Exploring the Use of Monotonic Loading Tests to Evaluate Rutting Performance of Asphalt Mixtures

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Abstract

Many state agencies are considering the use of Balanced Mix Design (BMD) method to design and produce asphalt mixtures for their roadways. The shift to the BMD method is an effort to make roadways more sustainable, longer lasting, and more economical by incorporating performance criteria for asphalt mixtures into mix design and production acceptance. In the BMD method, asphalt mixtures are designed and evaluated through a suite of laboratory tests to ensure adequate performance. Rutting, or permanent deformation, is one of the main distress modes of asphalt pavement. In Virginia, the current rutting test used for mix design acceptance as part of the BMD method is the asphalt pavement analyzer (APA) test, which is both time consuming and costly. Therefore, it is important to have simpler and more practical but still reliable and accurate screening tools to test asphalt mixtures for rutting resistance.

The goal of this study was to investigate more time efficient and cost effective performance-based tests to evaluate the rutting resistance of asphalt mixtures. Based on an extensive review of available literature, three monotonic loading tests that showed promising potential to characterize rutting of asphalt mixtures were evaluated including the indirect tensile (IDT) test at high temperatures, rapid rutting test (RRT or also known as ideal rutting test [IDEAL-RT]), and Marshall stability (MS) test. The experimental program of this study was divided into two phases.

In Phase 1, sixteen asphalt mixtures were tested under the IDT test, IDEAL-RT, MS test, and APA test. These tests were evaluated in terms of variability, sensitivity, and correlations among rutting indices. Phase 1 experimental results were used to assess the ability of the monotonic loading tests to determining rutting resistance of asphalt mixtures and were further used to develop corresponding preliminary threshold criteria. In Phase 2, six asphalt mixtures were further evaluated using Asphalt Mixture Performance Tester (AMPT) tests including the dynamic modulus (DM) test, stress sweep rutting (SSR) test, and the repeated load triaxial test (RLTT). Phase 2 experimental results were compared and correlated to the IDT, IDEAL-RT, and APA test results to further evaluate the ability of monotonic loading tests to characterize rutting resistance of asphalt mixtures.

Additionally, this study looked at the utilization of digital image correlation (DIC) as a technique for examining the failure mechanism of asphalt specimens when tested under monotonic tests typically performed at relatively high temperatures. This was a preliminary study of how DIC can potentially be utilized to select, identify, and/or develop parameters that characterize rutting resistance from these monotonic loading tests.

Based on this study, it was found that monotonic loading tests, specifically IDT test at high temperature and IDEAL-RT, can be used to evaluate rutting performance of asphalt mixtures. Preliminary rutting performance threshold criteria were developed for the IDT test and IDEAL-RT based on correlations to the APA test. Further evaluation of these two monotonic loading tests and parameters is recommended to fully develop a specification for agencies and contractors to use a monotonic loading test to evaluate rutting performance of asphalt mixtures.

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1. Introduction

1.1 Background and Motivation

Rutting, or permanent deformation, is one of the primary ways asphalt pavements deteriorate [1]. Rutting in early stages is due to inadequate rutting resistance of the surface layer of the asphalt. In addition to safety issues (i.e., hydroplaning, and other wet weather accidents), premature rutting is extremely costly to taxpayers in repairs that also cause traffic delays [2]. To be confident that asphalt mixtures used for roadways will resist rutting, asphalt mixtures are tested to ensure adequate rutting resistance before being put into use. The asphalt pavement analyzer (APA) test is currently used to screen mixtures for rutting resistance in Virginia. While the APA test gives an effective prediction of the rutting resistance of asphalt mixtures, it takes approximately at least 8.5 hours to complete the test (i.e., from specimen conditioning to conducting the test). In addition, the APA machine and its frequently required maintenance are costly, and the APA machine is not readily available in laboratories of many contractors. For these reasons, contractors and state agencies find it challenging to use the APA test to screen for rutting resistance during the mix-design process and impractical for use in quality assurance during plant production. Therefore, a performance based test, that is less time consuming (e.g., simple and practical) and less costly (i.e., affordable), is desired as an alternative way to screen mixtures for rutting.

Previous studies [3-12] indicated that conducting the indirect tensile (IDT) test at high temperatures can be utilized as an evaluation of rutting performance of asphalt mixtures. Therefore, the high-temperature IDT test was selected for evaluation of its potential to be used as a rutting screening tool. Additionally, a U-shape fixture, inspired by the three-point bending beam test setup, was developed by researchers at Texas Transportation Institute (TTI) [13]. The U-shape fixture is meant to be used as a specimen support platform (i.e., the test fixture). The report by TTI concluded that shear failure is induced within an asphalt specimen using this U-shape fixture which may more properly characterize rutting resistance of asphalt mixtures when compared to the standard IDT test at high temperatures [13]. This test is known as the ideal rutting test, or IDEAL-RT [13], and was selected for evaluation in this study. Lastly, the

Marshall stability and flow (MS) test, as standardized in ASTM D6927 *Standard Test Method for Marshall Stability and Flow of Asphalt Mixtures* [14], AASHTO T 245 *Resistance to Plastic Flow of Asphalt Mixtures Using Marshall Apparatus* [15], and ASTM D5581 *Standard Test Method for Resistance to Plastic Flow of Bituminous Mixtures Using Marshall Apparatus (6 in. Diameter Specimen)* [16] was also evaluated in this project for its use as a rutting screening tool for asphalt mixtures. The MS testing setup is similar to the IDT test and IDEAL-RT setups except that the specimen is placed between two steel halves which induces a different stress state in the specimen than those induced by the IDT and IDEAL-RT tests. While there are more than these three monotonic tests that could be evaluated for their ability to be used as a rutting test, the three selected monotonic tests in this study were chosen based on their strong potential to be a rutting test from previous literature as well as their simplicity and availability in the laboratories used. Therefore, these three monotonic loading tests, namely the IDT test, IDEAL-RT, and MS test, were selected for evaluation of their ability to measure rutting performance in asphalt mixtures.

1.2 Purpose and Scope

The purpose of this study was to evaluate the use of a monotonic loading test for evaluating the rutting potential of asphalt mixtures. To that extent, three tests were selected for evaluation including the IDT test, IDEAL-RT, and MS test. A literature review was conducted at the beginning of this study to better understand how these monotonic loading tests, along with other state-of-the-art asphalt rutting tests, are used in asphalt mixture testing.

In Phase 1 of this project, each of these tests (IDT, IDEAL-RT, and MS) were conducted on sixteen different asphalt mixtures. These sixteen mixtures were also tested using the APA test. The BMD special provision in Virginia requires a rut depth threshold of 8 mm at 64°C after 8000 loading cycles for asphalt mixtures with A and D designations [17]. This set of testing was conducted in order to evaluate the sensitivity and variability of each test as well as establish correlations between the APA test and the three monotonic tests.

In Phase 2 of this study, six asphalt mixtures were tested and evaluated using the asphalt mixture performance tester (AMPT). The tests conducted in this phase included the dynamic modulus (DM) test, stress sweep rutting (SSR) test, and the repeated load triaxial test (RLTT). The AMPT-based tests are performed to measure fundamental properties of the evaluated asphalt mixtures. These tests are known to be both time consuming and relatively complex. The determined fundamental rutting properties of the six evaluated mixtures were then compared to results from the monotonic loading tests as well as the APA test. Finally, Digital image correlation (DIC), which is a full-field, optical, non-contact measurement technique [18], was utilized with monotonic tests to explore the ability of DIC to examine the mechanism by which asphalt specimens fail in these test configurations.

Conclusions were drawn from each phase of this study regarding the ability of a monotonic loading test to predict rutting performance of asphalt mixtures. Further studies are recommended to further refine rutting performance thresholds for a monotonic loading test and determine if such a test can be used in place of the APA test. This would allow contractors and agencies to use machines they already own to conduct quality control and assurance tests for rutting resistance efficiently and effectively. The specimen preparation time is the same for the APA and monotonic loading tests, but the specimen conditioning and test time required would significantly decrease from over eight hours (APA test) to less than 2.5 hours (high-temperature monotonic loading test).

1.3 Organization of Thesis

First, this thesis includes a literature review on the three monotonic tests that show potential to be utilized for rutting performance evaluation in asphalt mixture design and quality testing. Literature on other rutting tests was also reviewed and summarized. This literature review also discusses digital image correlation (DIC) and its use in asphalt mixture testing.

Next, the experimental program is outlined with discussions on materials, mixture properties, and methods. The experimental program was divided into two phases of testing, namely Phase 1 and Phase 2. The experimental testing program, evaluation of tests, and experimental results for each phase are presented.

The thesis next presents experimental testing utilizing DIC with discussions on the procedure for DIC testing with cylindrical asphalt specimens, examples of results that can be obtained from DIC analysis, and discussions on what can be gained from this technique in regard to developing a monotonic loading test to screen for rutting resistance. This section also includes discussions on future work incorporating DIC to examine alternative parameters of the proposed monotonic loading tests that characterize rutting resistance. Finally, overall conclusions from this study are summarized and future research is discussed.

2. Literature Review

Agencies across the United States have recently increased their interested in the BMD concept. Central to the BMD method are performance-based tests conducted to ensure adequate failure resistance in asphalt mixtures. This testing is focused on the two primary modes of distress: cracking and rutting [19]. If index-based tests are used, the BMD method leads to more simple and quick ways to evaluate asphalt mixture performance through performance tests. In recent years, several simple and quick monotonic loading test methods have been standardized as means to evaluate cracking in asphalt, even more recently these tests are being considered as means to evaluate rutting. There is a current need for a quick and simple test for rutting as part of the efforts toward implementing the BMD method. In an effort to better understand the use of monotonic loading tests to evaluate rutting potential of asphalt mixtures both in the mixture design and production stages, a literature review was conducted on relevant asphalt mixture tests. This literature review provides information on asphalt mixture tests including the IDT test, IDEAL-RT, MS test, Simple Punching Shear Test (SPST), and deformation strength (SD) test. Additional details and discussions on these tests can be found elsewhere [20]. Moreover, a review literature on the use of the digital image correlation (DIC) method, a non-contact measurement technique, was performed and summarized.

2.1 Indirect Tensile (IDT) Test

The indirect tensile (IDT) test is a simple test method that has been used for evaluation of asphalt mixtures for several decades [21]. In this test, a constant displacement-controlled load rate is applied to the diametrical plane of a cylindrical asphalt specimen. The IDT test can be performed at different temperatures and loading rates to estimate the potential susceptibility of asphalt mixtures for various modes of distress. For instance, this test is used along with two other tests, as described in AASHTO T 322 [22], to evaluate low-temperature properties of asphalt mixtures, predict long-term stripping susceptibility of asphalt mixtures in AASHTO T 283 [23], and to evaluate cracking potential of asphalt mixtures at intermediate temperatures in ASTM D8225 [24]. In the last two decades, the IDT test conducted at high temperatures as a means to evaluate rutting performance of asphalt mixtures has been the subject of many studies. While there is not a standardized protocol for evaluating rutting performance using the IDT test, specimens are typically conditioned at a relatively high temperature for a period of time prior to conducting the test. Then, specimens are placed under a constant displacement-controlled load. This load rate can be slower when a temperature controlled chamber encloses the test apparatus. When the test apparatus is at room temperature, the load rate is recommended to be faster in order to prevent the loss of specimen test temperature during the test. Figure 1 shows the typical IDT test setup at room temperature used for rutting performance evaluation of asphalt mixtures.

Figure 1 - IDT test setup for rutting evaluation

The IDT strength is typically used as a measure of rutting performance of asphalt specimens. The IDT strength (S_t in kPa) is calculated using Equation 1 where P is the maximum load in N, t is the specimen thickness in mm, and D is the specimen diameter in mm.

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

Equation 1

Christensen et. al. [5] studied the IDT test as a simple test to evaluate rutting performance of dense-graded asphalt mixtures. The authors stated that high tire pressures induce significant tensile stresses at the pavement surface which can result in high shear stresses at or near the pavement surface. This stress state is somewhat identical to that of the IDT test, indicating that the IDT test at high temperature can be a good predictor of rutting performance of asphalt mixtures. In this study, the IDT test specimens were compacted to a height of 100 mm and diameter of 150 mm with 4% air voids. The test loading rate was selected to be 3.75 mm/min and the tests were performed at 33°C. The IDT strength results were compared to the maximum permanent shear strain (MPSS) from the repeated shear at constant height (RSCH) test, which is used to quantify rutting performance of mixtures. The RSCH test was conducted at 53°C on 4% air void specimens with dimensions of 50 mm in height and 150 mm in diameter. For both tests, specimens were subjected to short term aging for four hours at 135°C. The researchers found a good linear correlation between IDT strength and MPSS with an R^2 value of 80%, as shown in Figure 2.

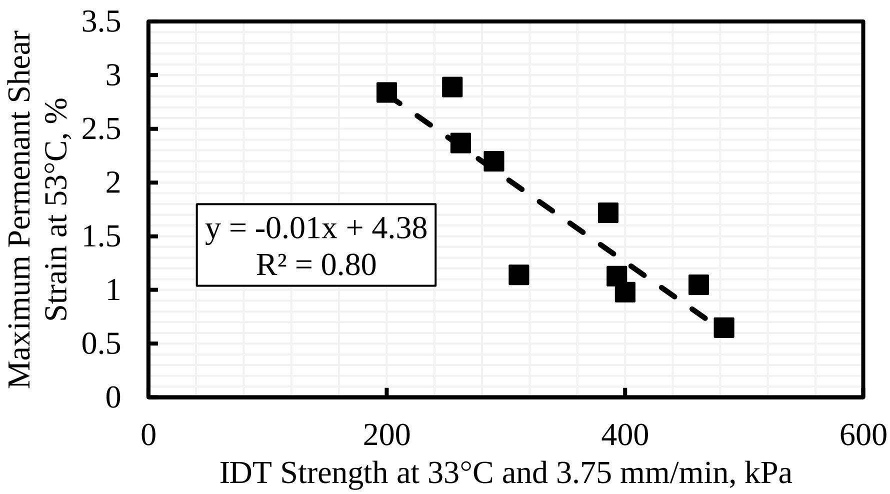


Figure 2 - Correlation between IDT strength and MPSS [5]

Christensen et. al. [5] also developed preliminary criteria for determining rutting performance of mixtures based on IDT strength as shown in Table 1. The authors stated that these criteria are only applicable to the test conditions specific to their study.

Table 1 - Preliminary rutting performance criteria from IDT test [5]

Rut Resistance Performance	IDT Strength Criteria, kPa
Excellent	IDT > 440
Good	320 < IDT ≤ 440
Fair	220 < IDT ≤ 320
Poor	IDT ≤ 220

Later, a verification study [8] was conducted to further evaluate the findings of Christensen et. al. [5]. The IDT tests were conducted under the same conditions used in the Christensen et. al. study [5]. This study confirmed earlier findings of a strong linear correlation between IDT strength and MPSS from the RSCH test with an R^2 of 88% [8]. Moreover, using the data from the verification study, Christensen et. al. [7] compared IDT strength results to the number of wheel passes at different rut depths from the Federal Highway Administration (FHWA) accelerated loading facility (ALF) test. The ALF is a full scale loading tool for evaluating asphalt mixtures for cracking and rutting. The authors found a strong correlation between IDT strength and the number of FHWA ALF wheel passes at different rut depths, shown in Figure 3. The fitted lines in this figure are based on an exponential fitting in a semi-arithmetic scale.

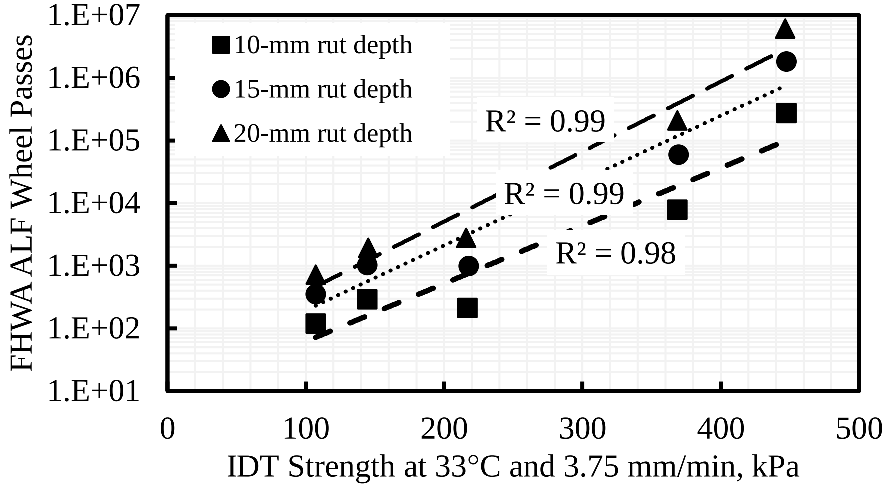


Figure 3 - Correlation between IDT strength and FHWA ALF wheel passes [7]

Zaniewski and Srinivasan [11] studied the feasibility of evaluating rutting potential of asphalt mixtures using the IDT test at a high temperature by comparing IDT strength results to rut depth measured by the APA test. Sixteen different mixtures were tested in this study. Test specimens with 7% air voids, height of 75 mm, and diameter of 150 mm were used for both the IDT and APA tests in this study. IDT test specimens were conditioned at 60°C using a water bath and tested with a load rate 50 mm/min. The APA tests were conducted at 60°C with a hose pressure of 100 psi and wheel load of 100 lbs. and the rut depth determined after 8000 wheel passes. The authors found an exponential correlation with an R^2 of 81% between IDT strength and APA rut depth using an exponential fit as shown in Figure 4.

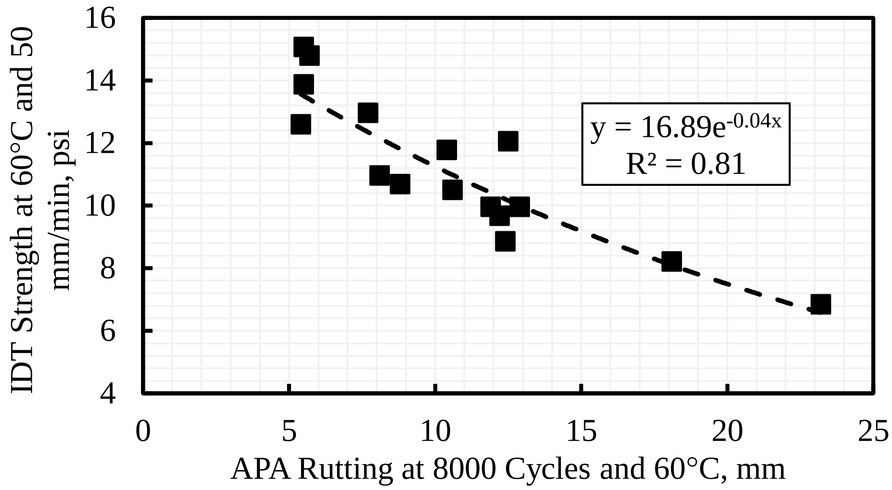


Figure 4 - Correlation between IDT and APA tests [11]

Christensen and Bonaquist [6] studied the feasibility of using the IDT test with a new procedure to evaluate rutting performance of asphalt mixtures. The authors conducted IDT tests at 10°C below the critical pavement temperature (the temperature at 20 mm below the pavement surface at 50% reliability, as determined by the Long-Term Pavement Performance Bind (LTPPBind) software for permanent deformation [20], as opposed to the temperature chosen by Christensen et. al. [5] of 20°C below the critical pavement temperature, and at a load rate of 50 mm/min. The load rate of 50 mm/min was chosen as it is the fixed loading rate used on the standard Marshall press which is commonly found in asphalt laboratories. Christensen and Bonaquist [6] conducted IDT tests using the original protocol (30°C and 3.75 mm/min load rate [5]) and the new protocol (40°C and 50 mm/min load rate [6]) and found an excellent linear correlation between the two procedures with an R^2 value of 99%. This confirmed that the IDT test could be conducted using this new protocol, at 40°C with a load rate of 50 mm/min, to evaluate rutting performance of asphalt mixtures.

Christensen and Bonaquist [6] revised guidelines for interpreting the IDT strength as a function of the design traffic level, shown in Table 2. Equation 2 estimates the allowable traffic for a mixture as a function of IDT strength where TR_{max} is the maximum allowable design traffic for a given mixture in million equivalent single axle loads (ESALs) and *IDT* is the IDT strength in kPa.

$$TR_{max} = 1.97 * 10^{-5} * IDT^{2.549}$$ *Equation 2*

*Table 2 - Guidelines for using IDT strength to evaluate rutting performance of asphalt mixtures**

Design Traffic Level** Million ESALs [at 70 km/h (44 mph)]	IDT Strength Range, kPa	Rut Resistance Performance
<0.3	< 50	Very Poor
0.3 to <3	50 to < 110	Poor
3 to < 10	110 to < 170	Minimal
10 to < 30	170 to <270	Fair
30 to < 100	270 to < 430	Good
100 to < 300	430 to < 660	Very Good
> 300	≥ 660	Excellent

* This table is the corrected version of the original table by Christensen and Bonaquist [6] using Equation 1.
**To adjust estimated traffic level to 70 km/h, multiply by (70/v), where v is the average traffic speed in km/h.

The traffic speed used to develop the guidelines in Table 2 above was based on 70 km/h (44 mph). Therefore, for other traffic speed levels the estimated traffic level should be adjusted by a factor of 70/v, where v is the average traffic speed in km/h. The criteria given in Table 2 are only applicable to gyratory-compacted specimens, as they were developed from specimens compacted to an air void content of 4.0 ± 0.5% with a 150 mm in diameter and a height of 115 ± 5 mm. The test temperature used was 10°C below the yearly, 7-day average, maximum pavement temperature at 20 mm below the pavement surface.

Khosla and Harikrishnan [25] explored the IDT strength at 25°C with a loading rate of 50 mm/min as a design and evaluation tool for rutting of Superpave mixtures. The researchers conducted IDT tests on specimens designed according to Superpave design guidelines with dimensions of 150 mm in diameter, 100 mm in height, and 7 ± 1% air voids. The IDT tests were conducted following AASHTO T 283 [23]. The rutting potential of the asphalt mixtures tested was quantified through the RSCH test conducted at 58.5°C on specimens with dimensions of 150 mm in diameter, 50 mm in height, and 7 ± 1% air voids. The authors found that the IDT strength is related to rut depth in that a higher IDT strength indicated a greater resistance to rutting [25].

A correlation between IDT strength and plastic shear strain from the RSCH test with an R^2 of 62% was determined using a polynomial regression. Based on this study, the authors recommended a threshold for adequate rutting resistance of a minimum IDT strength of 517.1 kPa using the test procedure from these experiments (25°C test temperature and 50 mm/min loading rate).

In 2013, Wen and Bhusal [10] explored the IDT test as a means of predicting rutting potential of asphalt mixtures by comparing IDT test results to that of the unconfined flow number (FN) test performed according to AASHTO TP 79 [26] (currently AASHTO T 378 [27]). The researchers tested Superpave-designed mixtures with a single binder type and varying recycled concrete aggregate content. In this study, IDT tests were conducted at 46°C with a load rate of 50 mm/min on specimens with dimensions of 38 mm in height, 100 mm in diameter, and air void content of 7%. The FN tests specimens were 150 mm in height and 100 mm in diameter with 7% air voids and were tested at 54°C. In the FN test, specimens were subjected to a deviatoric stress of 600 kPa with a contact stress of 10 kPa. An excellent linear relationship was found between IDT strength and flow number, a measure of permanent axial strain, with an R^2 of 99%.

Takahashi and Tran [9] explored the relationship between IDT strength and the rutting measurement (dynamic stability) from the Japanese wheel tracking test (WTT) using 13 different asphalt mixtures. The air voids of the specimens used in varied from 4% to 6%. The specimens had a height of 25 mm or 30.8 mm depending on the type of mixture. All specimens in the study had a diameter of 101.7 mm. For the IDT test, load rates of 2.5 mm/min or 3 mm/min depending on specimen height were used at a test temperature of 30°C. The WTT test was conducted at 60°C, a wheel speed of 42 cycles/min, and load on the wheel of 686 N. The authors found a linear correlation between IDT strength and WTT rutting with R^2 values of 85% or 80%, depending on specimen dimensions and air void content. The authors recommended a threshold for adequate rutting resistance of an IDT strength of at least 300 kPa, which is specific to the types of mixtures in this study.

Bennert et. al. [4] conducted a study comparing IDT test results to APA test results to examine the potential of using the IDT test as a performance test to determine rutting in asphalt mixtures for the New Jersey Department of Transportation (NJDOT). In this study, the IDT test was performed following AASHTO T 283 [23] on specimens 150 mm in diameter and 95 mm in height using a Marshall compression machine. These IDT tests were conducted at 44°C with a loading rate of 50 mm/min. The researchers conducted APA tests using a hose pressure of 689.5 kPa and vertical wheel load of 45.4 kg. The air voids for specimens were kept consistent for a given mixture, although they varied across mixtures used in the study. An exponential fit correlating the IDT strength and APA rutting results was determined with an R^2 of 80%. In this study, Bennert et. al. [4] found the coefficient of variation (COV) for IDT tests was lower than that for APA tests, with average COVs of 6% and 9.6%, respectively. The authors proposed IDT strength-based pass/fail criteria for rutting in asphalt mixtures as shown in Table 3. These criteria were based on previously established APA criteria.

Table 3 - Proposed rutting limits for IDT strength for NJDOT [4]

NJDOT Asphalt Mixture Type	APA Rutting Limit, mm	IDT Strength Limit, kPa
High-performance thin overlay	< 4	> 324.1
Bituminous-rich intermediate course	< 6	> 206.8
High RAP-surface course	< 4	> 324.1
High RAP-inter/base course	< 7	> 172.4

RAP = reclaimed asphalt pavement.

Zielinski [28] investigated using the IDT test to evaluate rutting performance of asphalt mixtures by comparing IDT test results to rutting test parameters from a wheel tracker test at 60°C conducted following the Polish specifications. This study consisted of 21 asphalt mixtures with various characteristics. For the IDT test, specimens of 100 mm in diameter and 50 mm in height were tested using a Marshall press at 40°C with a load rate of 50 mm/min. The COVs for IDT test results in this study were below 10%. Using a power function, the author found a good correlation between IDT results and the wheel tracker test rutting parameter with an R^2 value of 82%.

Yin et. al. [29] studied the IDT test and its potential as a surrogate rutting test to the Hamburg Wheel Tracker Test (HWTT) utilizing five different asphalt mixtures in a testing program. In this study, the IDT test temperature was 50.2°C and the load rate was 50 mm/min. The IDT test specimens were 62 mm in height and 150 mm in diameter with 7 ± 0.5% air voids. The HWTT test was conducted at 50°C following AASHTO T 324 [30]. This study showed a linear correlation between the IDT test and HWTT with an R^2 of 63%. Additionally, the IDT test results showed a maximum COV of 15.1%.

In a subsequent study to Bennert et. al. [4], Bennert et. al. [31] further evaluated the IDT test as a predictor of rutting performance. The researchers updated their initially proposed IDT performance criteria by conducting both IDT and APA tests on 54 different asphalt mixtures. IDT tests were conducted at 44°C with a load rate of 50 mm/min. IDT specimens were 95 mm in height based on AASHTO T 283 [23], conditioned for 2 hours ± 10 minutes in a water bath without bags, and tested within 2 minutes of removal from the water bath. APA tests were conducted at 64°C based on AASHTO T 340 [32] and the rut depth at 8000 cycles was compared to IDT strength results. Air void content was consistent for all mixtures tested. Using a logarithmic based linear trend line, a high correlation was found between IDT strength and APA rut depth with an R^2 of 89%. The authors proposed tentative rutting criteria for the IDT test based on existing APA performance criteria, shown in Table 4 [31].

Table 4 - Tentative rutting resistance limits using IDT test [31]

Asphalt Mixture Type	APA Rutting Limit, mm	IDT Strength Limit, kPa
High-performance thin overlay	< 4	> 324.1
Bituminous-rich intermediate course	< 6	> 206.8
High RAP-surface course (PG64E-22)	< 4	> 324.1
High RAP-surface course (PG64S-22)	< 7	> 158.6
High RAP-inter/base course (PG64E-22)	< 4	> 324.1
High RAP-inter/base course (PG64S-22)	< 7	> 172.4

RAP = reclaimed asphalt pavement; PG = performance grade; S and E = standard and extremely high traffic.

The Alabama Department of Transportation (ALDOT) developed a BMD special provision to design and place asphalt mixtures on local roads in 2020 [33], requiring the IDT high temperature test be conducted to evaluate the rutting performance of asphalt mixtures. Based on this provision [33], specimens of 62 mm or 95 mm in height, depending on the mixture nominal maximum aggregate size (NMAS), and 150 mm in diameter with air voids of 7 ± 0.5% are tested with the IDT test after short-tern oven conditioning for four hours at 135°C. The IDT tests are performed at 50°C, after two hours of conditioning at this test temperature, with a loading rate of 50 mm/min. The provision states a minimum IDT strength of 137.9 kPa is required for passing rutting performance.

2.2 Ideal Shear Rutting Test (IDEAL-RT)

In an effort to further develop a simple monotonic test to evaluate rutting performance of asphalt mixtures, Zhou et al. (2019) [13] recently developed an ideal shear rutting test (IDEAL-RT) with eight (8) desirable features: simplicity, efficiency, practicality, low cost, repeatability, sensitivity, manifesting rutting mechanism, and good correlation with field rutting performance. Due to the significant impact of rutting resistance on pavement performance and road safety, it is critical to have a practical and rapid test for asphalt rutting resistance for routine use by agencies and contractors in the processes of laboratory mix design, plant production, and field placement. The authors determined a shear rutting mechanism for the IDEAL-RT inspired by the three-point bend beam test and IDEAL cracking test (IDEAL-CT). This ideal shear fixture was developed in two forms: a portable fixture that can be used with any loading frame and a detachable fixture that can be attached to any universal machine. The IDEAL-RT involves cylindrical specimens, a deformation-controlled loading rate of 50 mm/min, and a test relatively high temperature. It was recommended to use the same specimen size as the HWTT: 150 mm diameter, 62 mm height, and 7 ± 0.5% air voids. Figure 5 shows the IDEAL-RT setup both before and after the specimen is placed for testing.

Figure 5 - IDEAL-RT setup with u-shape fixture

The rutting potential from this test is quantified through the shear strength. The maximum shear strength (τ_{max}) can be calculated using Equation 3 below where P is the peak load in kN.

$$\tau_{max} = 0.356 * P \qquad \textit{Equation 3}$$

Zhou et. al. (2019) [13] proved that the IDEAL-RT is sensitive to key components of asphalt mixtures (asphalt binder content, binder type, air voids, aggregates, reclaimed asphalt pavements (RAP) and recycled asphalt shingles (RAS), and aging conditions). The IDEAL-RT was also found to be repeatable with a maximum COV of 6.7%, much lower than that of other standard rut tests including the HWTT and APA. Additionally, the IDEAL-RT correlates well with the HWTT and the RLTT, two established laboratory rutting tests, with the trend being the larger the IDEAL-RT shear strength the more rut resistant the mixture. Moreover, the IDEAL-RT was validated by field tests, showing good correlation with Texas Field test sections on FM468, MnROAD 2008 test sections, and WesTrack test sections. It was determined that due to different traffic conditions and climate differences, more field validation remains necessary. Other recommendations include a ruggedness test to refine the test procedure and an inter-laboratory study to define precision and bias of the IDEAL-RT.

Zhou et. al. (2020) [34] tested 18 dense-grade asphalt mixtures with different characteristics under both the IDEAL-RT and APA test. The IDEAL-RT was conducted under the same conditions as the previous study [13] and the APA test was conducted at 64°C following AASHTO T 340 [32] on specimens with 7 ± 0.5% air voids. This study demonstrated a good correlation between the IDEAL-RT and APA rut depth at 8000 cycles with an R^2 value of 92% for an exponential fit. Based on this relationship and Equation 3 shown previously, a reasonable minimum shear strength threshold for the IDEAL-RT test was found to be 0.85 MPa for asphalt mixtures subjected to loose mixture conditioning for 4 hours at 135°C. Additionally, Zhou et. al. (2021) [35] also established a linear correlation between the IDEAL-RT and HWTT.

In addition to their study on the IDT test, Yin et. al. [29] also evaluated the IDEAL-RT for its ability to replace the HWTT as a rutting test for asphalt mixtures. In this study, the IDEAL-RT was conducted at 50.2°C with a loading rate of 50 mm/min, specimen dimensions of 62 mm height and 150 mm diameter, and specimen air voids of 7 ± 0.5%. The HWTT was performed according to AASHTO T 324 [30] at the test temperature of 50°C. This study found no correlation between the IDEAL-RT and HWTT; however, when one particular data point was removed a linear correlation was found with an R^2 value of 73%. Of note, the maximum COV for the IDEAL-RT was 12.6%.

The American Society for Testing and Materials (ASTM) is currently exploring the IDEAL-RT, or rapid rutting test, for use as a rutting test for asphalt mixtures, detailed in ASTM WK71466 *Standard Test Method for Determination of Rutting Tolerance Index of Asphalt Mixture Using the Rapid Rutting Test* [36]. Of note, this standard is still under review. The

IDEAL-RT method outlined in ASTM WK71466 [36] is for cylindrical specimens or pavement cores and uses a load rate of 50 ± 2.0 mm/min. The laboratory compacted specimen dimensions are dependent on the NMAS of the mixture, with dimensions of 62 mm height and 150 mm diameter for NMAS of 19 mm or smaller, and dimensions of 95 mm height and 150 mm diameter for NMAS of 25 mm or greater. Air voids for these IDEAL-RT specimens are to be 7.0 ± 0.5%. Although this standard [36] is still undergoing technical review, it is of note that the authors proposed a rutting tolerance index, or RT_{Index}, as the rutting parameter as opposed to the IDEAL-RT shear strength used in their previous studies. In ASTM WK71466 [36], the shear strength (Pa) is calculated as $\tau_f = 0.356 \times \frac{P}{t*w}$ where *P* is the peak load (N), *t* is specimen thickness (m), and *w* is the width of the upper loadings trip (0.0191 m). Equation 4 [36] shows the calculation of the RT_{Index} where $1P_a$ is a unit cancelation factor and 6.618×10^{-5} is a scaling factor.

$$RT_{Index} = 6.618 \times 10^{-5} \times \frac{\tau_{max}}{1P_a} \qquad \text{Equation 4}$$

2.3 Marshall Stability and Flow (MS) Test

The Marshall stability and flow test protocol is outlined in three different standards including ASTM D6927 [14], AASHTO T 245 [15], and ASTM D5581 [16]. The MS test is conducted on asphalt specimens to determine Marshall stability and flow for Marshall mixture design and evaluation and also used as a quality assurance (QA) tool during asphalt mixture production. The MS test measures an asphalt mixture’s resistance to plastic deformation. The testing apparatus consists of a breaking head made up of two cylindrical segments of which the lower segment should be mounted on a base with two guide rods or posts. Figure 6 shows the MS test setup.

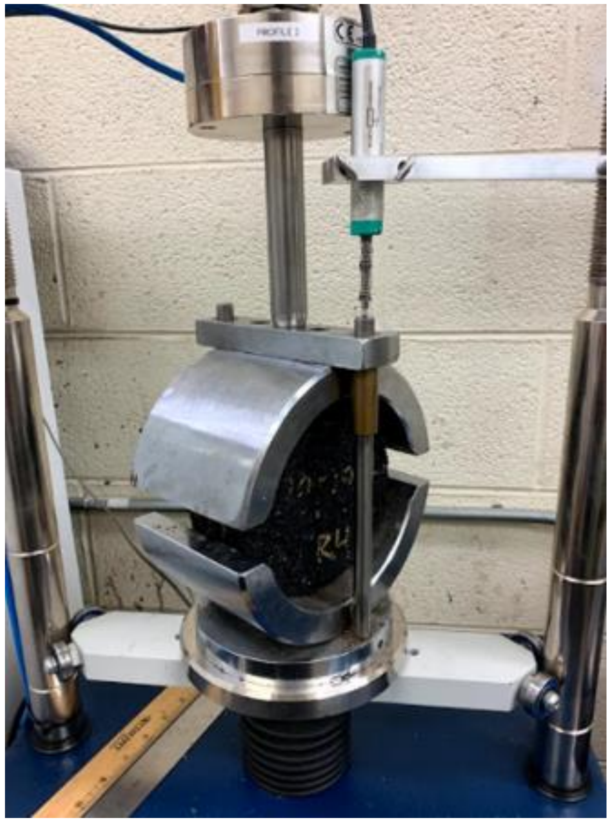


Figure 6 - Marshall stability and flow test setup

For the MS test, a load rate of 50 ± 5 mm/min is used. Cylindrical asphalt specimens are placed in between the two cylindrical segments (test heads) and loaded until failure. Marshall stability is determined from the peak resistance load during the constant rate load test before the specimen reaches failure. Marshall flow is determined based on the deformation at the peak load. There are various criteria and acceptance limits from different agencies for Marshall stability and Marshall flow.

In other literature it is reported that this test is sensitive to changes in aggregate type, gradation, shape, maximum aggregate size, and asphalt content [37, 38]. The MS test was widely used by agencies in the United States in the 1980s [37, 39] and is still in use by some agencies both in the United States and around the world. However, the ability of the MS test to accurately capture rutting (permanent deformation) performance of asphalt mixtures is still debated.

For example, Kandhal and Koehler [39] presented the state-of-the practice of the MS test in the United States in 1985. This study reported significant differences in procedures and applications of the Marshall Method in different states across the United States. The authors specifically look at the different methods used for determining stability and flow using the Marshall Method. It was found that most states specify a significantly higher minimum value for stability than the Asphalt Institutes recommendation of 2,224 N. These values among the states range from 2,224 N to 8007 N. Some states, including Minnesota, Montana, and Ohio, also specify a maximum limit for stability. Specification for flow ranges by each state also differ, with the most common ranges being 8-16 and 8-18 flow units. Based on the work by Kandhal and Koehler [39], while there were discrepancies between the criteria for the MS test, it was widely used for characterizing asphalt mixture performance at the time the paper was published. In contrast, it has been reported that the MS test is a poor indicator of rutting performance of asphalt mixtures when compared to mixture performance in the field [37. 40].

2.4 Simple Punching Shear Test (SPST)

Faruk et. al. (2015) [41] explored the Simple Punching Shear Test (SPST) as a potential laboratory test for evaluating shear properties of HMA mixtures. Since shear failure is one of the main mechanisms of HMA rutting, the authors claimed the SPST is suitable for characterization of rutting susceptibility because it allows for the evaluation of shear strength. Faruk et. al. developed the SPST as a supplementary and/or surrogate test for existing asphalt rutting test since existing rutting tests do not capture shear properties of asphalt mixtures. The SPST involves a cylindrical hot mix asphalt (HMA) specimen being compressed vertically by a steel punch, or loading head, with the load applied to the flat surface of the specimen. The authors used the following input parameters for the SPST: specimen dimensions of 63.5 mm in height and 152.4 mm in diameter; specimen air voids of 7 ± 1%; test temperature of 50°C; displacement-controlled loading rate of 12 mm/min; and loading head diameter of 38.1 mm. Shear strength is determined from the load-displacement curve resulting from the SPST as a means to quantify the rutting performance of the mixture. In the Faruk et. al. (2015) [41] study as well as subsequent studies by Walubita et. al. [42-44], the SPST was found to be repeatable with a COV of less than 20%. The SPST was also shown to be sensitive to changes on asphalt mixture properties including asphalt binder content and type, mixture type, and test temperature. In addition, SPST results were correlated with fundamental rutting tests including the repeated load permanent deformation test and simulative tests such as the HWTT, and also showed good correlation with field performance with an R^2 value of 85% to 93%. The authors also developed preliminary SPST threshold criteria to screen for rutting resistance in asphalt mixtures. Based on the criteria established, an SPST shear strength greater than or equal to 1.4 MPa indicates adequate rutting resistance.

2.5 Deformation Strength (SD) Test

The deformation strength (SD) test, also known as the "Kim Test", was introduced by Kim et. al. [45] as a new test protocol for evaluating rutting performance of dense-graded asphalt mixtures. The developers of this test designed the test to capture the mechanism by which rutting occurs due to vehicle tires on asphalt pavement roads. When asphalt ruts, the pavement deforms directly beneath the tire while surrounding pavement acts as a confining barrier. This test was designed to capture the two stresses that cause rutting in asphalt: compressive and shear stress. To accomplish this, the test uses a steel column with a round edge as the loading head. This monotonic test applies a load rate of 30 mm/min on the center of the flat side of a cylindrical asphalt specimen. The asphalt specimen must have an air void content of 4 ± 0.5% and dimensions of 63 ± 2 mm in height and either 100 mm or 150 mm in diameter. The test specimens must be conditioned in a water bath at 60°C for half an hour and then tested immediately. Similar to the MS test, the peak load and deformation at the peak load are used to calculate the SD value. The authors found the SD test to be repeatable and correlated with the rutting parameters from the APA test as well as the dynamic shear rheometer test [45-47].

2.6 Asphalt Pavement Analyzer (APA) Test

The Asphalt Pavement Analyzer (APA) test is currently used in Virginia as a rutting test [17]. The APA test is standardized in AASHTO T 340 *Determining Rutting Susceptibility of Hot Mix Asphalt (HMA) Using the Asphalt Pavement Analyzer (APA)* [32].

In Virginia, the APA test is conducted at 64°C on cylindrical asphalt specimens of 75 mm in height and 150 mm in diameter with 7 ± 0.5% air voids [17]. Specimens are conditioned for a minimum of 6 hours (to a maximum of 24 hours) in an environmental chamber prior to testing and the APA machine itself is a chamber kept at 64°C throughout the test. A hose pressure of 700 ± 35 kPa and wheel load of 445 ± 22 N are used [48]. The APA machine must be calibrated properly prior to each test. Test specimens are placed in cylindrical 150 mm diameter by 75 mm depth rut test molds [48]. Each mold holds two specimens, and two or three molds can be tested at the same time for a total of four or six specimens per APA test depending on whether the APA junior or regular APA machine are being used. During the test, each wheel passes over the two asphalt specimens simulating vehicle wheels on pavement. The rut depth created by these wheel passes is recorded up to 8000 cycles of wheel passes.

Using this procedure, the current threshold for rutting performance in Virginia is 8 mm rut depth at 8000 cycles, meaning rutting resistance is adequate if the rut depth is less than 8 mm at 8000 cycles [17].

A review of current APA criteria used by state DOTs as of May 1st, 2019, was reported in AASHTO MP46-2020, *Standard Specifications for Balanced Mix Design* [49]. The findings of this review are in Table 5.

Table 5 - Summary of Asphalt Pavement Analyzer criteria used by state DOTs [49]

State DOT	Binder / Mixture Types	Criteria (maximum rut depth at 8000 cycles)
Alabama	Mixtures subjected to 10 to 30 million ESALs	4.5mm at 67°C
Alaska	All	3.0mm at 40°C
Arkansas	75 and 115 gyrations 160 and 205 gyrations	8.0mm at 64°C 5.0mm at 64°C
Georgia	19mm and 25mm NMAS 9.5mm and 12.5mm NMAS	5.0mm at 49°C 5.0mm at 64°C
Idaho	75 and 100 gyrations	5.0mm at binder high PG temp.
North Carolina	9.5mm NMAS, <0.3 million ESALs 9.5mm NMAS, 0.3 to 3 million ESALs 9.5mm MNAS, 3 to 30 million ESALs 9.5mm NMAS, >30 million ESALs 12.5mm NMAS, 3 to 30 million ESALs 12.5mm NMAS, >30 million ESALs	11.5mm at binder high PG temp. 9.5mm at binder high PG temp. 6.5mm at binder high PG temp. 4.5mm at binder high PG temp. 6.5mm at binder high PG temp. 4.5mm at binder high PG temp.

New Jersey	High performance thin overlay Bituminous rich intermediate course Bridge deck waterproof surface course Bituminous rich base course High recycled asphalt pavement mix, PG 64-22 High recycled asphalt pavement mix, PG 76-22	4.0mm at 64°C (mix design) 5.0mm at 64°C (production) 6.0mm at 64°C (mix design) 7.0mm at 64°C (production) 3.0mm at 64°C 5.0mm at 64°C 7.0mm at 64°C 4.0mm at 64°C
Ohio	Non-polymer mix Heavy surface & high stress mix Bridge deck waterproofing mix	5.0mm at 48.9°C 3.0mm at 54.4°C 4.0mm at 64°C
Oregon	80 gyrations, PG 58-xx 80 gyrations, PG 64-xx 80 gyrations, PG 70-xx 100 gyrations, PG 64-xx 100 gyrations, PG 70-xx 100 gyrations, PG 76-xx	6.0mm at 64°C 5.0mm at 64°C 4.0mm 64°C
South Carolina	PG 76-22 PG 64-22	3.0mm at 64°C 5.0mm at 64°C
South Dakota	Truck ADT <75 Truck ADT 76 to 250 Truck ADT 251-650 Truck ADT >651	8.0mm at binder high PG temp 7.0mm at binder high PG temp 6.0mm at binder high PG temp 5.0mm at binder high PG temp

*PG = performance grade

2.7 Digital Image Correlation (DIC)

2.7.1 Basic Principles of DIC

Digital image correlation (DIC) is a full-field, optical, non-contact measurement technique that has gained popularity in recent years [18]. DIC measures quantities such as deformation and strain using comparative analysis of digital images of a specimen taken at different deformation states during a test. The deformed images are correlated to a reference image (undeformed image) using a discrete matrix of the pixel gray level in each subset of pixels within the images [50]. DIC is capable of measuring large strains up to 100% elongation and has a measuring sensitivity up to 1/100,000 of the field view, making it a powerful tool for deformation analysis [51]. DIC can be used to provide full-field two-dimensional or three-dimensional measurements of shape, displacement, and strain [52]. The DIC technique is especially attractive for evaluating material properties because it can characterize material parameters well into the plastic deformation range. DIC can determine the location and amplitude of maximum deformation or strain. DIC is also ideal for evaluating fracture mechanics because the full-field measurements provide information on local and global strain distribution and crack growth.

The implementation of DIC for deformation measurements can be described in three steps [53]. First is the speckle pattern fabrication. A speckle pattern is painted on the surface of the specimen that the DIC camera captures to ensure the specimen surface has a carrier of deformation information. Speckle patterns on specimens need to have high contrast and randomness to allow for full-field displacement mapping, isotropy (no directionality in the speckle pattern), and stability (good adhesion to the specimen surface) [53]. The speckle pattern is crucial for achieving sufficient accuracy in DIC measurements. It is important that the paint layer be thin so that the DIC tracks the specimen deformation, not paint deformation. The second step is image acquisition in which specimen surface images are captured at different states within a test [53]. This can be done in two dimensions using a single camera or in three dimensions with two synchronized cameras. Three-dimensional DIC analysis allows for measuring out of plane movement of the specimen surface. The third step in DIC implementation is image analysis. In this step, the deformed specimen images captured during a test are compared to a reference image using a correlation algorithm that determines displacement and strain fields [53].

Accurate measurements with DIC require special attention to a number of parameters. Environmental and instrumental background noise can greatly affect the accuracy of DIC measurements; therefore, it is vital to minimize background noise when implementing the DIC technique. For example, a temporal average filtering process can be employed to significantly decrease the background noise and obtain a greater signal-to-noise ratio, which increases the accuracy of displacement field measurements [54]. The noise and error in DIC analysis may be greater than traditional measurement gauges. Sources of noise and error include mechanical vibrations, inappropriate lighting, digital read noise, pattern noise, camera misalignment, optical distortion, and parameters used in the DIC analysis phase such as subset size, step size, and strain filter size [55].

Methods have been established in an effort to minimize these sources of noise and error [55]. Mechanical vibrations can negatively impact DIC results and are caused by movement of the specimen or the camera during testing. The camera and testing machine must be completely stabilized in order to minimize mechanical vibrations. To avoid error caused by the light source, lighting of the specimen should be cool, constant, and uniform [55]. To limit digital read noise and pattern noise, a high-quality camera at low gain settings should be used. Other causes of noise in DIC are subset size, step size, and strain filter size [55]. Subset size affects the accuracy of results in the matching process and these errors depend on speckle pattern, image dynamic range, and intensity of the strain gradients. Step size controls density of the data points used to construct contour plots. A smaller step size results in higher accuracy of measurements but requires more processing power. Lastly, strain filters can be used to smooth strain results from DIC analysis [55]. Larger strain filters reduce noise and work well for specimens with low strain values or no strain concentrations. Smaller strain filters result in more realistic strain contours around strain concentrations and damaged areas of specimens.

2.7.2 DIC in Asphalt Mixture Testing

For the purposes of this thesis, literature on the use of DIC in asphalt mixture testing was reviewed. Numerous studies utilizing DIC for asphalt mixture characterization were found, typically for asphalt testing at low and intermediate temperatures. However, not much was found on using DIC for high temperature asphalt mixture testing, such as the high temperature monotonic testing done in this thesis. Therefore, while a lot is learned from previous low and intermediate asphalt testing with DIC, there is more work to be done to develop exact procedures for incorporating DIC into high temperature asphalt testing. The studies that were found are summarized below.

Birgisson et. al. (2008) [56] presented the comparison between predicted and measured crack patterns developed in hot-mix asphalt (HMA) mixtures during common fracture tests. The study utilized a DIC system to obtain displacement and strain fields for detecting crack patterns. It was found that predicted fracture initiation and crack propagation patterns were consistent with the observed cracking behavior. The DIC system consisted of three elements: hardware (camera and lights), specimen set up, and software (image acquisition and processing). The authors state that experimental analysis of HMA is enhanced by using DIC which is capable of generating dense and accurate displacement and strain fields of composite materials at the microstructural level. The results of this study showed that crack propagation patterns can easily be captured using DIC, making the technique a powerful tool in the analysis of full-field two-dimensional displacement and strain during asphalt fracture testing.

Later, Birgisson et. al. (2010) [57] studied key mechanism and mixture properties that influence fracture in asphalt concrete by using three monotonic-load laboratory test configurations, including the indirect tension (IDT) test, on both unmodified and polymer-modified asphalt mixtures. DIC was used to capture localized stress distributions in asphalt mixtures and to detect first fracture more accurately than traditional techniques. The authors used a high-resolution digital camera to capture images of a 4 cm by 4 cm section of the specimens during testing. Images taken during testing were correlated based on pixel gray values using the well-established techniques of Area-Based Matching and Least Square Matching. The authors found the accuracy of compressive and tensile strain measurements was 0.04% and the accuracy of shear strains was 0.03%. The DIC system used overcame the shortcomings of traditional on-specimen strain measurement devices and achieved sufficient accuracy when compared to strain gauges.

Yi-qui et. al. [50] investigated the deformation and fracture characteristics of asphalt mixtures through IDT tests along with the DIC technique. The DIC technique was selected because asphalt mixtures are a heterogeneous material making fracture behavior difficult to quantify using traditional measurement techniques. In this study, the DIC technique was used to develop and evaluate full-field strain maps, crack location, Poisson’s ratio, and relationships between horizontal strain and the distribution of aggregate in specimens. The specimens were conditioned at 25°C for 12 hours prior to the IDT test, which was performed at a load rate of 10 mm/min. This study utilized Vic-3D 2010 software from Correlated Solutions, Inc. [18], which measures shape, displacement, and strain of surfaces in three dimensions. A lighting system was used to properly illuminate the specimen during testing, and it was recommended that the DIC system be calibrated before each test. The specimen dimensions were 100 mm in diameter and 65.5 ± 1.3 mm in thickness. Using water-based paint, a speckle pattern was painted on the face of each specimen to allow for implementation of the DIC method. The camera collected images at ten frames per second allowing optimal strain accuracy over time and efficient processing time and data storage. The study found that strains obtained by DIC fluctuated along the horizontal direction, differing from strains calculated using the elastic solution [50]. This variance of horizontal strains corresponded with aggregate distribution in the horizontal direction, implying that the distribution of aggregate in the specimen affects strain distribution. Also, since asphalt contains some larger stone, critical analysis dimensions (the area of the specimen surface to which DIC is applied) must be determined with enough aggregates and mortar to allow DIC to capture realistic deformation. The authors determined the minimum analysis dimensions for this study by implementing DIC over areas of dimensions 5 mm^2, 10 mm^2, 15 mm^2, 25 mm^2, 35 mm^2, and 45 mm^2. From this analysis, they found the larger the analysis dimensions the more realistic the deformation measurements [50]. For this particular study, the authors found a minimum analysis dimension of 35 mm^2 was required to achieve the required accuracy and computational efficiency of the DIC system. Overall, DIC was found to be useful in investigating deformation and fracture properties of asphalt mixtures, specifically with the IDT test.

Romeo [58] stated four applications of DIC for asphalt materials: assessment of adequate testing procedures, local gradients due to material heterogeneities, cracking characterization, and validation of models. According to this author, the advantages of using DIC for asphalt mixture testing are it is non-contact; it provides analysis pinpointing the location of crack initiation; it accounts for non-uniform strain distributions; it provides flexibility by allowing back-analysis calculation of the strain field; and it can measure large deformations without losing image resolution [58]. Uncertainties presented by two-dimensional DIC include misalignment between specimen/load direction and camera, out-of-plane movement of specimen during testing, and specimen roughness [58]. These uncertainties can be fixed by using a three-dimensional DIC approach which can capture out-of-plane movement of the specimen. This is especially important for utilizing of DIC for IDT tests as the specimens bulge out during testing. The author also stated the importance of minimizing camera vibrations to accurately measure displacements with DIC [58].

Buttlar et. al. [59] illustrated different DIC applications for measuring strain distribution during laboratory testing and described specific applications of DIC for evaluating crack initiation and crack propagation in asphalt materials. This study examined mode one and mode two fractures in asphalt concrete using a disk-shaped compact tension (DC(T)) configuration and a double shear test (DST). The authors used a technique called Area Based Matching (ABM) to track images captured during the tests. ABM extracts image correspondences based on similarities between grey values in the images. To evaluate similarities between gray values in images, typically either the Cross-Correlation technique or Least Square Matching (LSM) technique is used. A speckle pattern was applied to the surface of the asphalt specimens prior to testing via a water-based paint because it does not affect the asphalt material behavior and enables DIC analysis. It was recommended that the speckle pattern consist of thin white paint overlaid with a black speckle pattern to create a homogeneous and randomly oriented texture [59]. The authors used a Tamron 55mm lens, LED light sources, and a Stingray F-201C CCD camera to conduct DIC. The camera, placed one meter from the sample, captured images at a rate of five images per second and of size 1,624 pixels x 1,234 pixels. By using DIC, displacements and strains of the surface of each specimen were tracked during testing. Based on the test results, the authors concluded that the advantages of using DIC for asphalt mixture testing include: it is a non-contact measurement technique, reducing setup timing and mounting errors; it pinpoints the location of crack initiation; it accounts for non-uniform strain distributions; and it allows for a “back analysis” of the resulting strain field [59].

Tan et. al. [60] investigated strain distribution characteristics of asphalt concrete using three methods: digital speckle correlation (DSC), elastic solution method, and linear variable differential transformer (LVDT) method. The digital speckle correlation method is another name for DIC. These methods were used to obtain strain values an IDT test. From the study it was found that the contour line of maximum strains correlated well with the fracture path and strains at failure moment determined by DSC. From using DSC in this study, the authors found that fracture predominantly exists at the interface of the aggregate and mortar. Also, DSC analysis showed strains in the horizontal direction are influenced by aggregate and asphalt mortar distribution [60].

Safavizadeh et. al. [55] studied the requirements for ensuring a reliable and accurate DIC system and explored areas where DIC could be used as a superior measurement technique to traditional measuring methods, specifically for asphalt mixture testing. The authors used two-dimensional DIC software, evaluated the parameters that affect the accuracy of the test results, and determined the proper analysis configurations for investigating cracked areas of asphalt specimens. The results showed that DIC is a powerful tool for asphalt mixture evaluation, specifically studying deformation progression and fracture characteristics in both fatigue and fracture testing. The authors found optimal camera and DIC configurations for this study to be as follows: the distance from camera to surface of the specimen was 75 cm; the images were acquired at 210 millisecond intervals; a 19-pixel subset size and step size of one were used. The authors concluded that although DIC noise and matching errors are inevitable, acceptable accuracy in measuring displacements can be obtained with proper DIC setup and analysis parameters. Digital imaging noise can be reduced significantly by using a composite image produced from averaging multiple frames together as the reference image. The quality of speckle pattern also influences the amount of strain noise. Overall, the authors concluded that full-field displacement and strain distributions obtained with a proper DIC setup are superior to conventional measurement methods for evaluating damage progression and cracking patterns of asphalt [55].

Recently, Guo et. al. [61] investigated the low temperature properties and cracking resistance of fiber-reinforced asphalt concrete using the DIC technique with the IDT test. IDT tests were conducted to obtain basic properties such as Poisson's ratio and moduli, and DIC was utilized to measure deformation and strain. Additionally, crack inhibition action was evaluated by failure time. The authors in this study used DIC to provide non-contact measurements of large deformation and record the fracture process of IDT in real time. The IDT test was conducted using the JTG E20-2011 standard [62]. For DIC measurements, the natural texture of asphalt mixtures was considered a speckle pattern and an industrial camera was adjusted to obtain high pixel resolution images of the specimens during IDT tests. The strain distributions obtained from DIC indicated that the addition of fibers improved the fracture resistance of the mixtures [61].

3. Materials and Methods

3.1 Materials

Seventeen plant-produced mixtures were collected from various plants in Virginia in 2018-2020 for both phases of this study. The sampled mixtures were dense-graded surface mixtures (SMs) having NMAS of 9.5 mm and 12.5 mm being used for maintenance paving operations. The mixtures were designated A through Q. Sixteen of these mixtures, designated A-P, were utilized for Phase 1 of this project. Six of these mixtures, designated G, K, L, O, P, and Q, were utilized for Phase 2 of this project.

Volumetric and aggregate gradation analyses were performed to determine basic mixture properties. The data collected included asphalt content and size distribution; bulk and Rice mixture specific gravities (G_{mb} and G_{mm}); air voids (voids in total mix [*VTM*]); voids in mineral aggregate (*VMA*); voids filled with asphalt (*VFA*); bulk and effective aggregate specific gravities (G_{sb} and G_{se}); dust/asphalt ratio; percent binder absorbed (P_{ba}); effective binder content (P_{be}); and effective film thickness (F_{be}).

Tables 6 and 7 present the volumetric properties and gradations for all mixtures used in this study. The virgin binder grade was PG64S-22 for all mixtures except mixtures H, M, and N, which had a virgin binder grade of PG58-28.

Table 6 - Volumetric properties for all mixtures

Mixture	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**	**M**	**N**	**O**	**P**	**Q**
Mixture Type	SM-9.5A	SM-12.5A	SM-12.5D	SM-9.5D	SM-9.5A	SM-9.5A	SM-9.5A	SM-9.5A	SM-9.5D	SM-9.5D	SM-9.5A	SM-9.5D	SM-9.5A	SM-9.5A	SM-12.5A	SM-12.5A	SM-9.5A
RAP Content, %	30	30	26	26	26	40	45	40	26	30	45	30	45	60	0	15	30
Property																	
NMAS, mm	9.5	12.5	12.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	12.5	9.5	9.5	12.5	12.5	9.5
Asphalt Content, %	5.64	5.04	5.39	6.19	5.47	5.61	6.96	5.45	6.03	6.09	6.34	5.755	6.16	5.88	5.26	5.8	5.42
Rice SG (G_{mm})	2.435	2.670	2.634	2.447	2.587	2.648	2.515	2.663	2.597	2.529	2.541	2.538	2.533	2.546	2.452	2.573	2.659
VTM, %	3.3	3.1	3.0	2.2	4.5	2.7	0.7	4.2	2.3	5.9	2.6	4.0	2.6	2.4	4.4	2.3	3.6
VMA, %	16.1	15.3	15.8	16.3	17.5	16.7	16.9	17.7	16.5	19.5	17.3	17.2	17.0	15.8	16.2	15.5	17.0
VFA, %	79.5	79.6	81.3	86.2	74.2	83.9	96.1	76.0	86.3	69.8	84.7	77.0	84.8	84.6	72.9	85.0	78.7
FA Ratio	0.87	1.28	1.36	1.03	1.25	1.13	1.25	1.23	1.10	1.01	1.23	1.03	1.20	1.33	1.02	1.42	1.27
Mixture Bulk SG (G_{mb})	2.355	2.586	2.556	2.392	2.470	2.577	2.499	2.550	2.538	2.380	2.474	2.437	2.467	2.483	2.344	2.513	2.563
Aggregate Effective SG (G_{se})	2.651	2.916	2.890	2.691	2.834	2.921	2.820	2.931	2.878	2.792	2.821	2.787	2.801	2.803	2.655	2.834	2.924
Aggregate Bulk SG (G_{sb})	2.648	2.901	2.872	2.680	2.830	2.920	2.799	2.930	2.858	2.776	2.801	2.773	2.789	2.777	2.649	2.800	2.921
Absorbed Asphalt Content (P_{ba}), %	0.04	0.18	0.22	0.16	0.05	0.01	0.27	0.01	0.25	0.21	0.26	0.19	0.16	0.34	0.09	0.44	0.04
Effective Asphalt Content (P_{be}), %	5.59	4.87	5.18	6.04	5.42	5.60	6.70	5.43	5.79	5.89	6.10	5.58	6.01	5.56	5.17	5.38	5.39
Effective Film Thickness (F_{be}), µm	9.7	7.8	8.4	10.4	8.4	9.2	10.2	8.7	10.0	11.4	9.9	9.7	9.9	8.7	10.5	8.0	8.5

RAP = recycled asphalt pavement; NMAS = nominal maximum aggregate size; SG = specific gravity; VTM = voids in total mixture; VMA = voids in mineral aggregate; VFA = voids filled with asphalt; FA ratio = fines to aggregate ratio

Table 7 – Aggregate gradations for all mixtures

Mixture	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**	**M**	**N**	**O**	**P**	**Q**
Mixture Type	SM-9.5A	SM-12.5A	SM-12.5D	SM-9.5D	SM-9.5A	SM-9.5A	SM-9.5A	SM-9.5A	SM-9.5D	SM-9.5D	SM-9.5A	SM-9.5D	SM-9.5A	SM-9.5A	SM-12.5A	SM-12.5A	SM-9.5A
RAP Content, %	30	30	26	26	26	40	45	40	26	30	45	30	45	60	0	15	30
Gradation, percent passing																	
¾ in (19.0 mm)	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	99.6	100.0
½ in (12.5 mm)	98.9	97.3	99.3	100.0	99.4	100.0	99.2	100.0	98.9	99.5	99.0	100.0	99.3	98.5	91.8	94.7	100.0
3/8 in (9.5 mm)	93.3	86.6	92.0	91.9	94.7	95.5	93.8	96.6	93.4	94.2	95.0	96.3	93.0	93.2	70.6	87.5	96.9
No. 4 (4.75 mm)	60.7	55.6	58.5	56.7	65.9	63.7	62.5	63.9	63.0	65.1	68.0	67.3	62.2	65.4	57.5	56.3	66.9
No. 8 (2.36 mm)	43.9	39.2	39.6	40.6	47.1	42.3	41.0	41.5	42.3	40.1	43.3	41.5	41.5	43.0	39.7	35.9	42.2
No. 16 (1.18 mm)	35.0	30.3	28.4	33.3	34.9	30.5	27.3	29.6	28.9	24.1	27.3	30.3	27.5	29.0	26.0	25.7	29.9
No. 30 (600 µm)	25.8	23.5	20.1	25.0	24.5	22.1	19.4	21.7	19.8	15.8	18.6	24.1	19.2	20.8	16.4	20.0	21.5
No. 50 (300 µm)	17.0	16.8	13.7	13.1	15.4	15.1	14.1	15.2	13.0	10.5	12.9	14.1	12.9	14.3	9.9	16.4	15.2
No. 100 (150 µm)	8.4	10.3	9.8	8.0	9.5	9.6	10.6	10.0	8.8	7.6	9.5	8.1	9.3	9.9	7.0	12.4	10.2
No. 200 (75 µm)	4.89	6.21	7.05	6.23	6.75	6.32	8.36	6.66	6.39	5.93	7.49	5.75	7.22	7.37	5.29	7.63	6.86

3.2 Methods

The purpose of this study was to evaluate three monotonic loading tests for their ability to predict asphalt rutting performance. Based on the literature review, a high temperature had to be selected for these tests. The work done to select a testing temperature is discussed in section 4.7 of this thesis.

The rutting tests conducted in this study can be divided into three categories: basic, intermediate, and advanced. These categories are based on the time, cost, knowledge, and expertise required to conduct and analyze the tests. The basic rutting tests include the IDT, IDEAL-RT, and Marshall tests and the aim of this project was to determine if one of these tests can be used for evaluating rutting resistance of asphalt mixtures. These tests are the simplest and least expensive of the tests conducted in this study. The intermediate test in this project is the APA test, which is the test currently used in practice to predict rutting in Virginia. This test is more costly and time consuming than the basic rutting tests, which is why it is desired to select a more basic test for state agencies and contractors to implement for characterizing rutting in mixtures. The advanced tests include tests that measure fundamental properties of asphalt mixtures and are the costliest and most time consuming of the tests conducted in this study. These advanced tests, conducted using the AMPT, include the dynamic modulus (DM) test, the stress sweep rutting (SSR) test, and the repeated load triaxial test (RLTT).

The experimental methods of this project are divided into two phases. In Phase 1, both the basic and intermediate tests were conducted on sixteen asphalt mixtures (A-P) and correlations were made between the currently used standard rut test (APA) and the proposed monotonic loading rut tests (IDT, IDEAL-RT, MS). To further examine how well the monotonic loading tests capture the rutting behavior of asphalt mixtures in Phase 2, the advanced rutting tests (DM, SSR, and RLTT) were all conducted and compared to APA and monotonic test results.

In Phase 1, mixtures A through P were used to validate and/or refine the selection of suitable asphalt rutting performance tests. This was done by performing a full testing matrix of the APA, IDT, IDEAL-RT, and MS tests on each of the mixtures. Then, the rutting indices for each test were evaluated based on their sensitivity, variability, and potential correlation among rutting indices.

In Phase 2, six acquired asphalt mixtures (G, K, L, O, P, and Q) were evaluated in the laboratory through conducting more advanced fundamental rutting tests that output fundamental properties of the mixtures. These tests included the following AMPT tests: DM, SSR, and RLTT. The results of these AMPT tests were analyzed and are presented in this study as well as correlations drawn between results of the AMPT tests and APA, IDT, and IDEAL-RT tests.

Finally, digital image correlation (DIC) was used on the six mixtures from Phase 2 (O, P, and Q) with the IDT test. Discussions on use of DIC for asphalt mixture testing, how it is conducted, potential findings from these tests, and recommended future work are included in this study.

4. Laboratory Testing Program: Phase 1

Laboratory testing was conducted on sixteen sampled mixtures (A-P) to achieve two objectives: (1) identify suitable asphalt rutting performance tests, and (2) develop performance-based threshold criteria. All of the evaluated mixtures were typical production mixtures, designed under VDOT specifications for mixtures with A and D designations.

Prior to Phase 1 testing, the high testing temperature for the monotonic loading tests was determined. This temperature selection process is discussed in section 4.7 of this thesis. It was concluded that the high temperature monotonic loading tests (IDT, IDEAL-RT, MS) be conducted at 54.4°C. The evaluation of the selected rutting performance tests (three monotonic loading tests and APA test) was accomplished by evaluating sixteen asphalt mixtures (A through P) through IDT, IDEAL-RT, MS, and APA testing. The rutting indices of the tests were evaluated in terms of sensitivity, variability, and correlations among the rutting indices for each test.

4.1 Specimen Preparation for Phase 1

First, asphalt specimens were prepared for Phase 1 testing. Each of the IDT, IDEAL-RT, and Marshall stability tests required the same size cylindrical specimens, 62 mm in height and 150 mm in diameter. The APA test required a slightly larger cylindrical specimens with a height of 75 mm and width of 150 mm. The specimen preparation process included multiple steps and took three days to complete for each box of sampled mixture. Each box can provide materials to compact 8-11 specimens. Each of these steps for specimen preparation were completed for all sixteen mixtures used in Phase 1 in order to create the necessary number of replicates for each test; three for monotonic tests and four for the APA test. The air void content is the most important factor when compacting asphalt specimens, and all specimens used in this testing were compacted to an air void content of 7 ± 0.5%.

The first step of specimen preparation involved splitting out a box of the specified asphalt mixture. The box of asphalt mixture was heated at approximately 143°C-149°C for three hours.

Next, the asphalt mixture was split out onto mixing table and homogenized. The mixture was then split out in buckets into specified weights for each specimen that results in 7 ± 0.5% air voids once compacted. These buckets of asphalt were then placed back in the oven until they reach the specified compaction temperature for each mixture, typically between 143°C and 149°C, which took around two hours. Temperature probes were used to monitor the temperature of the asphalt and, once compaction temperature was reached, each bucket was taken out of the oven one at a time for compaction. Compaction involved pouring the asphalt from the bucket into a mold, and a gyratory compactor was used to compact the specimen to the proper dimensions. The number of gyrations required to compact the specimen was recorded and checked for consistency across all specimens for a specific mixture and was found to be typically consistent around 20-30 gyrations. Once compaction was completed, the specimen was removed from the compaction mold and placed on a table to cool off. It took at least six hours for the specimens to cool back to room temperature, and specimens were typically left to cool overnight. Pictures showing these first steps of the specimen preparation process are shown in Figure 7.

Figure 7 - Asphalt specimen preparation for Phase 1

The following day, specimens were measured to make sure they had the proper dimensions. Four separate height and width measurements were taken for each specimen and the average of these measurements was recorded. Next, the air voids were determined through a process called bulking, in which the dry weight, weight under water, and surface saturated dry weight of each specimen were recorded. From this data, air voids were calculated to ensure specimens within the tolerance limit of 7 ± 0.5% air voids prior to testing. Then, the specimens were placed on a table to dry for 24 hours before testing. Typically, three replicates were tested for each test configuration to establish repeatability of each test. Examples of the measuring and bulking processes are shown in Figure 8.

Figure 8 - Specimen measurements and air voids determined as part of specimen preparation process

4.2 Selection of Load Rate for IDT, IDEAL-RT, and MS Tests

A loading rate of 50 mm/min was utilized for the monotonic tests for several reasons including practicality and consistency. It is practical because the selection of this loading rate results in very short testing duration thus allowing for testing at room temperature (no need for a testing chamber during the testing itself) without significantly compromising the higher temperature of the specimen. It provides consistency as the selection of this loading rate matches with other tests such as the IDT cracking and moisture damage tests, which will avoid confusion and the frequent change of machine setups. Moreover, it is very uncommon for the Marshall Press testing equipment to perform at other loading rates (in case this equipment is utilized to perform the rut test).

4.3 Asphalt Pavement Analyzer (APA) Test

Testing was performed in accordance with *AASHTO T 340, Determining Rutting Susceptibility of Hot Mix Asphalt (HMA) Using the Asphalt Pavement Analyzer (APA)* [32], using a test temperature of 64 ± 0.5°C. Specimens were conditioned in an oven at this temperature for at least six hours prior to testing in accordance with AASHTO T 340 [32]. An APA junior test machine was used such that two replicate tests consisting of two specimens each (total of four specimens) were conducted for each mixture. This test simulates rutting in the laboratory by applying a loaded wheel back and forth over a pressurized rubber tube located along the surface of the test specimen. The deformation of the specimen is measured over the course of 8000 wheel cycles. Specimens were compacted to an air void content of 7 ± 0.5%, thickness of 75 mm, and diameter of 150 mm. The specimens were pre-loaded for 25 cycles. A loading rate of 60 cycles per minute was used and the rut depth at 8000 cycles was used as the rutting performance criteria. Figure 9 shows a picture of the APA test and an example of the test results.

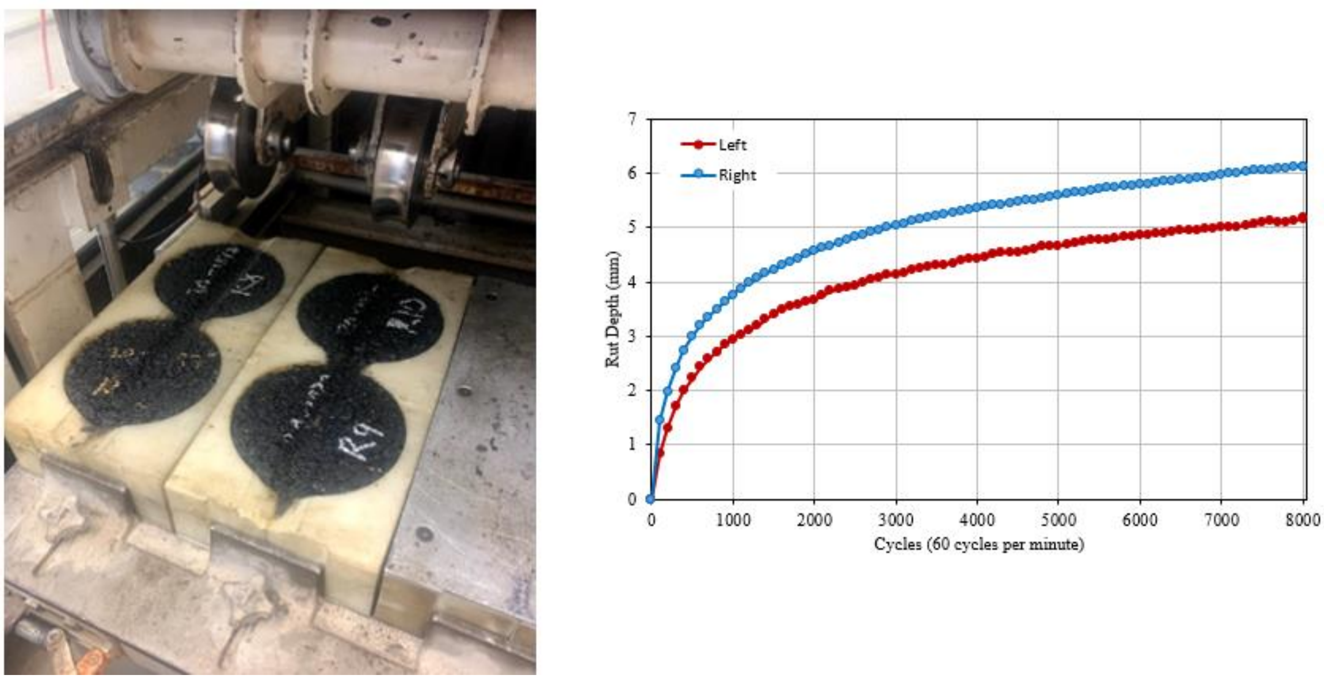


Figure 9 - APA test setup and example of results

4.4 Indirect Tensile (IDT) Test

IDT tests were conducted in accordance with *ASTM D 8225, Standard Test Method for Determination of Cracking Tolerance Index of Asphalt Mixture Using the Indirect Tensile Cracking Test at Intermediate Temperature* [24], with the exception that selected high temperature of 54.4°C was used. Specimens were conditioned in an oven at 54.4°C for two hours prior to testing. Testing was conducted using a load frame with a 15 kN load cell. A minimum of three replicate specimens were tested for each mixture. Specimens were compacted to an air void content of 7 ± 0.5%, thickness of 62 mm, and diameter of 150 mm. A loading rate of 50 ± 2 mm per minute was used and the IDT strength was used as the rutting performance criteria. The IDT strength (in kPa) was calculated using Equation 5 below where *P* is the peak load (N), *t* is the specimen thickness (mm), and *D* is the specimen diameter (mm). Figure 10 shows the IDT test setup and an example of the test results.

$$IDT\ Strength = \frac{2000P}{\pi t D} \qquad \text{Equation 5}$$

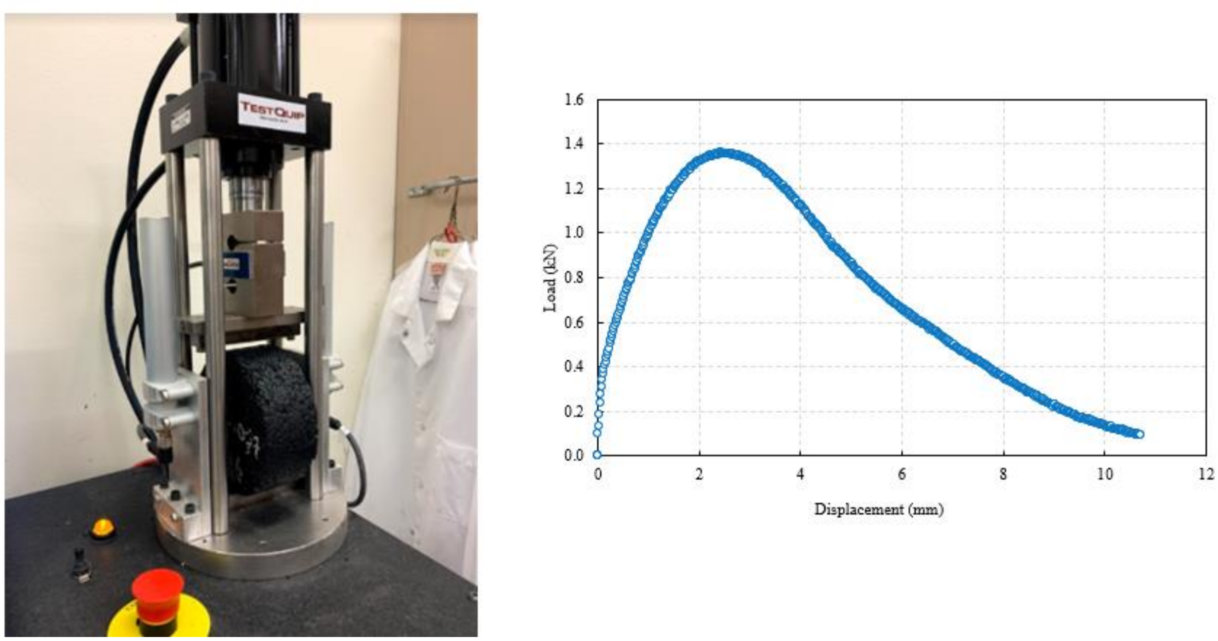


Figure 10 - IDT test setup and example of resulting load vs. displacement curve

4.5 IDEAL Rutting Test (IDEAL-RT)

IDEAL-RTs were conducted in accordance with *ASTM D8225, Standard Test Method for Determination of Cracking Tolerance Index of Asphalt Mixture Using the Indirect Tensile Cracking Test at Intermediate Temperature* [24], with the exception that selected high temperature of 54.4°C was used and the testing configuration included a U-shape fixture underneath the specimen to induce a shear failure. Specimens were conditioned in an oven at 54.4°C for two hours prior to testing. Testing was conducted using a load frame with a 15 kN load cell. A minimum of three replicate specimens were tested for each mixture. Specimens were compacted to an air void content of 7 ± 0.5%, thickness of 62 mm, and diameter of 150 mm. A loading rate of 50 ± 2 mm per minute was used and the shear strength was used as the rutting performance criteria. Based on a study by Zhou et. al. (2020) [34] as well as the rapid rutting test [36], the maximum shear strength (in MPa) was calculated using Equation 6 below where *P* is the peak load (kN). While there is also a newly proposed rutting parameter for the IDEAL-RT called the RT_{Index} recently proposed in ASTM WK71466 [36] and detailed in the literature review chapter of this thesis, this equation was not available when analysis for this thesis was conducted. The rutting parameter for the IDEAL-RT used in this thesis is the shear strength as shown in Equation 6.

$$Shear\ Strength = 0.356\ x\ P$$

Equation 6

Figure 13 shows the IDEAL-RT test setup and an example of the test results.

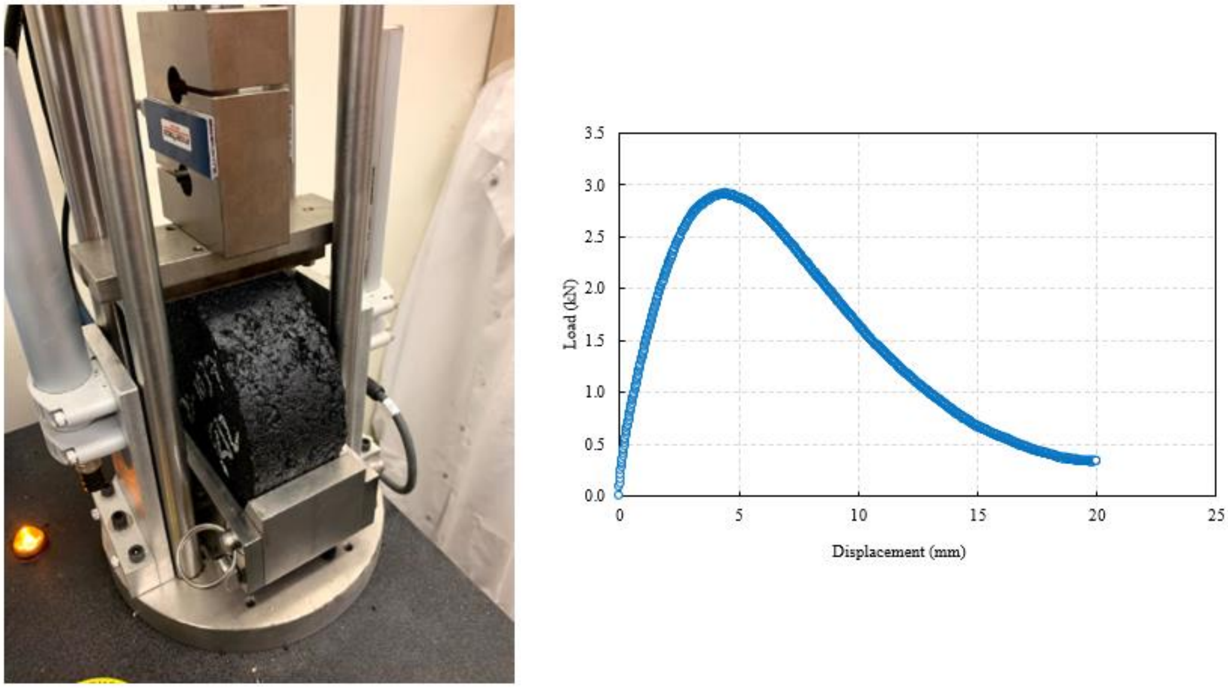


Figure 11 - IDEAL-RT setup and example of resulting load vs. displacement curve

4.6 Marshall Stability (MS) Test

MS tests were conducted in accordance with *ASTM D5581 Standard Test Method for Resistance to Plastic Flow of Bituminous Mixtures Using Marshall Apparatus (6 in. Diameter Specimen)* [16], with the exception that selected high temperature of 54.4°C was used. Specimens were conditioned in an oven at 54.4°C for two hours prior to testing. Testing was conducted using a loading frame and a minimum of three replicate specimens were tested for each mixture. Specimens were compacted to an air void content of 7 ± 0.5%, thickness of 62 mm, and diameter of 150 mm. A loading rate of 50 ± 2 mm per minute was used and the peak load (in kN) was used as the rutting performance criteria. Figure 12 shows the Marshall stability test setup and an example of the test results.

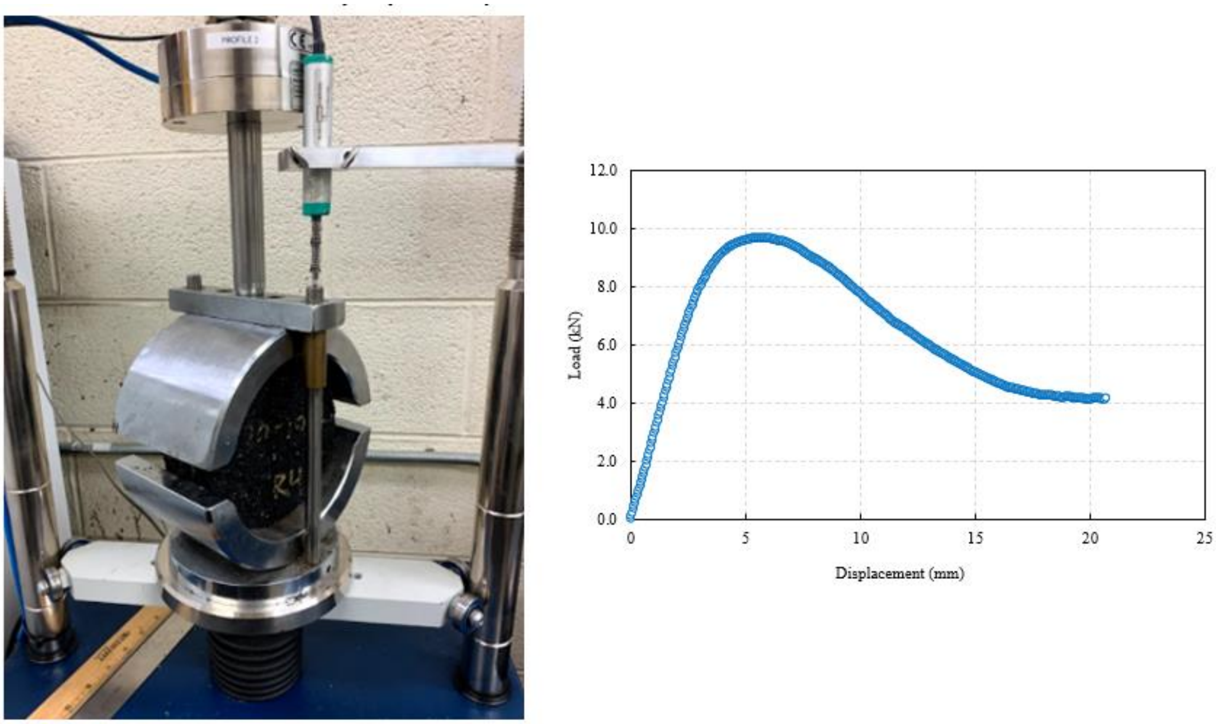


Figure 12 - Marshall stability test setup and example of resulting load vs. displacement curve

4.7 Temperature Selection

A high temperature was selected for high temperature IDT, IDEAL-RT, and MS tests. This temperature was selected in a way to represent rutting and to consider different sensitivity of various mixture types.

Four approaches were considered for determining a critical high testing temperature for IDT, IDEAL-RT, and MS tests, taking into consideration the need to represent rutting of different types of mixtures at this temperature.

First, methods were used to determine a testing temperature based on climate conditions in Norfolk, VA using MERRA-2 (Modern-Era Retrospective analysis for Research and Applications Version 2) and LTTPBind (Long-Term Pavement Performance Bind) climatic database.

Approach A considered climate conditions in Norfolk, VA. This method was used to assess the required PG binder grade (desired binder) for a surface course layer on projects located near Norfolk Virginia using the LTPPBind software. Based on the average 7-day high temperatures average for 20 years and the lowest average single day temperatures also for 20 years obtained using climatic data extracted from MERRA-2 grid-point worldwide data set as of July 1st, 2017 and the LTPP older climatic database (prior to July 1st, 2017), the required binder PG grading is proposed so it will be able to function properly under the expected environmental conditions. This work was done for a specified traffic (number of EASLs is fixed to 9 million to simulate a traffic where "D" mixes are typically used). Table 8 summarizes the findings from this method. It could be noticed that the high average pavement temp at 7-days at 50% reliability was 56.1 and 59.4°C using MERRA and LTPP data base, respectively. The resultant testing temperatures are usually selected to be 5°C lower than these high average pavement temperatures, resulting in potential testing temperatures of 51.1°C and 54.4°C, respectively. The current practice in Virginia still considers the use of LTPP database, thus leading to 54.4°C being a testing temperature candidate.

Table 8 - Determination of high testing temperature following Approach A.

Climatic Data	**MERRA**	**LTPP**
Lowest Yearly Air Temp (°C)	-16.3	-21.30
Lowest Air Temp Stdv (°C)	3.28	3.37
Yearly Degree-Days > 10°C (°C)	2813.63	5145.63
High Air Temp of high 7 days (°C)	32.69	35.51
Stdv of high 7 days (°C)	1.62	1.47
Low Pavement Temp 50% reliability (°C)	-10.00	-12.29
Low Pavement Temp 98% reliability (°C)	-16.60	-18.89
High Avg Pavement Temp of 7 days 50% (°C)	56.10	59.42
High Avg Pavement Temp of 7 days 98% (°C)	60.06	63.30

Approach B considered the use of the high PG temperature of virgin binder used to produce corresponding mixtures in Virginia. Thus, 64°C was another candidate testing temperature. This temperature is also used to perform the APA rut test.

Approach C referred to findings from literature. According to Christensen and Bonaquist [6], the critical high testing temperature could be considered as 10°C lower than the pavement critical temperature at 50% reliability and 20 mm deep into pavement structure (59.4°C). Thus, 49°C was another candidate testing temperature.

In Approach D, the effective high pavement temperature was determined using Equation 7 in accordance with National Corporation Highway Research Program (NCHRP 09-22) Report 704 *A Performance-Related Specification for Hot-Mix Asphalt* [63]. The climatic station in Norfolk was selected to compute the effective high pavement temperature. Table 9 summarizes all the necessary climatic inputs for Equation 7. Having all climatic input and the dynamic modulus master curve of typical D mixtures, the critical high analysis temperature was determined at the selected location (Norfolk, VA) and was found to be around 40°C. Table 10 shows the results of this approach.

$$T_{eff-high} = 14.62 - 3.361Ln(Freq) - 10.940(z) + 1.121(MAAT) + 1.718(\sigma_{MAAT}) - 0.431(Wind) + 0.333(Sunshine) + 0.08(Rain) \quad \text{Equation 7}$$

where;

$T_{eff\text{-}high}$: modified Witczak temperature, °F;

z: critical depth, inch (considered as 1 inch from the top of the AC layer);

Freq: loading frequency, Hz;

MAAT: mean annual air temperature, °F;

σ_{MAAT}: standard deviation of the mean monthly air temperature, °F;

Rain: annual cumulative rainfall depth, inches;

Sunshine: mean annual percentage sunshine, %; and

Wind: mean annual wind speed, mph.

Table 9 - Climate inputs for Approach D

Property	**Measurement**
MAAT (°F)	60.0
σ_{MAAT} (°F)	14.1

Rain (inch)	47.3
Sunshine (%)	55.8
Wind (mph)	9.6

Table 10 - Results of Approach D

Climatic Station in Norfolk, VA	Rutting target distress at 25.4mm depth
Mean effective temperature, °C	40°C
Standard deviation	0.17°C
Mean ± 1 st dev	40.1°C
Mean ± 2 st dev	40.3°C
Mean ± 3 st dev	40.5°C

In summary, the approaches discussed above led to the consideration of four critical high testing temperatures: 40°C, 49°C, 54.4°C, and 64°C. A limited experimental program was performed to select a single high testing temperature. The four temperatures were cut down to two temperatures (49°C and 54.4°C) using an elimination process. On one end, 40°C may not be sensitive to discriminate rutting potential of typical mixtures in VA. On the other end, 64°C was found to be a relatively high temperature and tricky for handling specimen in an IDT mode (the specimen may collapse based on its weight at this high temperature).

IDT, IDEAL-RT, and Marshall stability tests were conducted at both 49°C and 54.4°C for mixtures A-E to determine which high testing temperature is optimal. For this analysis, the obtained rutting parameters for the IDT, IDEAL-RT, and Marshall stability tests were IDT strength, peak load, and peak load, respectively. These tests were conducted to evaluate which test temperature should be used for an monotonic loading rutting test.

Figures 13-15 show the IDT test, IDEAL-RT, and Marshall stability test results at the two different temperatures, with error bars denoting the standard deviation of test results for the respective mixtures.

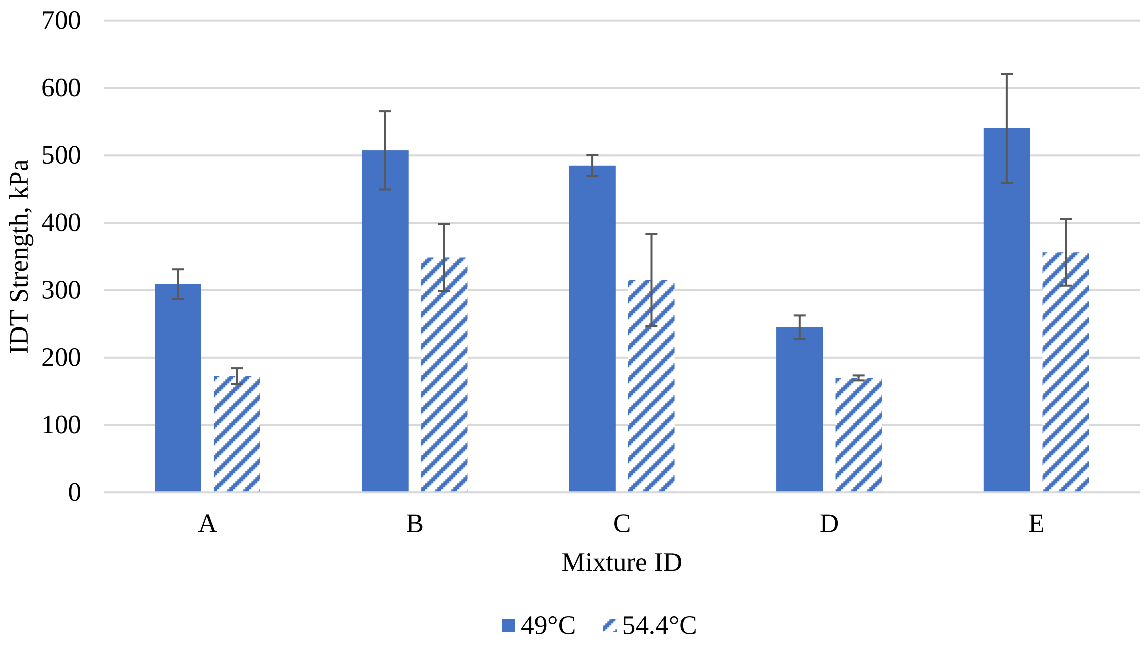


Figure 13 - IDT strength results at 49°C and 54.4°C, error bars denote standard deviation of test results

For the IDT test at 49°C, test results ranged from 245 kPa to 540 kPa across the five mixtures tested. The COVs of these test results ranged from 7.0% to 15.1% with an average COV of 8.8%. For the IDT test at 54.4°C, test results ranged from 170 kPa to 356 kPa. The COVs of these test results ranged from 2.2% to 21.8% with an average COV of 11.8%. Both of these average COV results are acceptable (under 15%).

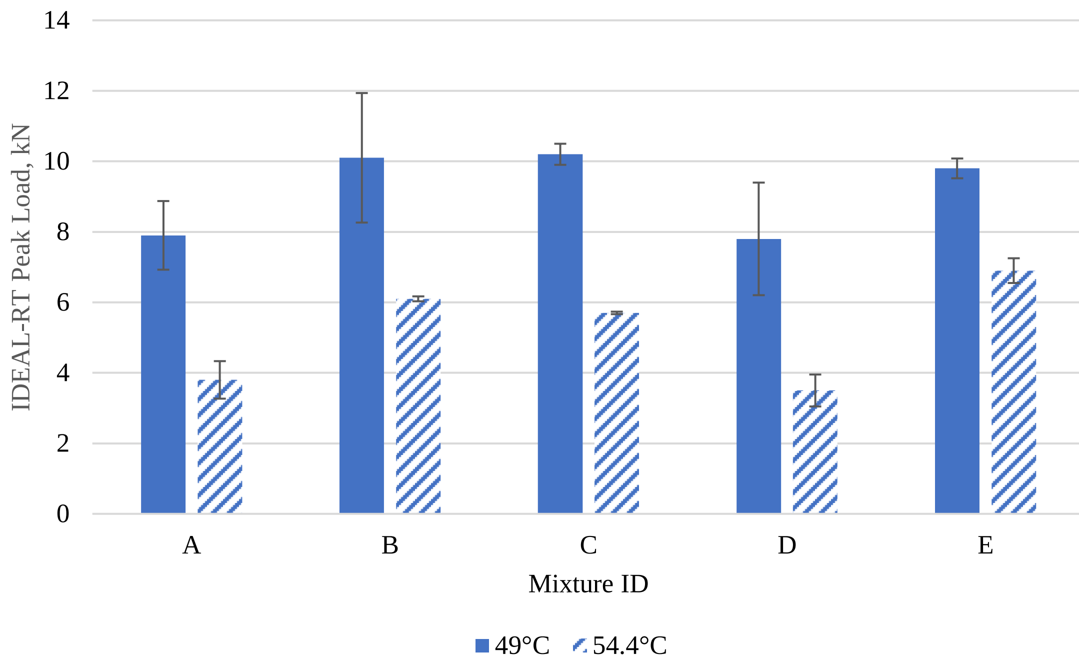


Figure 14 - IDEAL-RT peak load results at 49°C and 54.4°C, error bars denote standard deviation of test results

For the IDEAL-RT test at 49°C, test results ranged from 7.8 kN to 10.2 kN. The COVs of these test results ranged from 2.9% to 20.5% with an average COV of 11.4%. For the IDEAL-RT test at 54.4°C, test results ranged from 3.5 kN to 6.9 kN. The COVs of these test results ranged from 0.6% to 14.0% with an average COV of 6.7%. Both of these average COV results are acceptable (under 15%).

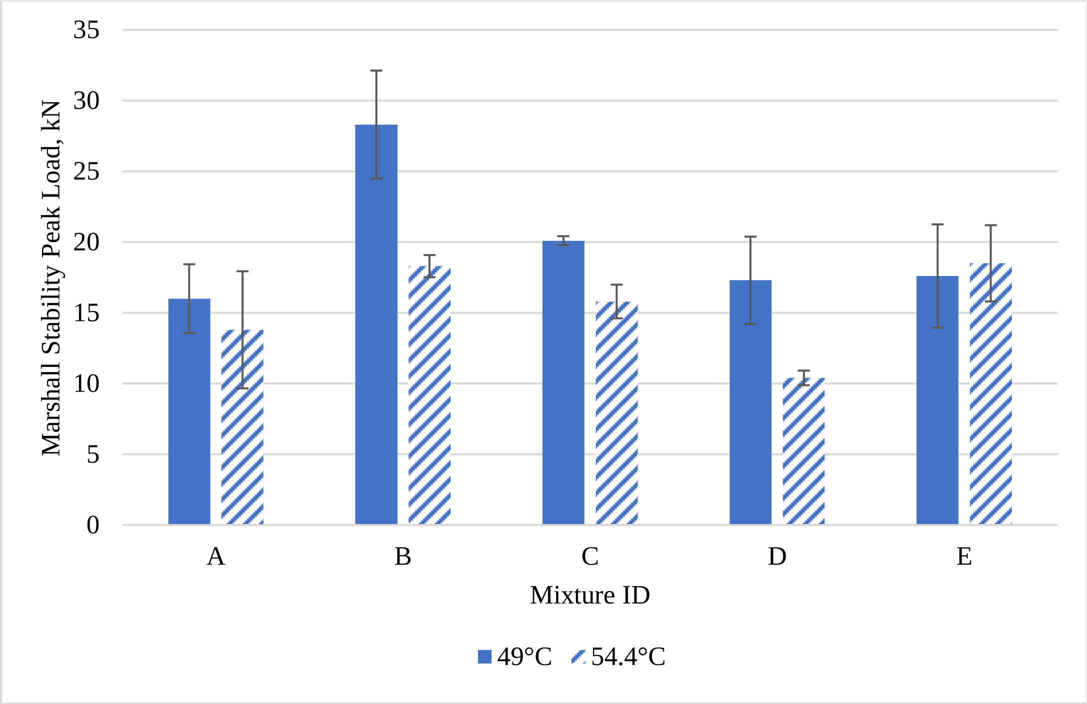


Figure 15 - Marshall stability peak load results at 49°C and 54.4°C, error bars denote standard deviation of test results

For the Marshall stability test at 49°C, test results ranged from 16.0 kN to 28.3 kN. The COVs of these test results ranged from 1.6% to 20.8% with an average COV of 13.8%. For the Marshall stability test at 54.4°C, test results ranged from 10.4 kN to 18.5 kN. The COVs of these test results ranged from 4.3% to 30.1% with an average COV of 12.3%. Both of these average COV results are acceptable (under 15%).

Figures 16-18 below show the correlation of test results at the two different temperatures, with 49°C on the vertical axis (y-axis) and 54.4°C on the horizontal axis (x-axis). These figures show that there is a high correlation between the test results at the two temperatures for the IDT and IDEAL-RT test, while the correlation is low for the Marshall stability test. Importantly, the 54.4°C tests show a higher discrimination potential, especially for IDEAL RT and MS test.

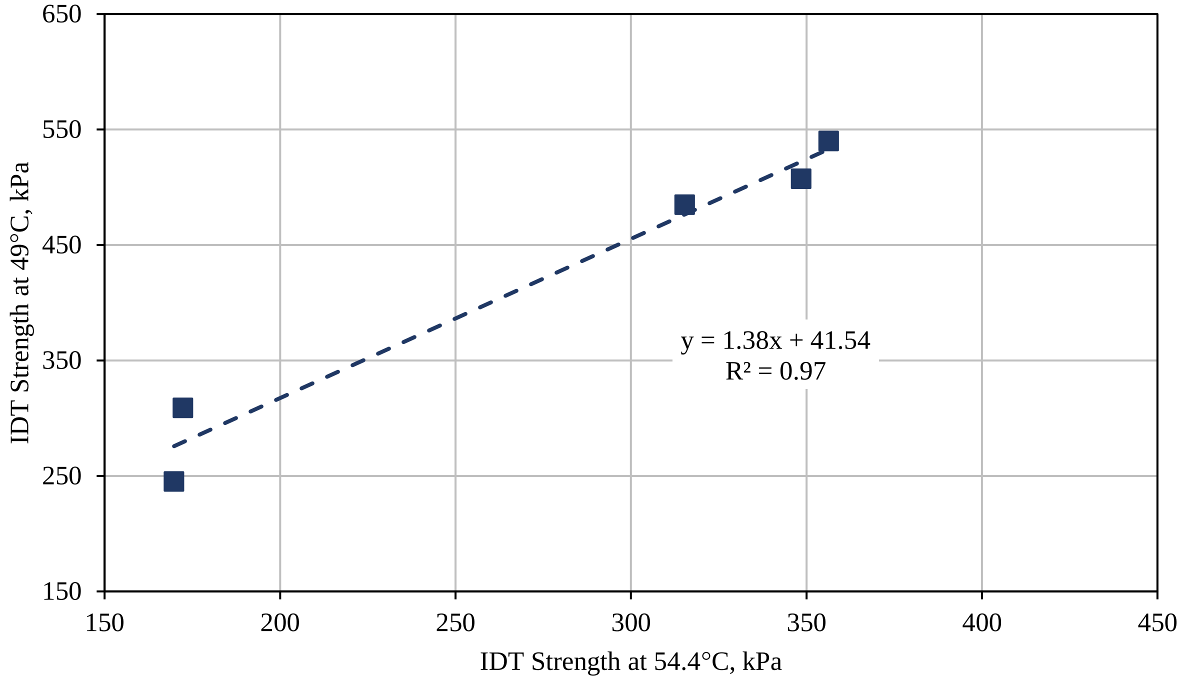


Figure 16 - Correlation of IDT strength results at 49°C and 54.4°C

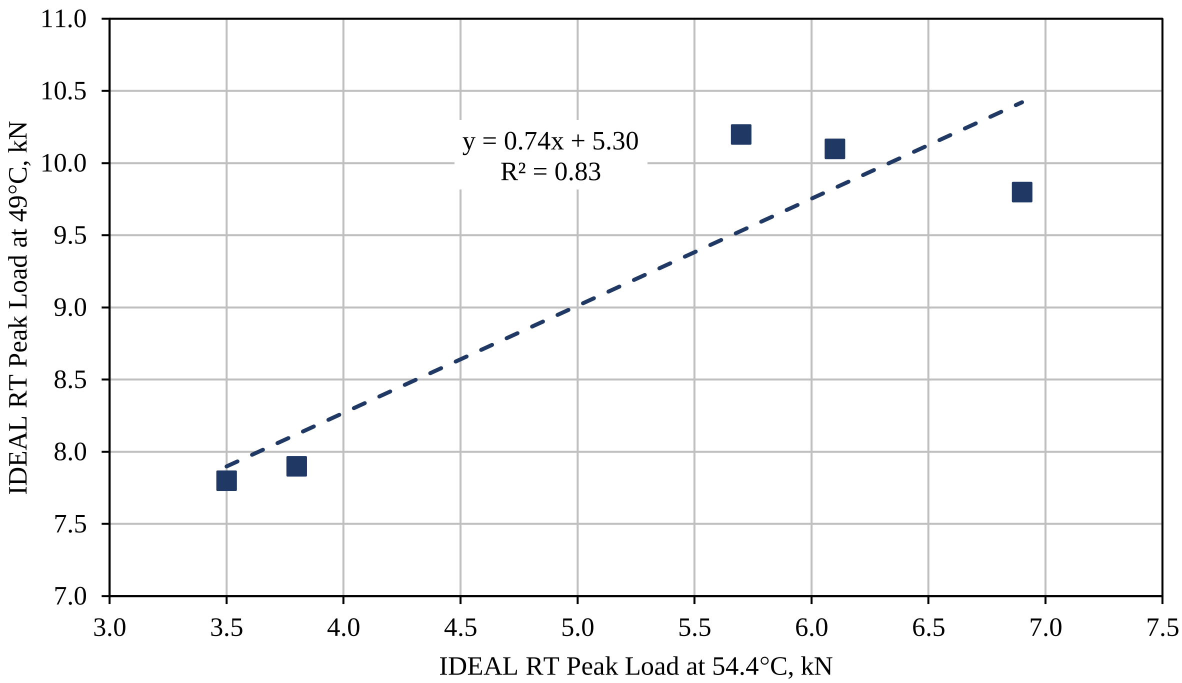


Figure 17 - Correlation of IDEAL-RT peak load results at 49°C and 54.4°C

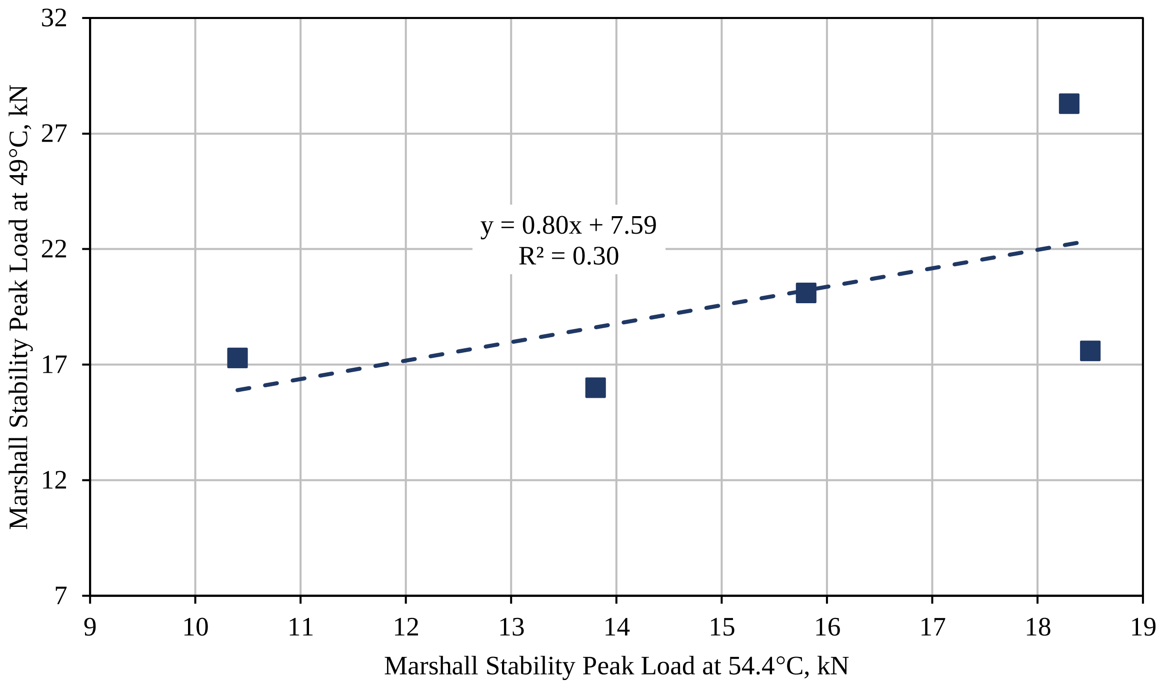


Figure 18 - Correlation of Marshall stability peak load results at 49°C and 54.4°C

Based on this analysis, 54.4°C was chosen as the high testing temperature for the monotonic loading tests in this study due to low variability and high discrimination potential.

5. Experimental Results: Phase 1

As indicated earlier, several rutting tests were considered for the development of BMD specifications in Virginia, specifically for rutting performance. As a result, the IDT, IDEAL-RT, and MS tests were selected for evaluation based on several factors including performance ranking, test repeatability, the ease of specimen preparation, speed of testing, and minimal cost of equipment.

The data collected in Phase 1 was analyzed to assess each test configuration (IDT, IDEAL-RT, MS, and APA) in terms of variability, sensitivity, and correlations among rutting indices from each test. Correlations to APA test measurements and among the test indices were established. Preliminary rutting performance thresholds were established for the IDT test and IDEAL-RT.

The APA test is used as part of VDOT's BMD implementation efforts. VDOT's provisional BMD specification limits the deformation depth in the APA test at 64°C and 8,000 cycles to 8 mm for surface mixtures (SMs) with A and D designations [17], the type of mixtures used in this study.

The rutting indices evaluated as part of this study are denoted in Table 11. All monotonic loading were conducted at 54.4°C using a constant loading rate of 50 ± 2 mm/min. Descriptions of each test are detailed in chapter 4 of this thesis.

Table 11 - Rutting indices evaluated for each test

Test	**Rutting Index/Parameter**
IDT	IDT Strength, kPa
IDEAL-RT	IDEAL-RT Shear Strength, MPa
Marshall Stability	MS Peak Load, kN
APA	Rut Depth at 8000 Cycles, mm

5.1 Results of All Phase 1 Tests

Asphalt mixtures A-Q were all tested under the IDT test, IDEAL-RT, MS test, and APA test. The results are presented in Figures 19-22. The expected trend is that a higher APA rut depth corresponds to a lower IDT strength, lower IDEAL-RT shear strength, and lower MS peak load. Of note, based on the APA test results, mixture G and O are rut susceptible with a rut depth exceeding 8 mm at 8000 cycles.

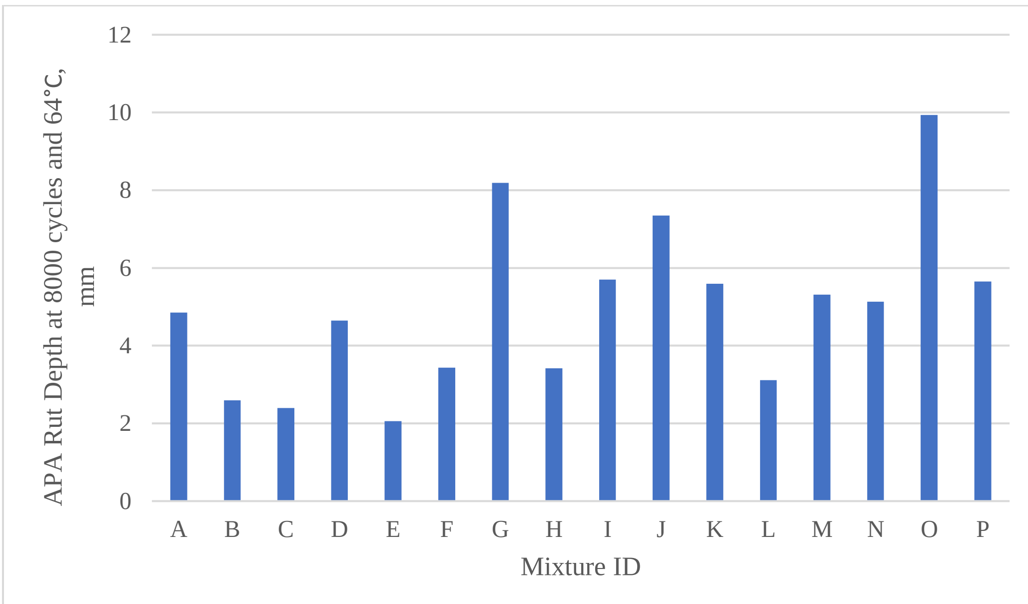


Figure 19 - APA test results from Phase 1

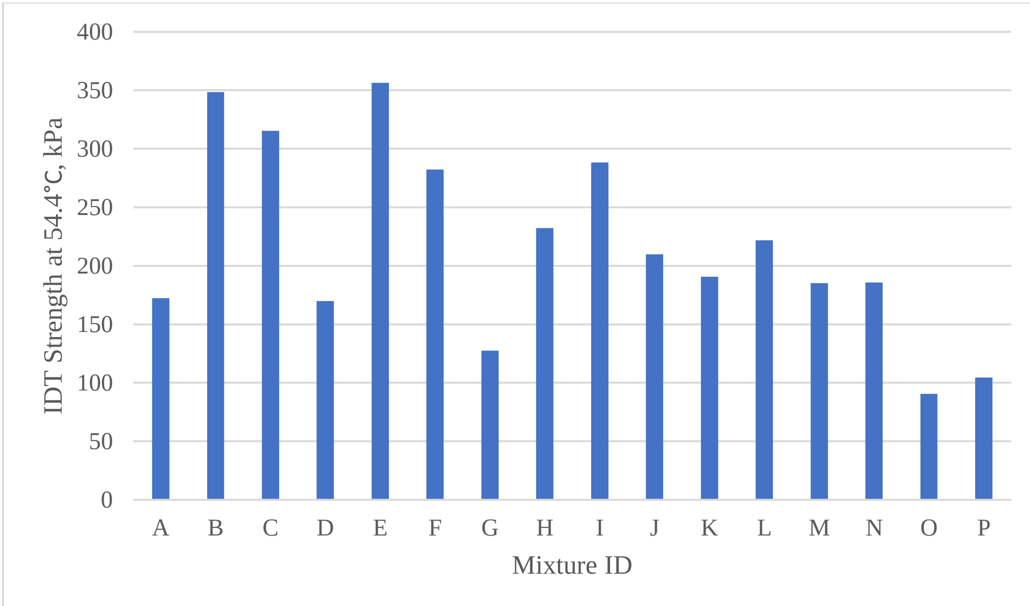


Figure 20 - IDT test results from Phase 1

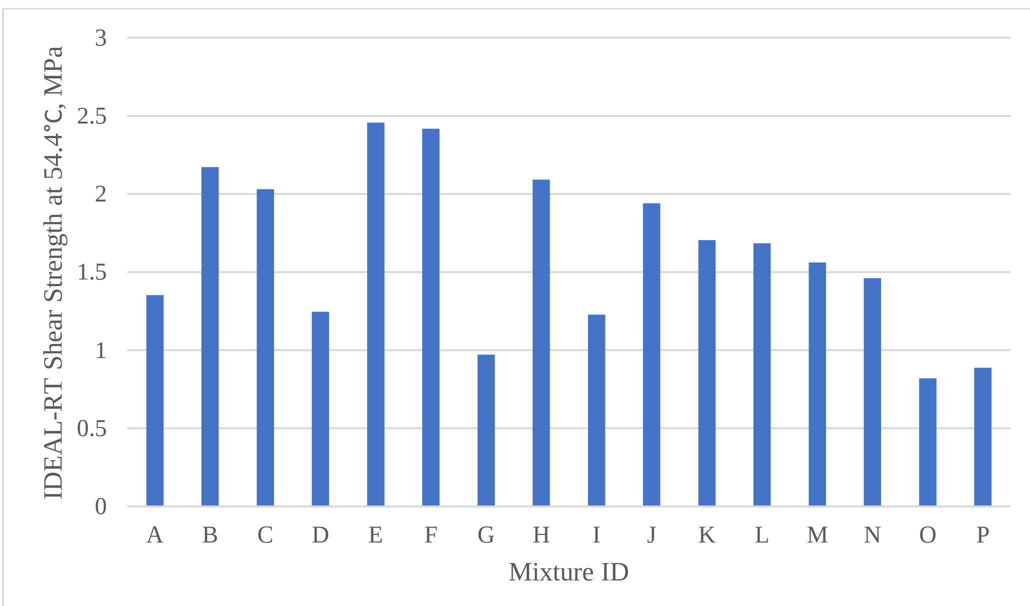


Figure 21 - IDEAL-RT results from Phase 1

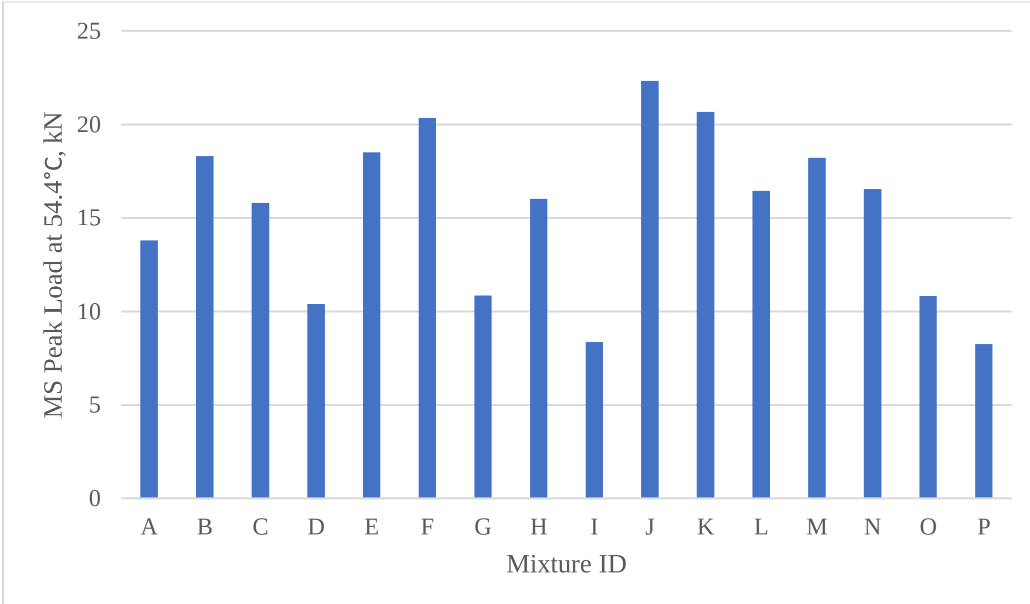


Figure 22 - MS test results from Phase 1

5.2 Variability

The variability of each of the four rutting tests was evaluated based on their COV among test results for each mixture. Figure 23 presents the box plot of the COV results of the rutting tests. In Figure 23, IRT designates the IDEAL-RT test. No data trimming (removal of outlier or minimum and maximum values of the replicates) was applied; the test data were analyzed including all tested replicates from the 16 mixtures evaluated in Phase 1.

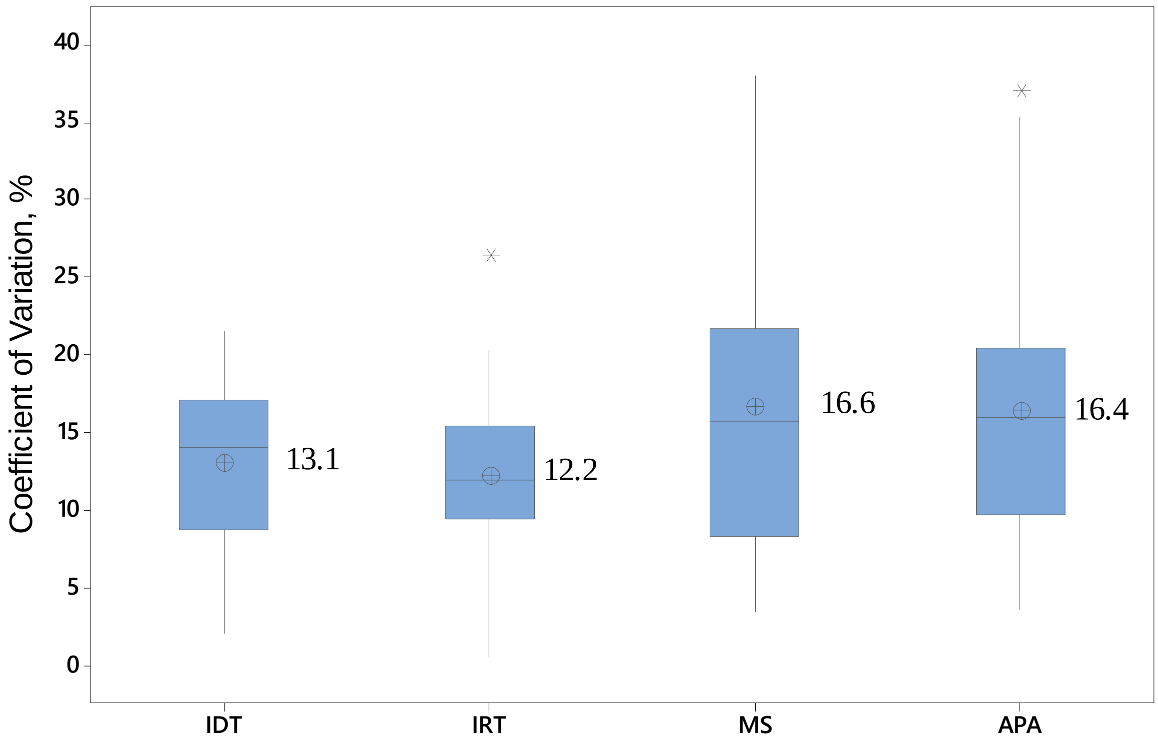


Figure 23 - COV results for each rutting test

The IDT test and IDEAL-RT showed the lowest variability in results based on the COV analysis as shown in Figure 23. Both of these tests have significantly lower variability than the Marshall stability test and APA test. This indicates that the IDT and IDEAL-RT might be optimal tests for evaluating rutting performance of asphalt mixtures from the testing variability perspective.

5.3 Sensitivity

Each of the four tests were evaluated in terms of their sensitivity to volumetric properties of the asphalt mixtures. An analysis of covariance (ANCOVA) at 95% confidence interval was performed using the test results to determine the statistically significant volumetric properties for each test. The volumetric properties included in this analysis were each gradation sieve, *D/B*, *VBE*, *VFA*, *VMA*, and *Gsb*. Table 12 shows the results of this statistical analysis. It is shown that the IDT test has the same number of statistically significant volumetric properties (six) as the APA test. This is followed by the IDEAL-RT (five) and the MS test (four).

Table 12 - Statistically significant volumetric properties for each rutting test based on ANCOVA analysis

Test	**Statistically Significant Volumetric Properties**
APA	$\frac{1}{2}$", No. 30, No. 100, D/B, Gsb, VFA
IDT	$\frac{3}{8}$", No. 4, No. 16, No. 50, Gsb, VBE
IDEAL-RT	$\frac{1}{2}$", No. 8, No. 50, Gsb, VFA
Marshall Stability	$\frac{1}{2}$", No. 4, No. 30, VFA

5.4 Correlation Among Rutting Indices

From Phase 1 test results, correlations were obtained between the rutting indices of the different tests. For the following figures, the dotted trendlines denote all mixtures included, while the solid trendlines exclude the circled outlier data points. Mixtures with NMAS of 12.5 mm are denoted with triangular data points and mixtures with NMAS of 9.5 mm are denoted with circular data points. Additionally, in some of these plots, outlier points are circled and the COVs and recycled asphalt pavement (RAP) percentage are denoted in parentheses for these outlier points.

Relationships between IDT strength and IDEAL-RT shear strength, as well as between IDT strength and Marshall stability peak load, all at 54.4°C, are shown in Figure 24. It was found that the correlation between IDT strength and IDEAL-RT shear strength is much better (R^2 = 69%) than the correlation between IDT strength and Marshall stability peak load (R^2 = 21%).

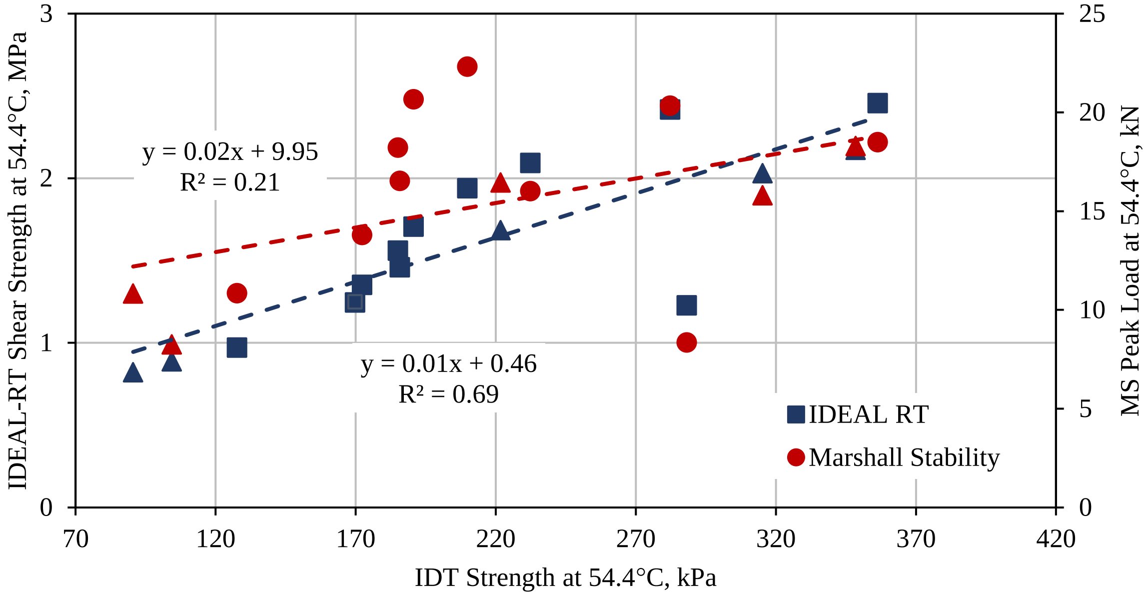


Figure 24 - Correlations between monotonic loading tests

A relationship between IDT strength and IDEAL-RT shear strength at 54.4°C was obtained as shown in Figure 25. The two indices show a correlation of 69% including all mixtures and a correlation of 85% when excluding one outlier mixture. Overall, this shows a good correlation between IDT strength and IDEAL-RT shear strength.

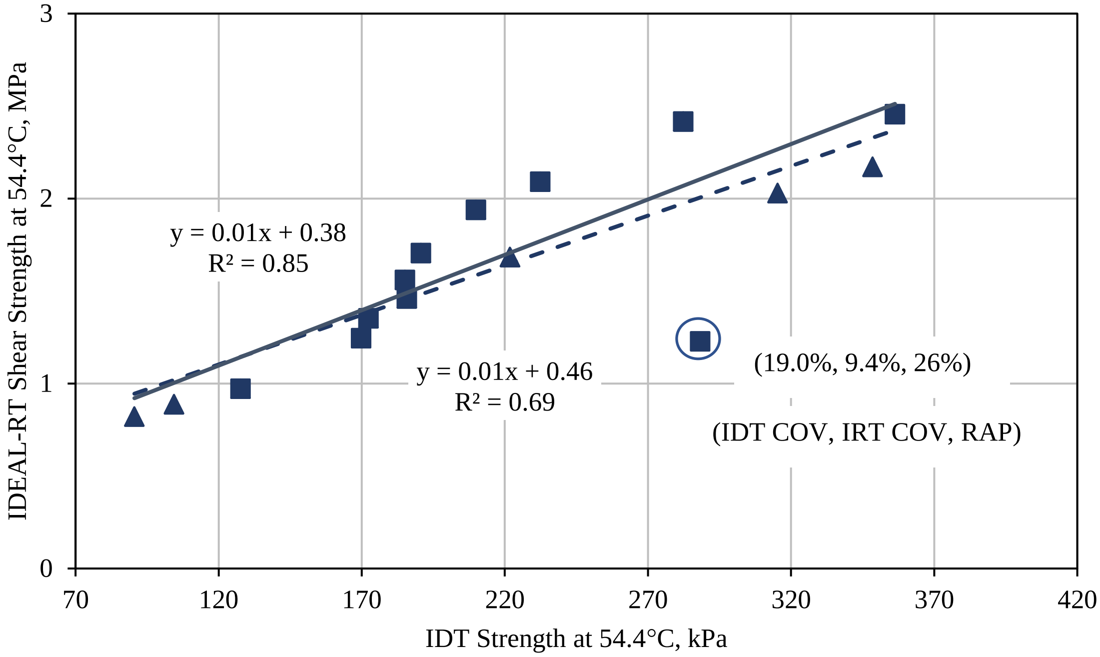


Figure 25 - Relationship between IDT strength and IDEAL-RT shear strength at 54.4°C

Additionally, each of the monotonic loading test results were correlated to APA rut depth at 8000 cycles. Figure 26 shows the relationship between the APA and IDT test results at 54.4°C for the 16 mixtures. The IDT strength correlates well to APA rut depth at 8000 cycles with a correlation of 70% with all mixtures included and 91% when three outlier data points are removed.

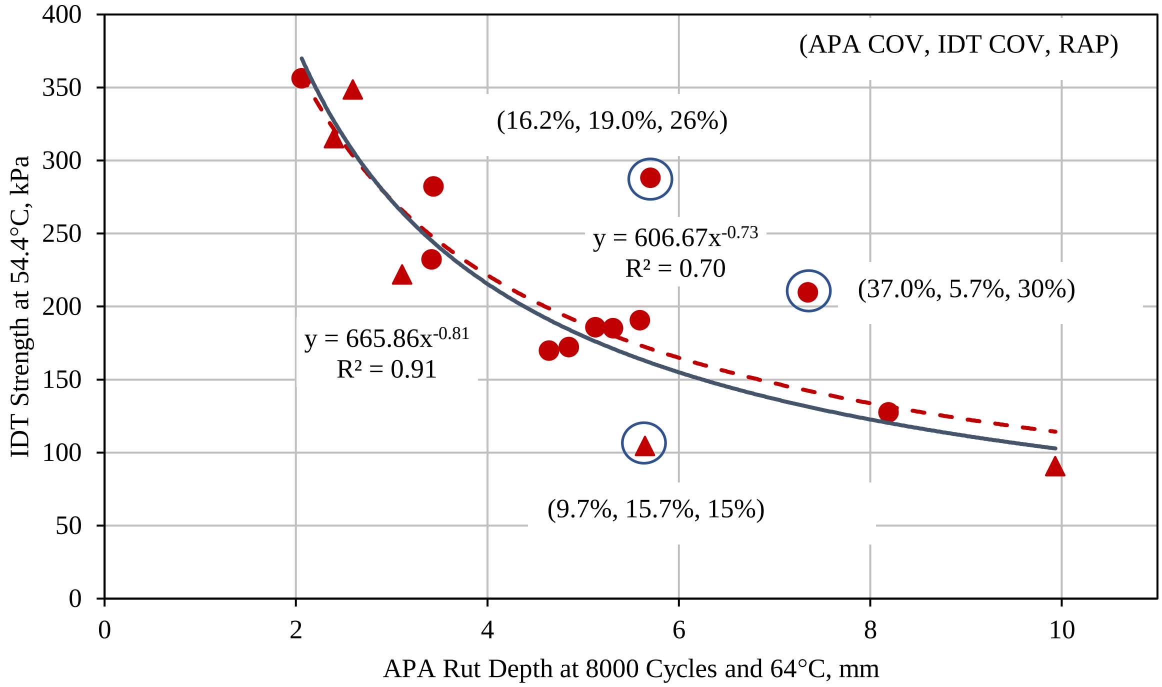


Figure 26 - APA vs. IDT test results

Figure 27 shows the relationship between the APA and IDEAL-RT test results at 54.4°C for the 16 mixtures. The IDEAL-RT shear strength correlates well to APA rut depth at 8000 cycles with a correlation of 61% with all mixtures included and 74% when one outlier data point is removed.

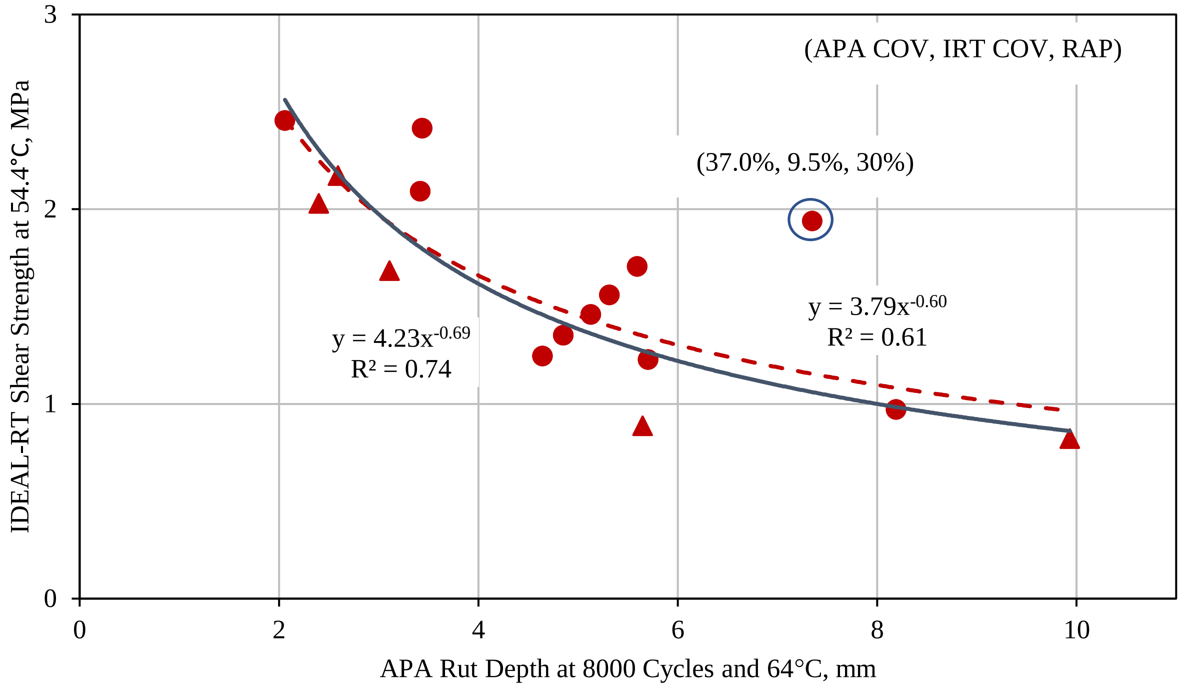


Figure 27 - APA vs. IDEAL-RT results

Figure 28 shows the relationship between the APA and Marshall stability test results at 54.4°C for the 16 mixtures. The Marshall stability peak load has a poor correlation to APA rut depth at 8000 cycles with a correlation of 13%.

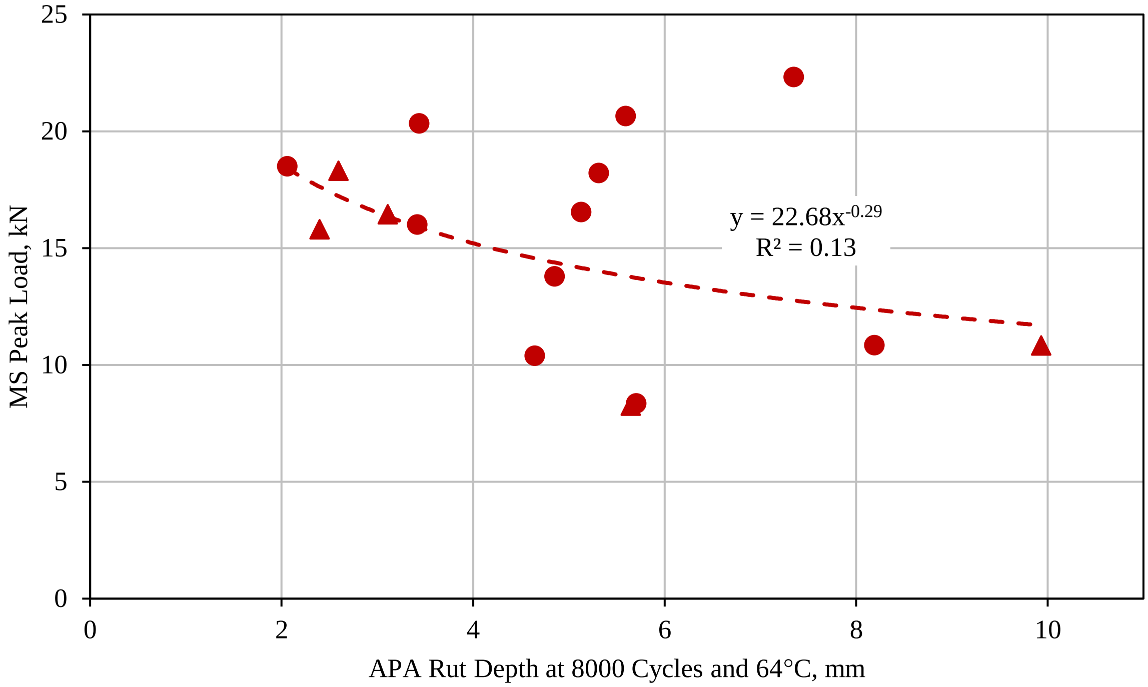


Figure 28 - APA vs. Marshall stability test results

Overall, it is found that the IDT test shows the best correlation to the APA test, followed closely by the IDEAL-RT test. The Marshall stability test does not correlate well with the APA test. Therefore, it was determined that the MS test could be eliminated as a potential test to characterize rutting in asphalt mixtures.

The above analysis provides an opportunity to establish threshold performance-based metrics for evaluating the rutting potential of asphalt mixtures using the monotonic tests. As stated earlier, VDOT's provisional BMD specification limits the deformation depth in the APA test at 64°C and 8,000 cycles to 8 mm for surface mixtures with A and D designations [17]. This rutting threshold of 8 mm rut depth at 8,000 cycles for the APA test along with the correlations to the monotonic tests were used to develop preliminary rutting thresholds for the IDT and IDEAL-RT tests.

The IDT test preliminary rutting performance threshold was established based on the trendline shown in Figure 29 below. An IDT strength of 133 kPa corresponds to an APA rut depth of 8 mm. Therefore, the preliminary rutting performance threshold for the IDT test determined from Phase 1 is an IDT strength of 133 kPa.

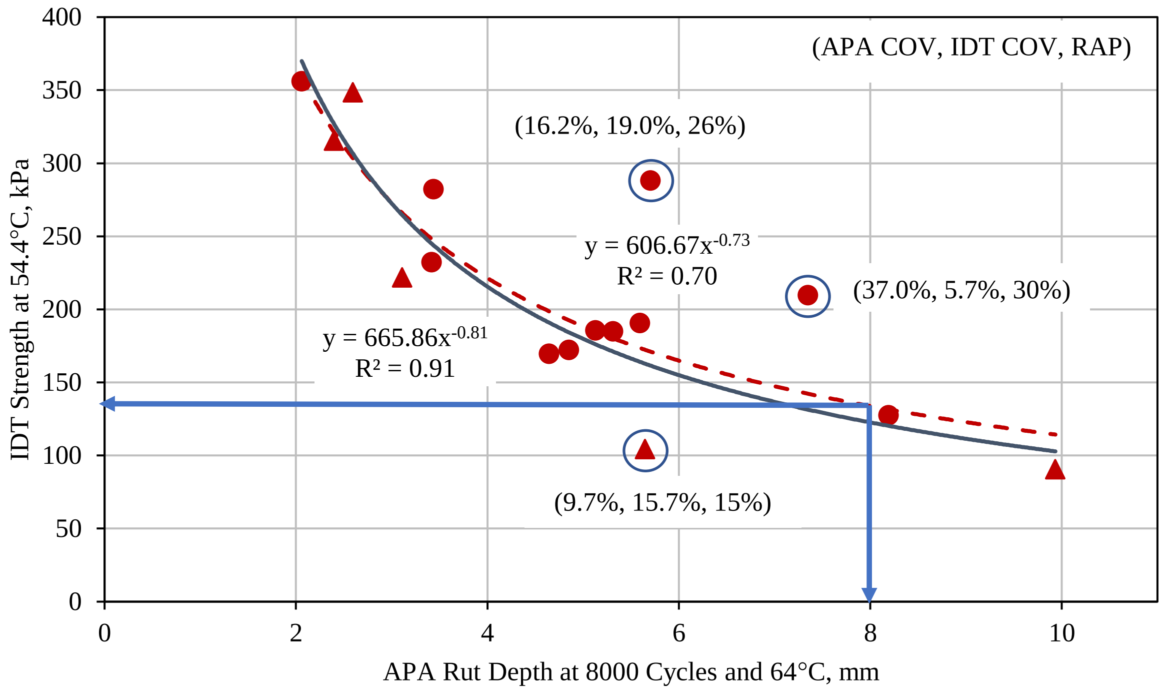


Figure 29 - Establishment of IDT strength threshold based on correlation to APA rut depth of 8mm

The IDEAL-RT preliminary rutting performance threshold was established based on the trendline shown in Figure 30 below. An IDEAL-RT shear strength of 1.07 MPa corresponds to an APA rut depth of 8 mm. Therefore, the preliminary rutting performance threshold for the IDEAL-RT determined from Phase 1 is a shear strength of 1.07 MPa.

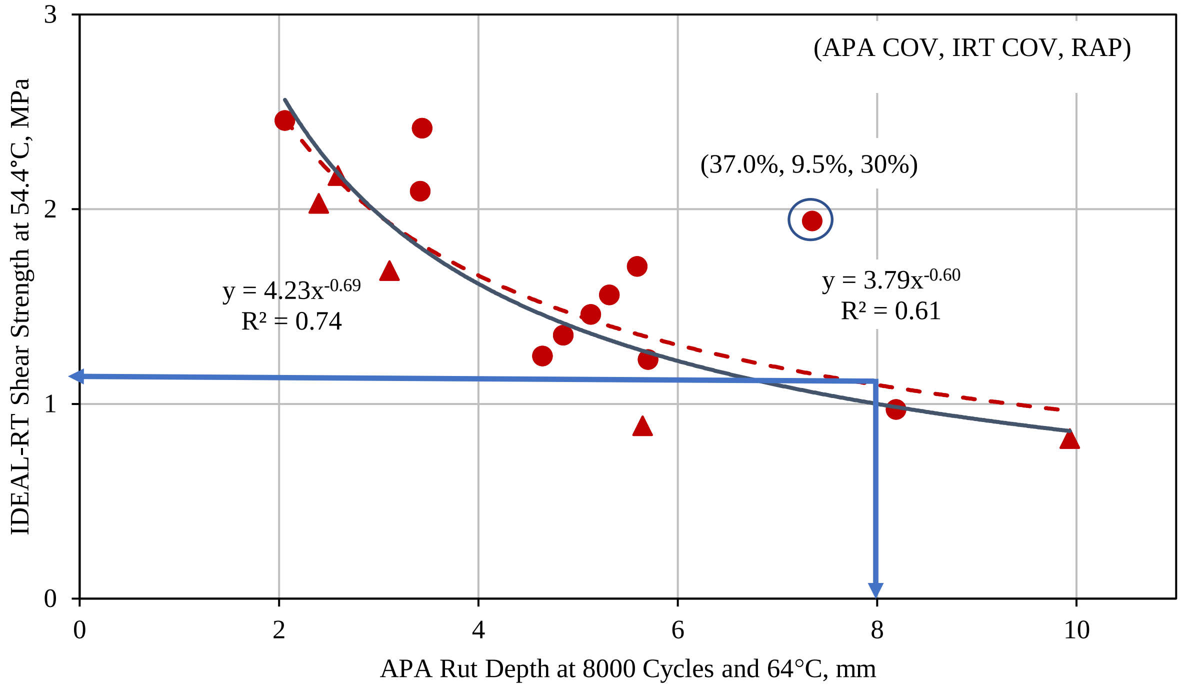


Figure 30 - Establishment of IDEAL-RT shear strength threshold based on correlation to APA rut depth of 8mm

Based on this analysis, the recommended rutting performance thresholds for the IDT test and IDEAL-RT are summarized in Table 13.

Table 13 - Summary of recommended monotonic tests and thresholds for rutting performance

Test	IDT	IDEAL-RT
Test Temperature	54.4°C	54.4°C
Air Void Content	7 ± 0.5%	7 ± 0.5%
Loading Rate	50 ± 2 mm/min	50 ± 2 mm/min
Specimen Thickness	62 mm ± 1 mm	62 mm ± 1 mm
Specimen Diameter	150 mm ± 2 mm	150 mm ± 2 mm
Conditioning Time	2 hours	2 hours
Standard	to be developed	to be developed
Criteria for Rutting Performance	IDT Strength > 133kPa	IDEAL-RT Shear Strength > 1.07MPa

Additionally, other states and institutions have developed rutting performance thresholds for the IDT test, as summarized in Table 14. The IDT strength threshold of 133 kPa determined from this study is reasonable compared to the thresholds developed in other studies.

Table 14 - IDT rutting performance thresholds developed by other states and institutions

Reference	Traffic/Mix Type	Temperature, °C	IDT Strength, kPa	Notes
Christensen and Bonaquist, 2007 [6]	3M ESALs	49	107.9	4%Va, 155mm tall specimens
Christensen and Bonaquist, 2007 [6]	10M ESALs	49	173.1	4%Va, 155mm tall specimens
Bennert et. al., 2021 [31]	High RAP-surface course (PG64E-22)	44	324.1	6.5%Va, 95mm tall specimens
Bennert et. al., 2021 [31]	High RAP-surface course (PG64S-22)	44	158.6	6.5%Va, 95mm tall specimens
Alabama DOT 2021 [33]	10M ESALs	50	137.9	7%Va, 62mm tall specimens
VDOT*	10M ESALs	54.4	133.0	7%Va, 62mm tall specimens

*VDOT refers to the work done in this thesis for determining preliminary IDT rutting performance threshold

In addition, Zhou et. al. (2020) [34] recommended a rutting performance threshold of 0.98 MPa for the IDEAL-RT test. This compares well to the IDEAL-RT shear strength threshold determined in this study of 1.07 MPa.

6. Laboratory Testing Program: Phase 2

To further evaluate the monotonic loading tests for their ability to determine rutting performance of asphalt mixtures, more complex tests to measure fundamental properties were conducted on six asphalt mixtures (mixtures G, K, L, O, P, and Q). Three tests were conducted on all six of these mixtures using the asphalt pavement performance tester (AMPT). The tests conducted were the dynamic modulus (DM) test, stress sweep rutting (SSR) test, and repeated load triaxial test (RLTT). The individual AMPT test results are presented as well as their correlations to the IDT and IDEAL-RT tests.

6.1 Dynamic Modulus (DM) Test

The method for determining the dynamic modulus (E*) of asphalt specimens using the AMPT is outlined in AASHTO T 378 [27]. In this test, a specimen at a specific test temperature undergoes a controlled sinusoidal compressive stress of various frequencies [27]. The stresses and axial strains are recorded to determine the dynamic modulus and phase angle [27]. In this study, DM tests were conducted in an unconfined condition meaning no latex membrane was used. Three LVDTs were attached to each DM test specimen as detailed in section 6.4 below. The specimen dimensions and air void content are also detailed in section 6.4. Dynamic modulus tests were conducted under the following conditions:

- 4°C: 25Hz, 10Hz, 1Hz, and 0.1Hz
- 21°C: 10Hz, 1Hz, and 0.1Hz
- 40°C: 10Hz, 1Hz, 0.1Hz, and 0.01Hz

6.2 Stress Sweep Rutting (SSR) Test

The methodology of the SSR test using the AMPT is outlined in AASHTO TP 134 [64]. In this study, SSR tests were conducted at two test temperatures with 26°C as the low temperature and 55°C as the high temperature. The SSR test is conducted under a confining pressure of 69 kPa (10 psi) with three 200-cycle loading blocks of three deviatoric stress levels

[64]. Specimen preparation for this test is detailed in section 6.4. The SSR test measures the permanent axial deformation of the specimen.

6.3 Repeated Load Triaxial Test (RLTT)

The flow number, a measure of permanent axial strain on an asphalt specimen, can be determined via the Repeated Load Triaxial Test (RLTT). The method for determining the flow number of asphalt specimens using the asphalt pavement performance tester (AMPT) and the RLTT is outlined in AASHTO T 378 [27]. During the RLTT, a specimen at a specific test temperature undergoes a repeated axial compressive load pulse of 0.1 seconds every 1.0 seconds [27]. The flow number, which is the number of load cycles corresponding to the minimum rate of change of permanent axial strain, is reported from this test [27]. In this study, the RLTT was ran as a confined test, meaning the specimens were under a confining pressure of 69 kPa during testing. These tests were conducted 30°C, 40°C, and 50°C with a deviatoric stress of 482.6 kPa and a contact stress of 17.2 kPa.

6.4 Specimen Preparation for AMPT Tests

AMPT tests fall under the advanced test category because they require more time in terms of specimen preparation, testing, and analysis. Specimen preparation for these tests conducted in Phase 2 differed from the specimen preparation in Phase 1 in that specimens had to be cut and cored after compaction to reach the desired specimen dimensions. AMPT specimens were first compacted to a height of 180 mm and diameter of 150 mm. Then, specimens were cored to a diameter of 100 mm. Next, the specimens were cut on either end to be sure the top and bottom are flat, and the height is 150 mm. This process created the desired 150 mm height by 100 mm width specimens needed for all three AMPT tests in accordance with AASHTO R 83 [65]. For Phase 2 testing, all AMPT specimens were compacted to 7 ± 0.5% air voids. The specimen dimensions and air void content were confirmed via the same bulking process used for Phase 1 specimen preparation. Figure 31 demonstrates this AMPT specimen preparation process.

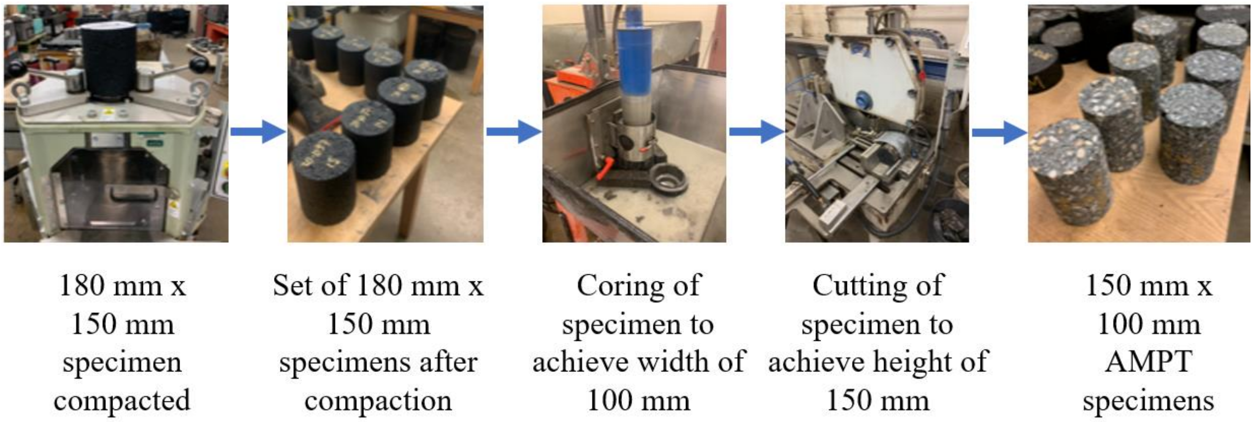


Figure 31 - AMPT specimen preparation

For the DM test, further specimen preparation was required in order to attach linear variable differential transformers (LVDT) sensors to the specimen to measure deformation during testing. This additional process is called targeting and involves gluing targets onto the specimen at specific spots where the LVDTs can be attached. This process is shown in Figure 32.

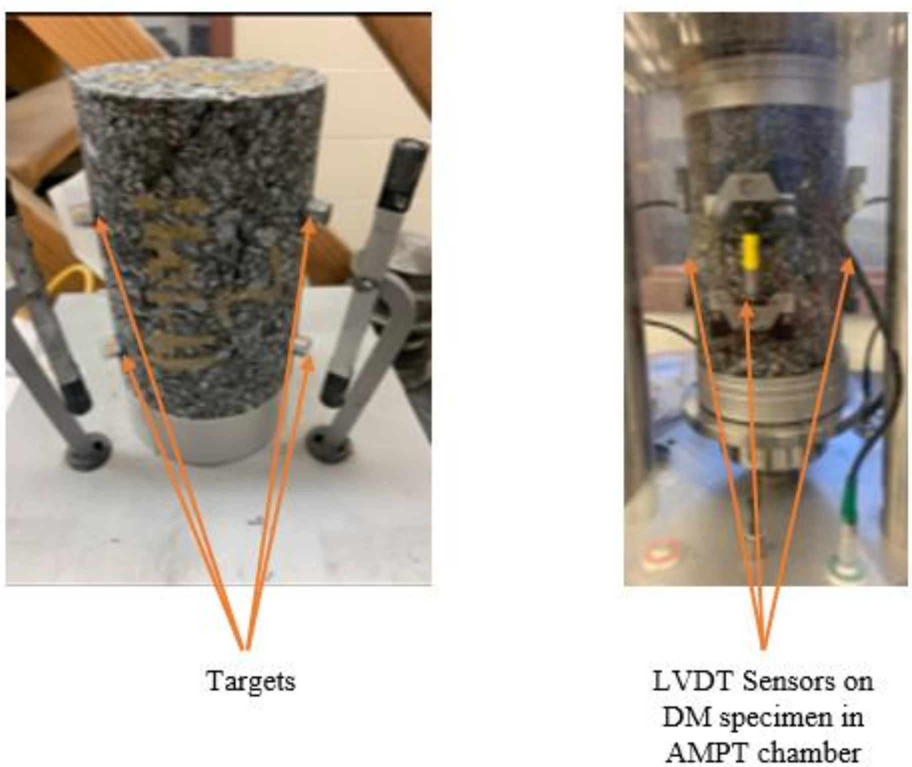


Figure 32 - Targeting of DM specimen and placement of LVDT sensor

For the SSR test and RLTT, a latex membrane must surround the specimen during testing to create a confining pressure. On the top and bottom of the specimen a single layer latex membrane was used for RLTT tests, and a double latex membrane was used for SSR tests. The AMPT chamber creates confining pressure on the specimen using this membrane to establish confinement of the specimen during testing. The membrane on the asphalt specimen is shown in Figure 33.

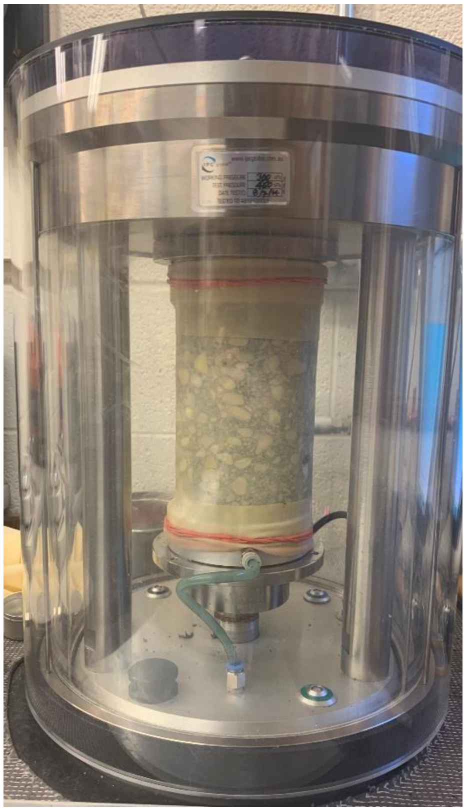


Figure 33 - Latex membrane on specimen in AMPT chamber

7. Experimental Results: Phase 2

7.1 Results from Individual AMPT Tests

7.1.1 Dynamic Modulus (DM) Results

The dynamic modulus test results included the dynamic modulus (E*) at each temperature-frequency combination for each mixture. The E* value is the dynamic modulus representing the stiffness of the asphalt material [66]. A higher E* value indicates a more rutting resistant mixture.

Through a generalized logistics model and polynomial shift factor [67] the E* values for each mixture at 38°C and 0.1 Hz as well as at 54.4°C and 10 Hz were plotted and presented in Figure 34. The E* at 38°C and 0.1 Hz was chosen for this report because Apeagyei et. al. [68] and Diefenderfer et al [17] showed a good correlation between this parameter and APA rut depth. The E* at 54.4°C and 10 Hz was also chosen for this report because 54.4°C is the critical high pavement temperature in Virginia and 10 Hz represents a vehicle traveling at 45 mph.

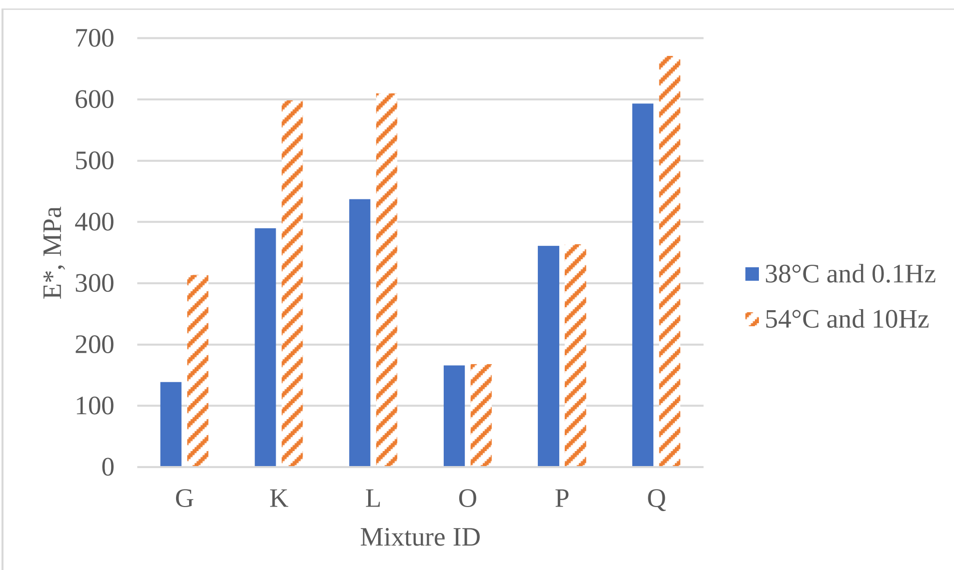


Figure 34 - E results from DM tests*

A higher temperature usually leads to a lower E* value because the asphalt material becomes softer at higher temperatures. However, a higher frequency usually means a higher E* value. Based on the results presented in Figure 34, the effects of the frequency factor are masking the effects of the temperature factor resulting in a greater E* value at 54.4°C and 10 Hz when compared to 38°C and 0.1 Hz, especially for mixtures G, K, L, and Q.

Additionally, the dynamic modulus (E*) master curves are shown in Figure 35. A reference temperature of 21°C was used and this figure was constructed using the generalized logistics model and the polynomial shift factor.

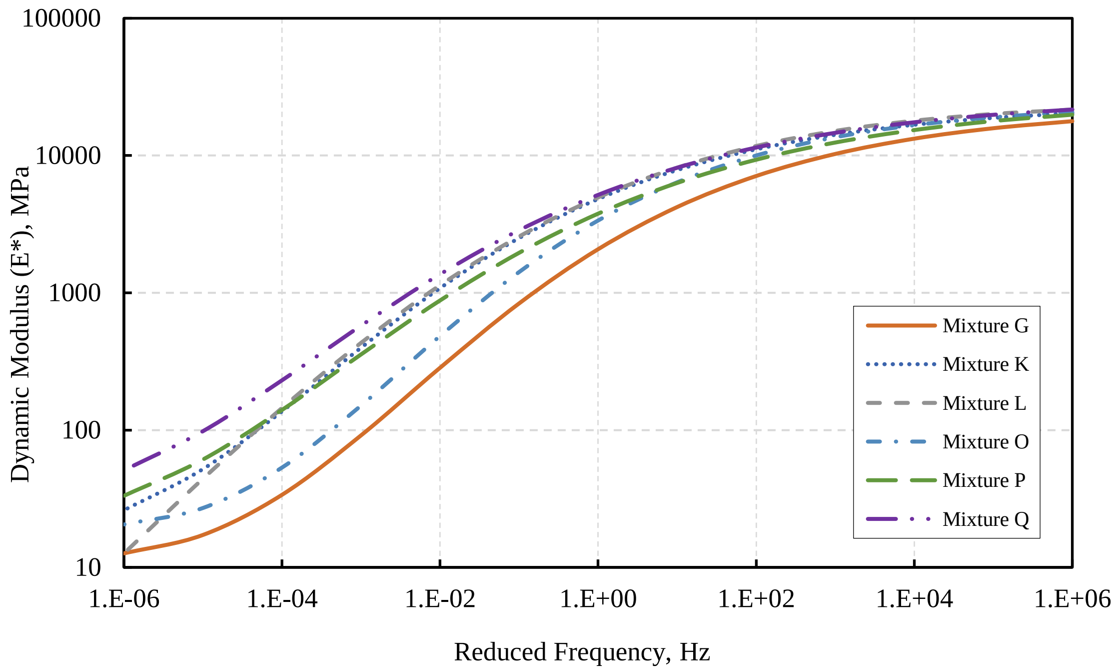


Figure 35 - E master curves from DM testing*

7.1.2 Stress Sweep Rutting (SSR) Results

The SSR test results were analyzed using FlexMAT-Rutting to determine the rutting strain index (RSI) for each mixture for 20 years of traffic. The recommended threshold values of RSI based on traffic level are shown in Table 15 [69].

Table 15 - Recommended threshold values of RSI [69]

Traffic Level (million ESALs)	**Tier**	**RSI Limits**
Less than 10	Standard	4 < RSI < 12
Between 10 and 30	Heavy	2 < RSI < 4
Greater than 30	Very heavy	1 < RSI < 2
Greater than 30 and slow traffic	Extremely heavy	RSI < 1

The RSI results for each mixture are shown in Figure 36. Mixtures G and P fall under the standard traffic tier, mixtures K and O falls under the heavy traffic tier, and mixtures L and Q fall under the very heavy traffic tier.

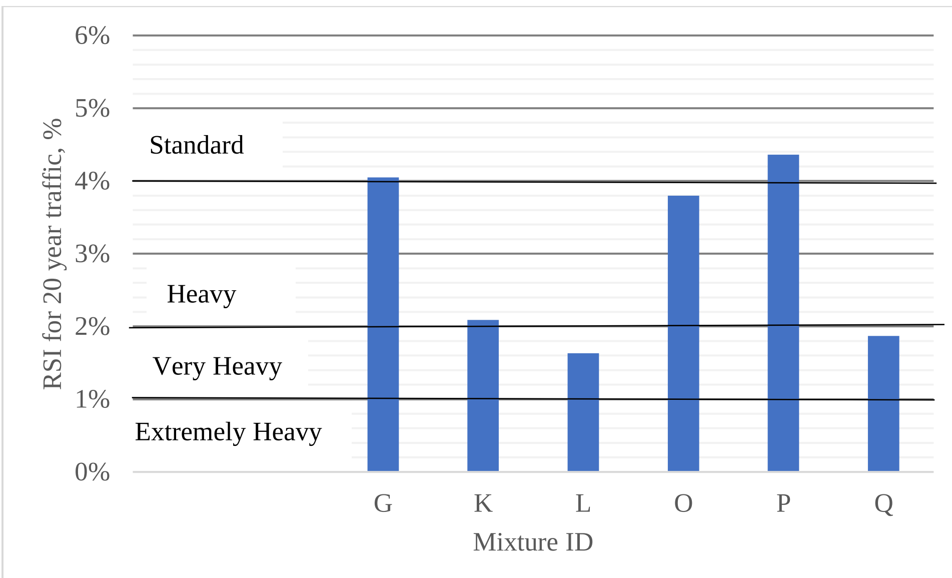


Figure 36 - RSI results and recommended traffic designation tiers

7.1.3 Repeated Load Triaxial Test (RLTT) Results

The RLTT results at 50°C are discussed in this section as this testing temperature most pertains to evaluating rutting of the mixtures. During the RLTT test, the axial deformation was recorded after each pulse. From this, the axial resilient strain (ε_r) can be determined as well as the cumulative permanent strain (ε_p) [70, 71]. In this RLTT analysis, the Franken model was used to numerically model the permanent strain-loading cycle relationship. The Franken model is shown in Equation 8 where $\varepsilon_p(N)$ is the permanent axial strain, N is the number of loading cycles, and $A, B, C,$ and D are regression constants. The Franken model combines a power model, which characterizes the primary and secondary stages, and an exponential model, which characterizes the tertiary stage [70]. The flow number (FN) is the number of cycles that corresponds to the inflection point at which the tertiary stage begins.

$$\varepsilon_p(N) = A * N^B + C * (e^{D*N} - 1) \quad \text{Equation 8}$$

One rutting relationship that comes from the RLTT analysis is the cumulative permanent axial strain over the resilient strain, $\varepsilon_p/\varepsilon_r$, as a function of the number of loading cycles, N. In Figure 37, the $\varepsilon_p/\varepsilon_r$ at 50°C calculated from the Franken model is plotted from 0 to 10,000 cycles for each mixture. In this plot, the curves higher up on the plot are indicative of a more rut susceptible mix. The curve for mixture G is much higher than the curves for other mixtures, which is expected because mixture G is a wet mix that may not be stable at higher temperatures. Also in this plot, a flatter curve means that mixture has less sensitivity to the change in loading, while a steeper curve means that mixture is more sensitve to the change in loading.

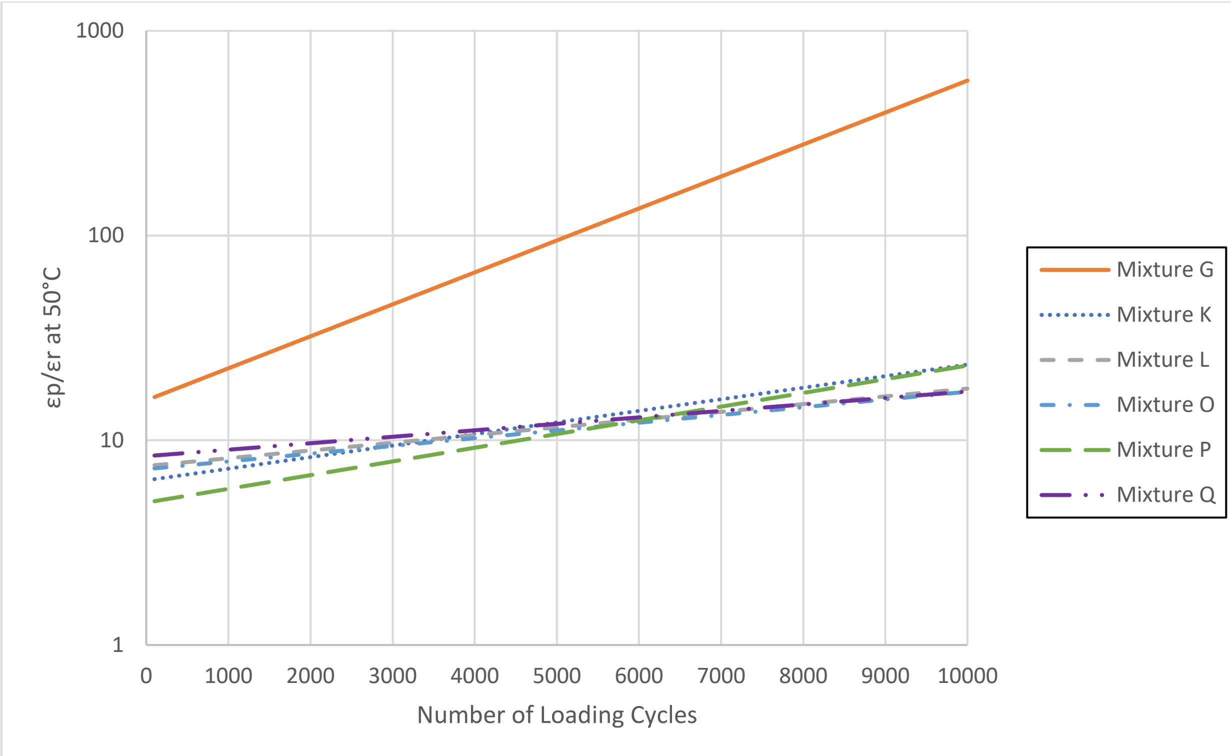


Figure 37 - RLTT rutting characteristics at 50°C

Additionally, the following rutting parameters from the RLTT at 50°C are presented in Figures 38-39 and Table 16: flow number (FN), $\varepsilon_p/\varepsilon_r$ at the flow number, and flow number index (FN index). Equation 9 shows how the $\varepsilon_p/\varepsilon_r$ at the FN was calculated. The FN index was calculated using Equation 10.

$$\frac{\text{εp}}{\text{εr}} at\ FN = \frac{A * \ FN^{B}}{\text{εr}} \qquad \textit{Equation 9}$$

$$FN\ index\ (\%) = \frac{A * \ FN^{B}}{FN} * 100 \qquad \textit{Equation 10}$$

Of note, all FN values used in these equations are the FN values reported from the AMPT machine data, not the model. The regression constants and ε_r values in these equations do come from the model.

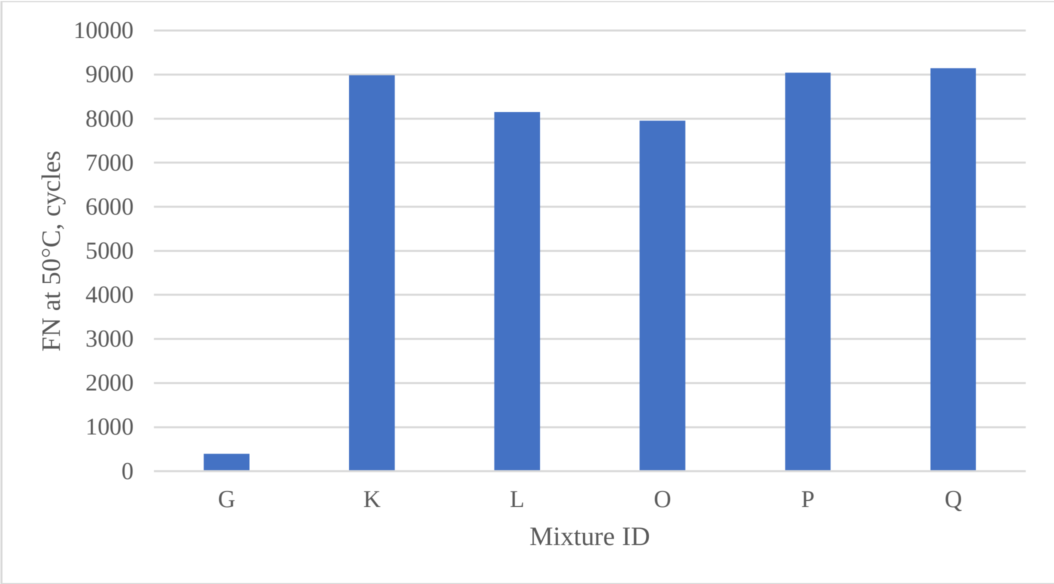


Figure 38 - FN at 50°C from RLTT

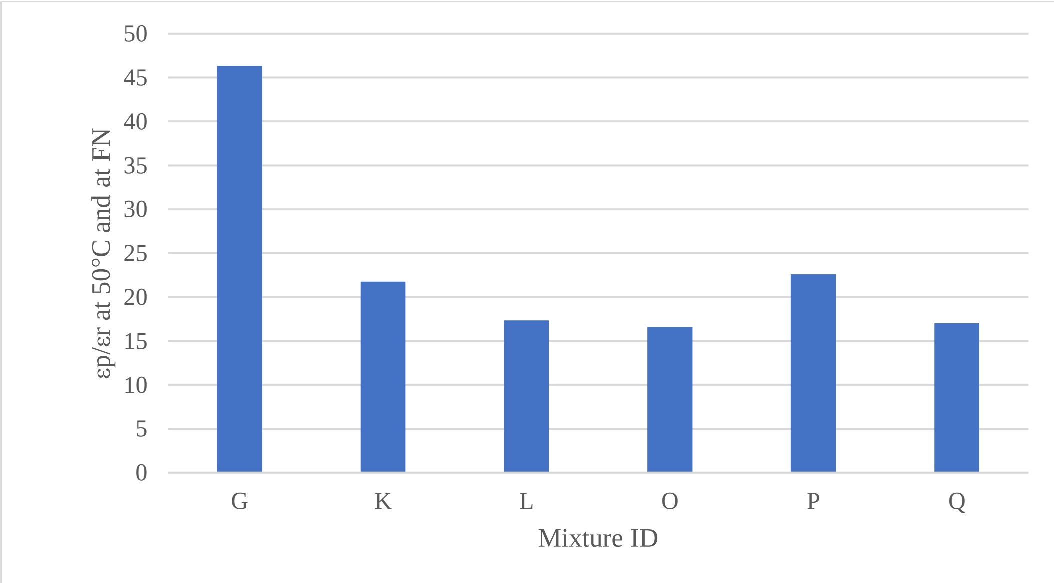


Figure 39 - εp/εr at 50°C and at FN from RLTT

Table 16 - FN Index at 50°C from RLTT

Mixture ID	FN Index (%) at 50C
G*	2.3269
K	0.0322
L	0.0215
O	0.0310
P	0.0332
Q	0.0201

*Mixture G is an outlier data point

Based on these results, it is shown that mixture G is an outlier in regard to the rest of the mixtures. This is because mixture G is a wet mix (i.e. a mix with a relatively high asphalt content) and may not stable be at 50°C, resulting in RLTT rutting parameters that would indicate high rutting susceptibility. More on this is discussed in section 7.2 of this thesis.

7.2 Correlations Among Rutting Indices

AMPT results were compared to APA test results with the expectation of a good correlation due to these being commonly used standard tests in the asphalt industry to measure rutting performance. In addition, AMPT results were compared to results from the monotonic test results (IDT, IDEAL-RT) to evaluate the ability of the monotonic loading tests to evaluate the "true" rutting performance.

First, the E* values at 38°C and 0.1 Hz determined from the Dynamic Modulus (DM) test were compared to the APA rut depth at 64°C results, the IDT strength at 54.4°C results, and the IDEAL-RT shear strength at 54.4°C results. These results are shown in Figures 40-42. The first comparison plot (E* at 38°C and 0.1 Hz vs. APA rut depth) yielded a linear correlation with an R^2 of 75%. The second comparison plot (E* at 38°C and 0.1 Hz vs. IDT strength) resulted in a linear correlation with an R^2 of 74%. The third comparison plot (E* at 38°C and 0.1 Hz vs. IDEAL-RT shear strength) resulted in a linear correlation with an R^2 of 71%.

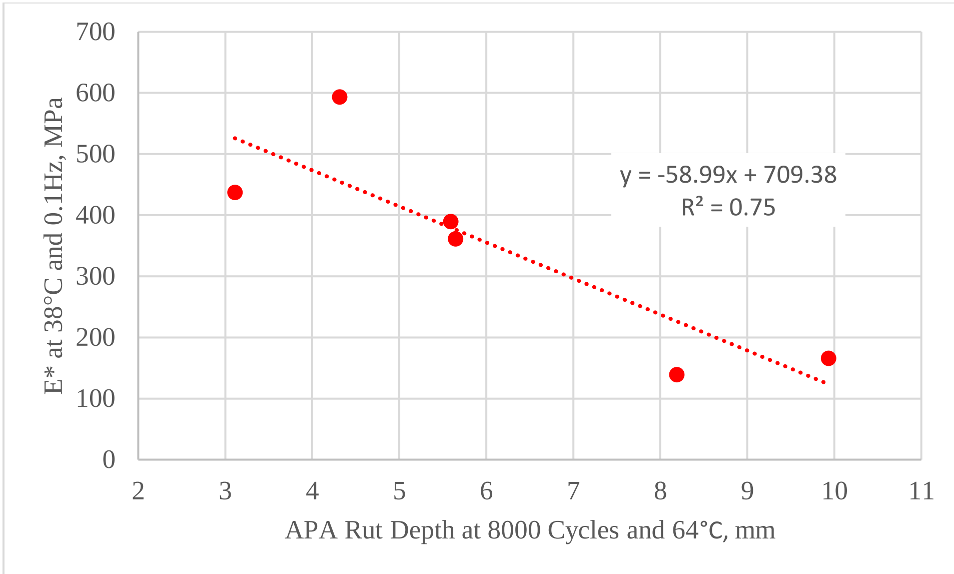


Figure 40 - Correlation between APA rut depth and E at 38°C and 0.1 Hz from DM test*

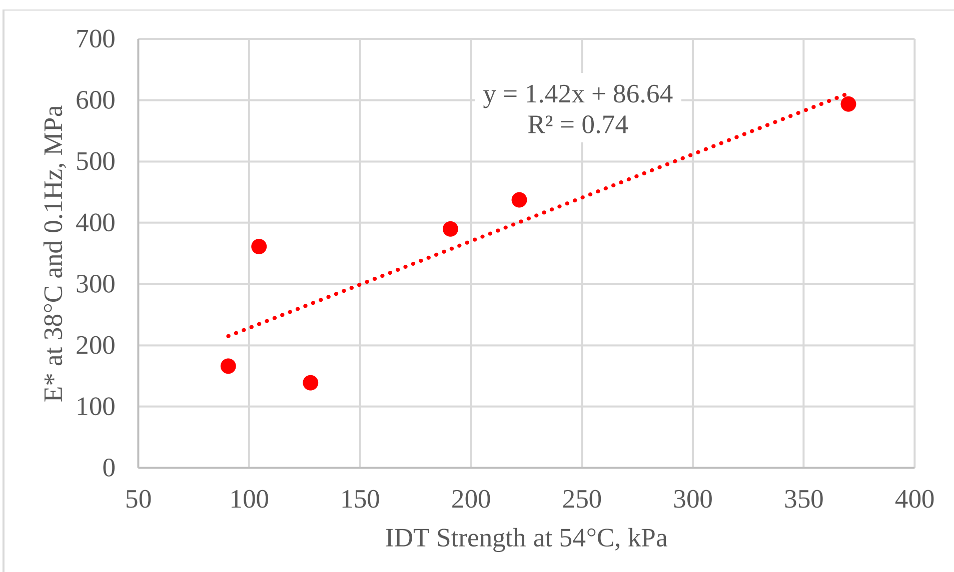


Figure 41 - Correlation between IDT strength and E at 38°C and 0.1 Hz from DM test*

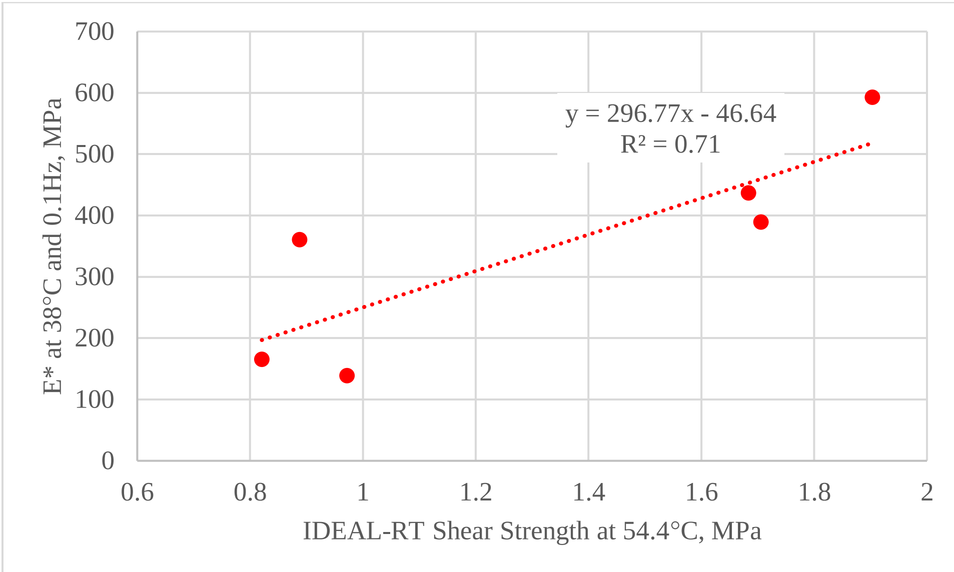


Figure 42 - Correlation between IDEAL-RT shear strength and E at 38°C and 0.1 Hz from DM test*

Next, the E* at 54.4°C and 10 Hz was compared to the to the APA rut depth at 64°C results, the IDT strength at 54.4°C results, and the IDEAL-RT shear strength at 54.4°C results as shown in Figures 43-45. The E* at 54.4°C and 10 Hz showed an exponential correlation to APA rut depth with an R^2 of 75%. The E* at 54°C and 10 Hz showed a power function correlation to IDT strength with an R^2 of 74%. The E* at 54.4°C and 10 Hz showed a linear correlation to IDEAL-RT shear strength with an R^2 of 93%.

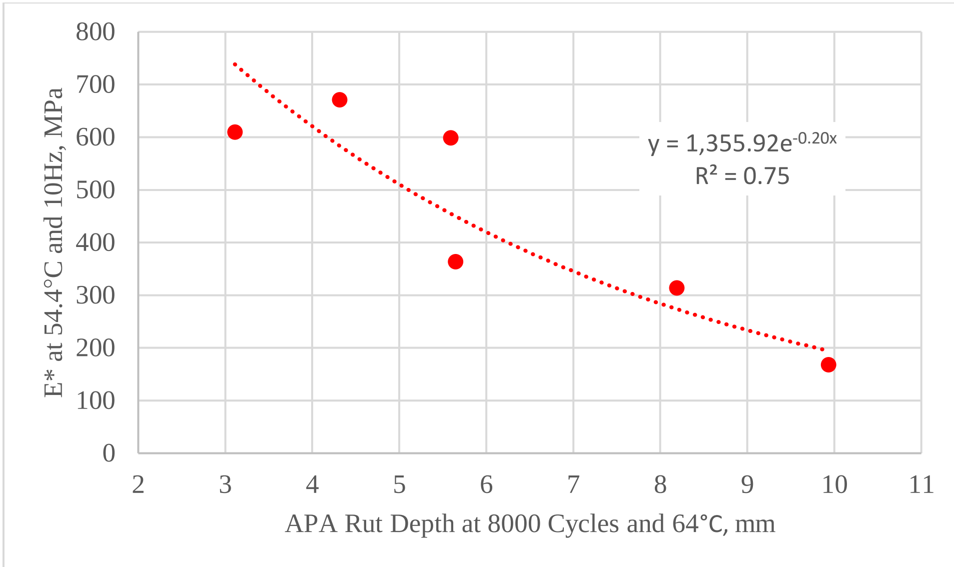


Figure 43 - Correlation between APA rut depth E at 54.4°C and 10 Hz from DM test*

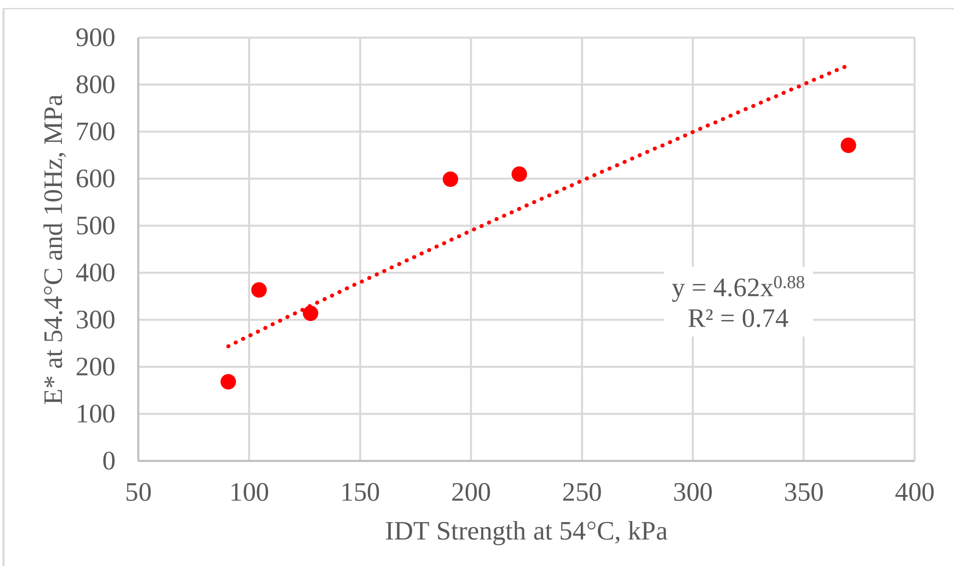


Figure 44 - Correlation between IDT strength and E at 54.4°C and 10 Hz from DM test*

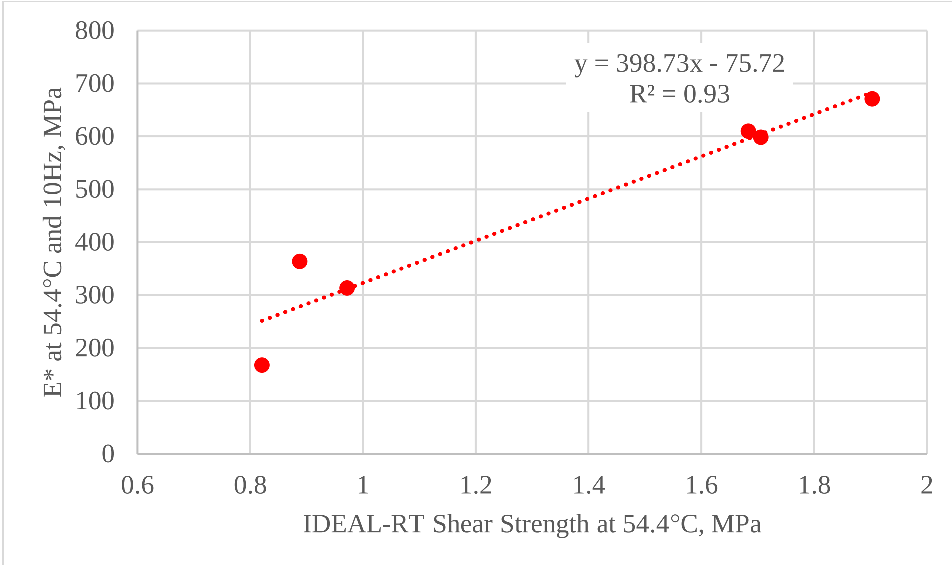


Figure 45 - Correlation between IDEAL-RT shear strength and E at 54.4°C and 10 Hz from DM test*

In Figures 40-45, the following expected trends were observed. As APA rut depth increased, the E* value decreased. As IDT strength increased, the E* value increased. As IDEAL-RT shear strength increased, the E* value also increased.

The E* at 38°C and 0.1Hz results showed the highest correlation with the APA test, followed closely by the IDT test and then the IDEAL-RT test. The E* at 54°C and 10 Hz results showed the highest correlation with the IDEAL-RT test, followed by the APA test and then the IDT test. While this E* at 54.4°C and 10 Hz parameter showed a higher correlation with the IDEAL-RT shear strength than APA rut depth and IDT strength, it is of note that these data points in the E* vs. IDEAL-RT shear strength plots are clustered into two groups and therefore this higher correlation may not necessarily be indicative that the IDEAL-RT is the better rutting test. Overall, the E* rutting parameter results from the DM test show good correlation to APA, IDT, and IDEAL-RT results, further validating the use of the monotonic tests as rutting tests.

Next, the rutting strain index (RSI) values at 20 year traffic reported from the SSR tests, expressed as a percentage, were compared to the APA rut depth at 64°C results, the IDT strength at 54.4°C results, and the IDEAL-RT shear strength at 54.4°C results shown in Figures 46-48. RSI vs. APA comparison yielded a power function correlation with an R^2 of 54%. The RSI vs.

IDT comparison resulted in a power function correlation with an R^2 of 79%. The RSI vs. IDEAL-RT comparison showed an exponential correlation with an R^2 of 92%.

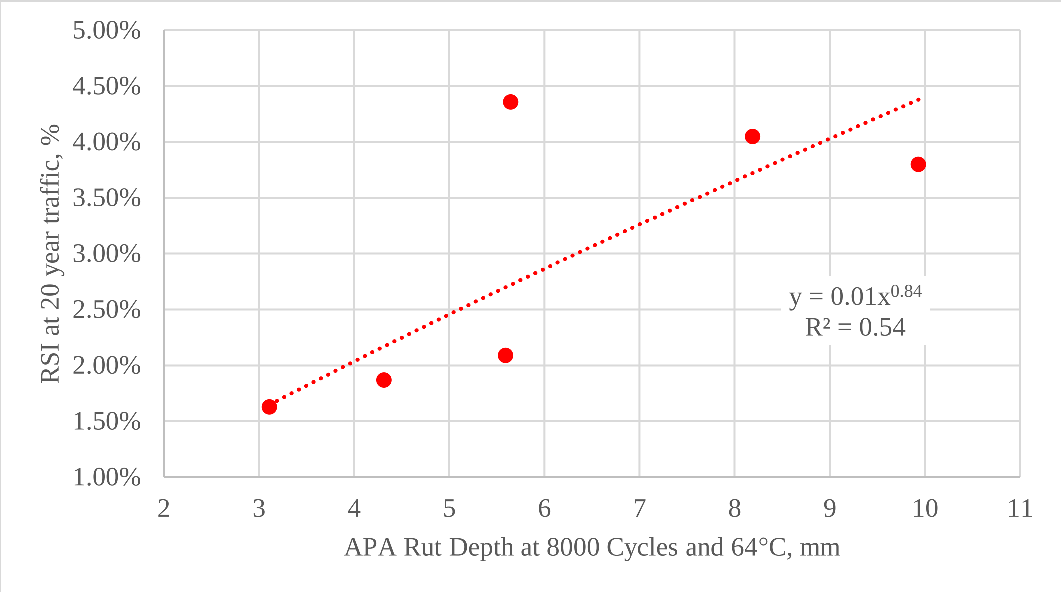


Figure 46 - Correlation between APA rut depth and RSI from SSR test

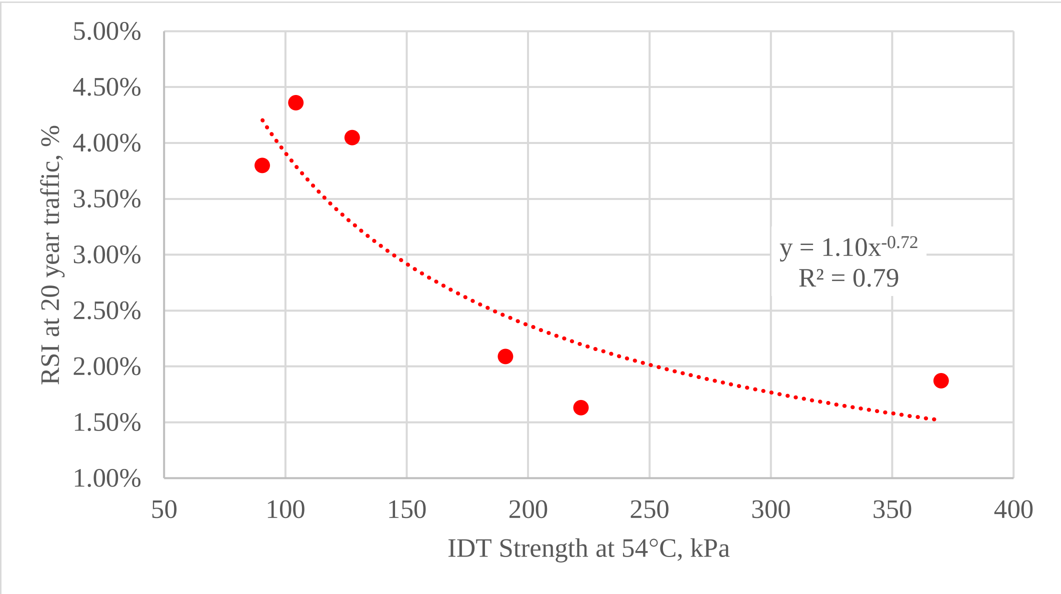


Figure 47 - Correlation between IDT strength and RSI from SSR test

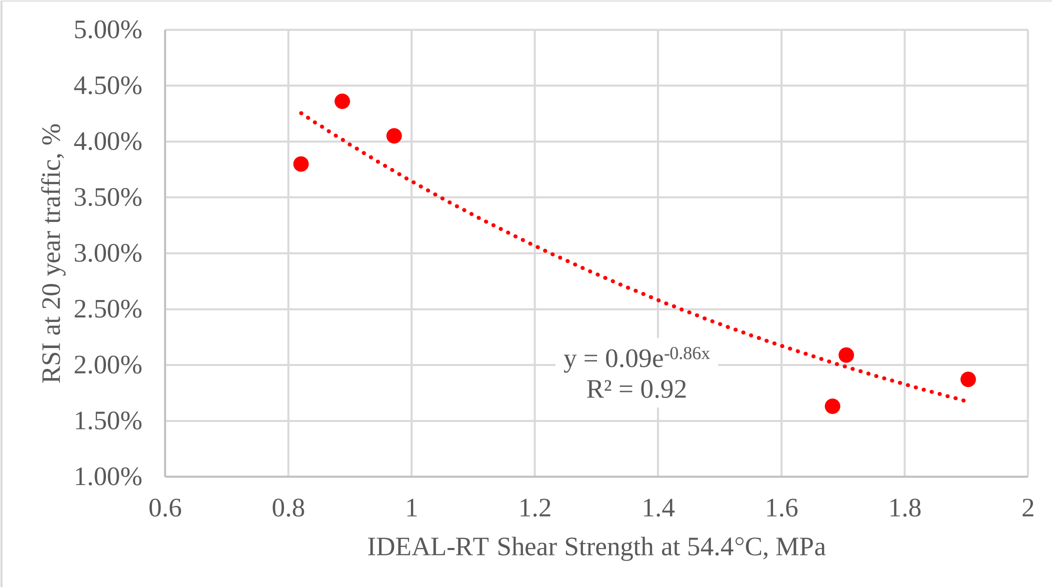


Figure 48 - Correlation between IDEAL-RT shear strength and RSI from SSR test

The following expected trends were observed in Figures 46-48. As APA rut depth increased, the RSI increased. As IDT strength increased, the RSI decreased. As IDEAL-RT shear strength increased, the RSI decreased. The RSI results yielded the best correlation with the IDEAL-RT test, followed by the IDT test and then the APA test. Of note, the IDEAL-RT results were clustered into two groups, and therefore this high correlation may not be indicative that this is the optimal rutting test. Both the IDT and IDEAL-RT tests showed good correlations to the RSI results, further validating their use as rutting tests.

Next, the FN index from the RLTT at 50°C, expressed as a percentage, was compared to the APA rut depth for all six mixtures, shown in Figure 49. Notably, there is an outlier point (mixture G). Mixture G is a wet mix that is not stable at high temperatures, so this FN index data point was deemed erroneous. Figure 49 is shown to demonstrate this erroneous data point.

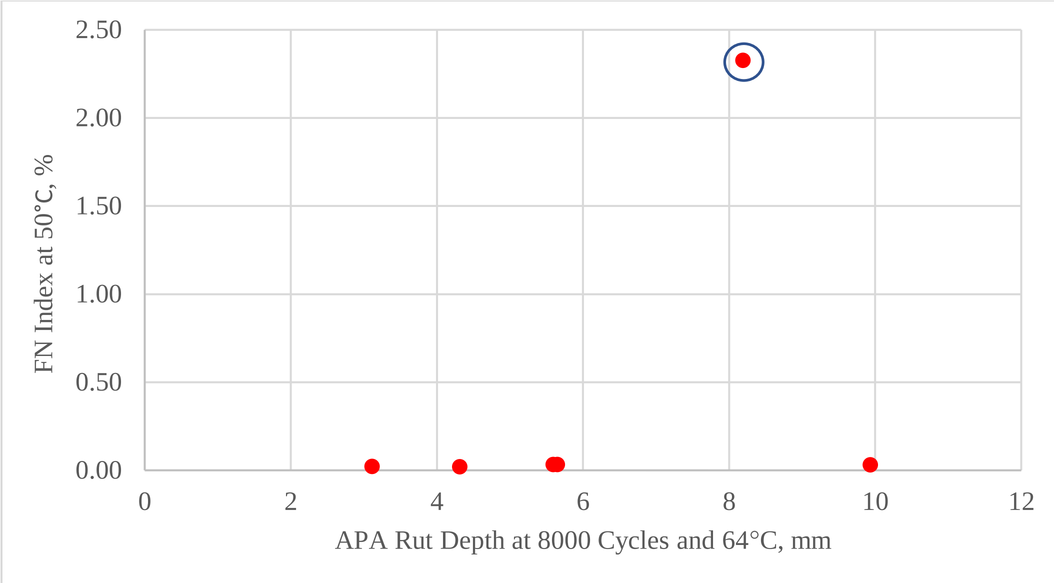


Figure 49 - APA rut depth vs. FN index including outlier

Excluding mixture G, the RLTT at 50°C rutting parameter of FN index was compared to the APA rut depth at 64°C results, the IDT strength at 54.4°C results, and the IDEAL-RT shear strength at 54.4°C results to explore correlations between rutting parameters. These FN index comparisons are shown in Figures 50-52. The FN index showed a power function correlation with APA rut depth with an R^2 of 45%. The FN index showed an exponential correlation with IDT strength and an R^2 of 70%. The FN index showed a linear correlation with IDEAL-RT shear strength and an R^2 of 49%.

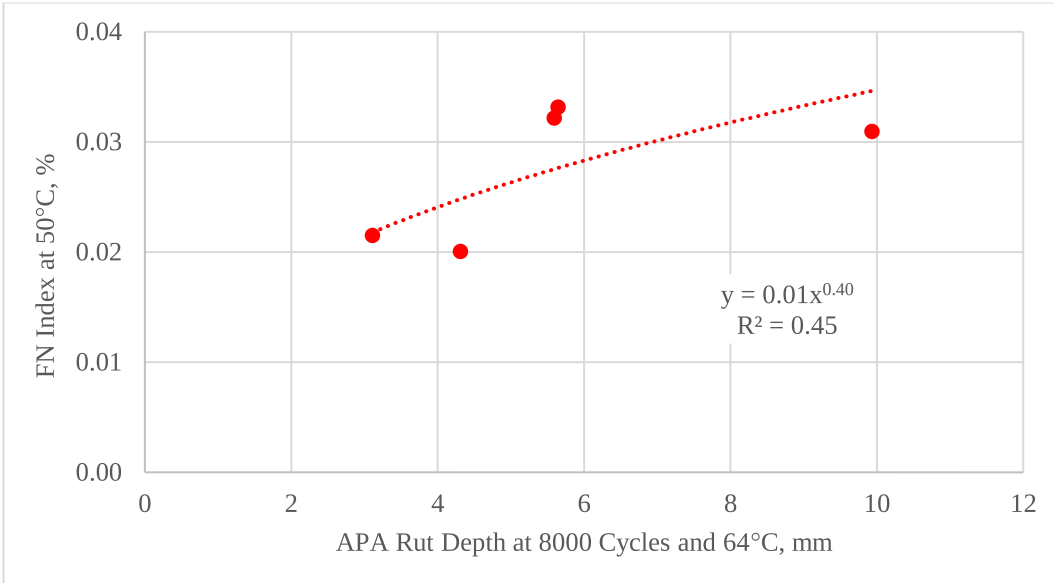


Figure 50 – Correlation between APA rut depth and FN Index from RLTT

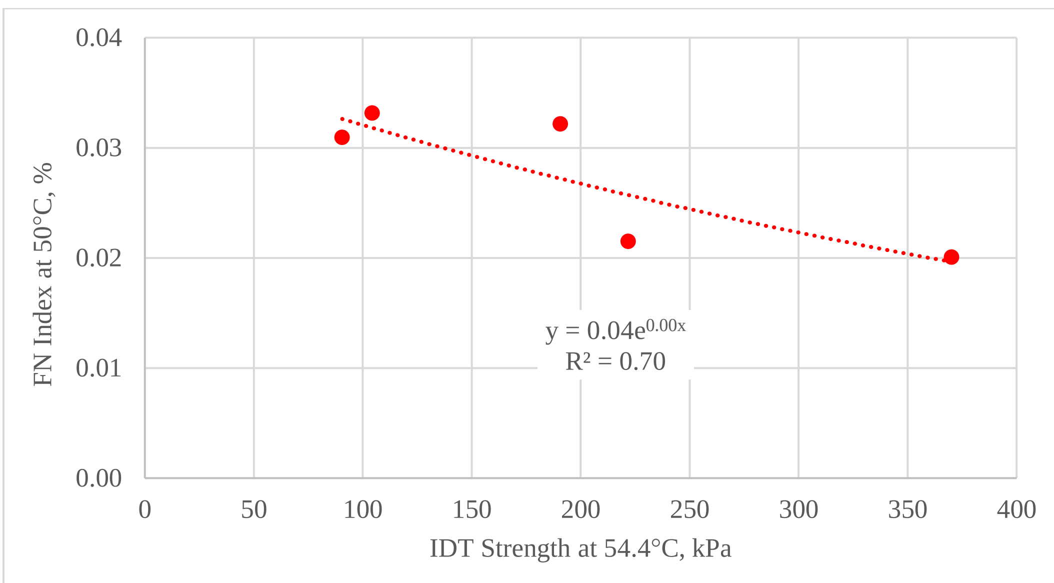


Figure 51 - Correlation between IDT strength and FN index from RLTT

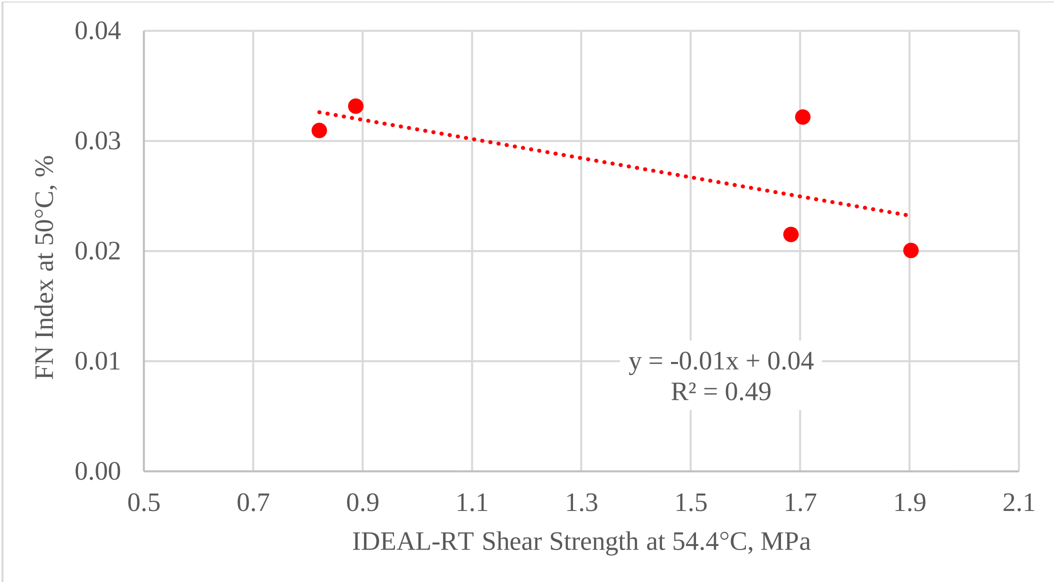


Figure 52 - Correlation between IDEAL-RT shear strength and FN index from RLTT

From these correlation plots, it is shown that the IDT strength had the highest correlation with the rutting parameter (FN index) from the RLTT, followed by the IDEAL-RT shear strength, and then the APA rut depth.

8. Monotonic Testing with Digital Image Correlation (DIC)

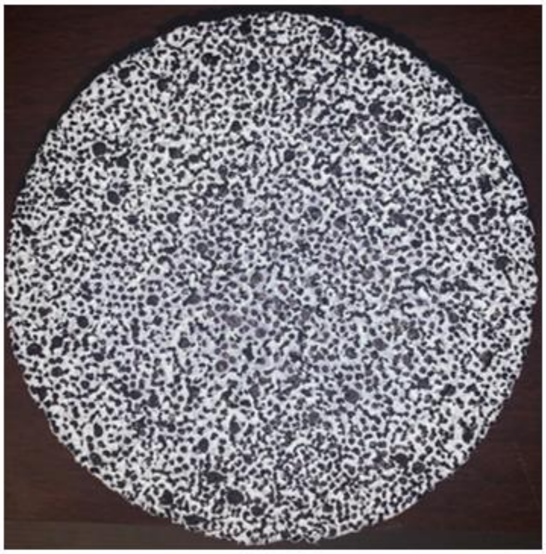
8.1 Specimen Preparation and DIC Test Setup

Specimens of asphalt mixtures O, Q, and P were prepared for IDT testing with 2-D DIC. First, each mixture was split out and compacted to the proper IDT test dimensions of 62 mm in height and 150 mm in diameter. Specimens were measured and bulked to confirm correct dimensions and air void content of 7 ± 0.5%.

Next, the DIC pattern was painted on each test specimen. A paint roller was used to apply flat exterior ultra-white paint onto the flat side of each specimen, shown in Figure 53.

Figure 53 - White surface of DIC specimen

Once the white paint was dry, the black speckle pattern was applied to each specimen. Different techniques were explored for the speckle pattern application including drawing the pattern by hand using permanent marker and using spray paint. The speckle pattern results of these two methods are shown in Figure 54.



Speckle pattern by hand with permanent marker

Speckle pattern using spray paint technique

Figure 54 - Speckle patterns on surface of DIC specimens

While creating the speckle pattern by hand yielded a good speckle pattern, it was difficult to create very small speckles which are useful for DIC analysis. This technique was also very time consuming. The spray paint technique yielded a variety of speckle sizes and very small speckles and was time efficient. For the tests in this thesis, a speckle pattern was applied to the specimen surface using matte black spray paint.

An alternative technique, not explored in this thesis, is to use the black surface of the asphalt specimen as the background and apply white speckles. This may be optimal because as more paint is added there is more of a potential for the paint to add stiffness to the specimen itself. Further work should be done to explore if this alternative technique is effective.

8.2 Experimental Testing Using DIC

Three mixtures (O, P, and Q) were tested with the IDT test using 2D-DIC for this study. The purpose of this testing was to explore the applicability of DIC for IDT-based monotonic testing of asphalt mixtures at high temperatures and to get an understanding of how DIC can be used as a powerful tool in analyzing the obtained data for rutting evaluation.

The 2D-DIC testing setup consisted of a load frame, a customized test fixture, a high-quality camera and tripod, a lighting fixture, a DIC calibration card, and a computer with Vic-Snap and Vic-2D software from Correlated Solutions [18]. The first issue addressed was the need for the camera to be able to capture the face of the specimen during the test. With the typical IDT and IDEAL-RT test setups, the face of the specimen is not entirely visible during testing as shown in Figure 55.

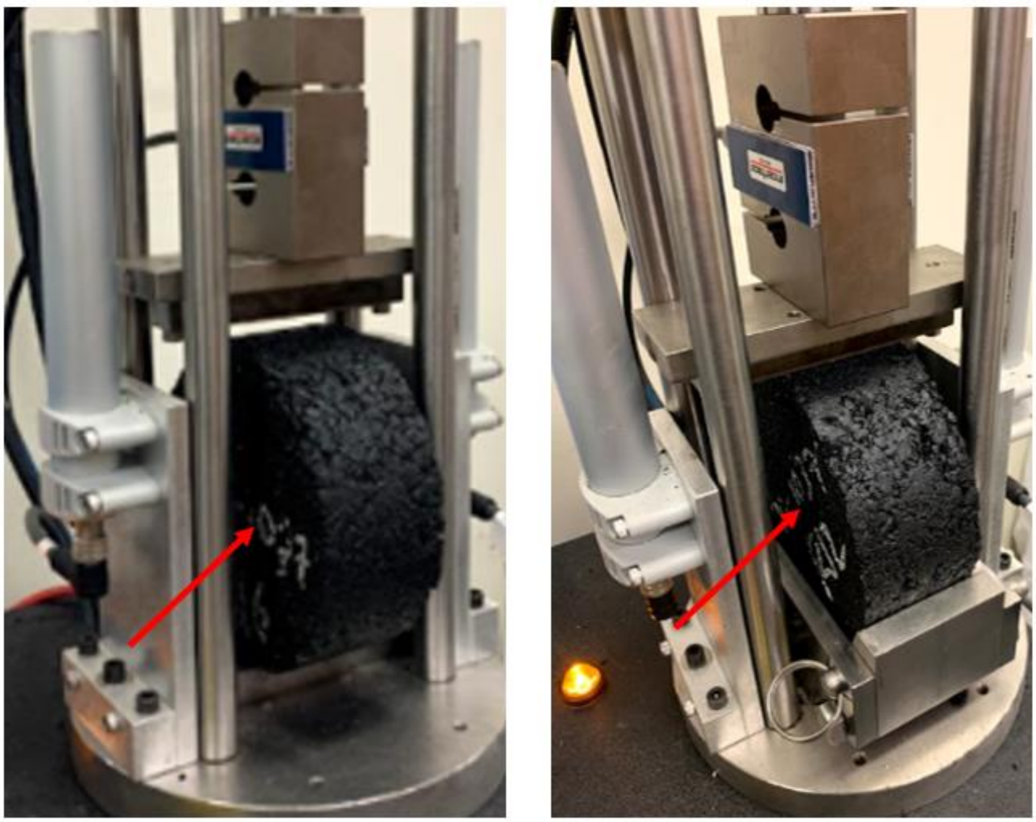
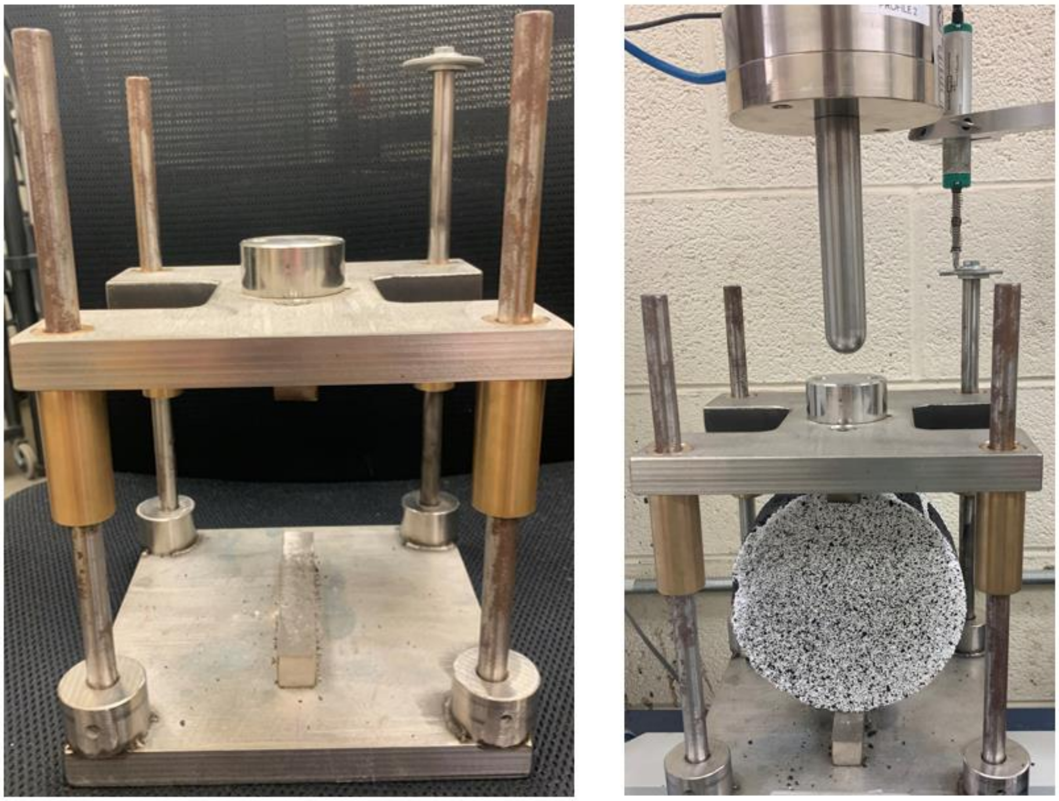


Figure 55 - Face of specimen unable to be captured by DIC camera with typical IDT and IDEAL-RT test setups

To overcome this challenge, a customized test fixture was created specifically for DIC testing with the IDT and IDEAL-RT tests as shown in Figure 56.



Customized test fixture for DIC

Specimen face visible with customized test fixture

Figure 56 - Customized test fixture for DIC with monotonic loading tests

Vic-Snap was utilized to capture images during the tests and Vic-2D was used to analyze the image data after testing, both software from Correlated Solutions [18]. A Point Grey camera and Schneider Kreuznach lens were used for image capture. A tripod was used to align the camera with the specimen making sure the optical axis of the lens was perpendicular to the specimen face. A lighting fixture was used to illuminate the face of the specimen during testing. Using Vic-Snap, the focus was set properly on the speckle pattern prior to each test. An image acquisition interval of 100 milliseconds was used for DIC tests in this study. The entire DIC test setup is shown in Figure 57.

Figure 57 - DIC Testing Setup

Three replicates of mixture O, P, and Q each underwent an IDT test at 54.4°C using DIC to capture images during each test. Specimens were conditioned in an environmental chamber at 54.4°C for 2 hours and tested within 2 minutes of removal from the chamber. Due to load frame limitations, the IDEAL-RT test was not conducted using DIC for this thesis.

8.3 Experimental Results from DIC Testing

DIC images captured during IDT tests for mixtures O, P, and Q were analyzed using the post-processing software Vic-2D. This software analyzes the images captured during testing and can calculate displacement and strains using an image matching technique. The first image, with no load applied to the specimen, is set as the reference image in which there is no deformation. A subset size of 71 was used to analyze the speckle pattern, chosen as each subset contained at least 4-5 speckles.

To illustrate the capabilities of DIC with IDT-based tests, the full-field strain distributions in the x-direction (ε_{xx}) and the y-direction (ε_{yy}) as well as shear strain distributions (ε_{xy}) were calculated and contour plots of these response parameters at different points along the load vs. displacement curve were created. This was done to show the progression of different strains on the specimen at different stages during the IDT test. The strain contours were calculated at the start of the test, 25% of the peak load, peak load, 75% of the post-peak load, and end of the test. These horizontal, vertical, and shear strain results are shown for mixture Q specimen 4 in Figures 58-60. It can be seen from Figure 58 that horizontal strains increase along the vertical plane formed by joining two loading points. Also, shear strains are concentrated closer to the top and bottom loading strips as shown in Figure 60. Overall, these results show that DIC can be used as a non-contact tool to measure strains across the whole specimen surface and analyze the failure mode of asphalt specimens during monotonic loading tests.

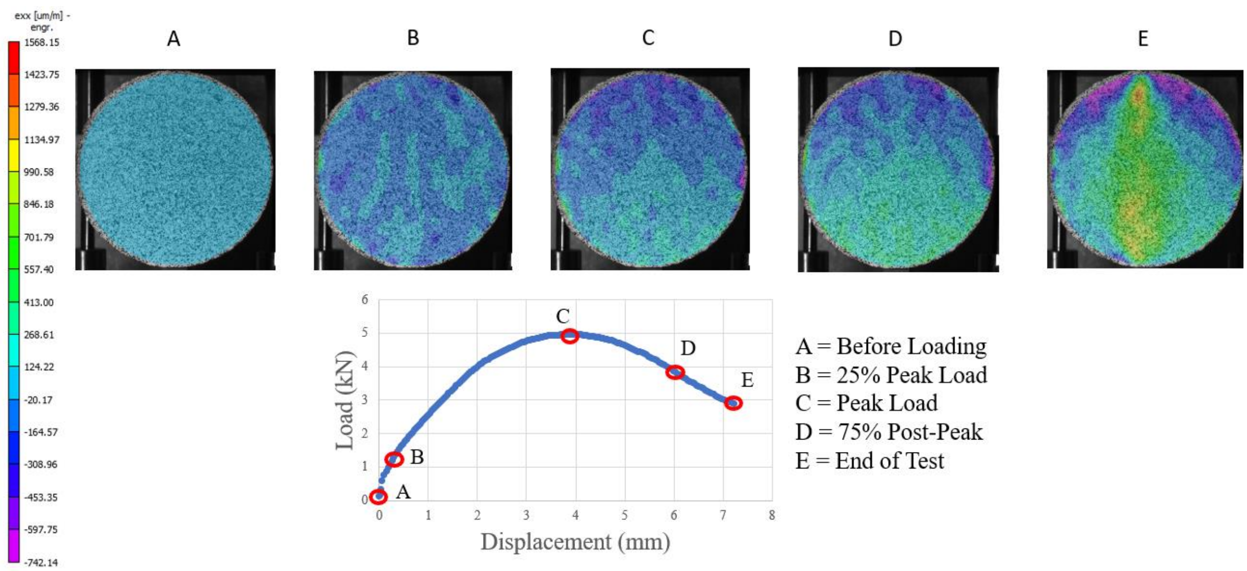


Figure 58 - $\mathcal{E}_{xx}$ contours at different stages of high temperature IDT test

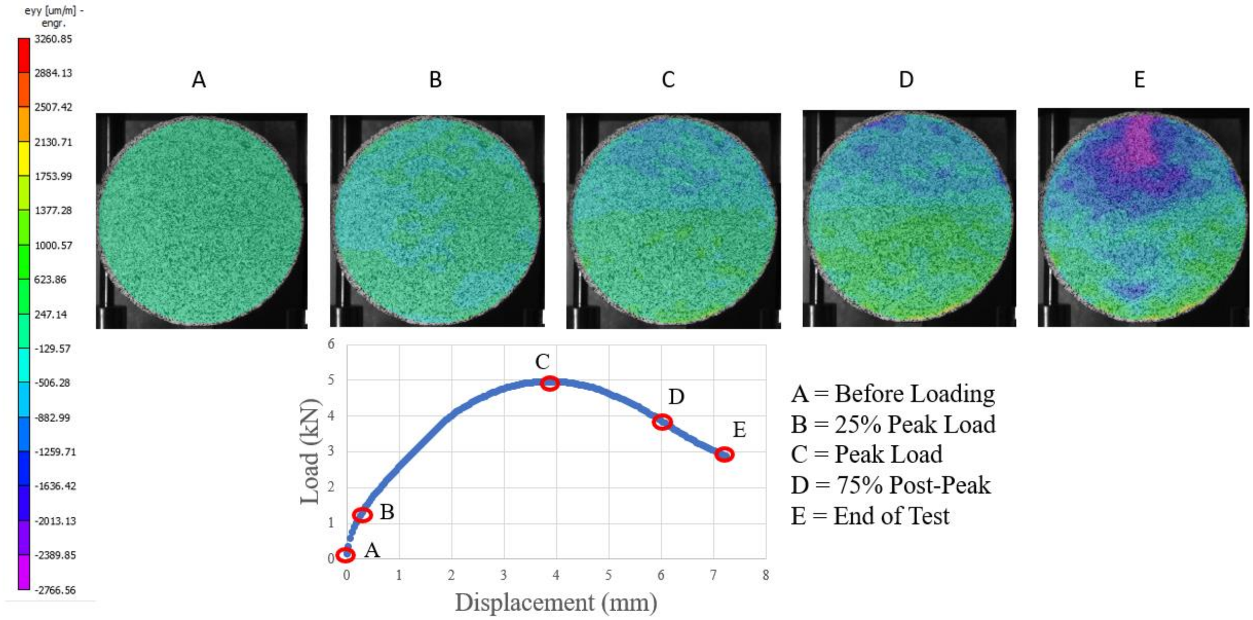


Figure 59 - $\mathcal{E}_{yy}$ contours at different stages of high temperature IDT test

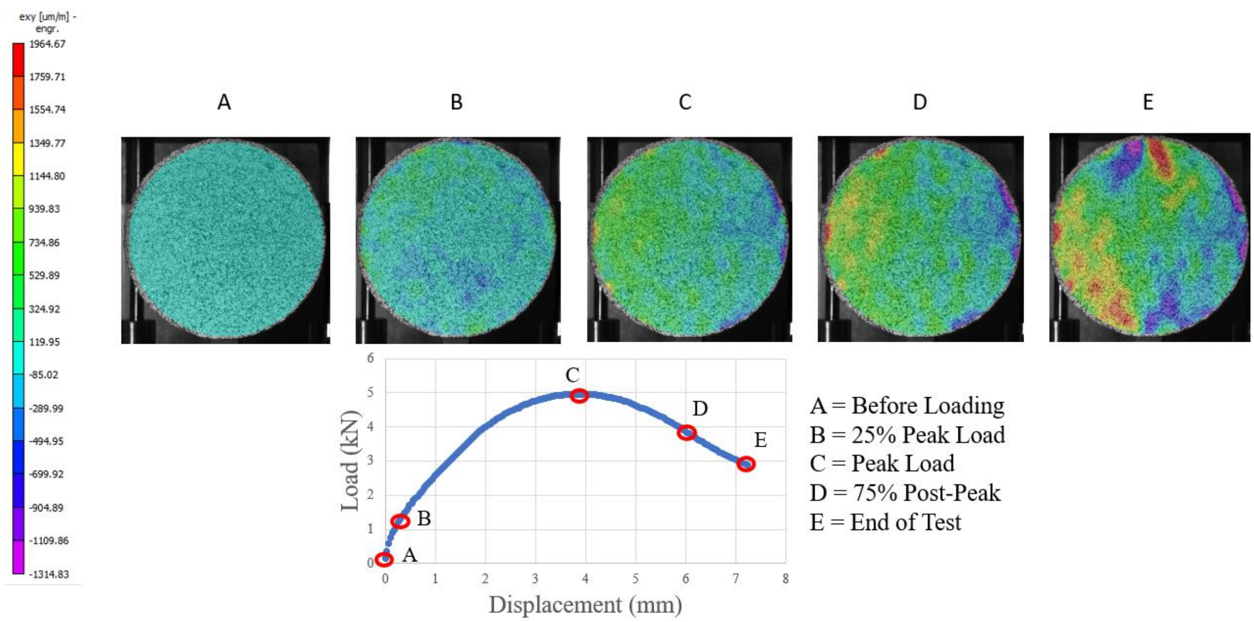


Figure 60 - $\mathcal{E}_{xy}$ contours at different stages of high temperature IDT test

The work done to determine how to conduct monotonic loading tests using DIC and how the data can be used to track different variables throughout the test shows promise for future use of DIC in this type of testing. It is recommended that future work be done to use DIC during both

IDT and IDEAL-RT tests and examine the results obtained from DIC to understand the main failure behavior during each test. In addition, the DIC results can be used to explore different parameters that may better characterize the rutting resistance of asphalt mixtures using these parameters.

9. Conclusions and Future Work

This study evaluated three monotonic loading tests (i.e., IDT, IDEAL-RT, and MS tests) for their ability to characterize the rutting resistance of asphalt mixtures. The purpose of this evaluation was as an effort to progress the industry shift to the balanced mix design (BMD) method in which a simple, quick, and cost-effective asphalt rutting test is desired.

In Phase 1 of the experimental program of this study, sixteen asphalt mixtures were testing using the IDT, IDEAL-RT, MS, and APA tests. The APA test was utilized in this study to draw correlations to the monotonic loading tests. The procedures for each of the monotonic loading tests for rutting performance were developed and summarized. The tests were evaluated for their sensitivity to asphalt mixture characteristics, variability of test results, and correlations among the rutting indices. The following conclusions were drawn from this testing and analysis:

- A high temperature of 54.4°C was determined to be a good test temperature for the monotonic loading tests to evaluate rutting in asphalt mixtures.
- The IDT test and IDEAL-RT showed better results when compared to MS in terms of test sensitivity and variability.
- When compared to the IDT strength, the IDEAL-RT shear strength showed a better correlation than the Marshall stability peak load.
- The IDT strength showed the strongest correlation to APA rut depth at 8000 cycles, followed by the IDEAL-RT test.
- The Marshall stability test did not show a strong correlation to APA rut depth at 8000 cycles.

The test results of Phase 1 were used to develop the rutting performance thresholds proposed for the IDT and IDEAL-RT tests. Rutting performance thresholds were developed for the monotonic tests because they showed the best correlation to the APA test. Based on the APA rutting threshold of 8mm rut depth at 8000 cycles, the following rutting performance thresholds for the IDT and IDEAL-RT tests were proposed. It is of note that the thresholds proposed are based on conducting the tests as detailed in this study:

- IDT Test: 133 kPa (mixtures with an IDT strength less than this are considered rut susceptible)
- IDEAL-RT: 1.07 MPa (mixtures with a shear strength less than this are considered rut susceptible)

In Phase 2 of the experimental program, six asphalt mixtures were tested using more complex fundamental asphalt tests called AMPT tests. These tests included the DM, SSR, and RLTT tests. Rutting parameters determined from these AMPT tests were compared to the results of the IDT and IDEAL-RT tests to further evaluate the ability of the monotonic loading tests to characterize rutting in asphalt mixtures. The AMPT results were also compared to APA test results. The following conclusions were drawn from this testing and analysis:

- The APA, IDT, and IDEAL-RT showed good correlations to the dynamic modulus (E*) at both 38°C/0.1Hz and 54.4°C/1Hz.
- The IDT and IDEAL-RT correlations to the SSR test were greater than the correlations between the APA and SSR tests.
- Excluding one outlier data point, the IDT test showed a good correlation with the FN index at 50°C. The APA and IDEAL-RT showed lower correlations to the FN index at 50°C.

Lastly, digital image correlation (DIC) was explored for its use in asphalt mixture testing with the IDT and IDEAL-RT tests. DIC was found to be a powerful, non-destructive way to examine strains under the applied loading of these tests. DIC analysis can be utilized to evaluate failure mechanisms in the IDT and IDEAL-RT tests.

The overall conclusions drawn from this thesis are as follows:

- Based on the evaluation of sensitivity and variability, the IDT and IDEAL-RT tests could be optimal for rutting performance.

- Based on mixture testing and analysis in Phase 1 and Phase 2, this study validated the use of the IDT and/or IDEAL-RT tests for rutting performance of asphalt mixtures.
- Based on correlations with the APA test results, new preliminary rutting performance thresholds were developed for the IDT and IDEAL-RT tests and these tests show promise for evaluating rutting susceptibility of asphalt mixtures.
- By implementing performance-based monotonic tests, such as the IDT and IDEAL-RT tests for rutting performance, state agencies and contractors can save money and time and optimize the rutting resistance of asphalt mixtures to make roadways more sustainable.

Future research can be conducted to build off of the work and findings of this thesis and eventually develop specifications for monotonic loading tests for rutting performance evaluation of asphalt mixtures, furthering the implementation of the balanced mix design (BMD) method. Further evaluation of the relationships between the monotonic loading tests (IDT and IDEAL-RT) and APA tests as well as fundamental tests, mechanistic-empirical simulations and analysis, and field performance can be done to ensure that the most appropriate rutting performance threshold criteria are applied for implementation of the BMD method. Further research should continue to address the differences in test results attributable to mixture reheating and to different specimen types, such as laboratory-compacted specimens and field cores. Furthermore, the IDT and IDEAL-RT tests can be further evaluated to establish acceptable variability and precision estimates for each test. Lastly, further evaluation and analysis of the IDT and IDEAL-RT tests using DIC can be done to examine different rutting parameters based on the failure mechanisms of these tests.

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