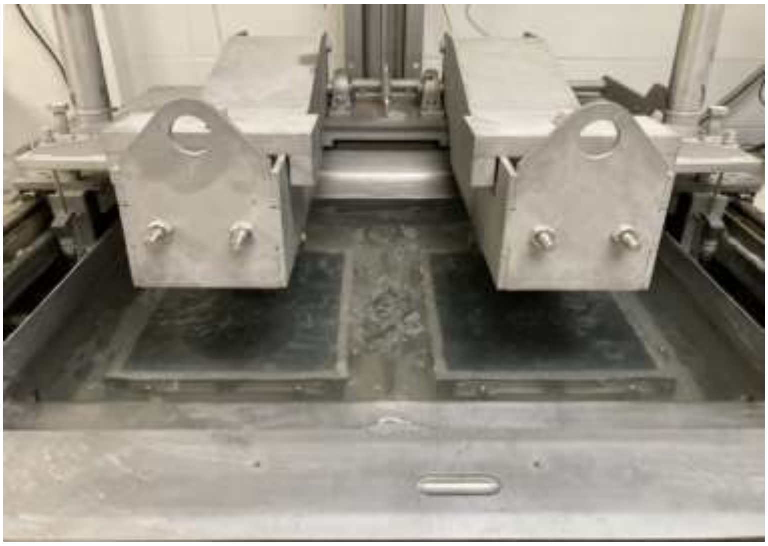


Figure 4. Hamburg Wheel Track Test Apparatus

gyratory compactor to achieve a height of 62 mm and a diameter of 150 mm. When running the HWTT, the steel wheel will make a total of 20,000 passes. Then the rut depth after the required number of passes is complete will be recorded as the rut depth for that mix design. In cases where a threshold (maximum rut depth) is specified, if the rut depth achieves that depth before completion of 20,000 passes, then the test will stop and the number of passes along with the corresponding rut depth will be recorded. For the mixtures used in this study, a total of 3 pairs (6 total specimens) were tested in the HWTT. The average rut depth of these three pairs was taken as the overall rut depth for that mixture.

In addition to evaluating the rutting resistance of asphalt mixtures, the HWTT also serves to determine the moisture-susceptibility of mix designs. Furthermore, the moisture-susceptibility is characterized by calculating the stripping inflection point (SIP). The SIP is obtained by plotting the rut depth versus the number of passes while identifying the intersection of the creep and the stripping slopes. Figure 7 illustrates a typical graph of these two parameters. For this study, the calculation of moisture-susceptibility was not relevant in the evaluation of the RRT and HT-IDT tests. Therefore, the resulting data for moisture resistance was not included.

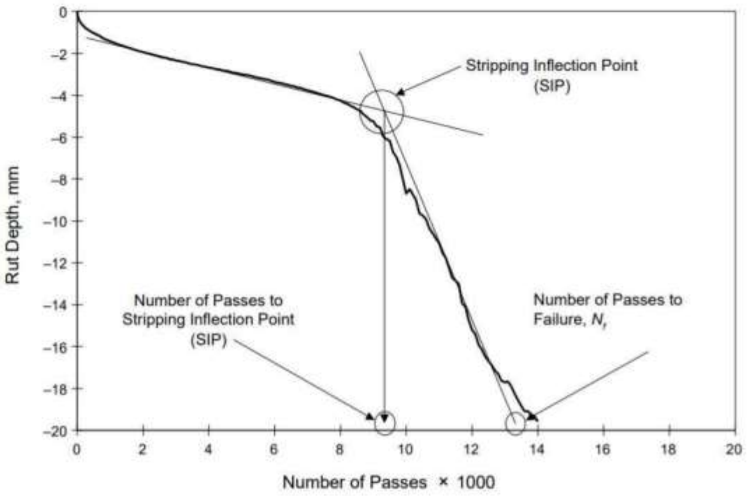


Figure 5. Hamburg Rut Depth Curve with Test Parameters (21)

4.3 Rapid Rutting Test (ASTM working standard WK71466)

The Rapid Rutting Test (RRT) was developed with the intention to provide a testing procedure that could rapidly determine an asphalt mixture's resistance to rutting. As previously discussed in the literature review, this test was developed by Zhou and colleagues at the Texas Transportation Institute so that it may be used to evaluate asphalt mixtures in mix design as

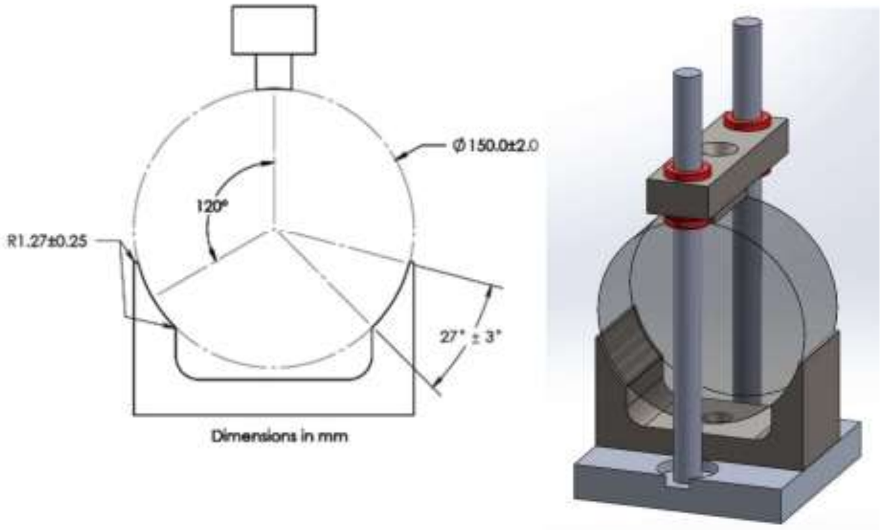


Figure 6. Rapid Rutting Test Cradle Feature Option A (ASTM WK71466)

well as quality control/assurance protocols. Contrary to typical rut resistance testing procedures used by DOTs like the Hamburg Wheel Track Test (HWTT) and the Asphalt Pavement Analyzer (APA) which are costly and time consuming, the RRT provides a testing procedure that can be performed in a timely manner. The significant decrease in the time taken to test various asphalt mixtures is beneficial to production plants wanting to rapidly verify the quality of their produced asphalt mixes.

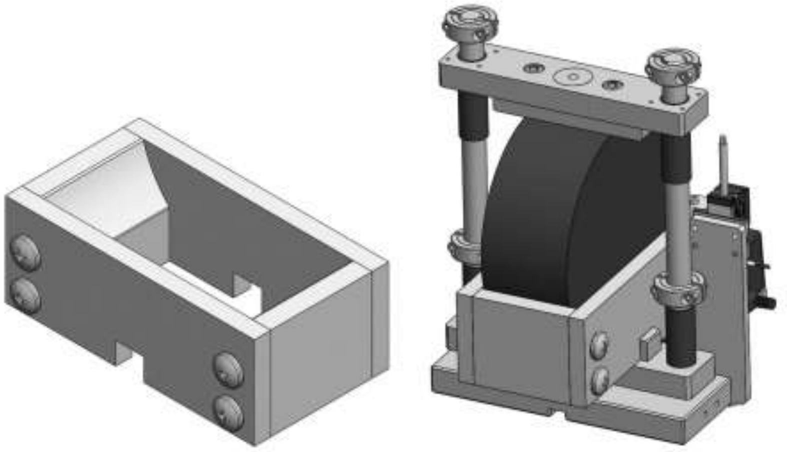


Figure 7. Rapid Rutting Test Cradle Feature Option B (ASTM WK71466)

The RRT utilizes the same set-up as the IDEAL-CT test, but also implements a cradle at the bottom of the fixture to hold specimens in place. According to ASTM working standard WK71466 (22), there are two options (option A and B) to select from for the cradle. Each of these two options can be seen in Figures 8 & 9 above. The option B cradle was purchased and used in this study. An in-lab illustration of the apparatus set up can be seen in Figure 11. This cradle provides support to the specimens, which also forces the formation of shear failure planes (Figure 10). The RRT is performed at a high temperature in the range of 50 ± 15 °C, depending on the local climate. For this study it was decided to use a testing temperature of 50

°C to maintain consistency with typical midwestern climate as well as consistency with the testing temperature used in the HT-IDT. When conditioning the specimens, an environmental chamber or water bath capable of maintaining the target test temperature within ± 1 °C is required. For this study, all specimens were conditioned using an environmental chamber for a total conditioning time of 150 ± 10 minutes in accordance with WK71466. The RRT uses a gyratory-compacted specimen with dimensions of 150 mm diameter and 62 mm thickness. Compacted specimens shall be short term aged before compaction. In this study, laboratory and plant reheated specimens were short term oven aged in accordance with ASHTO R 30.

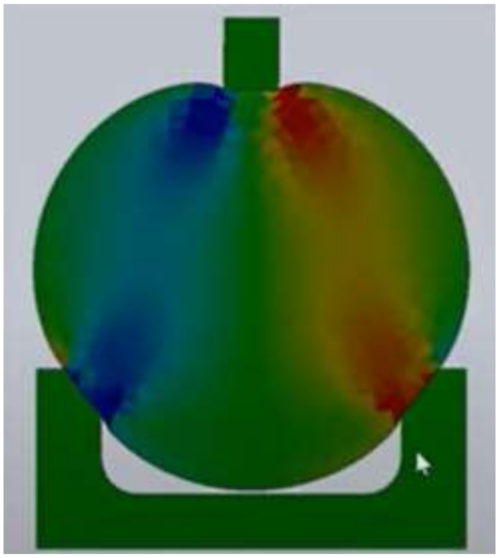


Figure 10. RRT Shear Failure Planes (2)

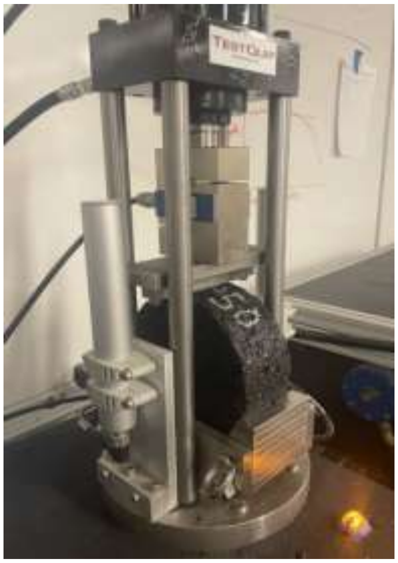


Figure 11. RRT Apparatus in MAPIL Laboratory

Upon proper compaction, aging, and conditioning of the specimens the test is performed at the specified high temperature under a constant loading rate of 50 mm/min from the upper loading strip until failure occurs, according to WK71466. The corresponding RT Index is then computed for each tested specimen. The RT Index is calculated using the shear strength of the specimen, which is subsequently calculated from the specimen dimensions and the peak load that is obtained after completion of the test. The shear strength of each specimen is calculated using equation 1 which was obtained from ASTM WK71466. After calculating the shear strength, the RT Index is calculated using equation 2 from ASTM WK71466. A higher RT Index value indicates higher rutting resistance.

$$Shear\ Strenght = \ \tau_f = 0.356 * \frac{P_{max}}{t*w} \qquad (1)$$

Where:

τ_f = shear strength (Pa)

Pmax = maximum load (N)

t = specimen thickness (m)

w = width of upper loading strip (= 0.0191 m)

$$RT_{Index} = 6.618 * 10^{-5} * \frac{\tau_f}{1Pa} \qquad (2)$$

Where:

RT Index = rutting tolerance index

τ_f = shear strength calculated from equation 1 (Pa)

4.4 High Temperature Indirect Tensile Test for HMA (ALDOT-458)

The High Temperature Indirect Tensile Test (HT-IDT) procedure was developed to provide another source to rapidly evaluate the rutting resistance of an asphalt mixture, much like the RRT. This test was developed by the Christensen, Bonaquist, and Jack in the year 2000 (23). This testing procedure utilizes the same apparatus as the IDEAL-CT test, with the key difference being that the HT-IDT is tested at a high temperature of 50 °C compared to a lower temperature of 25°C used in the IDEAL-CT test. Furthermore, another key difference in the HT-IDT and the RRT is that in the HT-IDT testing procedure, no extra cradle component is needed to be used when holding the specimen in place. Figure 12 Illustrates the configuration of the specimen in the testing apparatus.

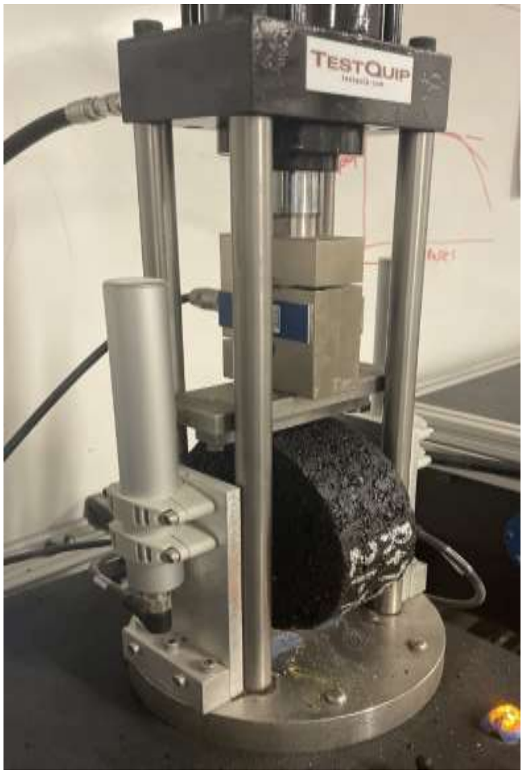


Figure 8. HT-IDT Testing Apparatus in MAPIL Laboratory

The HT-IDT procedure follows typical procedures when it comes to the compaction and aging of asphalt specimens before testing. Specifically, specimens were compacted using a gyratory compacter conforming to AASHTO T 312. When aging the specimens, ALDOT-458 calls for aging loose mixture for 4 hours at a temperature of 135 °C and aging plant reheated mixtures until they reach their compaction temperature, both in accordance with AASHTO R 30. In this study, the aging protocol was followed for plant reheated mixtures, but the loose mixtures were aged at for 2 hours at their compaction temperature.

The procedure of implementing the HT-IDT test is as follows. First, the specimen's height are to be measured in inches at three evenly spaced locations around the circumference. However, the height of the specimen can also be recorded as the height the is reported by the gyratory compactor. In this study the latter was used, resulting in all specimen's height to be recorded as 62.0 mm. Next, the asphalt specimens must be conditioned in a forced draft oven at a test temperature of 50 °C ± 1°C for 2 hours ± 10 minutes. Upon properly conditioning the asphalt specimens, the next step is to remove one specimen at a time from the oven to then be tested in the HT-IDT apparatus. The time between removing the specimen from the oven and testing of the specimen shall be within 2 minutes. Once the HT-IDT test has begun, the testing fixture will apply the vertical compression loading with a displacement rate of 2in./min. After completion of the test the peak load is recorded to then be used in the calculation of the HT-IDT strength. When evaluating the rutting resistance of tested asphalt specimens based on their corresponding HT-IDT strength, higher strength values indicated a higher resistance to rutting.

The equations used to calculate the HT-IDT strength values can be seen below in equation (3). As per ALDOT-458, the diameter and height of the specimens are to be recorded in inches and the peak load is to be recorded in pounds. However, in this study the dimensions were recorded in mm and the peak load was recorded in newtons as SI units are the typical units recorded within the MAPIL laboratory. Therefore, recorded dimensions and loads were simply converted into English units to calculate specimens HT-IDT strength in psi.

$$HTIDT\ Strength = \frac{2*Peak\ Load}{\pi*D*H} \qquad (3)$$

Where:

HT-IDT Strength is in psi

Peak Load is in pounds

D = average diameter in inches

H = average height in inches

4.5 Target Number of Replicate Specimens Tested

In this study, the author decided upon a target number of specimens to be tested for each mixture in each test that would enhance the overall evaluation of the RRT and HT-IDT tests. Furthermore, it is typical practice among other asphalt pavement performance tests to include at least 3 to 4 replicates to satisfy the need for enough specimens to make the data results practical and encompassing. For this study, it was decided to bump these numbers up to a total of 8 replicates per mix design, so that the data results would be more meaningful. However, due to time and material constraints as well as some minor issues during the conditioning of the specimens, some of the mixtures did not satisfy the target number of specimens. Below in Table 1, it is shown the total number of specimens that were tested for each mix in each of the two rutting tests that had within specification air void content. Furthermore, that number of specimens was used for the statistical analysis conducted in later chapters.

Mix Names	RRT Specimens Tested?		HT-IDT Specimens Tested?	
	Lab	Plant Reheat	Lab	Plant Reheat
CTL1	8	4	6	8
CTL2	8	NA	8	NA
CTL3	8	NA	8	NA
10ECR	4	8	8	8
50PE	8	4	8	4
25PE	8	8	4	8
50PEL	8	8	8	4
IKT3	7	NA	NA	NA
SMA(U1)	8	8	8	8
SMA(U2)	8	8	8	8
SMA(R1)	8	8	7	5

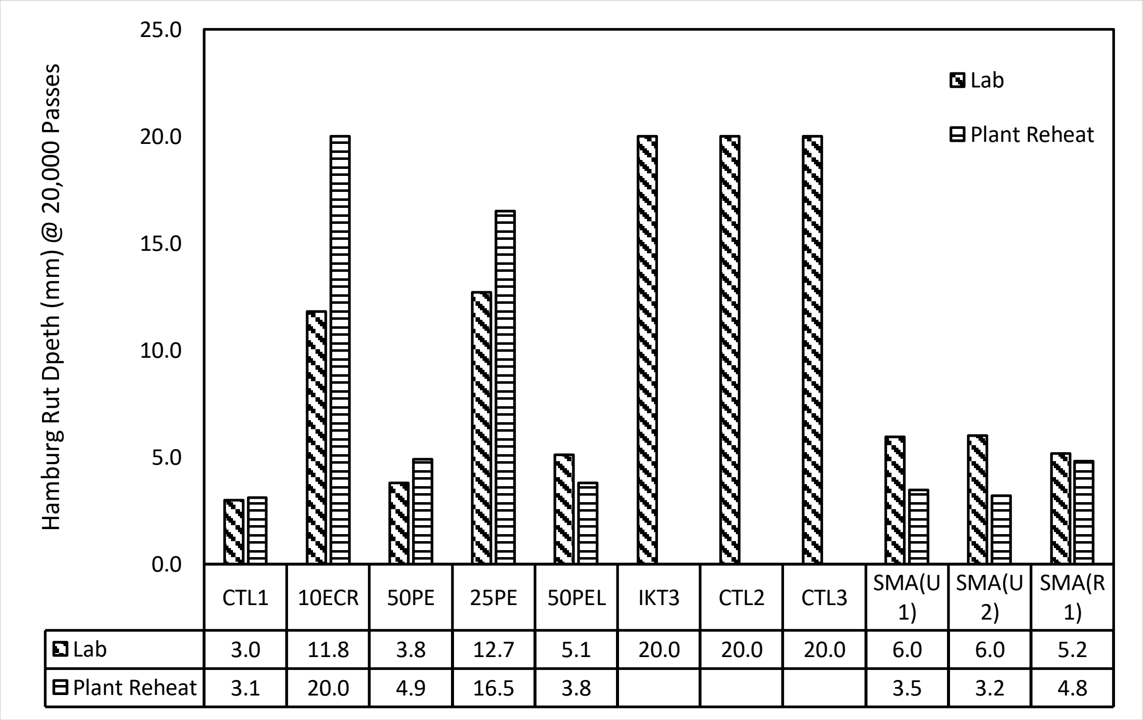
Table 1. Total Number of Replicates Tested for Each Mixture

Chapter 5. Results and Discussion

5.1 Hamburg Wheel Track Test Data Results

This section will detail the HWTT rut depth results for the 11 mixtures tested in this study. It should be noted that all the mixtures tested in this study, except the CTL2 and CTL3 mixtures, were tested prior to the author's arrival at the University of Missouri. Therefore, the HWTT data used in this study was not obtained by the author, except for the additional control mixes (CTL2 and CTL3) created at the end of the study. For this reason, the proceeding discussion of HWTT rut depth results should be credited to (1).

Figure 13 illustrates the resulting mean rut depth in mm for each dense graded and SMA mixture tested in this study. For each mixture tested in the HWTT, there was a total of 6 replicate specimens in which an average rut depth was calculated. As the figure indicates, these are the rut depths obtained after 20,000 passes in the HWTT. It should be noted however for lab mixtures CTL2, CTL3, IKT3 and plant reheat mix 10ECR, the rut depths of 20.0 mm were



	CTL1	10ECR	50PE	25PE	50PEL	IKT3	CTL2	CTL3	SMA(U1)	SMA(U2)	SMA(R1)
▨ Lab	3.0	11.8	3.8	12.7	5.1	20.0	20.0	20.0	6.0	6.0	5.2
⊟ Plant Reheat	3.1	20.0	4.9	16.5	3.8				3.5	3.2	4.8

Figure 9 – Hamburg Wheel Track Test Rut Depths for Tested Lab and Plant Reheat Mixtures

obtained prior to 20,000 passes. First looking at the dense graded mixtures, the original control (CTL1) mixture and the two 0.5% plastic mixes showed the best performance with the lowest rut depths, which should be an expected trend. Specifically, it should be expected that the CTL1 yielded a smaller rut depth than the other mixtures because it used a higher quality binder grade (PG 64-22V) compared to the PG 58-28 binder graded used for the remaining mixtures. The jump in quality from a PG 58-28 to a PG 64-22V is very significant in terms of the increased rut resistance. Specifically, the high temperature grade (the first number in the PG grade) jumps 6 degrees. Additionally, the "V" portion of the binder grade indicates that it is designed for "very high" traffic levels. Therefore, it is a fact that the PG 64-22V binder is significantly better performing in terms of rut resistance. Furthermore, it should also be expected that the two 0.5% plastic mixes yielded small rut depths because of the stiffening of the mix via the addition of plastic. When looking at the three SMA mixes, small rut depths were obtained for each mixture with a relatively low spread between the results. It should be expected that these mixtures perform well in the HWTT because of the previously discussed characteristics of SMAs being high performers in rutting resistance.

5.2 Hamburg Wheel Track Test Correlations and Rankings

The first area of focus in this study involves taking the data results from the HWTT and comparing them to the data results obtained from the two new rutting tests (RRT and HT-IDT). This section will illustrate these comparisons by graphing the HWTT rut depths against the RT Index and HT-IDT strength to evaluate the correlation between the results of each test. In addition to evaluating the strength of the correlations, this section will also serve to illustrate the similarities in ranking of performance between the three tests. The primary goal of this section is to quantitatively evaluate the strength in correlation between the rutting parameters (rut depth, RT index, HT-IDT strength) of each test method by determining if the calculated R^2 values indicate strong relationships. Dr. Fujie Zhou's research on the correlation between the rut depth and RT index resulted in R^2 values ranging from 85% to 91% (2). Therefore, values close to or within this range are required to confidently say that there is a strong relationship between the HWTT and the RRT/HT-IDT test procedures.

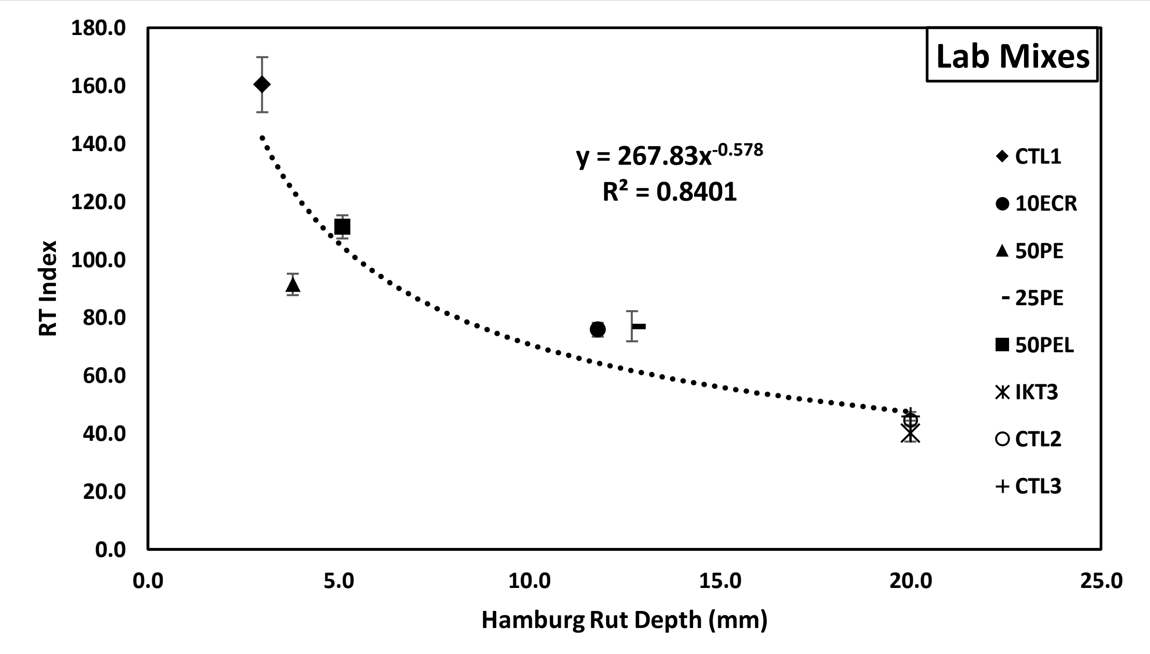


Figure 10 – HWTT Rut Depth vs. Rapid Rutting Test RT Index for Dense Graded Lab Mixtures
Note: error bars indicate +/- one standard deviation

Lab Mixes				
Mix	Hamburg Rut Depth (mm)	RT Index	HWTT Ranking	RRT Ranking
CTL1	3.0	160.4	1st	1st
50PE	3.8	91.4	2nd	3rd
50PEL	5.1	111.3	3rd	2nd
10ECR	11.8	75.8	4th	5th
25PE	12.7	77.0	5th	4th
CTL3	20.0	45.9	6th	6th
CTL2	20.0	44.5	7th	7th
IKT3	20.0	40.2	8th	8th

Table 2 – HWTT and RRT Rutting Performance Ranking Comparisons for Dense Graded Lab Mixtures

Figure 14 illustrates the rut depth in mm versus the corresponding RT index value obtained for each of the laboratory compacted mixtures. Looking at the correlation between the data results from the two rutting tests on lab mixtures, there is a strong correlation for rut depth and RT index given an R^2 value 84% was obtained which is very close to that obtained by Dr. Zhou. It was found that a power-law trendline provided the best fitting curve with the highest R^2 value. Table 2 illustrates the performance ranking for the HWTT and RRT tests. Looking at this table, it shows that the RT index follows a similar trend in performance ranking as the HWTT because there are only a few instances in which the order of performance varies. Therefore, it can be said that the HWTT and RRT tests tend to indicate a similar ranking of rutting resistance among the lab compacted dense graded mixtures.

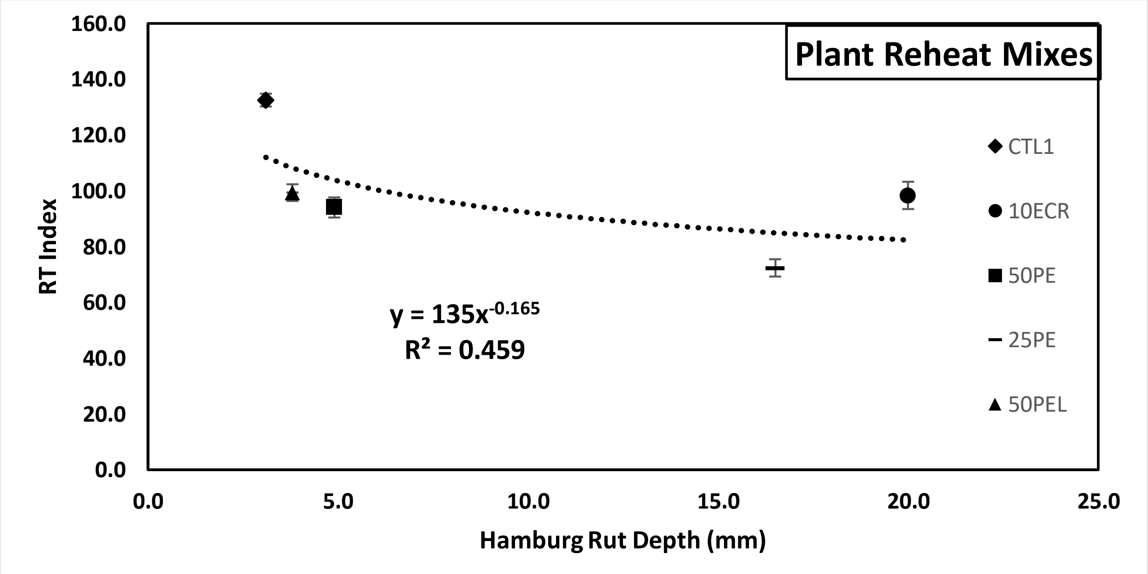


Figure 11. HWTT Rut Depth vs. Rapid Rutting Test RT Index for Dense Graded Plant Reheat Mixtures
<u>Note:</u> error bars indicate +/- one standard deviation

Plant Reheat				
Mix ID	Hamburg Rut Depth (mm)	RT Index	HWTT Ranking	RRT Ranking
CTL1	3.1	132.5	1st	1st
50PEL	3.8	99.4	2nd	3rd
50PE	4.9	104.2	3rd	2nd
25PE	16.5	72.4	4th	5th
10ECR	20.0	98.4	5th	4th

Table 3. HWTT and RRT Rutting Performance Ranking Comparisons for Dense Graded Plant Reheat Mixtures

Figure 15 illustrates the rut depth in mm versus the corresponding RT index value obtained for each of the reheated plant mixtures. Looking at the correlation between the data results from the two rutting tests, there is a poor correlation for rut depth and RT index given an R^2 value 45.9% was obtained. This correlation is half of that described by Dr. Zhou, which indicates that there is a weak relationship between HWTT rut depth and RT index for reheated plant mixtures. It was found that a power-law trendline provided the best fitting curve with the highest R^2 value. Table 3 illustrates the performance ranking for the HWTT and RRT tests. Looking at this table, it shows a similar trend in performance ranking. The CLT1 mixture is the best performing mixture for both tests. Furthermore, there are only slight differences in the remaining rankings, much like the lab mixtures. Although there is a similar trend in performance ranking between these two tests, the key takeaway from the plant reheat data is that the relationship between HWTT rut depth and RT index is far below desirable when considering the RRT as a replacement rutting test for the HWTT.

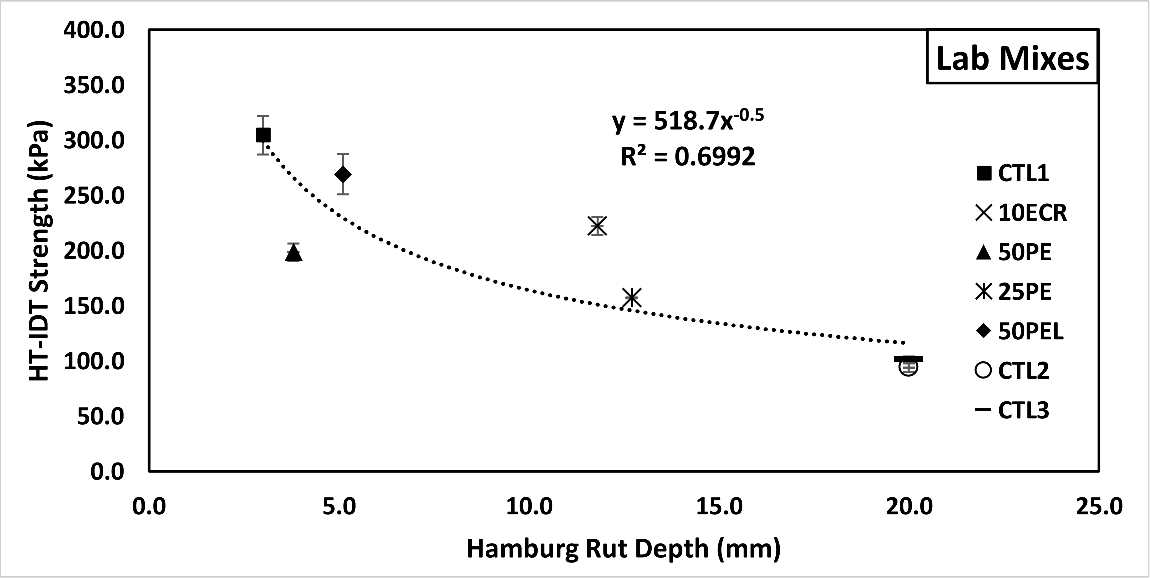
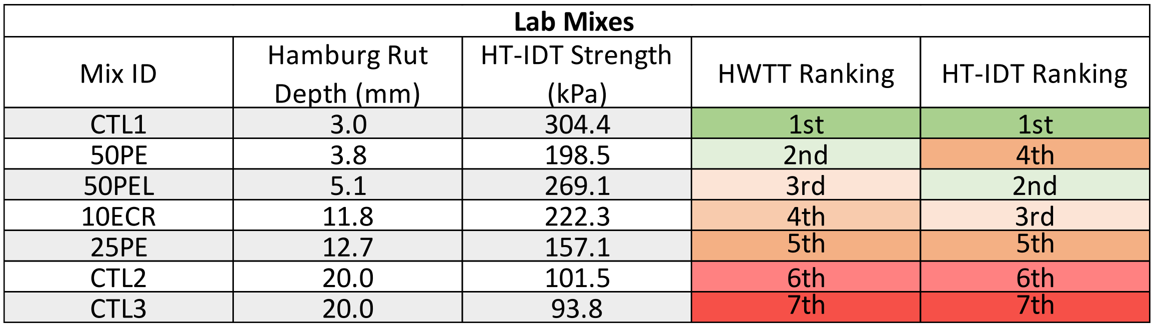


Figure 12. HWTT Rut Depth vs. HT-IDT Strength for Dense Graded Lab Mixtures
<u>Note:</u> error bars indicate +/- one standard deviation



Lab Mixes

Mix ID	Hamburg Rut Depth (mm)	HT-IDT Strength (kPa)	HWTT Ranking	HT-IDT Ranking
CTL1	3.0	304.4	1st	1st
50PE	3.8	198.5	2nd	4th
50PEL	5.1	269.1	3rd	2nd
10ECR	11.8	222.3	4th	3rd
25PE	12.7	157.1	5th	5th
CTL2	20.0	101.5	6th	6th
CTL3	20.0	93.8	7th	7th

Table 4. HWTT and HT-IDT Rutting Performance Ranking Comparisons for Dense Graded Lab Mixtures

Figure 16 illustrates the relationship between HWTT rut depths in mm and the corresponding HT-IDT strengths obtained when testing dense grade lab mixtures in the two different rutting tests. As seen in the chart, the R^2 value for this relationship is equal to 69.9% which is indicative of an average to good relationship. A power-law trendline was found to provide the best correlation for this graph. Next looking at Table 4, there is a similar trend in ranking of performance between the two rutting tests for the dense graded lab mixtures. Specifically, the highest ranking as well as the lowest three rankings are an exact match. There appears to be slight variation with the 2^{nd} through 4^{th} place rankings, but overall, this table shows that each of the two rutting tests results in similar performance rankings. Compared to the dense graded lab mixtures tested in the RRT, there is slight drop from 84% to 69.9% in the strength of correlation. Furthermore, this drop in correlation strength indicates that rut depth and HT-IDT strength have a less than desirable relationship when comparing these results to Dr. Zhou’s.

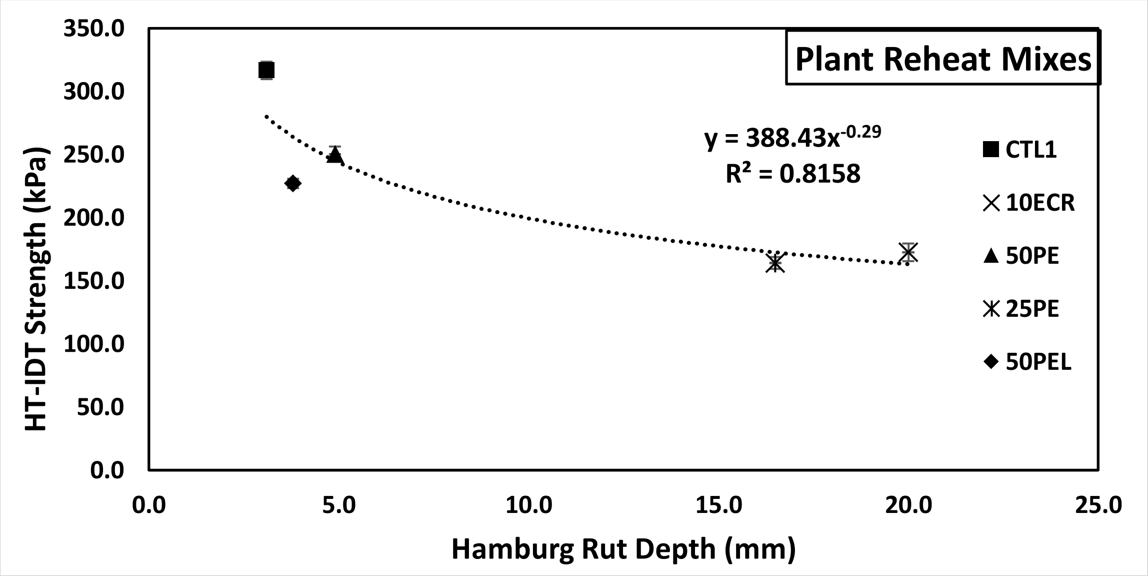


Figure 13. HWTT Rut Depth vs. HT-IDT Strength for Dense Graded Plant Reheat Mixtures
<u>Note:</u> error bars indicate +/- one standard deviation

Plant Reheat Mixes				
Mix ID	Hamburg Rut Depth (mm)	HT-IDT Strength (kPa)	HWTT Ranking	HT-IDT Ranking
CTL1	3.1	316.6	1st	1st
50PEL	3.8	227.1	2nd	3rd
50PE	4.9	250.4	3rd	2nd
25PE	16.5	164.1	4th	5th
10ECR	20.0	172.6	5th	4th

Table 5. HWTT and HT-IDT Rutting Performance Ranking Comparisons for Dense Graded Plant Reheat Mixtures

Figure 17 illustrates the relationship between HWTT rut depths in mm and the corresponding HT-IDT strengths obtained when testing dense graded plant reheat mixtures in the two rutting tests. Looking at this figure, the correlation coefficient R^2 is equal 81.6%. A power-law trendline was used to obtain the R^2 value. This value indicates that the dense graded plant reheat mixes tested in the HT-IDT test results in a stronger correlation that the lab mixes. Furthermore, the calculated R^2 value of 81.6% is just shy of the minimum value found by Dr. Zhou, indicating that the correlation between rut depth and HT-IDT strength is very close to desirable when considering the HT-IDT test as a replacement for the HWTT. Table 5 illustrates the performance rankings for the two rutting tests. In this table, there appears to be a matching trend in ranking with only slight variation of the 2nd/3rd and 4th/5th places being switched. Overall, the HT-IDT test exhibited correlations to the HWTT that can be viewed as desirable for plant reheat mixtures and slightly less than desirable for lab mixes.

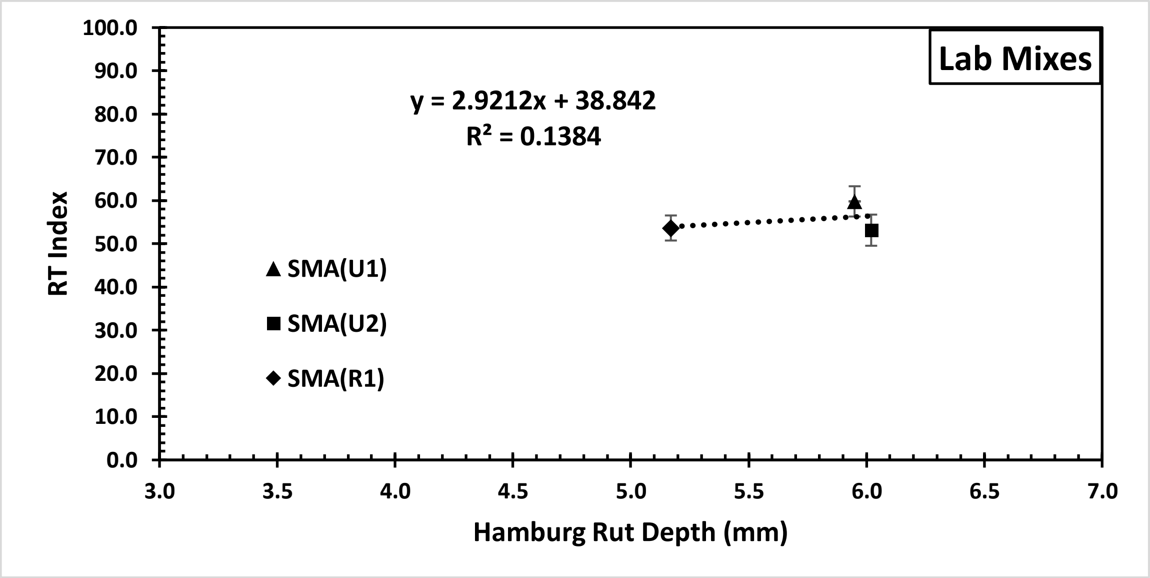


Figure 18. HWTT Rut Depth vs RT Index for SMA Lab Mixtures
Note: ***error bars indicate +/- one standard deviation***

Lab Mixes				
Mix ID	Hamburg Rut Depth (mm)	RT Index	HWTT Ranking	RRT Ranking
SMA(U1)	6.0	59.8	2nd	1st
SMA(U2)	6.0	53.1	2nd	3rd
SMA(R1)	5.2	53.7	1st	2nd

Table 6. HWTT and RT Index Performance Rankings for SMA Lab Mixtures

Figure 18 illustrates the HWTT rut depth in mm versus the corresponding RT index values for the lab compacted SMA mixes. The trendline found to provide the best R^2 value was linear. The R^2 for this chart was found to be 13.8%, which is significantly lower than the previous dense graded mixture correlations. Although the correlation value is very low, a poor correlation could be expected in this case due to the limited number of mixes and data points for SMA mixtures. Furthermore, looking at Table 6 it shows that the HWTT and RRT did not exhibit similar performance rankings further demonstrating that there appears to be no quantitatively strong relationship between these two test methods.

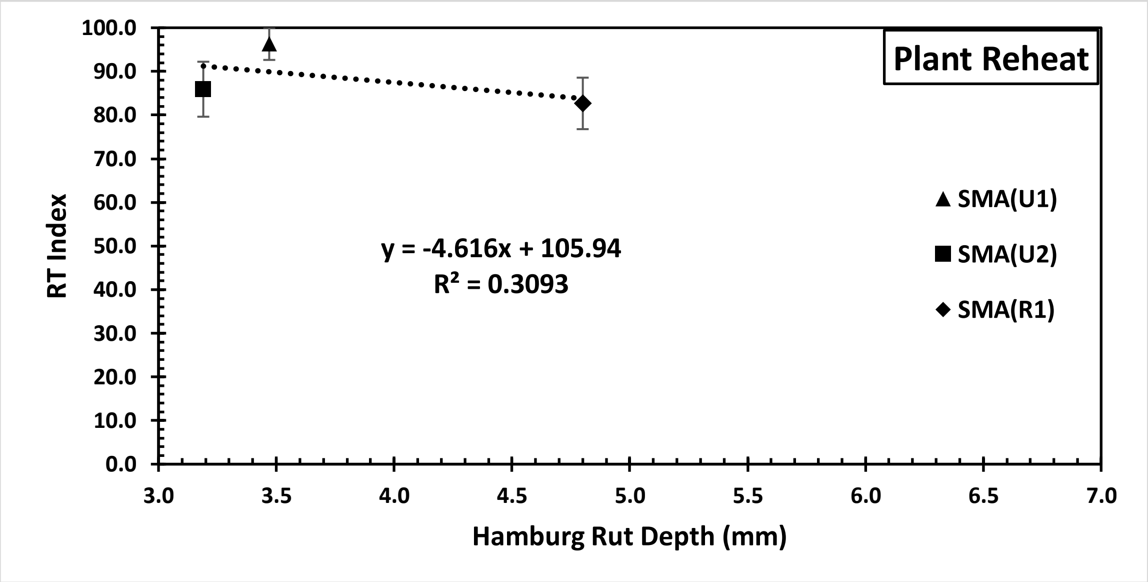


Figure 19. HWTT Rut Depth vs. RT Index for SMA Plant Reheat Mixtures
<u>Note:</u> error bars indicate +/- one standard deviation

Mix ID	Hamburg Rut Depth (mm)	RT Index	HWTT Ranking	RRT Ranking
SMA(U2)	3.2	85.9	1st	2nd
SMA(U1)	3.5	96.3	2nd	1st
SMA(R1)	4.8	82.7	3rd	3rd

Table 7. HWTT and RT Index Performance Rankings for SMA Plant Reheat Mixtures

Figure 19 illustrates the HWTT rut depth in mm versus the corresponding RT index values for the plant reheated SMA mixes. Like the lab mixes, the best fitting trendline was linear. This trendline provided a R^2 value of 30.9%. As previously stated, this correlation is most likely much lower than the dense graded mixtures due to limited data points. However, it should be restated that this correlation value is indicating that there is not a strong relationship between the RRT and HWTT test procedures. Furthermore, when looking at Table 7 there appears to be a similar ranking in performance for the plant reheated mixes with only the 1st and 2nd place mixtures being flipped. However, the important quantitative data in this case is the strength in correlation, which was much lower than desirable, as it is three times less than the correlations observed by Dr. Zhou.

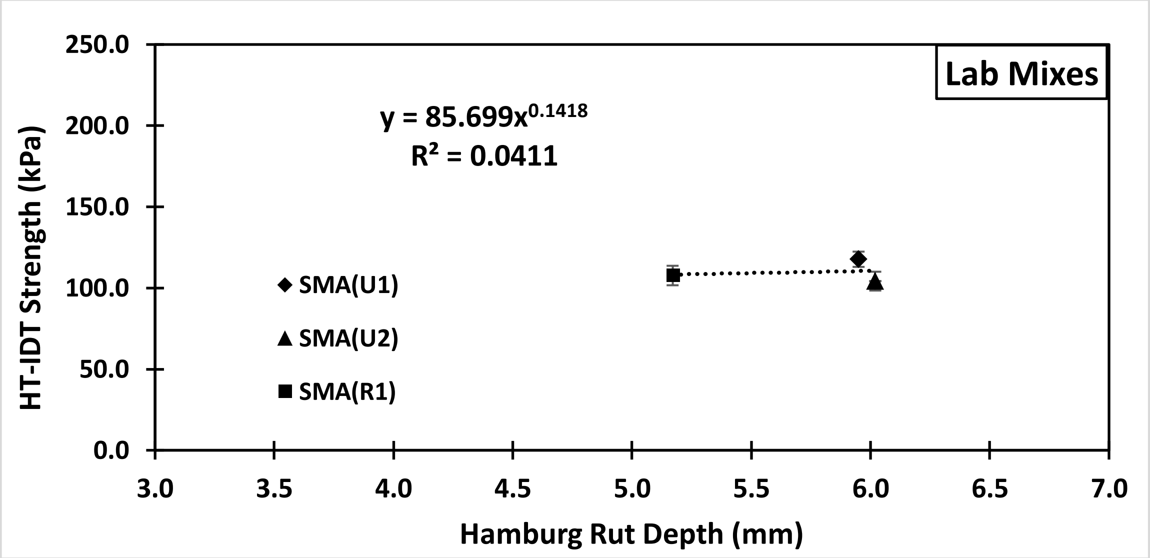


Figure 20. HWTT Rut Depth vs. HT-IDT Strength for SMA Lab Mixes
<u>Note:</u> error bars indicate +/- one standard deviation

Lab Mixes				
Mix ID	Hamburg Rut Depth (mm)	HT-IDT Strength (kPa)	HWTT Ranking	HT-IDT Ranking
SMA(U1)	6.0	117.7	2nd	1st
SMA(U2)	6.0	104.2	2nd	3rd
SMA(R1)	5.2	107.7	1st	2nd

Table 8. HWTT and HT-IDT Performance Rankings for Lab SMA Mixes

Figure 20 illustrates the HWTT rut depth in mm versus the corresponding HT-IDT strength values for the lab SMA mixes. Like the lab mixes, the best fitting trendline was linear. This trendline provided a R^2 value of 4.1%. As previously stated, this correlation is most likely much lower than the dense graded mixtures due to limited data points. However, it should be restated that this correlation value indicates that there is a very weak relationship between the

HT-IDT and HWTT test procedures. Furthermore, when looking at Table 8 it is shown that there is not a similar performance ranking between the two test procedures, further iterating that there is no evidence of any type of desirable correlation between the two tests when considering the HT-IDT as a replacement rutting test specifically for SMA mix types.

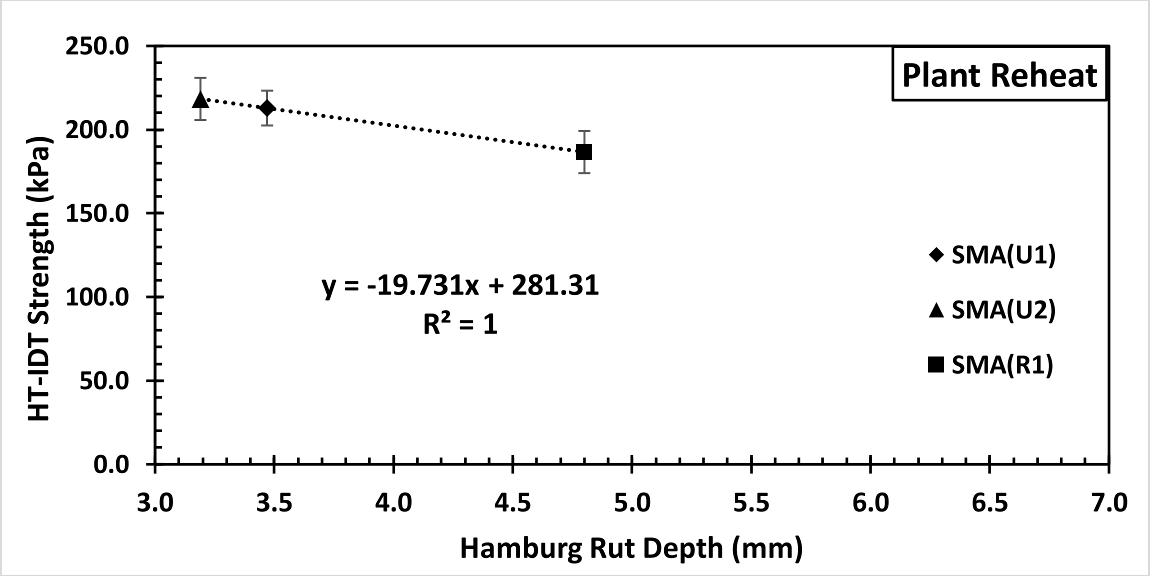


Figure 14. HWTT Rut Depth vs. HT-IDT Strength for SMA Plant Reheat Mixes
<u>Note:</u> error bars indicate +/- one standard deviation

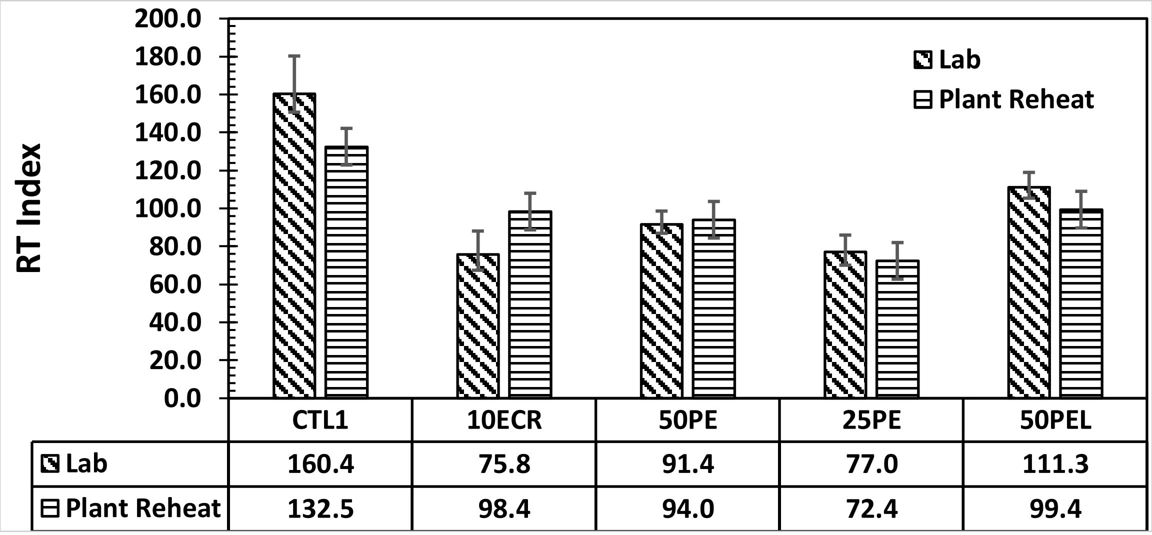
Plant Reheat Mixes				
Mix ID	Hamburg Rut Depth (mm)	HT-IDT Strength (kPa)	HWTT Ranking	HT-IDT Ranking
SMA(U2)	3.2	218.3	1st	1st
SMA(U1)	3.5	212.9	2nd	2nd
SMA(R1)	4.8	186.6	3rd	3rd

Table 9. HWTT and HT-IDT Performance Rankings for Plant Reheat SMA Mixes

Figure 21 illustrates the HWTT rut depth in mm versus the corresponding RT index values for the plant reheated SMA mixes. Like the lab mixes, the best fitting trendline was linear. This trendline provided a R^2 value of 100%. In this case, the correlation between the two test can be seen as perfect, although this may be an isolated anomaly. Based on the correlations obtained for the previous SMA data results, the perfect correlation in Figure 21 should not indicate that there is a strong relationship between the HWTT and HT-IDT.

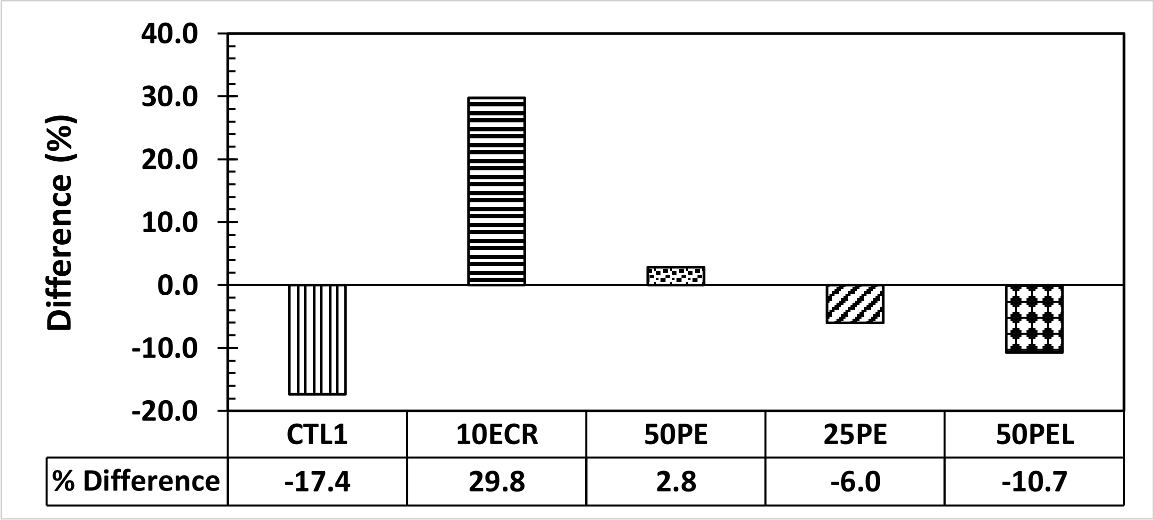
5.3 Effects of Reheating Asphalt Mixtures

This section's focus is placed on the effects of the RRT and HT-IDT testing results due to the variation in the levels of aging that each mixture has experienced. To do so, comparisons between lab mixes and plant reheat mixes were made. Of the 11 mixtures tested in this study, six dense graded and 3 SMA mixtures were included because of the presence of both lab and plant reheat specimens. Moreover, the only three mixes that were not included were the CTL2, CTL3, and IKT3 mixtures. The control mixes were not included because they were never produced at an asphalt plant and the IKT3 mix was not included because there were no plant reheated materials available to the author's lab. The proceeding discussion will detail the differences in mixture performance in the RRT and HT-IDT. Considering the effects of aging on rut resistance, the expected outcome before analyzing the data is that plant reheated specimens should results in better rut resistance performance because aging of asphalt leads to the stiffening of the binder, which inherently makes the overall mix design more resistant to rutting. The increase in aging is directly due to the reheating of the mixture. Specifically, in this case the lab mixes is heated once and then compacted. Furthermore, the plant reheated specimens are heated once during production and then sampled in buckets that are left alone for the asphalt to cool. Then the specimens are taken out of the bucket and reheated to compaction temperature to make plant reheat specimens. Therefore, in this process, the reheating of the mix will result in the plant reheat mixtures experiencing an increase in aging.



	CTL1	10ECR	50PE	25PE	50PEL
▧ Lab	160.4	75.8	91.4	77.0	111.3
⊟ Plant Reheat	132.5	98.4	94.0	72.4	99.4

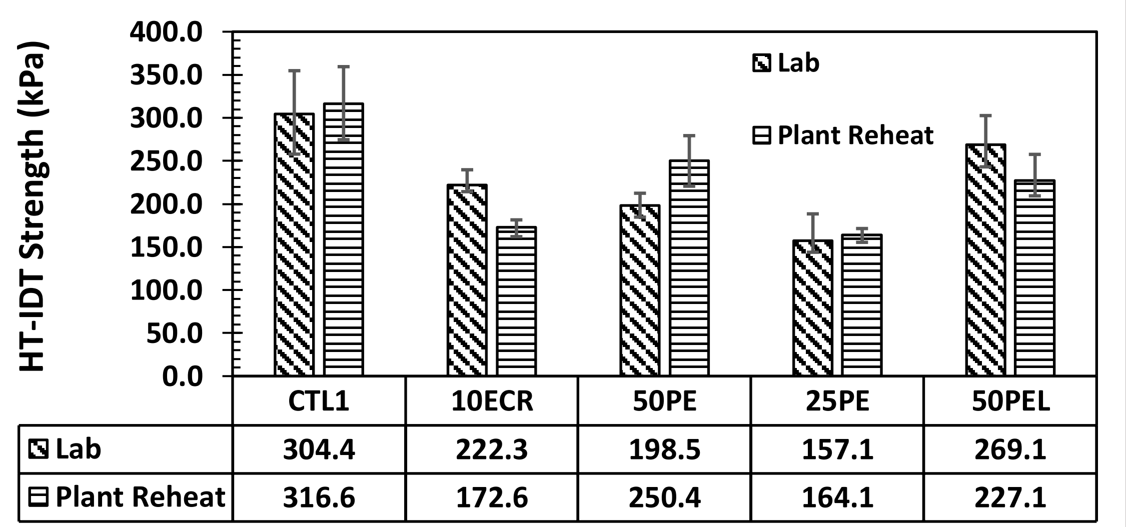
Figure 22. Mix Performance of Dense Graded Laboratory & Plant Reheat Specimens in the Rapid Rutting Test



	CTL1	10ECR	50PE	25PE	50PEL
% Difference	-17.4	29.8	2.8	-6.0	-10.7

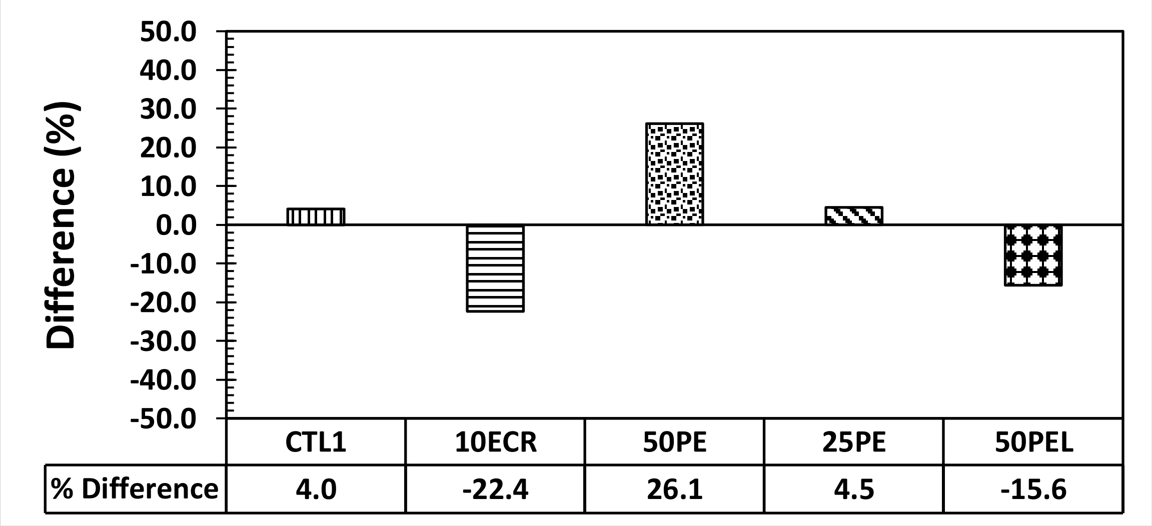
Figure 15. Percent Difference Between Lab and Plant Reheat Dense Graded Mixtures in the RRT Test

Figure 22 shows the RT index results for dense graded mixtures where both laboratory and plant reheated specimens were obtained and tested in the Rapid Rutting Test. Figure 23 shows the percent difference between lab and plant reheated specimens for each different mixture. When looking at Figure 23, a positive value indicates that the plant reheat specimens averaged a higher RT index and vice versa for a negative value. Considering the previously stated ideology of increased aging leading to increased rut resistance, it should be expected that reheated plant specimens would yield a higher RT index value than laboratory compacted specimens because reheated plant mixtures have experienced more time aging. When looking at Figure 23, there does not appear to be definitive support for this ideology. Specifically, only two of the five mixtures result in higher RT index values for reheated plant specimens (10ECR and 50PE). However, for the other three mixtures (CTL1, 10ECR, 50PEL) the percent difference values are positive, indicating that the expected trend of plant reheated producing higher rut resistance results was not followed.



	CTL1	10ECR	50PE	25PE	50PEL
▧ Lab	304.4	222.3	198.5	157.1	269.1
⊟ Plant Reheat	316.6	172.6	250.4	164.1	227.1

Figure 24. Mix Performance of Dense Graded Laboratory & Plant Reheat Specimens in the HT-IDT Test



	CTL1	10ECR	50PE	25PE	50PEL
% Difference	4.0	-22.4	26.1	4.5	-15.6

Figure 16. Percent Difference Between Lab and Plant Reheat Dense Graded Mixtures in the HT-IDT Test

Figure 24 illustrates the HT-IDT testing results for the five dense graded mixtures where both lab and plant reheated specimens were tested. Figure 25 illustrates the percent difference in the testing results between lab and plant reheated specimens for each mixture. In Figure 25, positive values indicate that the plant reheat specimens averaged a higher HT-IDT strength. whereas negative values indicate the lab specimens resulted in a higher average HT-IDT strength for each mixture. Like the RRT results, there appeared to be no definitive trend in the data that supported the idea that plant reheated specimens (higher amounts of aging) resulted in higher HT-IDT strengths (higher rut resistance). Specifically, there were three mixtures that followed the expected trend (CTL1, 50PE, 25PE).

Comparing the differences in testing results for lab and plant reheated mixtures for both new rutting tests, similar results were obtained for the RRT and HT-IDT with respect to the fact that neither test tended to follow the expected trend of reheated specimens yielded better rutting resistant testing results. Furthermore, there was only one instance where both tests had a mixture following this trend (10ECR mix). However, looking at the percent difference values, the range in values for percent difference was relatively low. Specifically, the RRT showed a range of -17% to 30% with most of the mixes being lower values much closer to zero and the HT-IDT showed a range of -22% to 26% with two of the mixes being closer to zero.

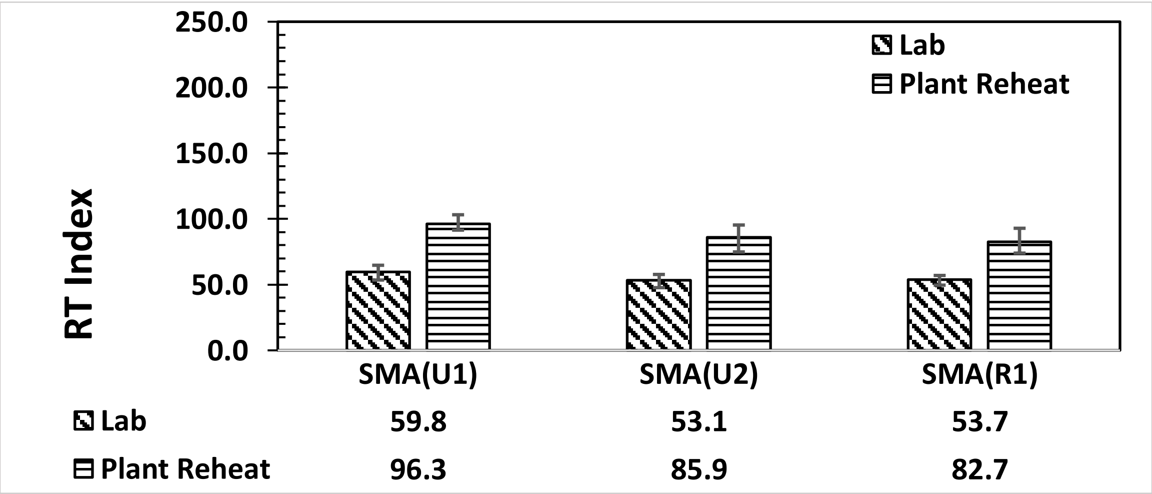


Figure 26. . Mix Performance of SMA Graded Laboratory & Plant Reheat Specimens in the RRT Test

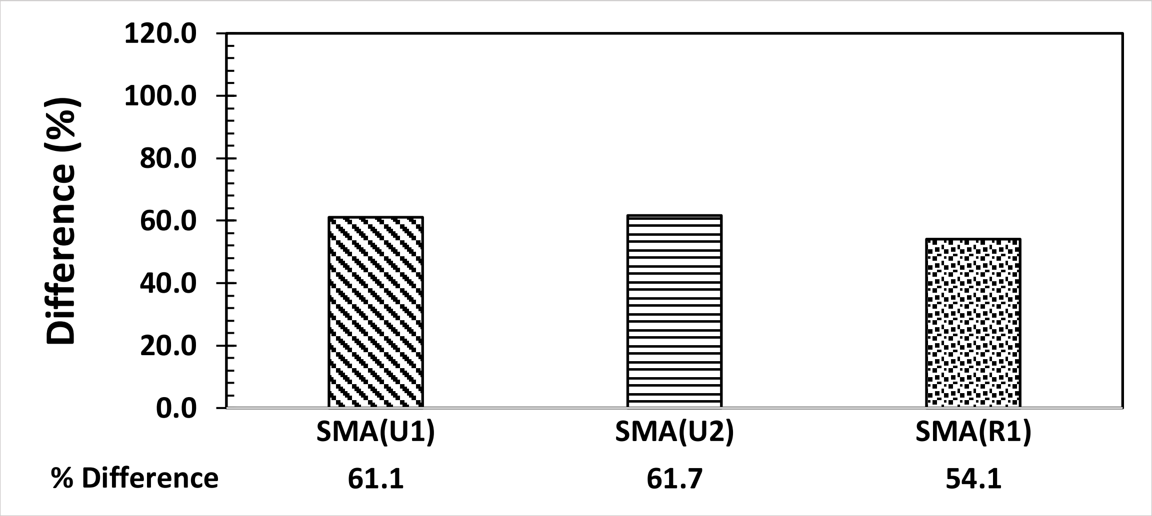


Figure 27. Percent Difference Between Lab and Plant Reheat SMA Mixtures in the RRT Test

Figure 26 illustrates the data results for the three SMA mixtures tested in the RRT for both lab and plant reheated specimens. Figure 27 illustrates the percent difference values between lab and plant reheated specimens for each of the three SMA mixtures. The positive values shown in Figure 27, represent that the plant reheated specimen data results were higher than the lab specimens. Contrary to the previously discussed dense graded results, all of the SMA mixtures followed the expected trend of reheated mixes (higher amounts of aging) yielded higher tests results (more rut resistant test results) due to their positive percent difference values. However, also comparing these results to the dense graded mixtures, it is shown that the percent difference values are significantly higher. Specifically, the maximum dense graded percent difference results were in the twenties to thirties whereas the SMA percent difference results are 2 to 3 times greater. Therefore, there is reassurance in the testing of SMA mixtures with the RRT for their tendency to follow the expected increased aging and rutting relationship. However, there may be some cause for concern that the difference in this relationship is significant.

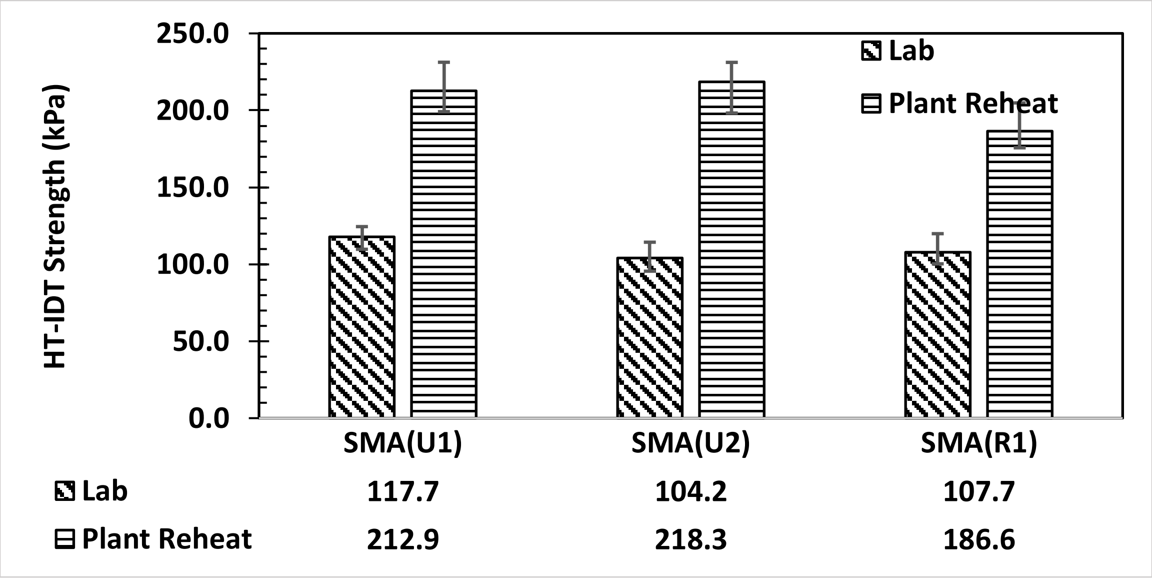


Figure 28. Mix Performance of SMA Graded Laboratory & Plant Reheat Specimens in the HT-IDT Test

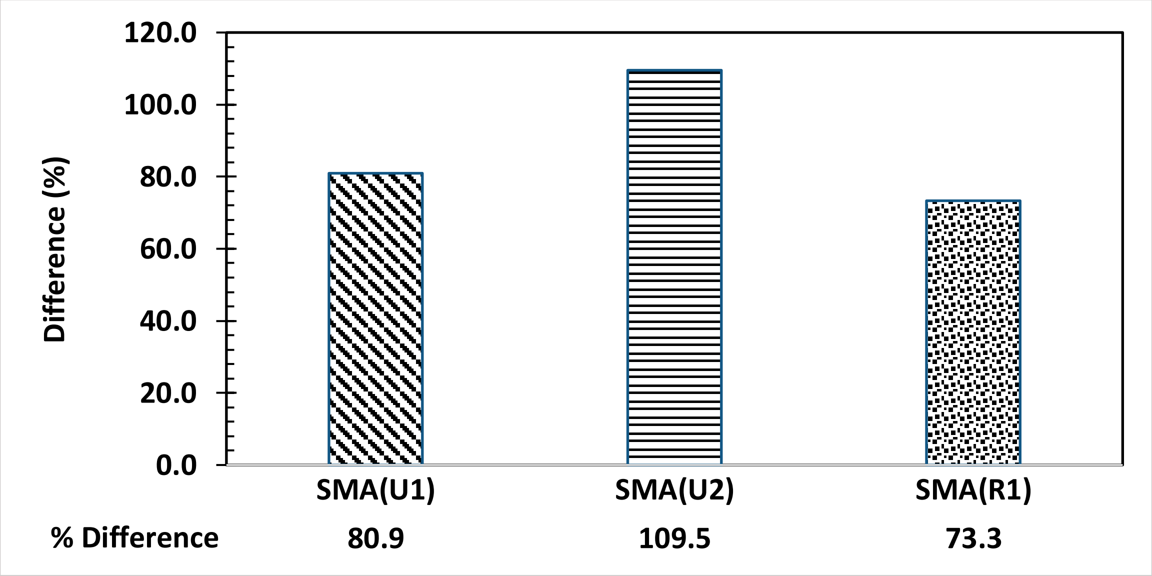


Figure 17. Percent Difference Between Lab and Plant Reheat SMA Mixtures in the HT-IDT Test

Figure 28 shows the data results for the HT-IDT strength obtained for each SMA mixture for both lab and plant reheated specimens. Figure 29 illustrates the associated percent difference between the lab and plant reheat data results for each of the three SMA mixtures. As shown in Figure 29, all three mixes resulted in positive percent differences indicating that the plant reheat specimens yielded higher average HT-IDT strength values. Much like the SMA results for the RRT, the expected increased aging and rutting relationship was followed throughout each SMA mixture when tested in the HT-IDT. Furthermore, the SMA mixtures tested in the HT-IDT also resulted in very large percent difference values like they did in the RRT. This time, the percent difference values ranged from 73% to 110% which is higher than the RRT results as well as being 3 to 5 times larger than the dense graded results. Therefore, it is once again reassuring to see the expected aging and rutting relationship being followed in the HT-IDT test, but concerning how large the differences in results are between lab and plant reheated specimens.

When evaluating the RRT as testing procedure to be used as a form of quality assurance and quality control between laboratory designed asphalt mixtures and what is ultimately produced at the plant, it can be said that there is some level of concern for both dense graded and SMA mixture types based upon these data results. When looking at the dense graded mixture results, there is cause for concern due to the unexpected trend of a majority of the five mixtures yielding higher RT index values. Furthermore, there is cause for concern for the SMA mixtures due to the very large difference in data results between the lab and plant reheated mixtures.

5.4 Effects of Modifiers and Additives

This section’s focus is on the effects of additives and modifiers (rubber, plastic, anti-strip) on the data results for the RRT and HT-IDT tests. For the 8 dense graded mixtures, only five mixtures were included in the analysis. Moreover, the CTL1 was not included due to the variation in binder type and content from the rest of the Stadium Blvd. project mixtures. Also, the IKT3 mix was not included as it was an entirely different mixture design from the Stadium Blvd mixtures, in terms of gradation, binder type, and lack of any inclusion of RAP. As previously discussed, the CTL2 and CTL3 mixtures were created in the laboratory specifically for this chapter so that an "apples to apples" comparison to the modified Stadium Blvd. mixtures could be analyzed. Due to the CTL2 and CTL3 mixtures only being developed in the lab late into this entire study, there was unfortunately no possibility of analyzing the effects of additives and modifiers for dense graded plant reheat mixtures. For the SMA mixtures, there were two unmodified mixes (SMAU1 and SMAU2) along with the rubber modified (SMAR1) variation of SMAU2. For these mixes, data was obtained for both lab and plant reheat specimens. Therefore, the second portion of this chapter will analyze the effects of rubber on SMA lab and plant reheat mixes.

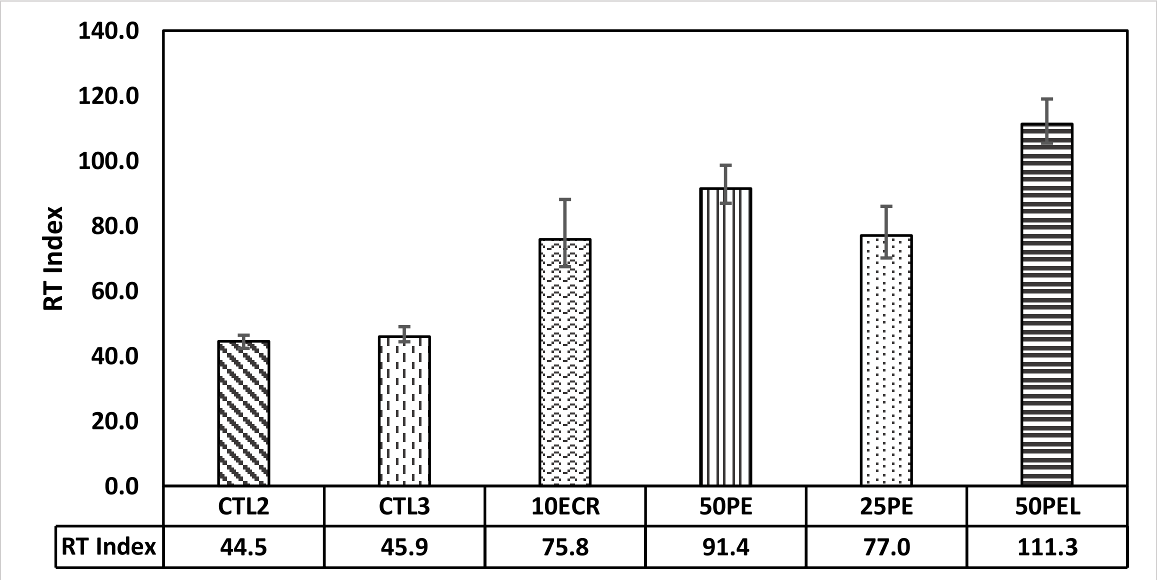


Figure 30. RT Index Results for Dense Graded Lab Mixtures with Varying Modifiers and Additives

Figures 30 and 31 illustrate the data results for the RRT and HT-IDT tests for dense graded lab mixtures implementing various forms and amount of modification. The CTL2 mixture in the chapter represents the true control mix, as it includes no rubber, plastic, or anti-strip in the mixture. The CTL3 mix is only slightly different than CTL2 because of the addition of 1.0% liquid anti-strip to the binder. Next, the 10ECR mix will illustrate the effects of rubber modification and the remaining PE mixes will illustrate the effects of plastic modification.

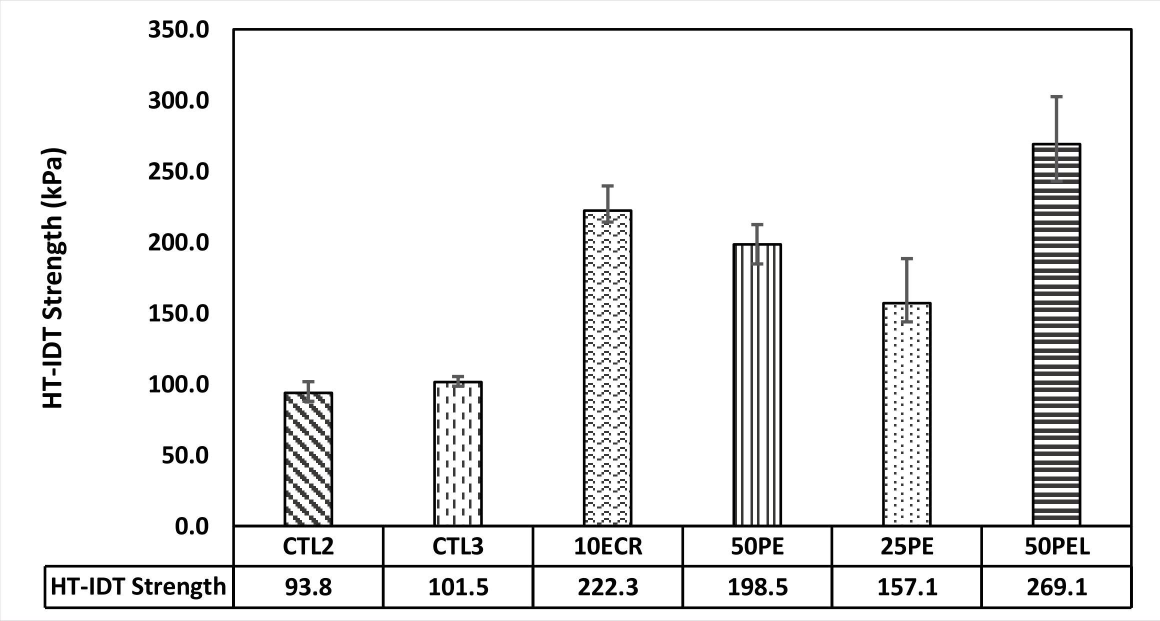


Figure 31. HT-IDT Results for Dense Graded Lab Mixtures with Varying Modifiers and Additives

Looking at the CTL3 mix in both figures, it is shown that the addition of a liquid anti-strip additive results in a negligible increase in the RRT and a slight increase in performance for the HT-IDT. The 10ECR mixture in both figures shows that the addition of the rubber modifier results in a significant increase in performance for both the RRT and HT-IDT. Lastly, the three remaining PE mixtures also show a similar increase in performance. Furthermore, it can be seen in the two figures that the same trend in performance is followed by both the RRT and HT-IDT. Specifically, the 50PEL mix performs the highest followed by the 50PE mix then the 25PE mix. Referring to the HWTT data in Figure 13, the previously described trend is also apparent in the rut depth data as the PE mixes yielded the smallest rut depths, followed by the 10ECR mix. Therefore, it can be said that the RRT and HT-IDT illustrate similar performance results when it comes to the effects that additives and modifiers have on the individual mix performance.

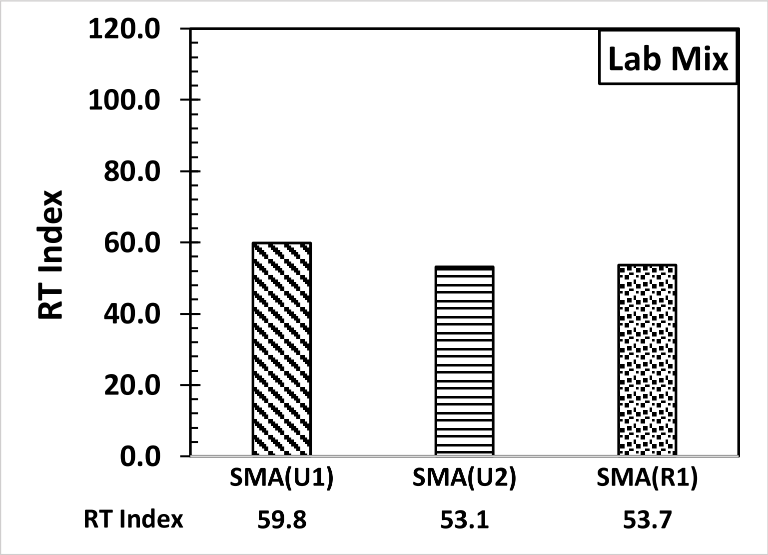


Figure 32. RT Indexes for Lab SMA Mixtures

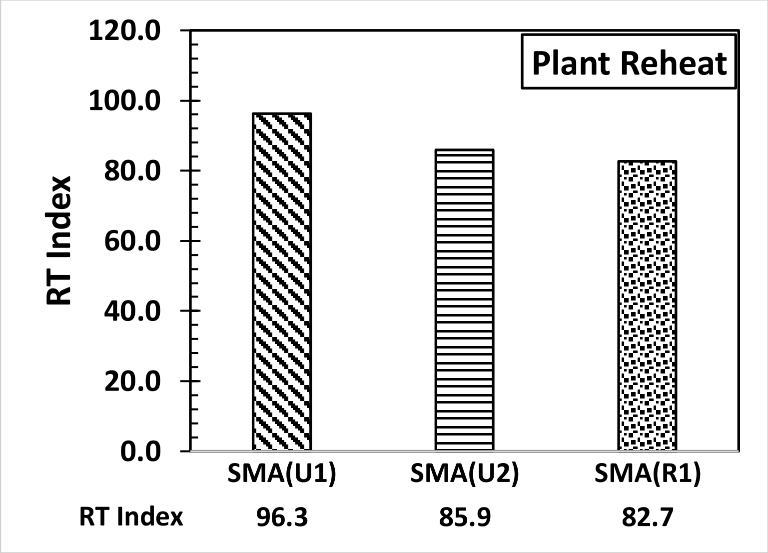


Figure 33. RT Indexes for Plant Reheat SMA Mixtures

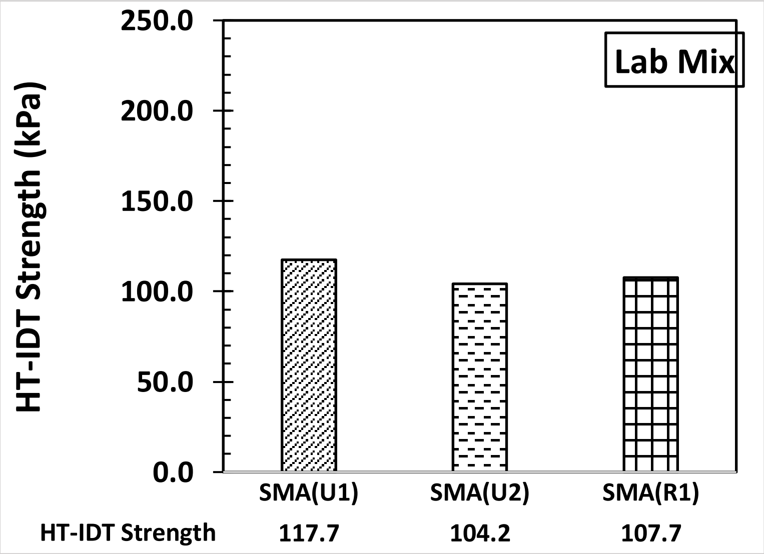


Figure 18. HT-IDT Strengths for Lab SMA Mixtures

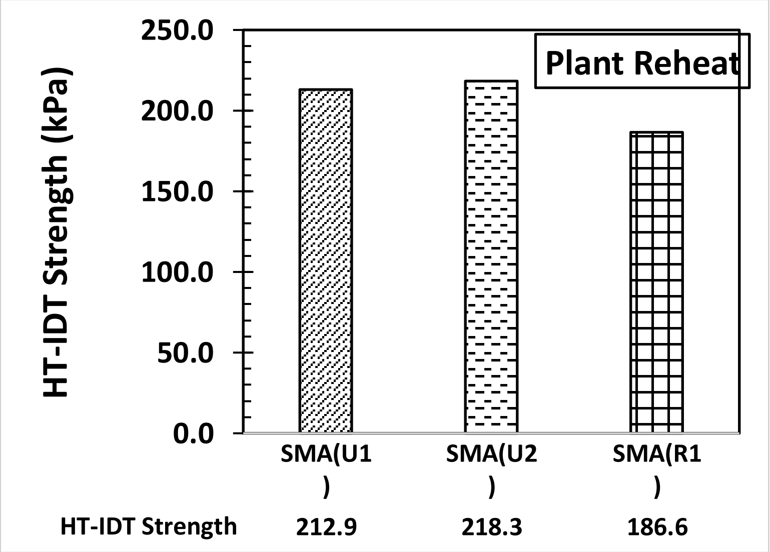
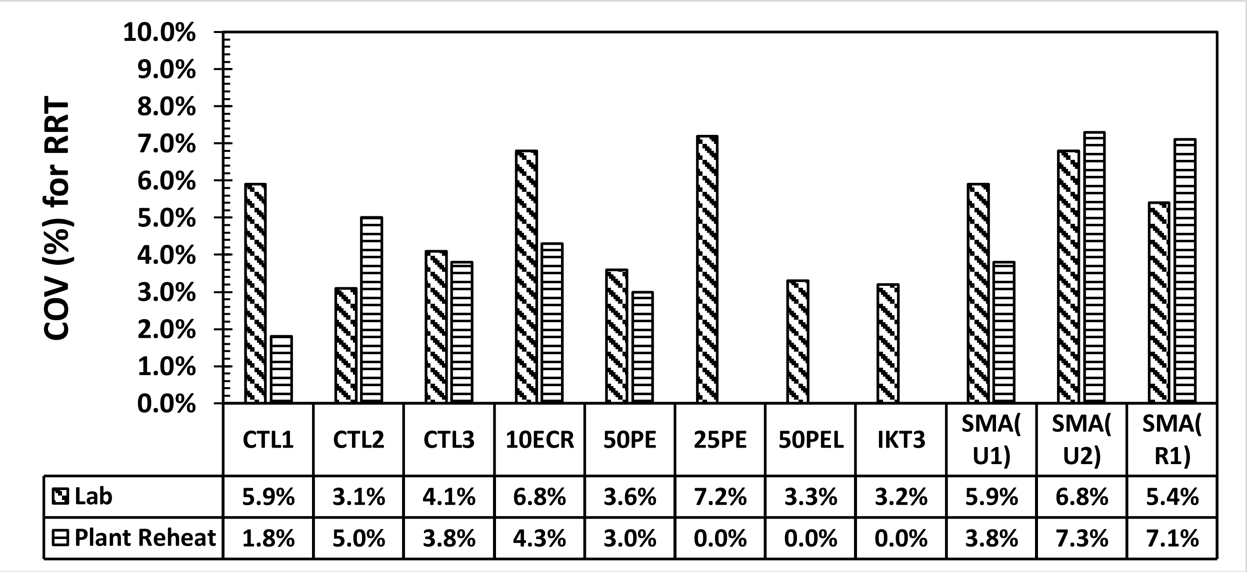


Figure 35. HT-IDT Strengths for Plant Reheat SMA Mixtures

Figures 32-35 illustrate the comparison of the three different SMA mixture's performance for the RRT and HT-IDT tests, considering both lab and plant reheat mixes. The purpose of these charts is to show the variation in performance specifically for the SMA(R1) mixture, as this mix is the only one of the three that is modified with rubber. Furthermore, as stated previously in the mixture characteristics section, the SMA(R1) mix is the same mix design as SMA(U2) with the only difference being the addition of rubber. Therefore, the direct comparison between these two mixtures is the most crucial. However, the SMA(U1) mixture is similar in its characteristics to SMA(U2), so it is also useful in making comparisons of performance with respect to the rubber mix. Looking at the lab specimen testing results for RRT and HT-IDT, the rubber mix (SMAR1) shows a negligible increase in performance compared to its co-mixture (SMAU2) and a slight decrease in performance compared to SMA(U1). For the plant reheated specimens, the rubber (SMAR1) mixtures show a small decrease in rutting performance when compared to the other two unmodified mixtures. Unlike the dense graded mixtures, the SMA's did not show a significant effect on performance when rubber modification was implemented. However, this trend could be expected due to the performance each SMA mix had in the HWTT. Specifically referring back to Figure 13, the rut depths for the three lab and plant reheat SMA mixtures were all very similar with a very small spread between them. Therefore, it should be expected that the same trend of similar performance would be replicated in the RRT and HT-IDT tests. This expectation is shown to be true as the negligible effects of rubber modification in the HWTT are also shown in the results of the RRT and HT-IDT.

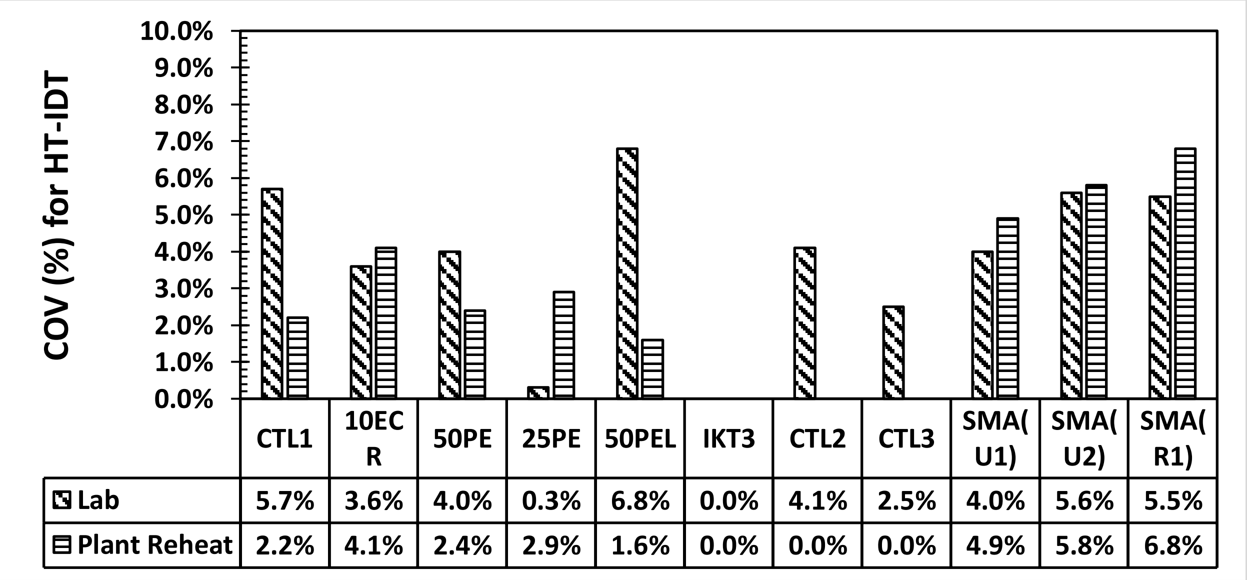
5.5 Statistical Analysis

This section's purpose is to analyze the data results for the RRT and HT-IDT tests from a statistical standpoint. The specific means of statistical analysis include determination of the coefficient of variation for data sets (lab and plant reheat) and using one way ANOVA analysis to determine the statistical significance of difference between lab and plant reheated specimens.



	CTL1	CTL2	CTL3	10ECR	50PE	25PE	50PEL	IKT3	SMA(U1)	SMA(U2)	SMA(R1)
▨ Lab	5.9%	3.1%	4.1%	6.8%	3.6%	7.2%	3.3%	3.2%	5.9%	6.8%	5.4%
⊟ Plant Reheat	1.8%	5.0%	3.8%	4.3%	3.0%	0.0%	0.0%	0.0%	3.8%	7.3%	7.1%

Figure 36. COV Calculation for All Lab and Plant Reheat Dense Graded and SMA Mixtures in RRT Test



	CTL1	10ECR	50PE	25PE	50PEL	IKT3	CTL2	CTL3	SMA(U1)	SMA(U2)	SMA(R1)
▨ Lab	5.7%	3.6%	4.0%	0.3%	6.8%	0.0%	4.1%	2.5%	4.0%	5.6%	5.5%
⊟ Plant Reheat	2.2%	4.1%	2.4%	2.9%	1.6%	0.0%	0.0%	0.0%	4.9%	5.8%	6.8%

Figure 19. COV Calculation for All Lab and Plant Reheat Dense Graded and SMA Mixtures in HT-IDT Test

Figures 36 and 37 illustrate the calculated coefficient of variation (COV) values for each of the 11 different mixtures tested in this study, for both lab and plant reheated specimens. Figure 36 shows the results for the RRT, while Figure 37 shows the results for the HT-IDT. As can be seen in the two figures, the data results for the RRT do not include plant reheat values for CTL2, CTL3, and IKT3 mixes. Data results for these three mixtures are also not shown for the HT-IDT test, with there also being no lab data for the IKT3 mix. As described at the beginning of the "Results and Discussion" section, the target number of specimens for each mixture was set to 8 specimens (contrary to the typical desired number of 3 to 4 specimens) to promote a better evaluation of each of the tests. However, for some of the mixtures the target number of specimens was not reached due to material and time constraints, as well as due to the previously described conditioning issues. Therefore, the above COV values obtained were calculated using the corresponding number of specimens tested for each mixture as shown in Table 1.

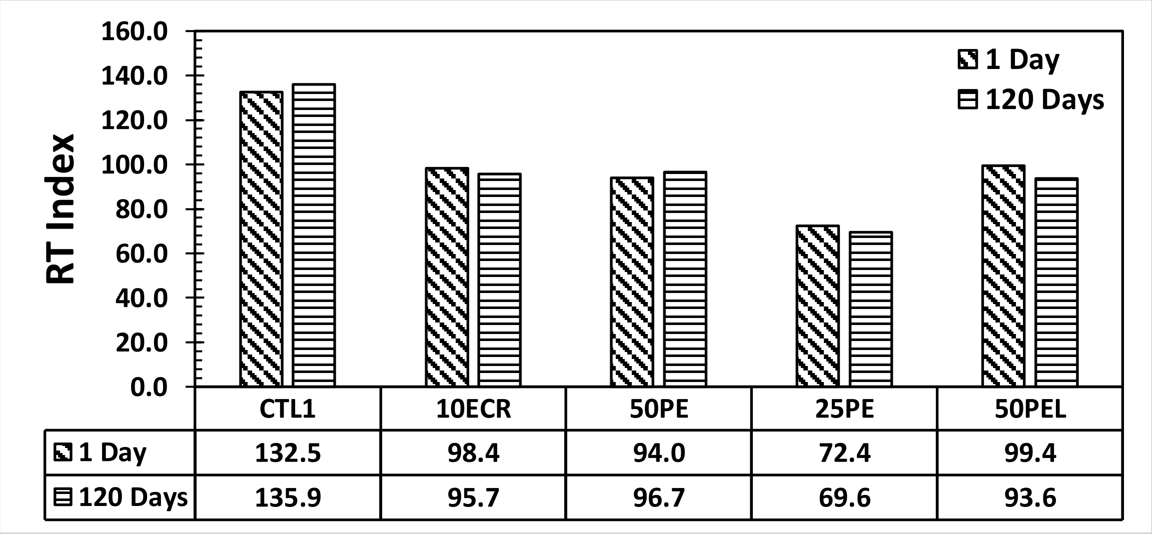
Looking at the calculated COV's for both dense grade and SMA mixture types, it is shown that the range of values obtained fell between 1% to 7%, roughly for the dense graded mixtures. Additionally, the range of values obtained for them were found to be 4% to 7%. Considering Dr. Fujie Zhou detailing that and "ideal rutting test" should be able to produce a COV of less than 10% for three replicates (2), it is safe to say that the data results found in this study support the idea that the RRT and HT-IDT should be considered ideal rutting tests because of their very low COV values for an even higher number of replicates. Furthermore, the low COV values obtained in this study can be viewed as extremely desirable in terms of repeatability when compared to other rutting test's typical COV ranges.

In addition to calculating the COVs for each of the lab and plant reheat mixtures, one way ANOVA analysis was conducted to determine the statistical difference between the lab and plant reheated specimens. For this analysis, an alpha value of 0.05 at a confidence level of 95.0%. From this analysis, it was found that for each dense graded mixture there was a significant statistical difference between the lab and plant reheated specimens, except for the 25PE mix (both in RRT and HT-IDT) and the CTL1 mix (HT-IDT test only). For the SMA mixtures, it was found that all of the mixtures showed a significant statistical difference between the lab and plant reheated specimens. This should be expected as the percent difference values for the SMA mixtures were exceptionally large.

5.6 Effects of Long-Term Shelf-Life Storage

The final analysis conducted in this study focused on the determination of the effects aging had on testing results due to long term storage of asphalt specimens at room temperature. This part of the study was not original in planning. However, in the process of splitting the plant reheated buckets of asphalt there were always roughly two to four extra specimens obtained and not tested because the target number of eight specimens was achieved. Therefore, it was decided by the author to leave these extra specimens on a shelf in the lab for 120 days. After the 120-day time period the specimens were then tested in both the RRT and HT-IDT tests. Below will illustrate the difference in results for dense graded mixtures tested one day after compaction and 120 days after compaction. Extra specimens were not able to be obtained for SMA mixtures, therefore this section will only focus on the dense graded mixtures used in the Stadium Blvd. project.

Figure 38 illustrates the data results for the RRT, showing the RT index values obtained for dense grade plant reheat mixtures at 1 and 120 days after testing. Figure 39 illustrates the percent difference values calculated between the two shelf lifetime periods, with positive values indicating that the 120-day old specimens resulted in higher RT index values. Looking at Figure 39, it is shown that there was no consistent trend in the 120-day old specimens testing higher. It should be noted, that much like the effects of reheating chapter, the expected trend would be that the 120-day old specimens would test higher due to their increased aging from sitting on the shelf as asphalt is continuously aging. However, in this case the level of increased aging is far less significant because simple shelf storage does not impose such a drastic level of aging. Although there was no identifiable trend as previously stated, the key take away from this data is that the percent difference is very low. Moreover, with the range of difference being from -6% to 3%, it is safe to say that dense graded plant mixtures do not exhibit large variation is testing results for the RRT when specimens are left on the shelf for extended periods of time. This is important for asphalt plants to know because it gives them the flexibility with respect to the timing in which they test their asphalt specimens.



	CTL1	10ECR	50PE	25PE	50PEL
▧ 1 Day	132.5	98.4	94.0	72.4	99.4
▤ 120 Days	135.9	95.7	96.7	69.6	93.6

Figure 38. Comparison of 1 Day and 120 Day RT Index results for Plant Reheat Dense Graded Mixtures in RRT Test

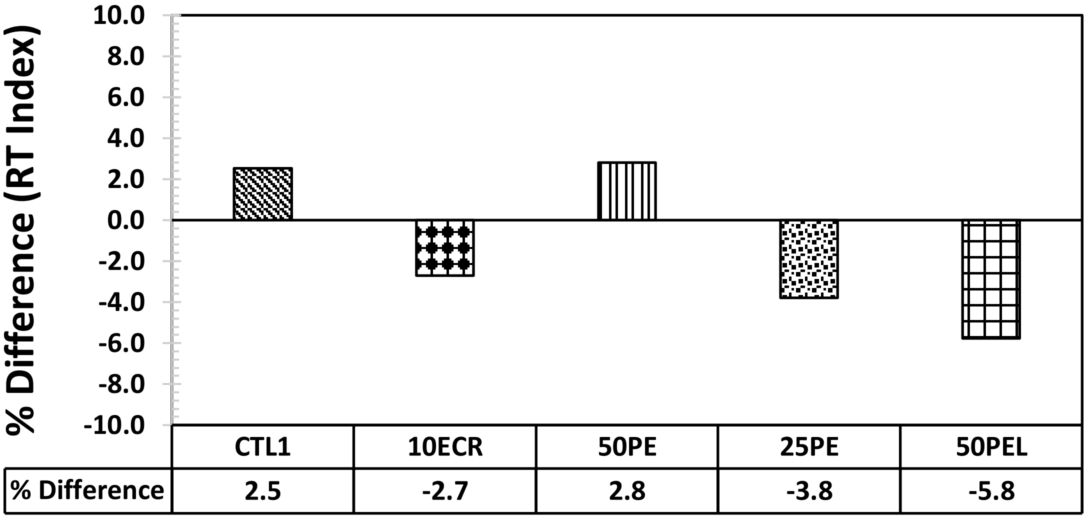


Figure 39. Percent Difference Between 1 Day and 120 Day Dense Graded Plant Reheat Mixtures in RRT

Figure 40 illustrates the data results for the HT-IDT, showing the HT-IDT strength values obtained for dense grade plant reheat mixtures at 1 and 120 days after testing. Figure 41 illustrates the percent difference values calculated between the two shelf lifetime periods, with positive values indicating that the 120-day old specimens resulted in higher HT-IDT strengths. Looking at Figure 41, a similar trend to the RRT results is shown in that there was no consistent trend in the 120-day old specimens testing higher. Although there was no identifiable trend as previously stated, the key take away from this data is that the percent difference is very low. Moreover, with the range of difference being from -3.7% to 3.3%, it is safe to say that dense graded plant mixtures do not exhibit large variation is testing results for the HT-IDT when specimens are left on the shelf for extended periods of time.

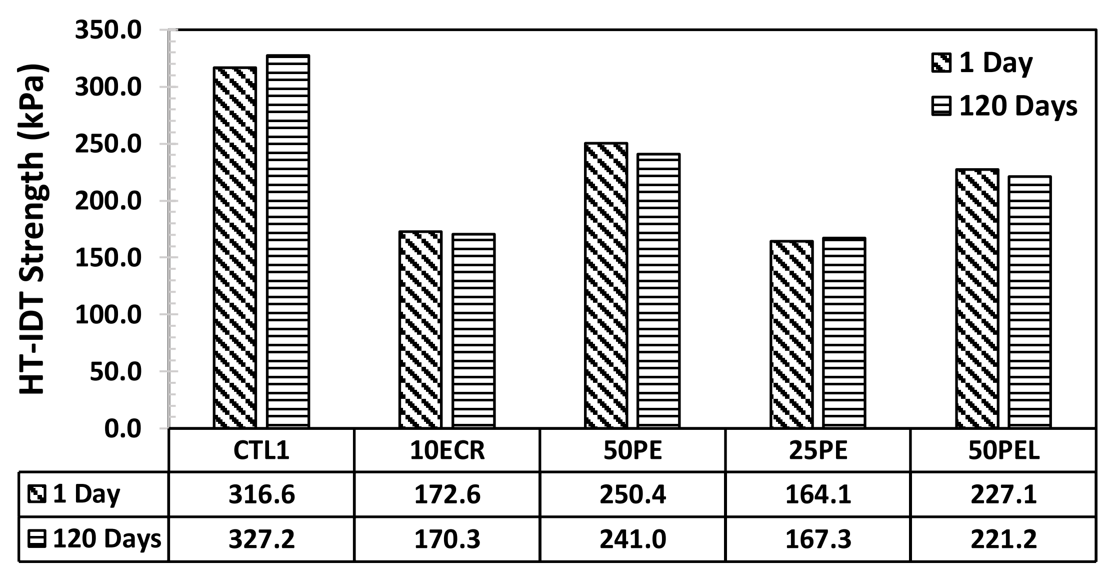


Figure 40. Comparison of 1 Day and 120 Day RT Index results for Plant Reheat Dense Graded Mixtures in HT-IDT Test

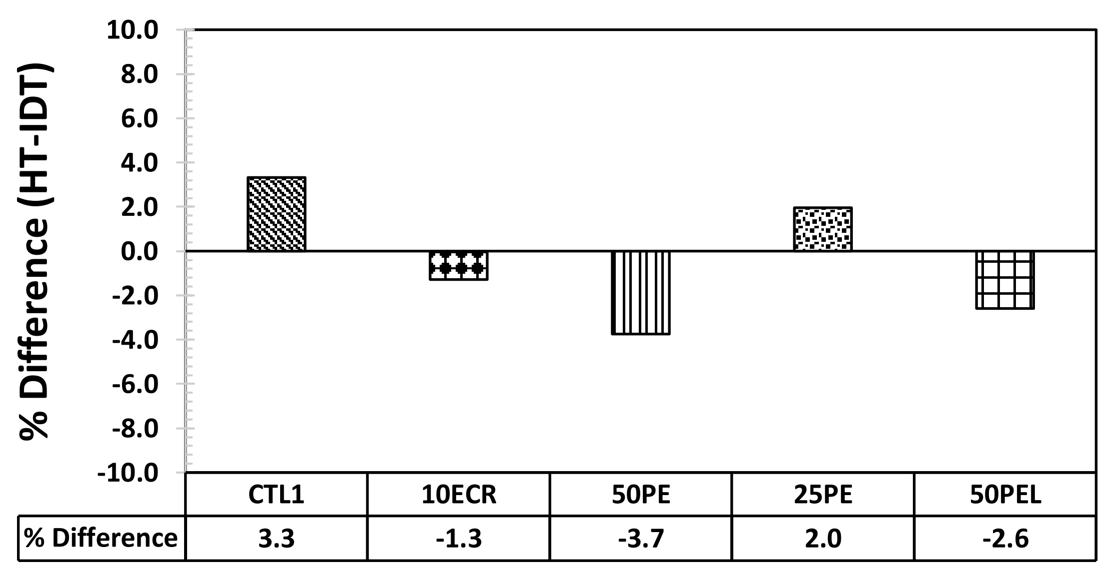


Figure 20. Percent Difference Between 1 Day and 120 Day Dense Graded Plant Reheat Mixtures in HT-IDT

Chapter 6. Conclusions

6.1 Rapid Rutting Test

- The dense graded mixtures tested in the RRT showed desirable correlations for lab mixes with the HWTT and poor correlations for plant reheated mixes. The lab compacted specimens resulted in a R^2 of 84.0%, indicating that the strength of relationship was comparable to that obtained by Dr. Fujie Zhou (85% to 95%). For the plant reheat mixtures, the resulting R^2 value was 45.9% which indicated that there was some level of relationship but not great enough to consider the RRT as a replacement to the HWTT. Due to this drop in correlation strength, it could be concluded that asphalt mixtures that are created at the plant do not correlate as well to HWTT data results as those same mixtures when designed and compacted in a laboratory setting. Furthermore, this drop in correlation strength could impose issues for asphalt plants when conducting quality control and quality assurance procedures.
- The relationship between RT index and HWTT rut depth for SMA mixtures was found to be much lower than the dense graded mixtures. The R^2 values obtained were 14.1% (lab) and 27.3% (plant reheat). Although these values were much lower, this can be attributed to the fact that only three different mixtures were tested compared to the eight tested dense graded mixtures. However, even considering this expectation, it should be concluded that there is a very poor relationship between the RRT and HWTT for SMA mixtures, and furthermore the replacing of the HWTT with the RRT for SMA mixtures should not be considered at this time

- Dense graded mixtures did not show a consistent trend in the effects of reheating. The expected trend would be for the plant reheat mixes to result in higher RT indexes due to their increase in aging and subsequently increased stiffness. However, it was found that only two of the five mixtures tested followed this trend. Therefore, it can be concluded that the effects of reheating were not evident or consistent when testing dense graded mixtures in the RRT.
- All three SMA mixtures did show the expected trend of plant reheated mixtures having higher RT indexes. Although the expected trend was followed, the difference in result was relatively high (54% to 62%). Therefore, it can be concluded that SMA mixtures show the expected trend of plant reheat specimens testing higher in the RRT, but it should be noted that the difference in results is large.
- The effects of additives and modifiers (rubber, plastic, anti-strip) were shown to be present in dense graded lab mixtures. It was found that the anti-strip had negligible effects on the RT index results. However, the addition of rubber and plastic showed a large increase in RRT performance as indicated that these modifiers would in the literature review. Therefore, it can be concluded that the recycled modifiers show the expected increase in performance for dense graded mixtures when tested in the RRT.
- The effects of modifiers in SMAs only pertained to the effects of rubber modification. From the data results for SMAs tested in the RRT, it was found that the addition of rubber into the asphalt mixtures resulted in a very slight decrease in performance for both lab and plant reheat specimens. Therefore, it can be concluded that rubber

modification of SMA mixtures results in almost negligible effects on performance in the RRT.

- The effects of long-term shelf-life storage on dense graded plant reheat mixtures indicated that 120 extra days of storage (increased aging) yielded negligible effects in RRT performance. It was found that there were not consistent 120-day specimens testing higher than 1-day old specimens. Additionally, the resulting percent difference values were found to be very low (<6%). Therefore, it can be concluded that long term shelf-life storage has negligible effects on the performance of plant reheated dense graded mixtures when tested in the RRT.
- Statistical analysis of the dense graded and SMA mixtures indicated a low variation and high repeatability of RRT data results. It was found that the COV for all 11 mixtures in this study ranged from 1% to 8%, which falls below the expected 10% range outlined by Dr. Fuji Zhou. Therefore, it can be concluded that the RRT is highly repeatable for both SMA and dense graded mixtures. When looking at the one-way ANOVA analysis, it was found that a majority of the mixtures, both SMA and dense graded, resulted in significant statistical differences between lab and plant reheated mixtures.

6.2 High Temperature Indirect Tensile Test

- The dense graded mixtures tested in the HT-IDT showed good correlations with the HWTT. The lab compacted specimens resulted in a R^2 of 69.9%, indicating that there was a strong relationship between the calculated RT index and the rut depth obtained in the HWTT. For the plant reheat mixtures, the resulting R^2 value was 81.5% which indicated that there was a stronger relationship. Therefore, it can be concluded that the HT-IDT strength of dense graded mixtures correlate slightly lower to comparable with Dr. Zhou's. Furthermore, based on these correlations it can be concluded that the HT-IDT test is more suitable as a potential replacement for the HWTT rather than the RRT.

- The relationship between HT-IDT strength and HWTT rut depth for SMA mixtures was found to be much lower than the dense graded lab mixtures. However, the correlation between plant reheated mixes was found to be exact with an R^2 equal to 100%. The lab R^2 value obtained was 4.1%. Although the lab value was much lower, this can be attributed to the fact that only three different mixtures were tested compared to the eight tested dense graded mixtures. However, with the very low correlation value it can be concluded that SMAs do not exhibit a relationship with the HWTT that would lead industry to consider the HT-IDT as a replacement for the HWTT for SMA mixtures.
- Dense graded mixtures did not show a consistent trend in the effects of reheating. The expected trend would be for the plant reheat mixes to result in higher HT-IDT strengths due to their increase in aging and subsequently increased stiffness. However, it was found that only three of the five mixtures tested followed this trend. Therefore, it can be concluded that the effects of reheating were not evident or consistent when testing dense graded mixtures in the HT-IDT.
- All three SMA mixtures did show the expected trend of plant reheated mixtures having higher HT-IDT strengths. Although the expected trend was followed, the difference in result was very high (73% to 110%). Therefore, it can be concluded that SMA mixtures

show the expected trend of plant reheat specimens testing higher in the HT-IDT, but it should be noted that the difference in results is very large.

- The effects of additives and modifiers (rubber, plastic, anti-strip) were shown to be present in dense graded lab mixtures. It was found that the anti-strip had negligible effects on the HT-IDT strength results. However, the addition of rubber and plastic showed a large increase in HT-IDT performance as indicated that these modifiers would in the literature review. Therefore, it can be concluded that the recycled modifiers show the expected increase in performance for dense graded mixtures when tested in the HT-IDT.
- The effects of modifiers in SMAs only pertained to the effects of rubber modification. From the data results for SMAs tested in the HT-IDT, it was found that the addition of rubber into the asphalt mixtures resulted in a very slight decrease in performance for both lab and plant reheat specimens. Therefore, it can be concluded that rubber modification of SMA mixtures results in almost negligible effects on performance in the HT-IDT.
- The effects of long-term shelf-life storage on dense graded plant reheat mixtures indicated that 120 extra days of storage (increased aging) yielded negligible effects in HT-IDT performance. It was found that there were not consistent 120-day specimens testing higher than 1-day old specimens. Additionally, the resulting percent difference values were found to be very low (<3.3%). Therefore, it can be concluded that long term shelf-life storage has negligible effects on the performance of plant reheated dense graded mixtures when tested in the HT-IDT.

- Statistical analysis of the dense graded and SMA mixtures indicated a low variation and high repeatability of HT-IDT data results. It was found that the COV for all 11 mixtures in this study ranged from 0.3% to 6.8%. Therefore, it can be concluded that the HT-IDT is highly repeatable for both SMA and dense graded mixtures. When looking at the one-way ANOVA analysis, it was found that a majority of the mixtures, both SMA and dense graded, resulted in significant statistical differences between lab and plant reheated mixtures.

6.3 Considerations for Implementation

Based on the data results that were found for the Rapid Rutting Test and High Temperature Indirect Tensile Test, recommendations were formed based upon the merits of each test, and including a determination of which tests were more suitable for mix design, quality control, and quality assurance. One of the most important takeaways from this thesis pertains to the repeatability of each test. As shown in the data results, it was found that both the RRT and HT-IDT exhibit very low COV values indicating that each of the two tests are highly repeatable. This is important when considering both tests for QA/QC purposes as there would be a low expectation of variation in data results over extended periods of time. When considering these two tests as potential replacements for the HWTT in mix design, it was shown that the HT-IDT performed better than the RRT. However, both test procedures failed to meet desirable relationships with the HWTT throughout the testing of dense graded and lab graded mixtures. Another major downfall of these two tests involved their performance at different levels of aging due to reheating of plant mixtures. Therefore, there should be caution when considering implementation of these two tests for QA/QC due to the inconsistencies found when comparing lab and plant reheat mixtures.

Chapter 7. Future Work

- One of the key items that this study further encourages more research be done pertains to increasing the number of mixes tested in both tests. For the dense graded mixtures, it would be beneficial to incorporate more mixes that do not use RAP, as RAP is known for increasing the variability of mixture performance of asphalt for all types of testing. Additionally, it would be beneficial to greatly increase the number of SMA mixes tested as in this study only three were used. Given that SMAs are highly resistant to rutting, it is important to provide more SMA mixtures with a larger spread in HWTT results so that a better understanding of the correlation between all three tests can be understood. Overall, increasing the number of mixes tested in the RRT and HT-IDT will be crucial for developing more accurate relationships between rut depth, RT index, and HT-IDT strengths.
- The next area of interest to further the spectrum on research on the RRT and HT-IDT pertains to the sensitivity of each testing procedure. As outlined by Dr. Fujie Zhou, an ideal rutting test should be sensitive to properties of asphalt mixtures such as binder content, binder type, aggregate type, air void content, recycled materials, and levels of aging. Therefore, it would be beneficial to further research how sensitive the RRT and HT-IDT tests are to these properties. By doing so, it will provide the industry with much

greater knowledge on how severe some of these properties affect the data results of each test.

- Tied in with sensitivity testing, it would be useful for the industry to better understand the ruggedness of these two tests. Therefore, beneficial research would be to run a ruggedness testing procedure in accordance with ASTM 1067. By doing so, it would allow industry to better detect and reduce sources of variation in the RRT and HT-IDT. Also, ASTM 1067 would allow for the evaluation of precision for each of these two tests.
- Lastly, it would be beneficial for research to further explore the effects of conditioning asphalt specimens in an air-controlled chamber (used in this study) as well as conditioning in a water bath. As briefly discussed in this study, there were instances of problematic conditioning in the air-controlled chamber which resulted in the exclusion of some data results. Therefore, it is important to further research this specific area so that industry has a better understanding of the impactful effects that conditioning can impose on the data results.

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APPENDIX A: IMAGES OF TESTED SPECIMENS IN HWTT

APPENDIX B: IMAGES OF TESTED SPECIMENS IN HT-IDT

APPENDIX C: IMAGES OF TESTED SPECIMENS IN RRT