DEVELOPMENT AND VALIDATION OF THE RUTGERS ASPHALT ANALYSIS

TOOL PACK SOFTWARE

By

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ABSTRACT OF THE THESIS

Development and Validation of the Rutgers Asphalt Analysis Tool Pack Software

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Asphalt mix design has historically been governed by volumetrics, or the weight-volume relationships of the asphalt binder, aggregate, and air voids. Volumetric mix design was a reliable choice for decades but is now in the process of being replaced by balanced mix design (BMD), which is a combination of volumetric criteria, rutting criteria, and cracking criteria. This new method is more cost-effective because it more accurately predicts pavement behavior for specific climates and traffic patterns, especially for mixes that contain recycled asphalt pavement (RAP) or polymer-modified binders. Still, many DOTs are hesitant to adopt BMD due to the difficulty involved with sample preparation, testing, and analysis. This paper focuses on the data analysis, as there has been little focus on this issue. Without a uniform method of calculation, individual calculations are left to the technician, which can lead to significant differences in results and can be especially hazardous when state agencies are enforcing pay adjustments for different levels of performance. Thus, this paper examines the difficulties of modern analyses and introduces a standard methodology of analyzing and presenting performance test data. A custom software suite was created using MATLAB to both reduce user error and to promote the use of promising new performance tests in the industry.

Acknowledgements

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Chapter 1: Background and Literature Review

1.1 Introduction

Hot mix asphalt (HMA) design is the process of creating a durable pavement that can withstand both traffic and environmental stresses. Historically, it has been governed by volumetrics, or the weight-volume relationship of asphalt's constituent parts. In the 1940s, Bruce Marshall developed the Marshall Mix Design Method, which uses the properties of stability, flow, and density to ensure proper mix volumetrics [1]. This test method was used to measure a pavement's performance in terms of stability and flow. The stability, or the maximum load the sample undergoes during the test, is a measure of strength. The flow, or the displacement at this maximum load, is a measure of the sample's flexibility. Minimum values for both parameters help to ensure a durable mix. This quickly became the most widely used HMA design procedure in the world due to its simplicity and quickness, but after criticisms that this method could not simulate proper field density and shear strength, the Strategic Highway Research Program (SHRP) introduced Superpave in 1987. Although there were originally three levels to the Superpave initiative, beginning with volumetric and moving onto performance-based specifications, the performance-based levels were never fully implemented. As a result, tests like the Superpave Shear Tester (SST) did not become mix design requirements. For a time, both Superpave and the Marshall Method were enough to design higher quality mixes with little to no recycled asphalt pavement (RAP) and recycled asphalt shingles (RAS). In the 2000s, however, increased oil prices caused agencies to increase RAP and RAS percentages to values of more than 30%. RAP and RAS are used as partial binder replacements, which reduces the amount of virgin material needed. This trend has caused mixes to become brittle, and thus cracking has become a prevalent issue in recent years. The industry's current solution to newer mix design is a balance of volumetric criteria, rutting criteria, and cracking criteria [2]. This is known as balanced mix design, or BMD. It greatly improves pavement life, especially for mixes that contain RAP, RAS, or polymer-modified binders. Thus, performance testing has evolved throughout the years to incorporate more and more failure modes and distresses.

1.2 Rutting Tests

According to a nationwide survey conducted in 2016 by Mohammad et al. regarding rut tests, 21 out of 50 states use the HWTT [3]. In the HWTT (AASHTO T324), steel wheels pass over a sample submerged in water to induce rutting [4]. The specimen undergoes creep and may encounter stripping if the binder de-bonds from the aggregate. Both rut depth and moisture sensitivity are determined using the HWTT.

Seventeen other states surveyed reported using the APA, a redesign of the Georgia Loaded Wheel Tester (GLWT). In the APA test (AASHTO T340), wheels are loaded onto a pressurized rack of hoses moving back and forth over samples to induce rutting without the presence of moisture [5]. The APA and HWTT are well-established across the nation.

Figure 1: The HWTT is used to measure rutting and moisture susceptibility.

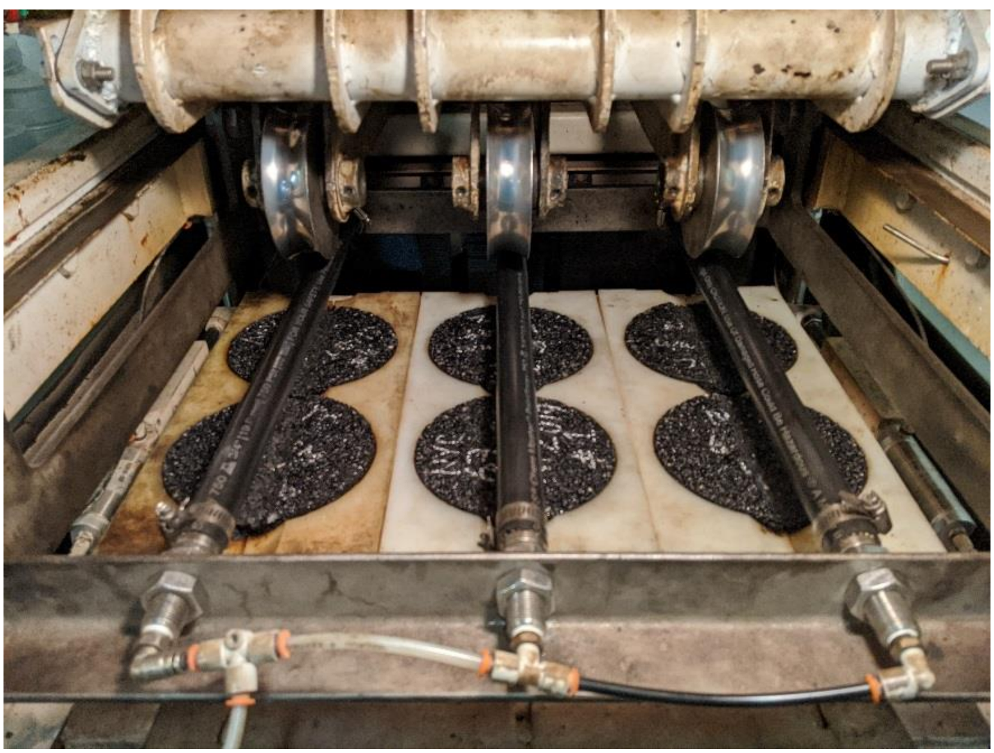


Figure 2: The APA Test measures rutting by loading wheels over pressurized hoses.

1.3 Cracking Tests

None of the cracking tests are used as widely as rutting tests. This may be due to the cost of the machines and the difficulty in operating them. Each one has its benefits and drawbacks. The Bending Beam Fatigue Test (AASHTO T321) is used in NJDOT specifications for bridge deck mixes. It is a four-point bending test used to estimate the fatigue life of asphalt under repeated traffic loading [6]. The OT is also used in New Jersey and Texas to predict cracking. In this test, a sample is glued onto two plates, and one plate remains stationary while the other moves back and forth. This is useful for simulating reflective cracking caused by the thermal expansion and contraction of joins beneath the pavement surface. They are sometimes used in conjunction, with the Bending Beam Fatigue Test being a strong measure of crack initiation and the OT being a strong measure of crack propagation.

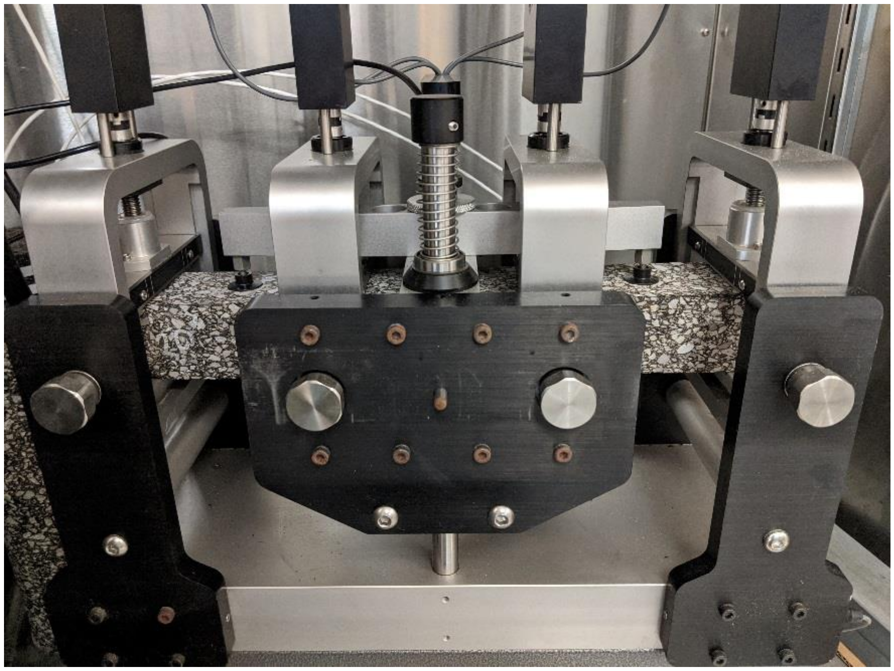


Figure 3: The Bending Beam Fatigue Test used to estimate fatigue cracking.

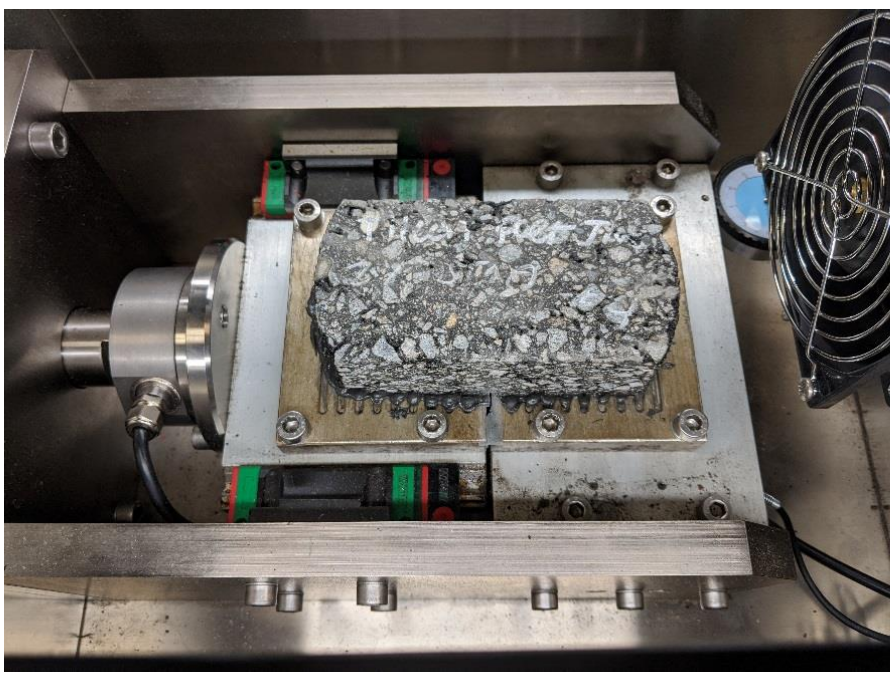


Figure 4: The OT predicts reflective cracking typically caused by the expansion and contraction of concrete joints underneath the pavment surface.

Other cracking tests include the Indirect Tension (IDT) and SCB. These have the advantage of being able to be performed on a Marshall Test setup retrofitted with a Lottman Frame, making these tests more accessible to laboratories that have this existing setup. The IDEAL-CT is used for intermediate temperature cracking, and the HT-IDT is used to measure HMA strength at higher temperatures [7,8]. The SCB test requires more sample preparation, as compacted samples must be cut into semicircular samples and notched before being compressed on two rollers to simulate the propagation of an already-initiated crack. Modifications of the SCB test are used for intermediate or cold temperatures. These variations include the Louisiana SCB Test (ASTM D8044), the Illinois Flexibility Index Test (AASHTO TP124), and the Cold Temperature SCB Test (AASHTO TP105) [9,10,11]. Lastly, the DCT (ASTM D7313) is a cold temperature test developed at the University of Illinois at Urbana-Champaign [12]. It is a method of finding the fracture energy of a sample under cold temperatures. DCT data is repeatable and has proven to be a reliable test, but it has more sample preparation than other tests such as IDEAL-CT. Both DCT and Cold Temperature SCB are both used in Wisconsin mix design specifications.

Figure 5: A Pine Instruments compression machine traditionally used for Marshall test specimens at Rutgers University. It has been adapted for IDEAL-CT testing.

Figure 6: The SCB sample above has been notched to initiate the cracking.

Figure 7: A DCT sample loaded in an MTS testing machine. The CMOD gauge controls the loading rate based on crack mouth opening width.

1.4 Direct Shear Tests

Bond strength, or interlayer shear strength, is used to characterize the adhesion between two asphalt pavement layers. This test is typically performed on asphalt pavement cores from in service pavements utilizing six-inch diameter cores. Shear failure may often be due to improper placement of tack coat between pavement layers. Because the bonding between layers is not a relatively high cost in pavement construction, this factor is often overlooked, and many failures have occurred in this mode [13]. AASHTO TP114 is used to find this interlayer shear strength [14]. The peak load and dimensions are used to calculate the maximum adhesive force.

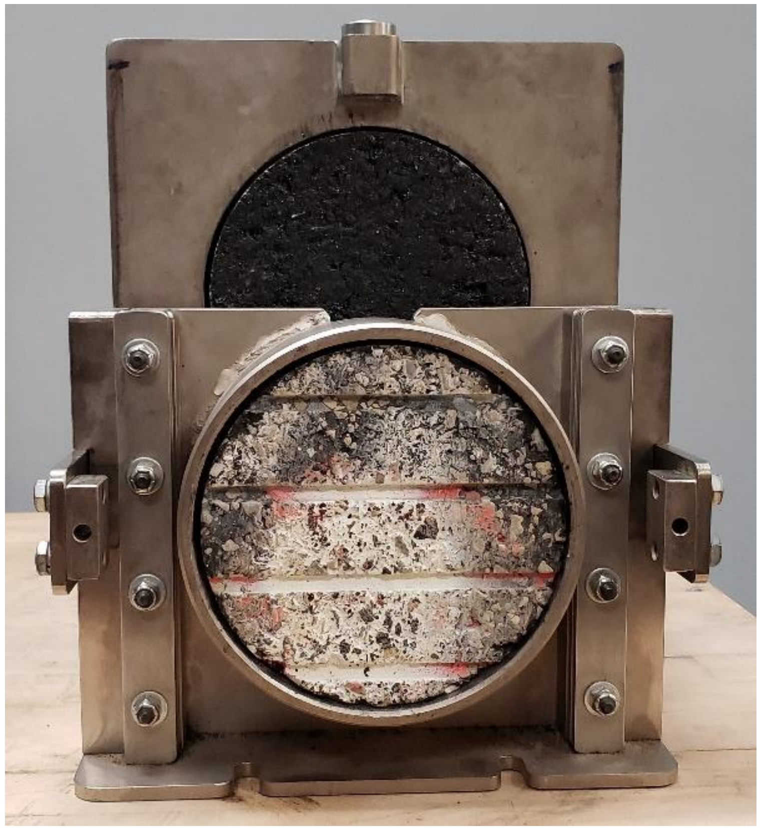


Figure 8: The sample shown has been broken to found the interlayer shear strength.

1.5 Dynamic Modulus Tests

Another test used in performance testing but not yet adopted for state mix design specifications is the dynamic modulus test. The Asphalt Mixture Performance Tester (AMPT) pictured below is used to find the dynamic modulus, which describes the behavior of the material under different temperatures and loading frequencies. It is also used to find the flow number, an estimator of rutting resistance. To find the dynamic modulus of a mix under any temperature and loading frequency, the user must generate a master curve from discrete dynamic modulus data by shifting individual isotherms. Testing is performed using AASHTO T324, and the construction of master curves follows AASHTO R62 and AASHTO R84 [15,16,17].

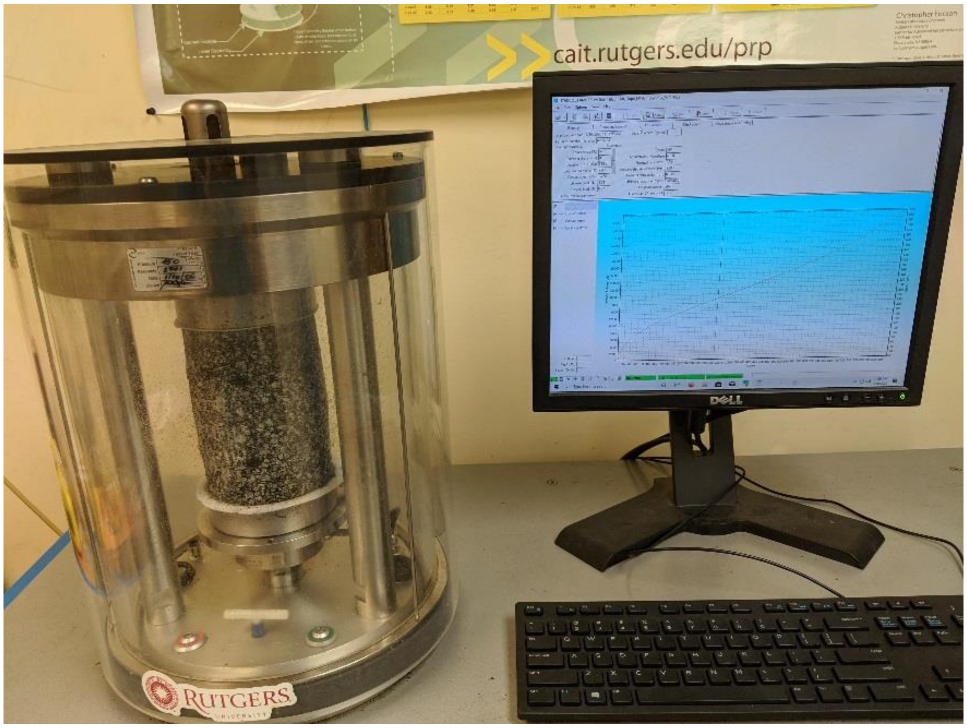


Figure 9: The Asphalt Mixture Performance Tester (AMPT) is used to find the Dynamic Modulus and Flow Number of asphalt mixes

1.6 Balanced Mix Design (BMD)

Balanced mix design improves on the Marshall Method and Superpave by considering several distresses including climate and traffic criteria. There are several approaches, as performance testing may be used to verify or modify volumetric design, or it may be used by itself. Under BMD, mixes are designed so that they are soft enough to resist cracking but also stiff enough so that they do not rut. Since asphalt is viscoelastic in nature, a pavement that performs well in rutting will not perform well in cracking, and vice versa. Therefore, this balance can be difficult to obtain, but it is made easier through performance testing. This relationship can be visualized as a four-quadrant graph as seen in Figure 10.

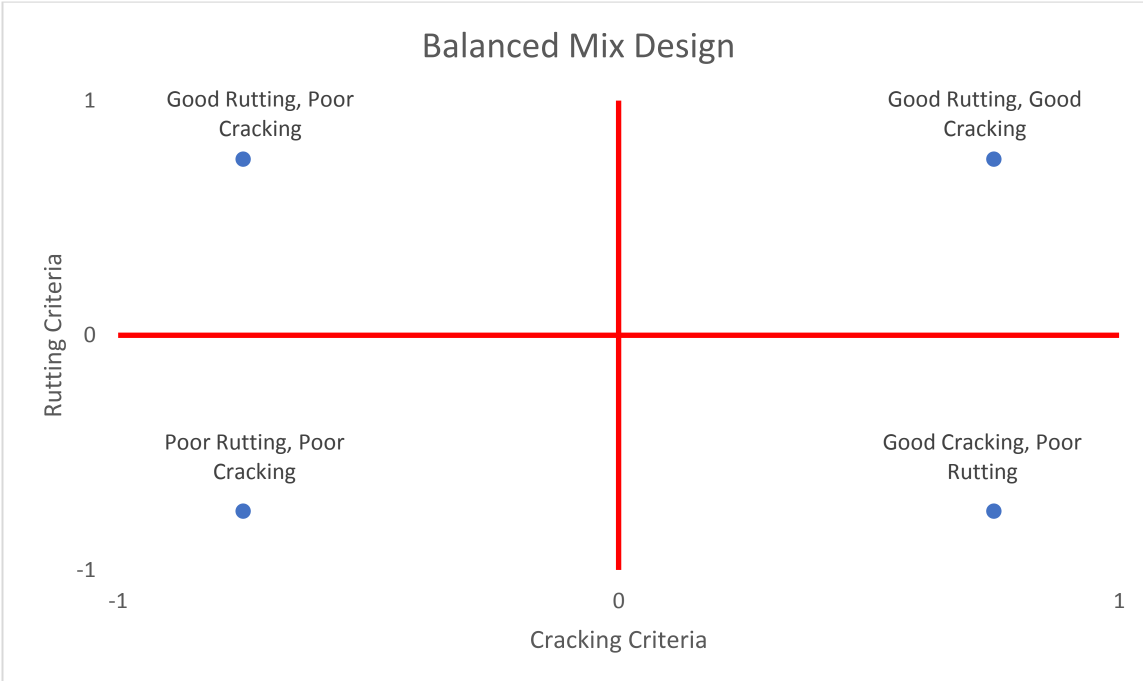


Figure 10: Balanced Mix Design is a Balance Between Rutting and Cracking Performance

The Hamburg Wheel Track Test (HWTT) and Asphalt Pavement Analyzer (APA) are the two rut tests commonly used in the United States. There is no established standard cracking test in the industry, and as a result, there are many different cracking tests in use. Cracking has recently become a major issue due to the increased use of RAP and RAS, which create more brittle pavements. The most common cracking tests in the United States include the Bending Beam Fatigue Test, Overlay Tester (OT), Semicircular Bend Test (SCB), Indirect Tensile Asphalt Cracking Test (IDEAL-CT), High Temperature IDT Test (HT-IDT), and the Disk-Shaped Compact Tension Test (DCT). Newcomb and Zhou’s 2018 report for Minnesota DOT summarizes nationwide efforts to adopt BMD [18]. Citing a survey conducted by Mohammed et. Al in 2016, they note that 21 DOTs include laboratory mechanical tests in their mix design specifications, and 14 of them use HWTT or APA for rutting. Only 6 states use both rutting and cracking tests as shown below.

Table 1: States Using both Rutting and Cracking Tests in Mix Design Specifications

State	Rut Test(s) Used	Cracking Test(s) Used
California	HWTT	Bending Beam Fatigue Test
Illinois	HWTT	I-FIT SCB Test
Louisiana	HWTT	Louisiana SCB Test
New Jersey	APA	Overlay Tester and Bending Beam Fatigue Test
Texas	HWTT	Overlay Tester
Wisconsin	HWTT	DCT and Low Temperature SCB

1.7 Challenges to BMD

Many states have begun the switch from Superpave to BMD, but the process is slow because of the complexity of the tests, specifically cracking tests. Bennert et al notes that the New Jersey asphalt industry is apprehensive to adopt many performance-related specifications due to the lack of equipment availability, the cost of equipment, and complexity involved with sample preparation, testing time, and analysis [19]. Researchers are looking to solve these issues with new tests such as the IDEAL-CT, HT-IDT, and SCB that offer simpler sample preparation and shorter testing time. Bennert et al found that both the IDEAL-CT and SCB-FI correlate strongly with the Overlay tester, which the NJDOT uses to determine HMA fatigue cracking. HT-IDT results also correlated well with APA results, showing that these tests may have the potential to replace older procedures in the future. In NCHRP Project 9-57, Zhou et al [20] identifies the following features to find the most ideal cracking test:

1) Simplicity

2) Practicality

3) Efficiency

4) Test Equipment Cost

5) Repeatability

6) Sensitivity

7) Correlation to Field Performance

Zhou et al developed the IDEAL-CT to meet all seven criteria [21]. It is a return to the original IDT methodology of the Marshall Method, and IDEAL-CT samples can be used on traditional Marshall Press retrofitted with a Lottman frame. The procedure is simpler than the Marshall Test, but the analysis is more complex. Whereas the stability and flow of the Marshall Test is found by locating a point on a load-displacement curve, the CT Index developed by Zhou is found by dividing the area under the load-displacement curve by the slope from 65% to 85% of the peak load. It is a more complex procedure, but it is a better predictor of fatigue cracking behavior in mixes that contain RAP, RAS, and polymer-modified binders. The IDEAL-CT test attempts to simplify the analysis involved with similar tests such as the SCB-Flexibility Index test. The SCB-FI is a measure of the area under the curve divided by the slope at the post-peak inflection point [22]. Both tests require use of a spreadsheet or analysis software, making them difficult. The tests have become simpler, but as the industry's knowledge of material behavior has grown, so has the complexity of the analyses. There is a clear industry shift toward simpler testing, but due to the growing complexity of the results, more standards are necessary for analysis and presentation of data.

1.8 Research Need

Although most tests have standards, personal methods of calculation can lead to significant differences in results, and this can be especially hazardous when state agencies are enforcing pay adjustments for different levels of performance. Therefore, there needs to be a standardized methodology for analyzing and presenting the test data. This report details the development of the Rutgers Asphalt Analysis Tool-Pack (RAAT-Pack), a software designed to reduce user error and to streamline much of the analysis process for a suite of tests.

1.8.1 Difficulty of Analysis

Newer, more complex analyses are providing parameters more indicative of mix behavior, but they are more difficult to calculate. In the past, technicians could run the analyses by hand. Now, they must use spreadsheets or other analysis software, and they must know calculus to find complex parameters. Many cracking tests involve the calculation of the fracture energy by finding the area under the load-displacement curve, which requires use of a spreadsheet or analysis software. Some performance tests such as the SCB-FI and HWTT instruct the user to find inflection points, which require calculus to find first and second derivatives. Perhaps the most difficult analysis is the dynamic modulus, in which a user must fit a master curve and solve for multiple variables simultaneously. Because of the logarithmic shifting of the data, an incorrect entry in the data may change the master curve drastically. Therefore, it is important to understand systems of equations and to fit these parameters correctly. All these parameters involve higher order math to analyze not one, but multiple samples at the same time. AASHTO and ASTM specifications do not provide analytical tools to aid in the calculations, and a result, most agencies use programs like Microsoft Excel spreadsheets and MATLAB. Some are available to the public, but none of them offer such a broad suite of tests like the ones included in the RAAT-Pack.

1.8.2 Reducing Error

Reduction of error is a critical detail to ensure proper test results. The RAAT-Pack reduces both user error and software error by addressing flexibility in the interpretation of the data, or a lack thereof. At one extreme, the user may have no input. That is, some "black box" machines use proprietary software to perform the analysis for the user upon testing. While this certainly has its appeal, the user's input is greatly restricted, and there may be no way to account for the machine's errors. In an inter-laboratory IDEAL-CT Round Robin study conducted by Rutgers University in 2019, several samples were tested incorrectly, yet a CT Index was still calculated by a black box device. This is shown below, where the post-peak portion of the curve loops back on itself due to premature unloading of the sample. The CT Index should not have been calculated, and the technician should have been able to remove this file from the results. There was, however, no indication from the machine.

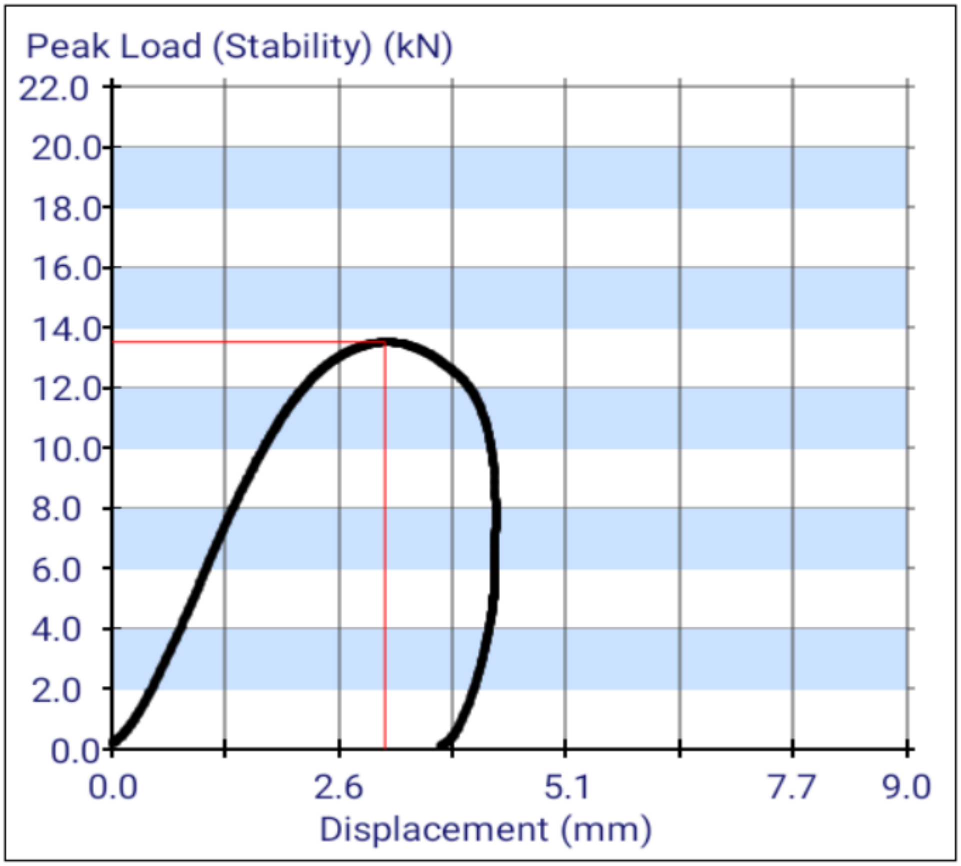


Figure 11: A CT-Index was found for this sample, despite it being tested incorrectly

On the other hand, if too much work is left to the technician, there is room for user bias and error. Personal spreadsheets are especially prone to mistakes, and often they require heavy knowledge of calculus formulas, Excel macros, visual basic, and the solver add-in. Technicians should not be responsible to know these difficult techniques, nor should they have to learn coding languages like MATLAB. The RAAT-Pack addresses this by both performing the analysis for the user and asking the user to verify certain calculations in case a mistake occurs during the analysis. This is especially useful when certain data files are difficult to fit using conventional spreadsheet formulas or solvers. The RAAT-Pack also performs the analysis for many samples at once so that the user does not have to repeat their calculations, which may lead to mistakes.

1.8.3 Presentation of Data

When it comes to data analysis, formatting and presentation are sources of error that are overlooked. Because there is so much variability in machines, technicians, and personal calculation methods, data is formatted different between laboratories. It is important to normalize the raw data, or to transform units, trim extraneous values, etc. to prepare the data for analysis. This is almost always required before analysis, and if this is done incorrectly, these errors may be compounded in calculations. A poorly formatted file is shown below in an example from Rutgers' interlaboratory IDEAL-CT Round Robin Study. In this case, the presentation of the data makes it almost impossible to analyze because multiple samples are included in the same file. If this file could not be interpreted, this would not only cause a delay, but the samples would have been wasted. Therefore, these mistakes can be costly, especially in QA/QC work.

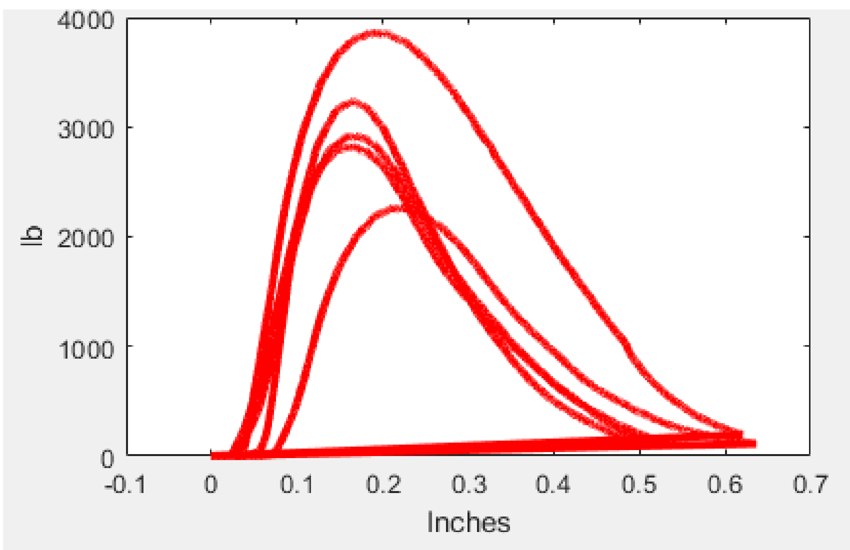


Figure 12: An IDEAL-CT File that was presented poorly during the IDEAL-CT Study

Presentation is also key when it comes to presenting results, as these go directly to contractors or state agencies. There should be no mistakes because at this stage, the results are likely already being used to verify mix designs. Depending on a lab's data acquisition system, units may need to be changed for reporting, and formatting must follow test specifications. The RAAT-Pack provides uniform summary sheets that provide test specification numbers, project information, sample identifiers, a uniform summary table, and graphs. They follow test specifications so that the technician does not need to worry about formatting errors.

Chapter 2: Detailed Work Plan

2.1 Goal of the RAAT-Pack

The Rutgers Asphalt Analysis Tool-Pack (RAAT-Pack), is a software created to provide technicians with a standard methodology of analyzing and presenting performance test data. It was made using the MATLAB coding language. The RAAT-Pack provides analyses for the tests in Table 2 due to their prevalence across the United States.

Table 2: Tests Included in the RAAT-Pack

Module	Test Designation
APA	AAHSTO T340-10
Bending Beam Fatigue	AASHTO T321-17
Bond Strength	AASHTO TP114-17
Cold Temperature SCB	AASHTO TP105
DCT	ASTM D7313-13
Dynamic Modulus	AASHTO T342-11, AASHTO R84, AASHTO R62
HWTT	AASHTO T324-17
HT-IDT	ASTM D6931-17
IDEAL-CT	ASTM D8225 − 19
Intermediate Temperature SCB-FI	AASHTO TP124

2.2 Creating a User Interface

The primary goal of the RAAT-Pack is to make data analysis more intuitive, and it does so with a Graphical User Interface (GUI). This GUI as shown below gives the user graphics like buttons, charts, checkboxes, etc. instead of requiring knowledge of coding.

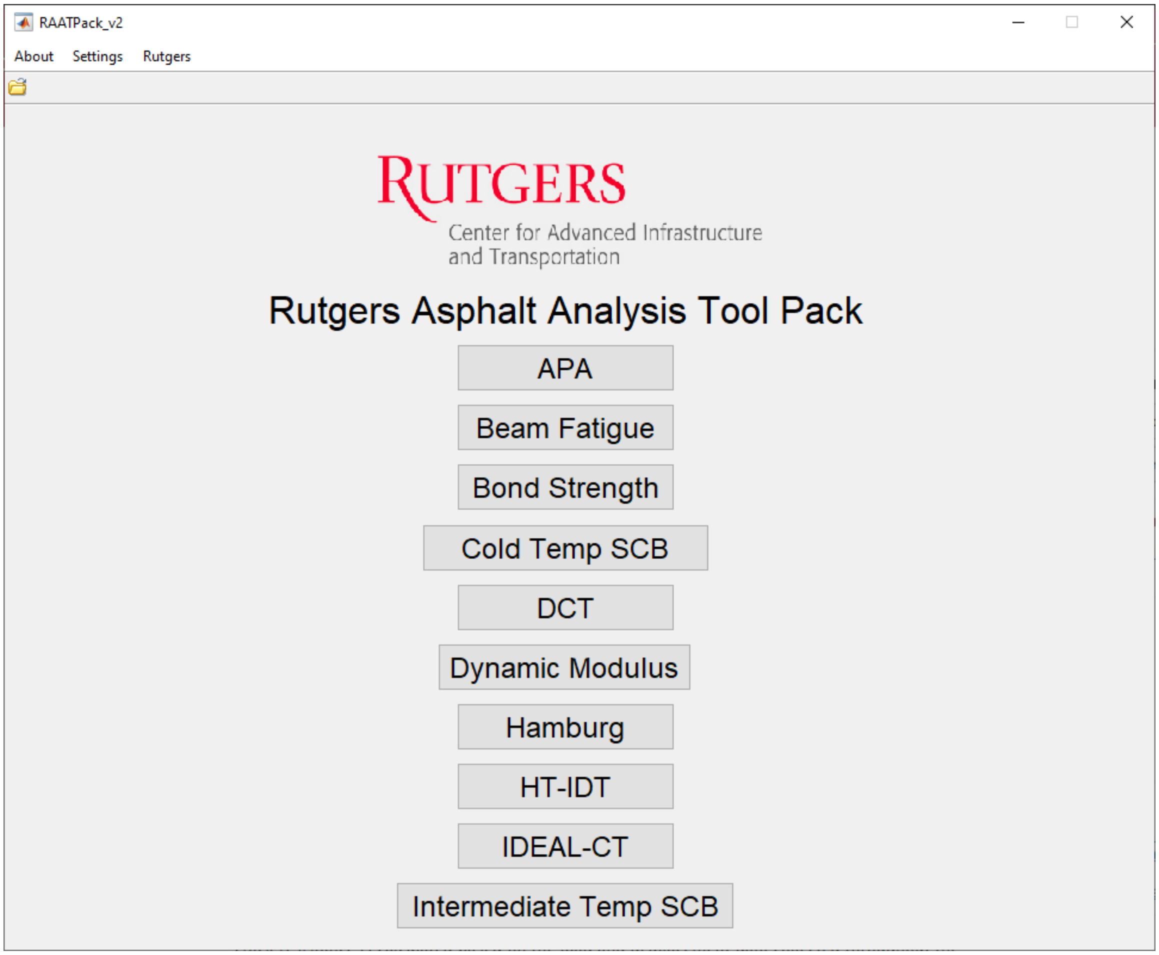


Figure 13: The RAAT-Pack home screen

MATLAB R2018a was used to create the program given its ability to handle large data matrices and because it has been used successfully for programs such as I-FIT. Additionally, MATLAB's GUI creation tool known as GUIDE appropriately converts the code into a standalone executable program that only requires the smaller MATLAB Runtime instead of the full MATLAB client. Out of two available RAAT-Pack installers, one is small and will download this runtime from the internet. The other is larger but includes the runtime in case firewall settings prevent access to the MATLAB website. The only requirement to run the software is a Windows computer equipped with Microsoft

Excel, as Excel is used to generate uniform summary sheets.

2.3 Unique Features

2.3.1 Multiple Tests

The RAAT-Pack is the first suite of software for asphalt mix performance testing. Other spreadsheets and software are typically designed for one performance test, whereas the RAAT-Pack is designed for 10 tests. This feature makes each analysis, or module, more accessible to technicians. Additionally, technicians can easily view their rutting and cracking tests results at the same time, which can potentially aid them in mix design. Each module is coded as separate MATLAB files because of the size and complexity of the data involved; however, MATLAB allows for them to be compiled into a single standalone file. This means that the user only needs to run one program as opposed to ten different ones. By clicking each button, a new window opens. The home screen serves as a hub for all the tests.

2.3.2 Single Click Analysis

Each module has a large “Run” button that performs an entire analysis in one single click by solving systems of equations, fitting models, iterative processes, and other calculus-based procedures. This accomplishes two things: it alleviates the burden of analysis on the technician while also reducing user error. Many sources of user error like unit conversions, search ranges, and integration are eliminated, and the user is also prompted to verify certain calculated parameters like slopes and inflection points. The software’s search range may then be narrowed to help it find the correct points, or certain samples can be removed. This separates the RAAT-Pack from other black box devices, as the user can reject poorly analyzed data due to hiccups in data or unusual behavior in the material. Ultimately, the work required is minimal, as the RAAT-Pack requires only sample dimensions to perform its functions. The unique methods and iterative processes developed in this software are discussed in this report, but they operate in the background to allow for a seamless experience.

2.3.3 Batch Analysis

Batch analysis refers to the software's ability to run multiple files at once. The feature removes much of the repetitiveness of performance test analyses and thus reduces user error. Many spreadsheets are only capable of solving one system of equations at a time, and others are simply not designed to analyze multiple samples. In the RAAT-Pack, not only is the analysis ran for every file selected, but minor steps like unit conversion and trimming of data are done automatically. At any point, the user may add or remove files using the large "Add Files" and "Remove Files" buttons.

2.3.4 Graphs

Presentation of performance data is often the source of confusion and error. The RAAT-Pack improves upon data presentation using organized summary tables and graphs. Because most features like inflection points are difficult to observe without use of a graph, the software is designed to plot multiple samples at once on the same axis. Using a "list box", the user may select or deselect which samples appear on the graph. Axes limits are automatically calibrated to the ranges of the files analyzed, so each file is kept to the same scale. This is especially important when visually interpreting features like slopes and peak loads. For instance, SCB or IDEAL-CT samples that are brittle may have sharp post-peak slopes, whereas softer samples may exhibit a shallower post-peak. In the figures below, sample #4 appears to be a different material from samples #1-#3. The user may simply deselect sample #4 to focus on the other 3 samples, and the software still stores the calculated information.

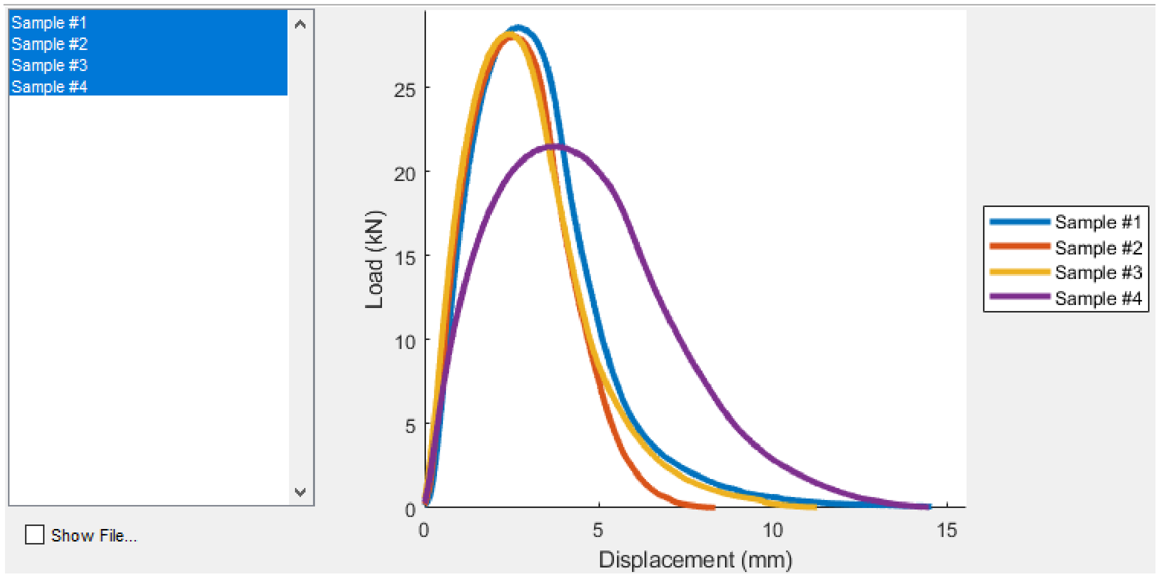


Figure 14: Visual differences in sample behavior are discernable using graphs

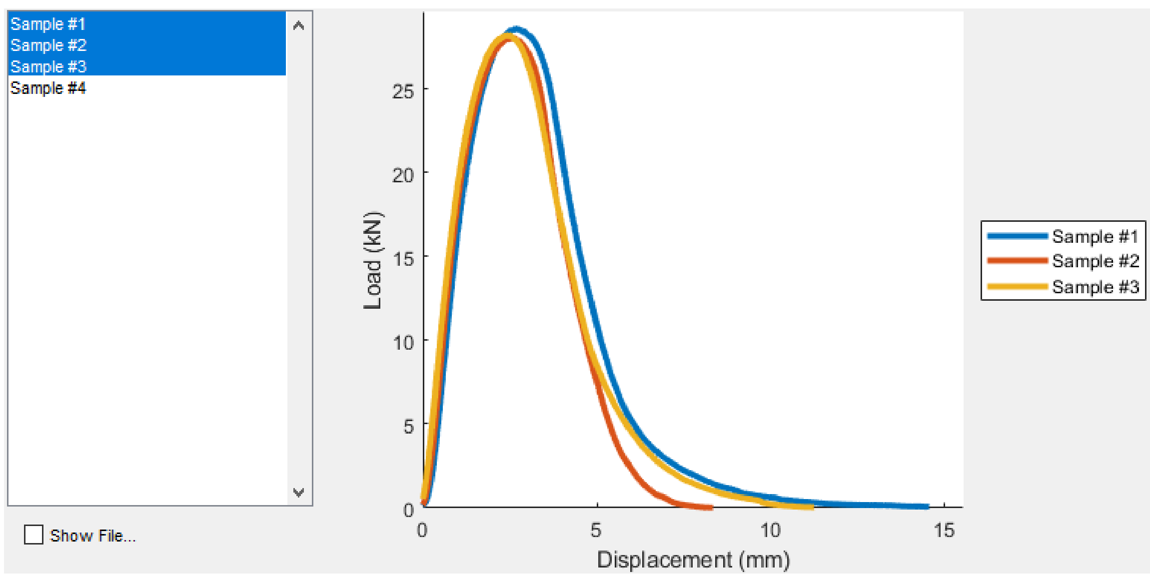


Figure 15: Files may be removed from the graph but still stored by the program

2.3.5 Templates

Another problem that the RAAT-Pack expedites is data normalization, or the transformation of raw data before an analysis can be performed. This may include changing units, deleting rows, deleting columns, making columns negative, or removing repetitious values. This process is tedious and often overlooked, as it is not part of the analysis itself but is still required before the analysis can be run. For instance, if a laboratory's displacement and load data for a cracking test is inches and pounds but the test specification requires metric results, the technician must transform this data in Excel or another program so that it is in millimeters and kilonewtons. Performing these transformations on each sample may lead to user error, but the RAAT-Pack addresses this with a template creator included in each module. The user may specify the starting data row, specific columns, transformations, and units. This feature makes the analysis more accessible to technicians because it allows them to normalize data from many different data acquisition systems. Templates may be created for files from different laboratories, allowing for easier comparison of inter-laboratory data. Alternatively, a default template can be used, which means data must be normalized manually before use in the RAAT-Pack. The two cold temperature tests DCT and Cold Temperature SCB use four columns of data as opposed to two, and thus they have more complicated templates. Because this feature is unique, written and video instructions are included in the software package to explain the template process and the functionality of each module.

2.3.6 Summary Sheets

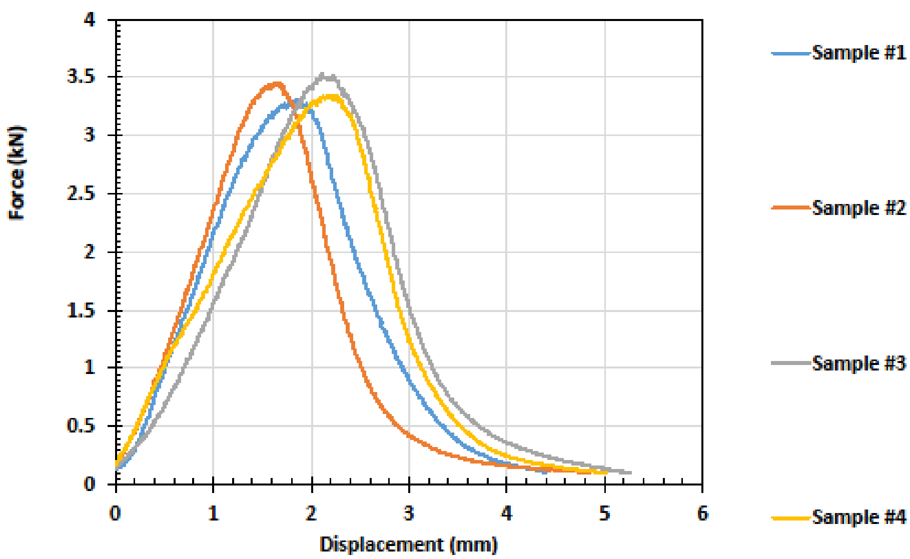
State agencies may enforce pay adjustments for different levels of performance, so mistakes in performance results can be costly. It is imperative that data is presented efficiently and formatted according to test specification requirements. Therefore, every RAAT-Pack module includes an export feature that generates uniform summary sheets as PDF files. Each sheet contains a table with a space for the technician, date tested, project name, institution, mix type, and test temperature. This may be useful for accountability and traceability purposes. Below is a summary table with averages, standard deviations, and co-variances of calculated parameters, as well as a graph of the samples. The formatting for each summary table is designed to meet the test specification in use. Additionally, each sheet clearly displays the specification number and test name, as well as space for a company logo. An example summary sheet is shown below, and sheets for each test may be found in Appendix A- Summary Sheets.

AASHTO TP 124: Standard Method of Test for Determining the Fracture Potential of Asphalt Mixtures Using Semicircular Bend Geometry (SCB) at Intermediate Temperatures

Project Name:		Institution:	
Mix Type:		Date Tested:	
Test Temperature:	25C	Technician:	

Specimen ID	Air Voids (%)	Thickness (mm)	Ligament Length (mm)	Max Load (kN)	Fracture Energy, G_f (J/m^2)	Slope (kN/mm)	Flexibility Index (FI)
Sample #1		50.00	59.00	3.31	2164.3	-3.02	7.17
Sample #2		50.00	59.00	3.46	1975.4	-3.76	5.25
Sample #3		50.00	59.00	3.52	2431.6	-3.41	7.13
Sample #4		50.00	59.00	3.34	2372.3	-3.68	6.45
Average		**50.00**	**59.00**	**3.41**	**2235.9**	**-3.47**	**6.5**
Std Dev		**0.0**	**0.0**	**0.1**	**208.1**	**0.3**	**0.9**
COV (%)		**0.0**	**0.0**	**3.0**	**9.3**	**-9.7**	**13.8**

Intermediate Temperature SCB



This report was developed using the Rutgers Asphalt Analysis Tool-Pack (RAAT-Pack)

Figure 16: RAAT-Pack summary sheets include test specification number, a project information table, a summary table, and a graph.

Because of the importance of presentation, extensive time and effort went into making these summary files in Excel. In total, there were 152 total template files created in Excel for the RAAT-Pack. Some modules only allow for one sample because of the amount of data involved. Others may have up to twelve samples on one summary page. Twelve individual Excel template files were created for the modules that support multiple files in the summary sheet so that the user does not need to manipulate graphs, tables, or formulas. Separate summary files were created for the Rutgers Asphalt Pavement Lab, which uses different headers and footers.

Chapter 3: Included Modules

3.1 Asphalt Performance Analyzer (APA)

The Asphalt Pavement Analyzer (APA) is a wheel track test that utilizes a steel wheel tracking over a rubber hose to simulate traffic loading, and it is used to determine early life rutting in asphalt pavements. The RAAT-Pack module operates using the standard global IPC output files from the APA machine, so there is no data normalization required. As many as three wheels can be run during one test. The program automatically detects which of the three wheels have been used and finds the average rutting at 8,000 cycles following AASHTO T-340. As such, this module is more of a presentation tool than analysis. What the RAAT-Pack provides is the ability to view multiple file sets at once. In Excel, it is cumbersome and difficult to graph multiple file sets because the IPC Global output sheets are only set up for one set of data. MATLAB is more effective for graphing multiple datasets at once, and thus the user can view many curves at the same time. Additionally, the rutting from each wheel may be averaged, shown together, or shown separately, allowing the technician to verify that each wheel is working correctly. Shown below are the effect of air voids on average APA rutting results for one mix. The batch analysis makes it easy to visualize trends without having to manually combine the data in Excel.

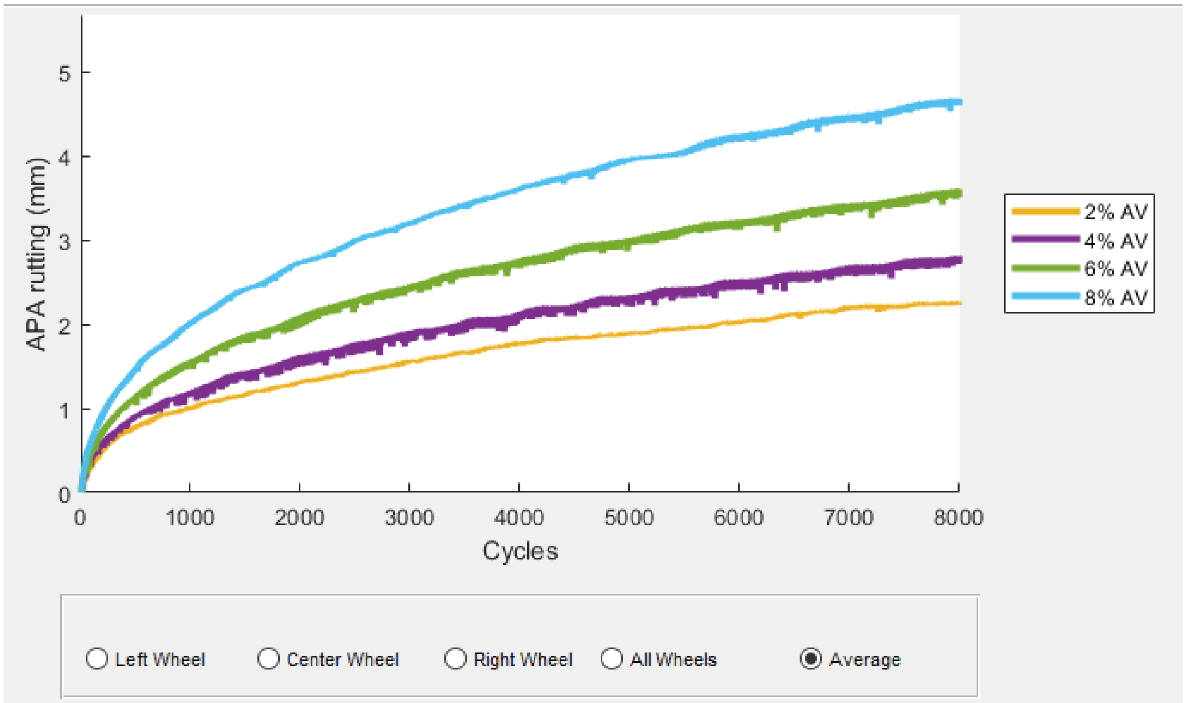


Figure 17: APA wheels can be observed separately or as an average value

3.1.1 Presentation

The APA module allows for summary sheets containing one sample. The rut depths are presented, as well as a graph of the rutting data. Two lines are displayed on the graph to demonstrate typical rutting criteria for an intermediate course and a surface course. This summary sheet is provided in Appendix A- Summary Sheets.

3.1.2 Verification

The APA module is more of a presentation tool rather than an analysis, so there are no calculations performed. The average rutting values at 20,000 cycles is given in the IPC global output file. The RAAT-Pack simply pulls these values from the spreadsheet. The benefit of using the RAAT-Pack is that it allows technicians to observe several files at once as opposed to just one in Excel.

3.2 Beam Fatigue

The four-point bending test has been used for years to determine the fatigue behavior of cut asphalt bricks. A sinusoidal load is applied to two inner clamps, and two outer clamps provide a reaction load, creating a bending moment around the center of the beam. The cycle at failure is typically used as a fatigue strength measure. The machine itself can be operated at constant stress levels or constant strain levels. The goal of the analysis is to find where the specimen reaches 50 percent of its initial stiffness, or its nf50 value.

3.2.1 Beam Fatigue Module Analyses

The beam fatigue module is unique in that it performs both AASHTO and ASTM analyses. As per AASHTO T321, an exponential trend is fitted to the data in Equation 1.

$$S = Ae^{bn} \tag{1}$$

Where A and b are constants.

This analysis is shown in Figure 18.

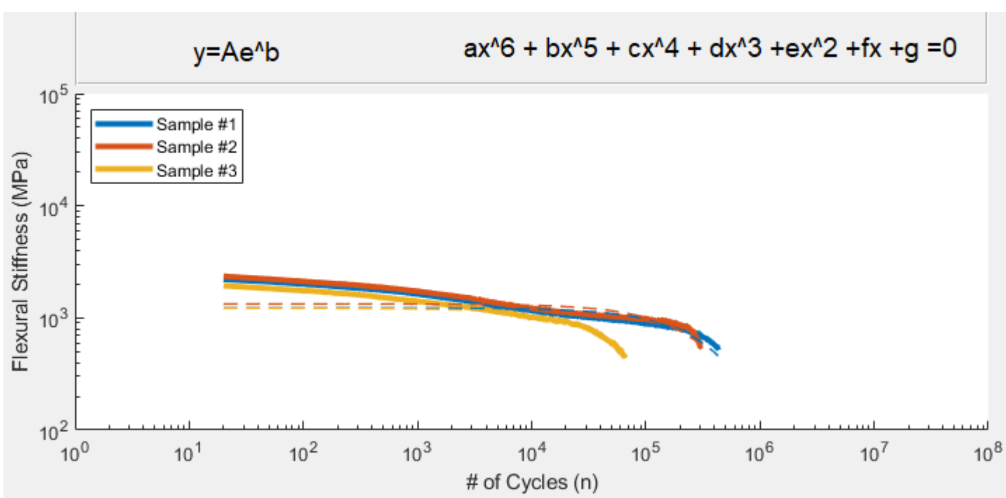


Figure 18: An additional plot is provided in the form of y=A*e^b.

As per ASTM D8237, the software fits a 6th order polynomial to the data, and the termination point is given as the point on this curve where the slope is equal to zero. This is evidenced in Figure 19 below. Both analyses are used in the industry, so it is important that both are represented.

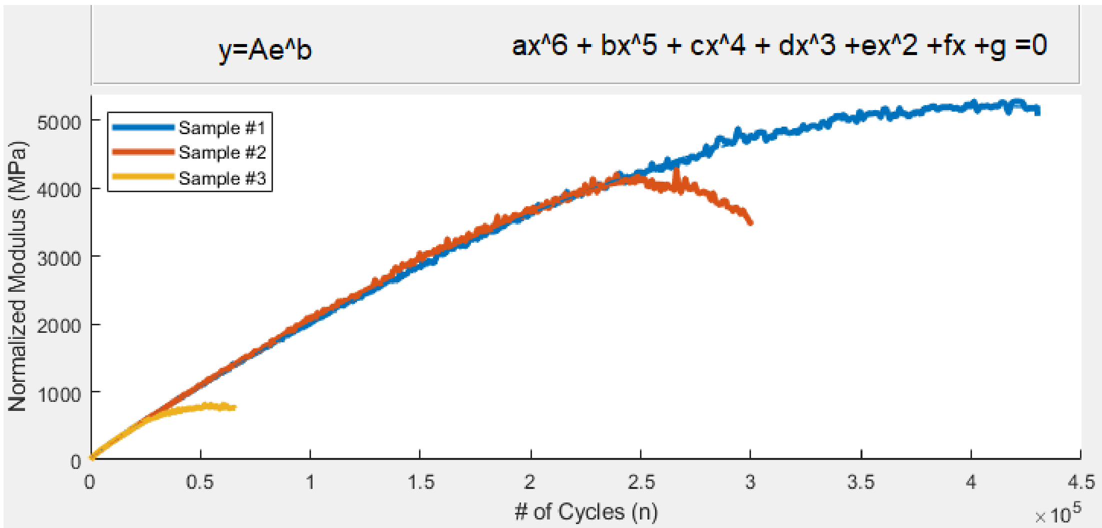


Figure 19: The Beam Fatigue analysis as a 6th order polynomial

3.2.2 Presentation

An example beam fatigue summary sheet can be found in Appendix A- Summary Sheets.

3.2.3 Verification

Both the nf50 value for ASTM and for AASHTO were compared between Excel and the RAAT-Pack. Two unique mixes- a DGA and a BDWSC- were compared to give a broad range of values. Because some of them are tested at different micro-strains each sample is graphed together in Figure 20 and Figure 21. With an R^2 value of almost 1, the results have low variability and are identical.

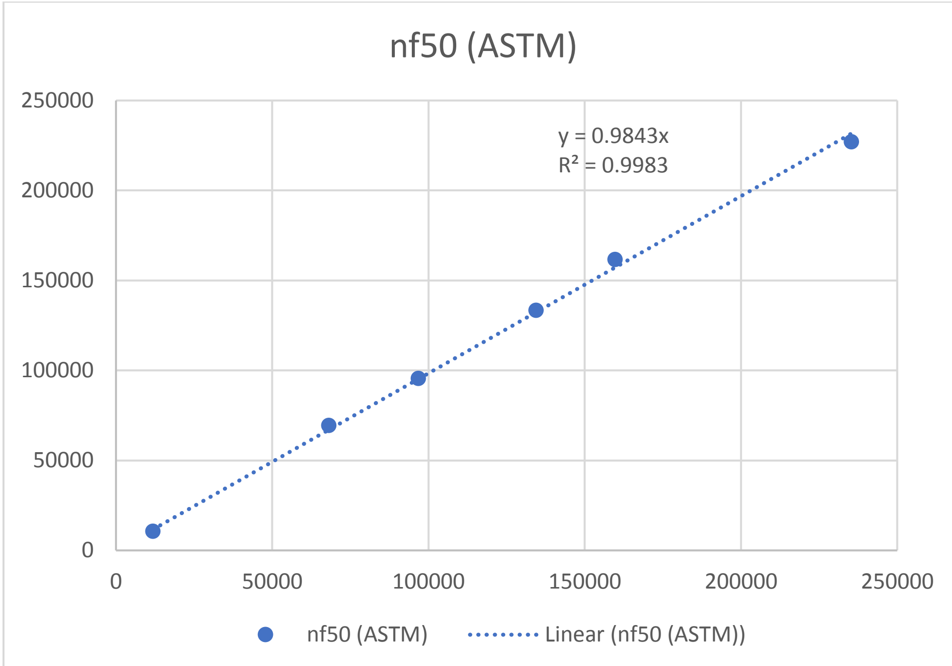


Figure 20: ASTM nf50 values between Excel and the RAAT-Pack verified

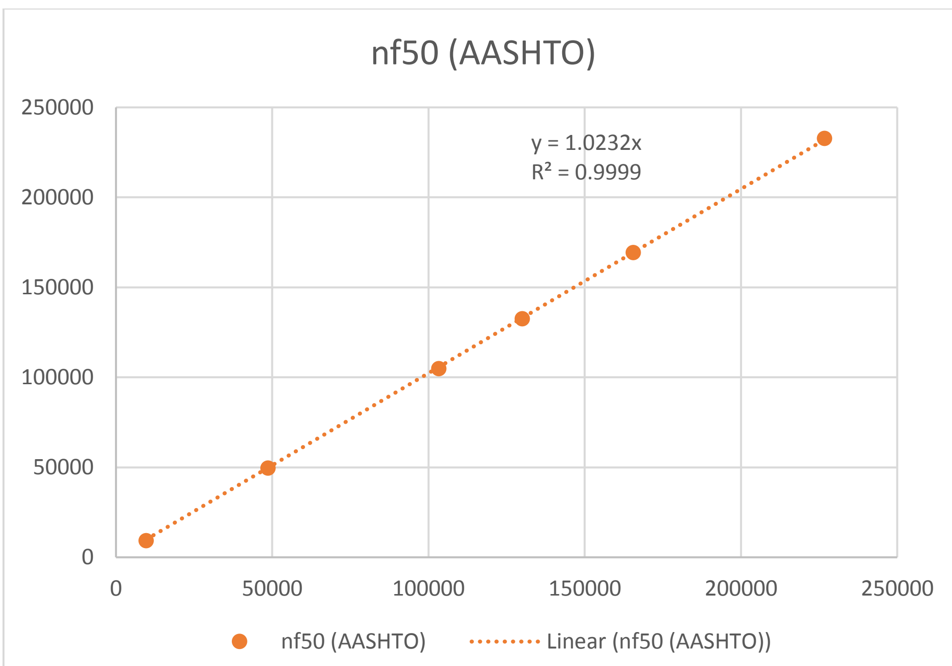


Figure 21: AASHTO nf50 values for several different samples are compared

3.3 Bond Strength

As governed by AASHTO TP114, the shear strength is found using Equation 2.

$$\mathrm{ISS} = \frac{\mathrm{P_{ult}}}{\left(\frac{\pi \mathrm{D}^2}{4}\right)} \tag{2}$$

Where

$\mathrm{ISS} = \text{interlayer shear strength, Pa}$

$\mathrm{P_{ult}} = \text{ultimate load, N}$

$\mathrm{D} = \text{sample diameter, m}$

3.3.1 Presentation

Bond strength results are presented according to AASHTO TP114. The length, diameter, peak load, displacement at peak load, and bond strength are given. A copy of this summary sheet can be found in Appendix A- Summary Sheets. Example bond strength results from the RAAT-Pack are shown below.

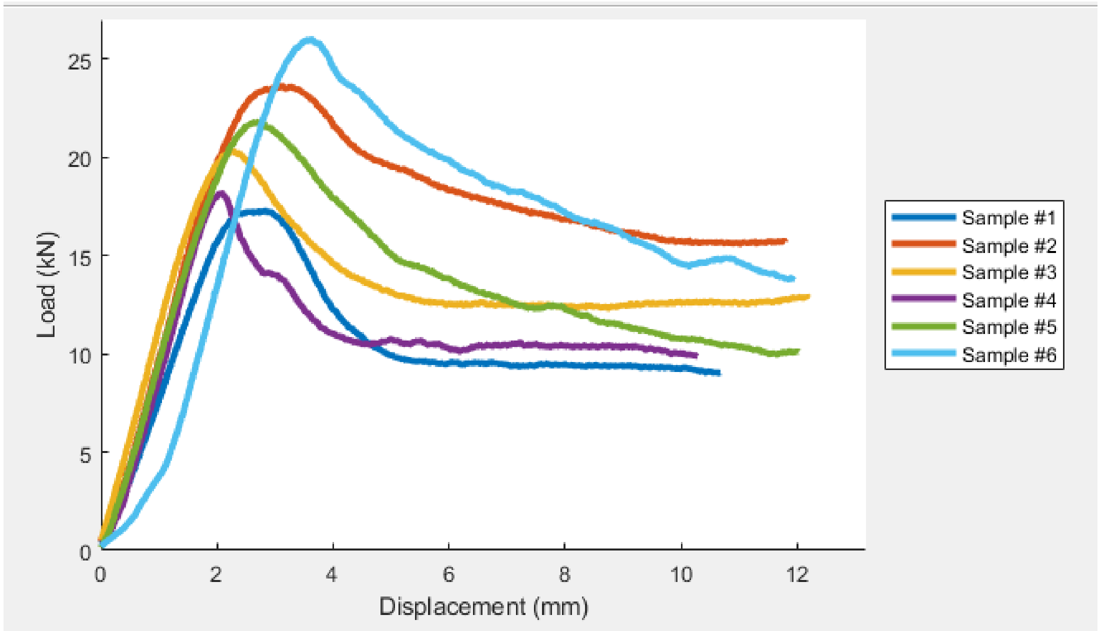


Figure 22: Bond strength results are often prepared for multiple cores. Batch analysis in the RAAT-Pack makes this easy.

3.3.2 Verification

Due to the simplicity of the math in this analysis, there is no difference in the way Excel and MATLAB calculate IDT strength. The analysis is simple and may even be done by hand. It may be easier to visualize differences through the graphs provided by the software. Typically, bond strength testing is done on multiple field cores, so this is a useful feature.

3.4 Cold Temperature SCB

Cold Temperature Semi-Circular Bend is utilized to determine the low temperature crack resistance of asphalt pavements using a semi-circular shaped asphalt sample. Low temperature crack resistance is calculated based on the load and displacement data collected throughout the test.

3.4.1 Normalizing Cold SCB Input

Depending on the data acquisition system, cold temperature SCB data may be divided into three sections. As per AASHTO TP-105, the test uses a crack mouth opening displacement (CMOD) gauge to measure the crack growth. This transition can lead to multiple headers in the data files. The RAAT-Pack will automatically detect these regions and combine them for each file, saving the user time. Additionally, the units for each data column (load, displacement, time, and CMOD) are normalized for the user for every file. Given the amount of data, this can reduce analysis time and error.

3.4.2 Cold SCB Tail Fitting

The biggest challenge to analyzing Cold SCB samples is fitting an extrapolated tail to the end of the data. AASHTO TP-105 specifies that the test must stop at about 0.5 kN of loading to protect the crack mouth gauge, but it also requires the user to extrapolate the data down to 0 kN of load. Following Equation 3, the technician must calculate the remainder of the test data using the portion of the curve below 60 percent of the peak load.

$$P = \frac{c}{u^2} \tag{3}$$

Where

P= Applied load (N)

c= a coefficient

u=average LLD load line displacement (m)

Using this remainder of the data, the technician must integrate the area under the curve due to the tail. If the curve is too steep, it may be difficult or impossible to fit a tail using the test specifications. In these cases, the RAAT-Pack notifies the user, thus saving them the time of attempting impossible fits. Due to the complexity of this procedure in Excel, the RAAT-Pack performs this entire process for the user but also gives the option of removing the tail if it is not visually acceptable. This is demonstrated in the figure below. Two samples could not be fitted accurately, so the user is saved the time of attempting to fit them.

Figure 23: If the cold temperature SCB tail is too steep to be fitted properly, a notification appears.

3.4.3 Cold SCB Additional Features

Two additional features are present in the Cold SCB module to serve as verification of certain parameters. The first of which is a graph of the pre-peak region of the curve. AASHTO TP-105 requires the reporting of the stiffness calculated using the pre-peak region, so the software allows the user to isolate this region on the graph. Additionally, the

RAAT-Pack summary report includes a verification of the CMOD gauge as the slope of time versus the gauge reading. This is a useful verification of the gauge's accuracy.

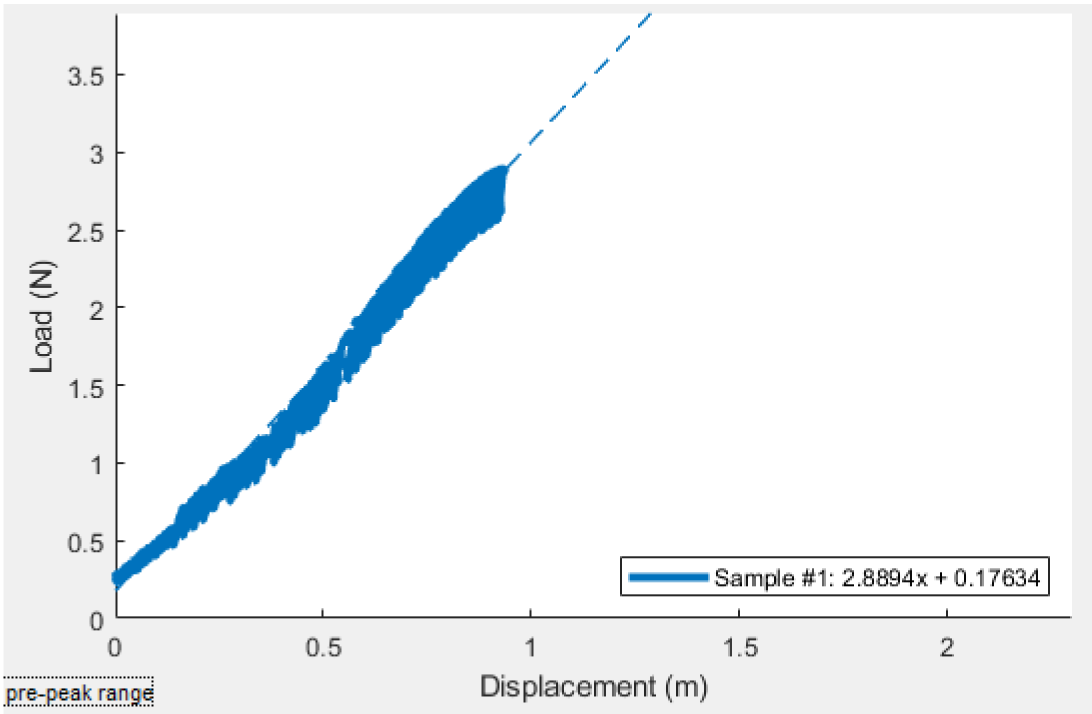


Figure 24: The stiffness of the cold SCB sample may be isolated in the RAAT-Pack in the pre-peak region of the graph.

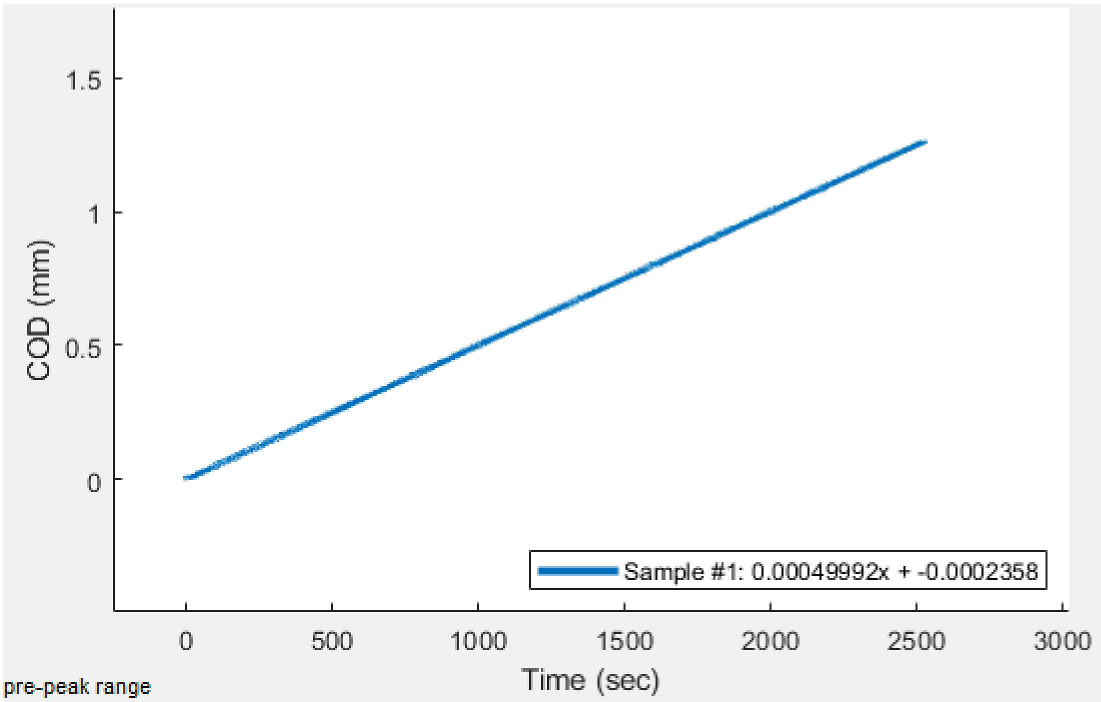


Figure 25: The slope of the CMOD gauge versus time is a measure of the gauge's accuracy. It is presented in the Cold SCB summary report.

3.4.4 Presentation

The cold temperature SCB summary report is in Appendix A.

3.4.5 Verification

Personal calculation methods may result in differences between Cold SCB results because the fracture energy is dependent on the area under the fitted tail. While the tail should have only a small effect on the final area, an incorrect fitting may increase the area greatly. Therefore, the cold SCB analysis procedure was conducted in both Excel and in the RAAT-Pack for three different mixes to ensure that personal calculation methods did not change the results significantly. Two unrelated SMA mixes and a DGA mix were tested at Rutgers University. They were chosen randomly to ensure accurate tail fitting for different types of samples. As shown in Table 3 and Table 4, there are no statistically significant differences between Excel and MATLAB. The results are presented in Figure 26. Ultimately, the process was much more difficult in Excel because the tail-fitting range had to be changed manually for each sample to obtain a proper fit. This had to be done for every file, as opposed to the RAAT-Pack's single click analysis for all files at once. From these results, it can be concluded that the RAAT-Pack calculates Cold SCB fracture energy just as well as Microsoft Excel, but it is much faster.

Table 3: Cold SCB Fracture Energy (J/m2) Results

Mix	Excel	RAAT-Pack
DGA	933.11	958.76
DGA	912.10	914.04
DGA	983.68	989.70
DGA	659.86	648.98
SMA 1	1501.14	1510.80
SMA 1	1781.28	1830.70
SMA 1	1390.22	1397.90
SMA 1	1191.12	1260.50
SMA 2	1395.10	1421.70
SMA 2	1736.91	1736.90
SMA 2	1871.95	1897.50

Table 4: Cold SCB Fracture Energy (J/m2) Results Comparison

Mix	Excel	RAAT-PACK	Std Dev (Excel)	Std Dev (RAAT-PACK)
DGA	872.19	877.87	144.70	155.72
SMA 1	1465.94	1499.98	246.26	243.08
SMA 2	1667.99	1685.37	245.79	242.05

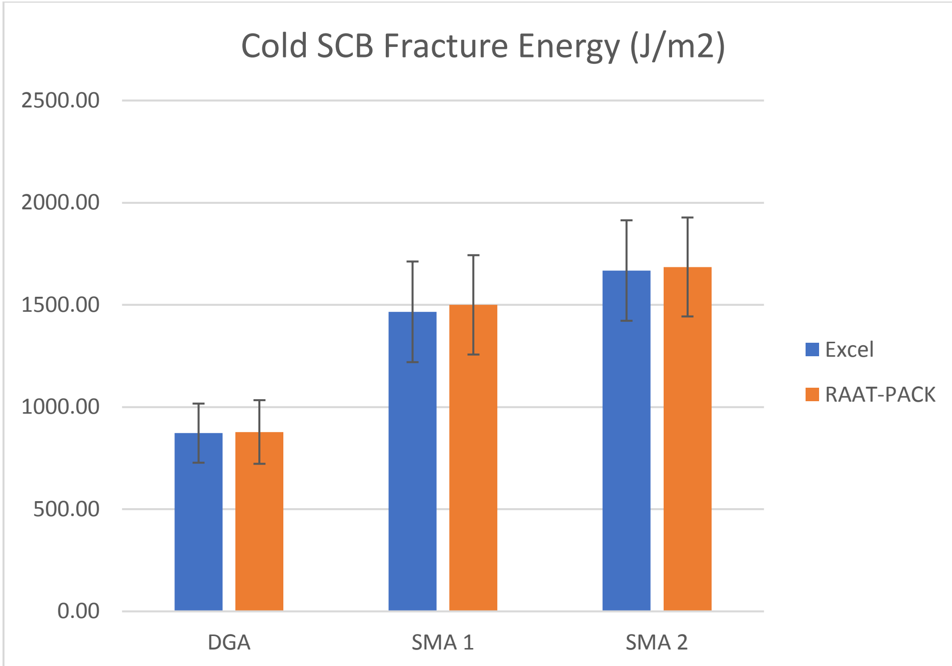


Figure 26: Cold SCB Results Comparison

3.5 Direct Compact Tension (DCT)

Direct Compact Tension (DCT) is a low temperature crack resistance test. A circular specimen with a single edge notch is loaded in tension. The area under the displacement-load curve is used to calculate the fracture energy of the material in cold temperatures. The fracture energy given by the DCT test is especially useful for discriminating polymer-modified asphalt mixes. The analysis requires use of a spreadsheet or analysis software to find the area under the curve. The RAAT-Pack expedites this process and normalizes up to four data columns for load, displacement, time, and CMOD gauge. Like Cold Temperature SCB, the CMOD gauge is used to measure relative crack growth. At any point during the test, the user may verify the CMOD gauge variability with a plot of CMOD versus time. The slope of this line is a measure of variability. Shown below are two DCT samples plotted in the RAAT-Pack.

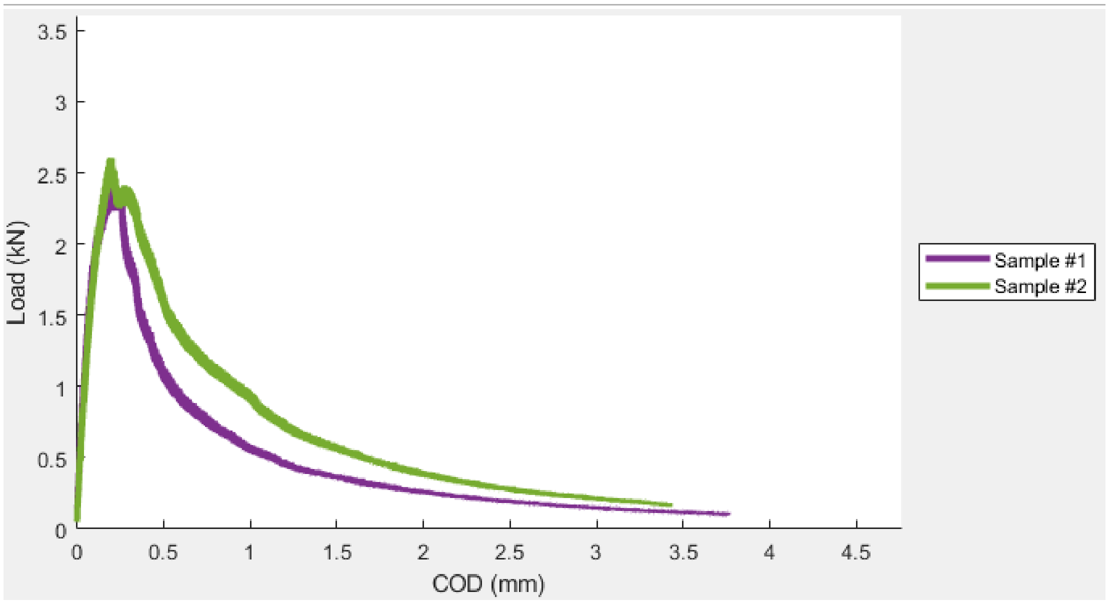


Figure 27: DCT results plotted against each other

3.5.1 Presentation

DCT results are seen in Appendix A.

3.5.2 Verification

DCT results are relatively simple to find, but the integration under the curve requires use of a spreadsheet or analysis software. Two separate DGA mixes and an SMA mix were tested at Rutgers University to verify the DCT module results across a broad spectrum of mixes. The results are given in Table 5 and Table 6. As shown by Figure 28, there are no statistical differences between Excel and the RAAT-Pack for DCT results.

Table 5: DCT Fracture Energy (J/m2) Results

Mix	Excel	RAAT-Pack
DGA 1	866.01	865.90
DGA 1	463.87	463.93
DGA 1	615.85	615.91
SMA	678.18	678.09
SMA	807.27	807.23
SMA	778.33	778.33
DGA 2	985.44	986.57
DGA 2	993.05	994.11
DGA 2	1034.27	1035.30

Table 6: DCT Fracture Energy (J/m2) Results Comparison

Mix	Excel	RAAT-PACK	Std Dev (Excel)	Std Dev (RAAT-PACK)
DGA 1	648.58	648.58	203.06	202.97
SMA	754.60	754.55	67.74	67.77
DGA 2	1004.25	1005.33	26.27	26.23

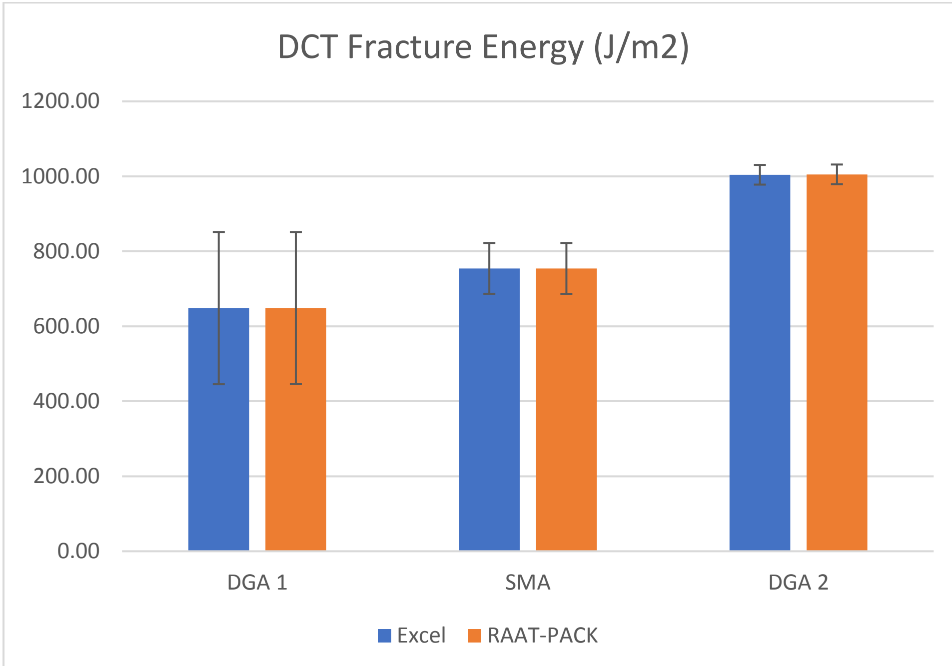


Figure 28: DCT Results Comparison

3.6 Dynamic Modulus

The dynamic modulus portion of the software contains the most complex analysis out of any module. The test is more research-based then the other performance tests, so a strong understanding of the material behavior is necessary for technicians to properly perform the analysis. Asphalt is viscoelastic in nature, which causes it to behave like a viscous liquid at warmer temperatures and an elastic solid at lower temperatures. As such, the dynamic modulus, or the stress to strain ratio under vibratory forces, is a measure of this behavior. It can be extrapolated for any given temperature and frequency by constructing a master curve, which is the dynamic modulus as a function of temperature and frequency created by shifting dynamic modulus data along a “log frequency” axis at a reference temperature. This procedure requires numerical optimization, which makes it difficult and requires the use of software like Excel or MATLAB. Optimization means that certain variables are optimized, or the sum of squared errors between the logarithm of the predicted modulus values and the logarithm of the measured values is minimized. Several coefficients must be solved at once. This may be done iteratively using the solver plug-in in Excel, but this requires the technicians to understand both calculus and Excel. What makes the RAAT-Pack unique is that it creates a standardized way of performing two master curve analyses. The first master curve follows AASHTO R84 and is created using Asphalt Mixture Performance Tester (AMPT) data. The second master curve conforms to AASHTO R62 and is constructed using both the AMPT data and asphalt binder data.

3.6.1 AASHTO R84: AMPT Master Curve

The master curve in AASHTO R84 follows the form of Equation 4:

$$\log|E^*| = \delta + \frac{(\mathrm{Max} - \delta)}{1 + e^{\beta + \gamma \log f_r}} \tag{4}$$

Where

$|E^*|$ = the dynamic modulus, psi

$\delta, \beta,$ and γ = fitting parameters

f_r = reduced frequency, Hz

Max = the limiting max modulus, psi

The reduced frequency is a function of the temperature, the reference temperature, and the activation energy, which may be treated as a fitting parameter. Therefore, the reduced frequency for each data point must be solved for during the optimization along with the fitting parameters. This curve also requires the following volumetrics to calculate the limiting max modulus: Voids filled with asphalt (VFA), Voids in Mineral Aggregate

(VMA), Maximum specific gravity of the mix (Gmm), bulk gravity of the aggregate blend (Gsb), average air voids (%AV), and asphalt content by mixture weight (%AC). The max limiting modulus is then calculated using Equations 5 and 6.

$$|E*|_{max} = P_c \left[4{,}200{,}000 \left(1 - \frac{VMA}{100}\right) + 435{,}000 \left(\frac{VFA \times VMA}{10{,}000}\right) + \frac{1 - P_c}{\frac{\left(1 - \frac{VMA}{100}\right)}{4{,}200{,}000} + \frac{VMA}{435{,}000(VFA)}} \right] \quad (5)$$

Where

$$P_c = \frac{\left(20 + \frac{435{,}000(VFA)}{VMA}\right)^{0.58}}{650 + \left(\frac{435{,}000(VFA)}{VMA}\right)^{0.58}} \quad (6)$$

Already the analysis is complicated. To make things easier, the RAAT-Pack loads AMPT machine outputs as data. The program utilizes the standard “sum” comma-separated value (csv) files given from the AMPT software. The user must select a project folder, and from there, the files can be selected from dropdown menus. This is intended to reduce the time required from copying and pasting data from up to nine different sum files. The program accepts the standard sum csv files from the AMPT machine itself, so no data normalization is required. The program will automatically detect which frequencies have been run. One to three samples may be used, but if there are less than three samples, the curve may not be as accurate. The program will display the black space data for each sample and will warn the user if the covariance between dynamic modulus values are high.

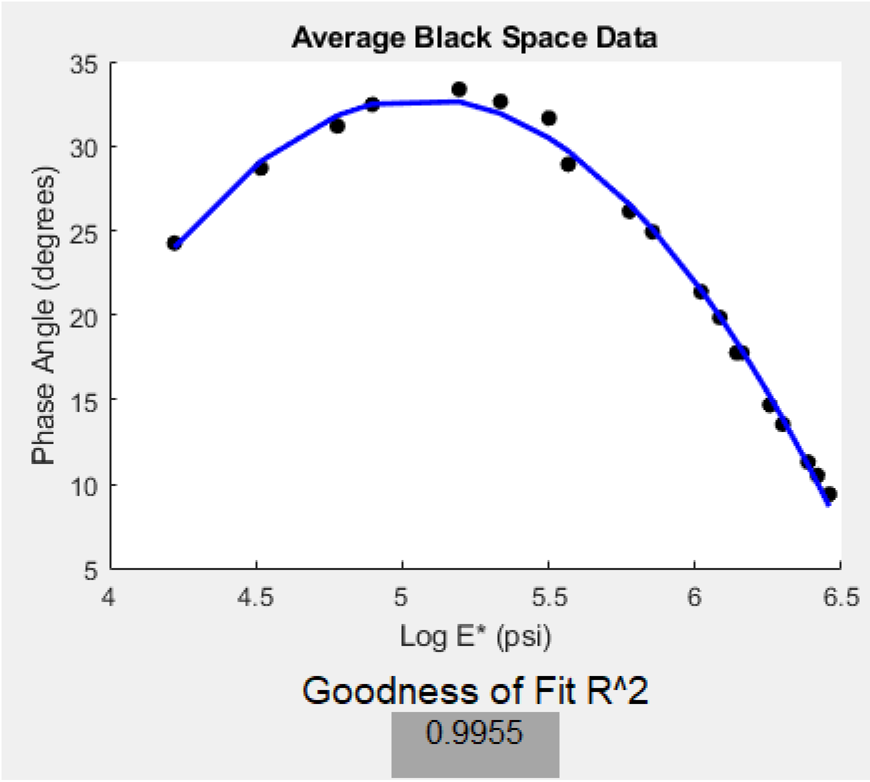


Figure 29: Average black space data is plotted along with the goodness of fit (R^2) as a measure of the covariance of the data.

The software will provide the coefficients used in the analysis, as well as the master curve sum of squared error. The phase angle versus reduced frequency and goodness of fit are also given. This shows the user how accurately the master curve fits their data.

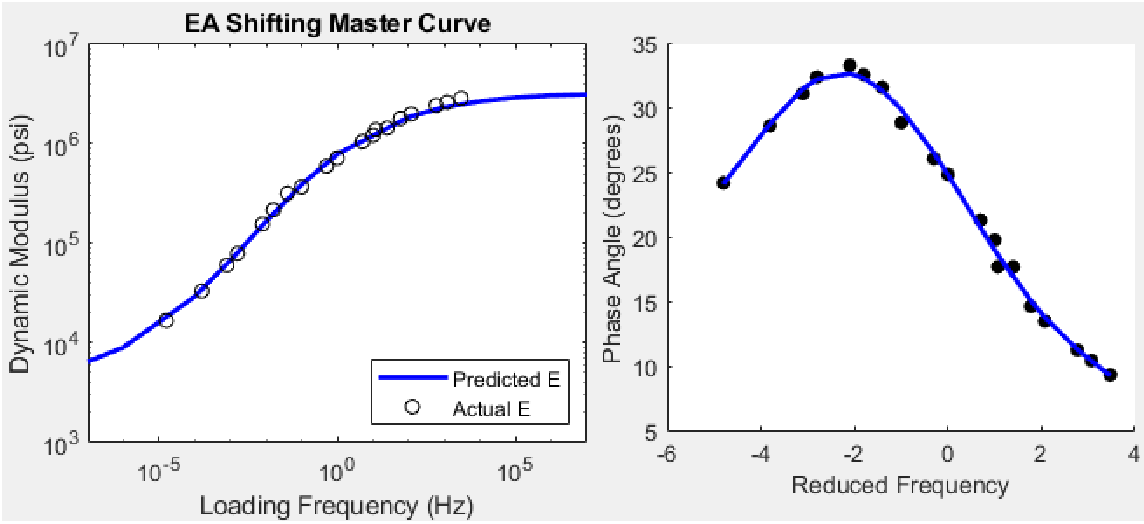


Figure 30: The master curve and a curve with the reduced frequency versus phase angle are given.

3.6.2 AASHTO R62: MEPDG Master Curve

AASHTO R62 is the standard method of finding the dynamic modulus master curve for MEPDG. The analysis requires the computation of A and VTS, the parameters of the binder viscosity-temperature susceptibility relationship in AASHTO R62. The user has several different options for calculating A and VTS. If dynamic shear rheometer data, penetration test data, or rotational viscometer data are available, the user may input these into the RAAT-Pack, which will calculate A and VTS automatically. Alternatively, if no binder data is available, the user may select a PG grade from a dropdown menu. The corresponding parameters A and VTS from NCHRP 1-37A are then used. Equation 7 is used for AASHTO R62.

$$\log|E^*| = \delta + \frac{(\alpha)}{1 + e^{\beta+\gamma\left\{\log f + c\left[10^{(A+VTS\log T)} - 10^{(A+VTS\log T_R)}\right]\right\}}} \tag{7}$$

Where

$|E^*|$ = the dynamic modulus, psi

α, δ, β, and γ = fitting parameters

f = loading frequency at test temperature, Hz

T = test temperature, °F

T_R = reference temperature, °F

A and VTS = binder viscosity/temperature susceptibility parameters

3.6.3 Chamber Temperatures

A unique feature of the dynamic modulus program is that it can generate the master curve for both the target temperatures and the recorded AMPT chamber temperatures. This may be useful for verification of the chamber temperatures. That is, if the sum of squared errors is too high for the chamber temperatures compared to the target temperatures, the AMPT chamber may need to be calibrated to reduce this error.

3.6.4 Presentation

A dynamic modulus summary report can be found in Appendix A.

3.6.5 Verification

The fitting parameters found in AASHTO R84 and AASHTO R62 are what give the master curve its shape. Fitting parameters found in both Excel and the RAAT-Pack are shown in Table 7 and Table 8. The results are identical, and the SSE between the software shows that the error is the same. Still, it is more difficult to use Excel to find dynamic modulus results if certain files are missing data. The RAAT-Pack will automatically detect which frequencies are included or excluded. If there are any problems in the Excel spreadsheet, the technician must be familiar with both systems of equations and the complex formulas given in AASHTO R84 and AASHTO R62. The RAAT-Pack eliminates this pressure from the technician. Therefore, the RAAT-Pack consistently gives accurate results and is more intuitive than Excel for technicians.

Table 7: Dynamic Modulus Fitting Parameters Using AASHTO R84

Mix	Software	delta (d)	beta (b)	gamma (g)	SSE
12.5ME	Excel	3.5734	-1.3134	-0.5380	0.0189
12.5ME	RAAT-Pack	3.5734	-1.3135	-0.5380	0.0189
HPTO	Excel	3.1309	-0.9123	-0.4787	0.0068
HPTO	RAAT-Pack	3.1309	-0.9123	-0.4787	0.0068
12.5M64 15R	Excel	2.2845	-1.2782	-0.4954	0.0100
12.5M64 15R	RAAT-Pack	2.2847	-1.2782	-0.4954	0.0100

Table 8: Dynamic Modulus Fitting Parameters Using AASHTO R62

Mix	delta (d)	beta (b)	gamma (g)	C	SSE
12.5ME	3.6210	-1.2389	0.5702	1.5038	0.0075
12.5ME	3.6211	-1.2388	0.5702	1.5034	0.0075
HPTO	3.0492	-0.9062	0.4730	1.2037	0.0163
HPTO	3.0493	-0.9062	0.4730	1.2034	0.0163
12.5M64 15R	2.1687	-1.2774	0.4934	1.0544	0.0162
12.5M64 15R	2.1688	-1.2774	0.4934	1.0541	0.0162

3.7 Hamburg Software

The HWTT is a test that can determine both rutting and moisture sensitivity of HMA. Metal wheels pass over submerged samples at 52 passes per minute for up to 20,000 cycles. Including sample preparation and conditioning, the test can easily span an entire workday, making a quick analysis critical. What makes HWTT results complicated is the effect of stripping, when asphalt binder separates from the aggregates due to moisture. In the presence of stripping, there are two steady-state portions in the data separated by an inflection point. The slope from the first steady-state portion is the creeping slope, and the slope of the second steady-state portion is the stripping slope. When the difference of the intercepts of the two portions over the difference in the slopes (the SIP ratio) is greater than 2, there is notable stripping. If it is less than 2, then there may be no inflection point, and the sample has not stripped. Currently, there are no standardized methods for finding these slopes. It is difficult to quantify the first steady-state versus the second steady-state, especially if the slopes are close in value. To calculate both in Excel, the solver add-in must be used for both parts of the curve. If the slopes cannot be found, reiterating this process may take a long time. Therefore, an iterative procedure was created in the RAAT-Pack to find these slopes, and the user is given the option of confirming them. If the slope is detected in an incorrect region, the user may double click on the correct region to narrow the search region. Much like the SCB and IDEAL-CT analysis, more than one inflection point may exist in the data. The software is coded with careful mathematics so that erroneous inflection points are ignored. In this way, the RAAT-Pack reduces error and makes the analysis easier for the technician. Given that this test takes over seven hours to perform, a slow analysis can easily make this test take longer than a single workday. With the RAAT-Pack, the analysis takes only seconds.

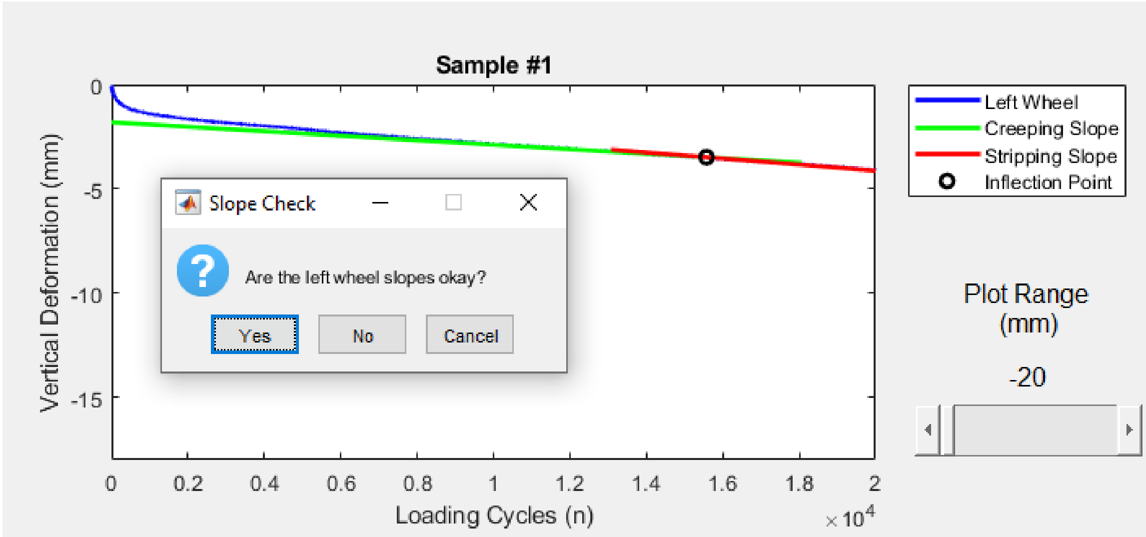


Figure 31: The HWTT module prompts the user to confirm creep and stripping slopes.

Another unique feature is a slider bar to control the axes of the graph. By sliding the bar, the user can magnify the graph to better visualize certain parts of the data. Given that these samples can run 20,000 cycles, this feature is useful for verifying the slopes and inflection points.

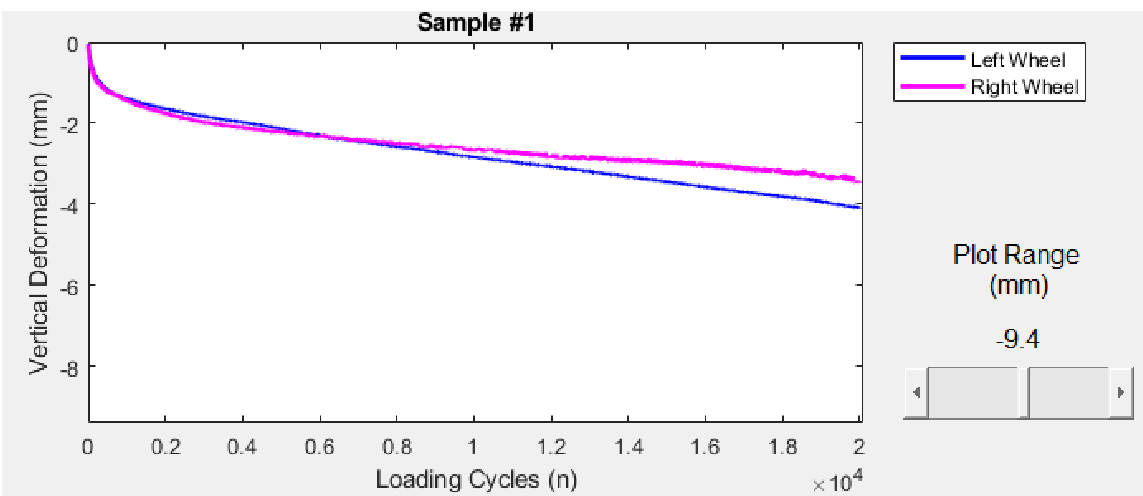


Figure 32: The view of the HWTT graph may be changed for easier viewing.

3.7.1 Presentation

HWTT results are seen in Appendix A.

3.7.2 Verification

To verify the accuracy of the RAAT-Pack analysis, HWTT results were found in the RAAT-Pack and in Excel. A lab-compacted DGA mix and a field core mix are compared in Table 9 and Table 10. Both types of samples are commonly used in the HWTT. The results differ slightly due to the complexity of the analysis, but they are within the standard deviations for either software.

Table 9: HWTT Results

		Excel		RAAT-Pack	
Mix	**Parameter**	**Left**	**Right**	**Left**	**Right**
19MM DGA	Rutting at 20,000 cycles (mm):	4.00	3.38	4.03	3.38
19MM DGA	Creep Slope (mm/cycle):	7.41E-05	4.91E-05	1.08E-04	4.92E-05
19MM DGA	Stripping Slope (mm/cycle):	1.86E-04	1.31E-04	1.46E-04	1.02E-04
Field Core	Rutting at 20,000 cycles (mm):	11.86	12.00	11.86	12.00
Field Core	Creep Slope (mm/cycle):	4.88E-04	7.28E-04	5.20E-04	8.05E-04
Field Core	Stripping Slope (mm/cycle):	2.47E-03	1.63E-03	2.40E-03	1.50E-03

Table 10: HWTT Results Comparison

		Excel	**RAAT-PACK**	**Std Dev (Excel)**	**Std Dev (RAAT-PACK)**
DGA	Rutting at 20,000 cycles (mm):	3.69	3.71	0.44	0.46
DGA	Creep Slope (mm/cycle):	6.16E-05	7.84E-05	1.77E-05	4.13E-05
DGA	Stripping Slope (mm/cycle):	1.54E-04	1.24E-04	3.18E-05	3.10E-05
Field Core	Rutting at 20,000 cycles (mm):	11.93	11.93	0.10	0.10
Field Core	Creep Slope (mm/cycle):	6.08E-04	6.63E-04	1.69E-04	2.02E-04
Field Core	Stripping Slope (mm/cycle):	2.05E-03	1.95E-03	5.93E-04	6.36E-04

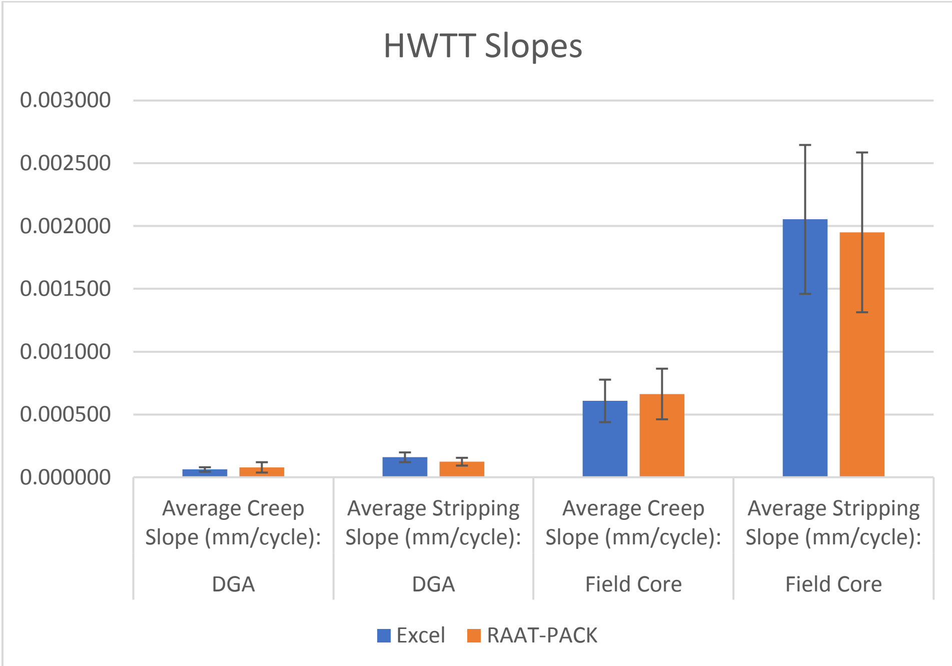


Figure 33: HWTT Results Comparison

3.8 High Temperature IDT

High Temperature Indirect Tensile Strength (HT-IDT) is a modified version of standard IDT testing using a higher conditioning and testing temperature. This test method utilizes a cylindrical sample loaded across its vertical diametral plane, to determine the peak load at failure to calculate the IDT strength. Samples may be tested on a Marshall Test machine retrofitted with a Lottman frame, meaning it can be easily adapted in laboratories that already possess Marshall Test machines. Rutgers University uses a universal loading frame to test HT-IDT samples. Calculation of the strength is simple, as it is a measure of peak load divided by the thickness multiplied by diameter. The RAAT-Pack HT-IDT module provides these results with the benefit of batch analysis.

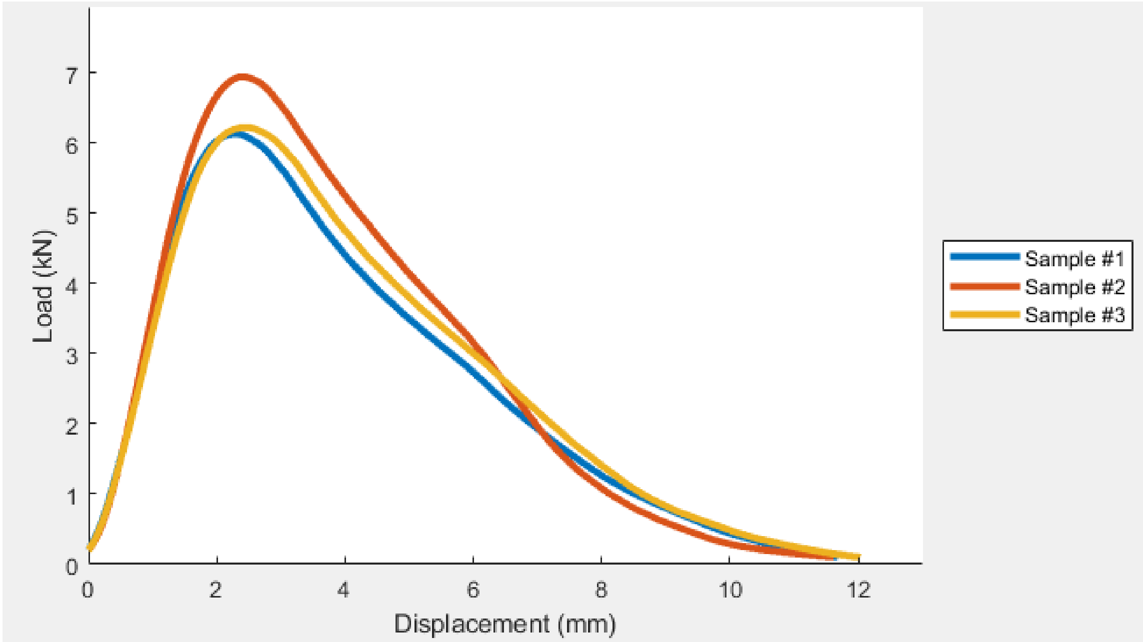


Figure 34: HT-IDT results

3.8.1 Presentation

HT-IDT results are presented in Appendix A.

3.8.2 Verification

The HT-IDT analysis is like the bond strength analysis in that it does not require any calculus. The math involved is just addition and division, so the results between spreadsheets like Excel and the RAAT-Pack are always the same. Therefore, a verification table is not provided.

3.9 IDEAL-CT

IDEAL-CT testing (ASTM D8225) is a crack resistance test that utilizes a full size Superpave Gyratory Compacted sample and line loading. Crack resistance is calculated using the load and displacement data from the test. It has the potential to be widely adopted by state agencies because of the simple sample preparation and testing, as well as its ability to be run on a retrofitted Marshall Testing machine. The analysis, however, requires use of a spreadsheet or software. The RAAT-Pack offers a standard analysis and reporting method based on ASTM D8225. The CT_{Index} according to the specification is calculated in Equation 8.

$$CT_{Index} = \frac{t}{62} \times \frac{l_{75}}{D} \times \frac{G_f}{|m_{75}|} \times 10^6 \tag{8}$$

Where

CT_{Index} = cracking tolerance index

Gf = failure energy (Joules/m2)

$|m_{75}|$ = absolute value of the post-peak slope m_{75} (N/m)

l_{75} = displacement at 75 % the peak load after the peak (mm)

D = specimen diameter (mm)

t = specimen thickness (mm).

What makes this analysis difficult is the calculation of area under the curve and post-peak slope. The area is calculated using the quadrangle rule, which may be cumbersome in Excel. The inclusion of an empty cell in this equation may drastically change the area, leading to error. The slope is calculated by fitting a linear regression between 85% peak and 65% peak. Finding these points may be done in Excel, but the spreadsheet becomes clustered if this procedure is done for every sample. The advantage of the RAAT-Pack is that these points are found automatically for any number of files. Lastly, the thickness for samples that are not 62mm is accounted for using the first term in the above equation. This allows the RAAT-Pack to test field cores and achieve the correct CT_{Index}.

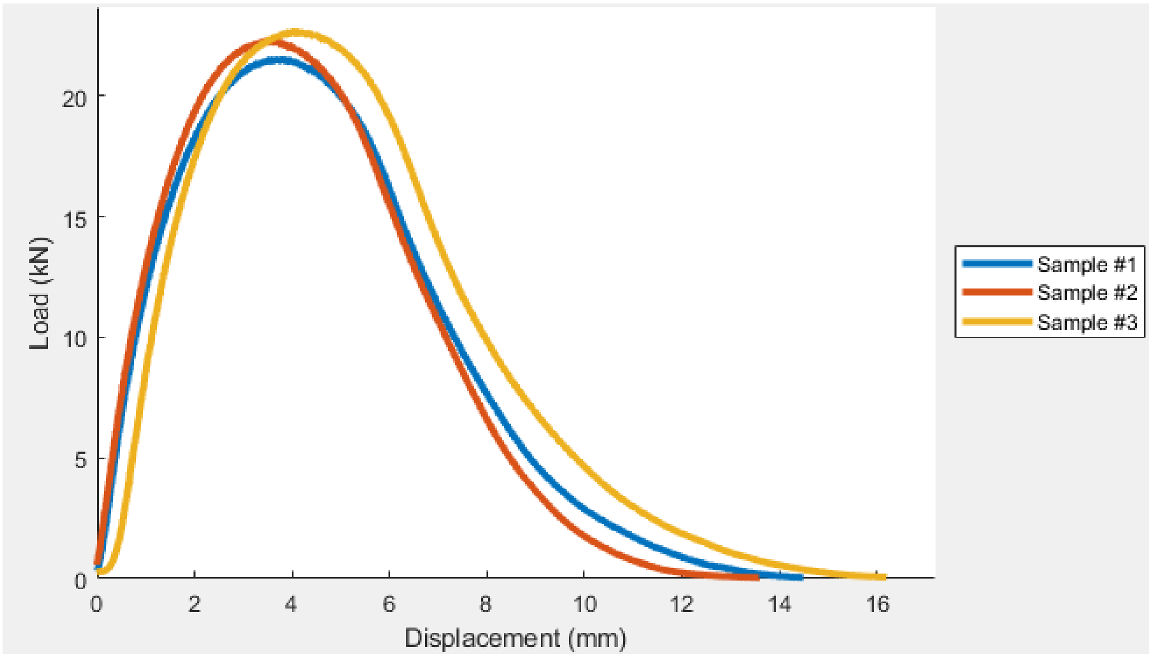


Figure 35: IDEAL-CT samples

3.9.1 Presentation

An IDEAL-CT summary sheet can be found in Appendix A.

3.9.2 IDEAL-CT Verification

To ensure the proper calculation of the post-peak slope, the CTIndex from three unique mixes are compared in Table 11 and Table 12. The materials exhibit a wide range of behavior, with HPTO mix showing a shallow post-peak slope and the RAP mix showing a sharp post-peak slope. This ensures that the software works despite the shape of the load-displacement curves.

Table 11: CTIndex Data

Mix	Excel	RAAT-Pack
12.5M64 30% RAP	5.55	5.59
12.5M64 30% RAP	4.27	4.30
12.5M64 30% RAP	4.62	4.66
DGA	18.43	18.31

DGA	26.22	26.12
DGA	24.71	25.59
HPTO	115.22	116.50
HPTO	106.20	108.99
HPTO	133.63	133.98

Table 12: CTIndex Result Comparison

Mix	Excel	RAAT-PACK	Std Dev (Excel)	Std Dev (RAAT-PACK)
12.5M64 30% RAP	4.81	4.85	0.66	0.67
DGA	23.12	23.34	4.13	4.36
HPTO	118.35	119.82	13.98	12.82

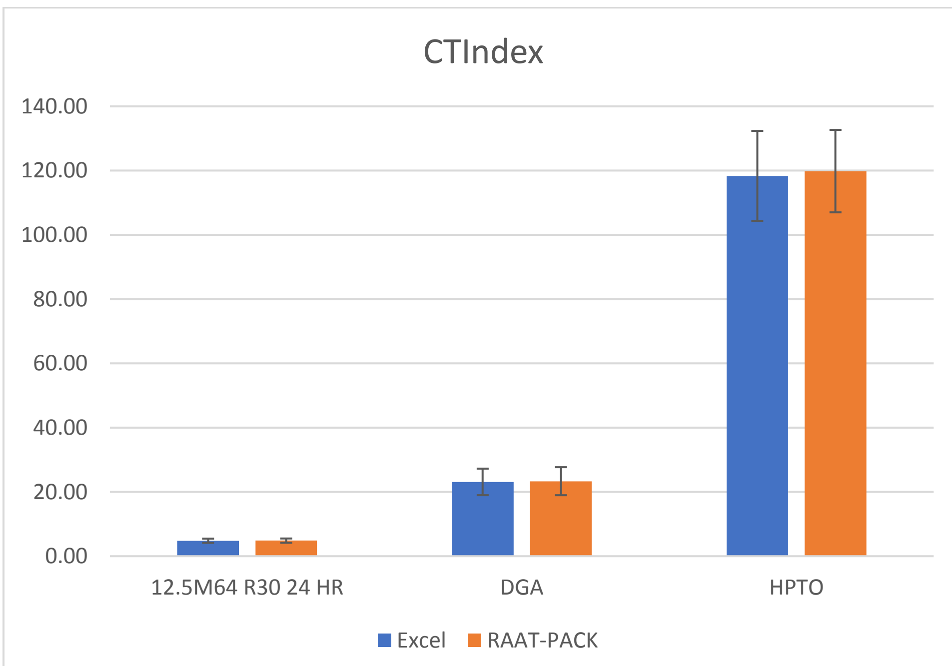


Figure 36: IDEAL-CT Results Comparison

3.10 Intermediate Temperature SCB

Intermediate Temperature Semi-Circular Bend (SCB) testing is an innovative crack resistance test for asphalt pavements. It uses a semi-circular (half-moon) shaped asphalt sample with an initiated crack to determine further resistance to cracking analyzing the load and displacement data. The analysis performed follows AASHTO TP124.

3.10.1 Calculation of the Flexibility Index

The primary goal of TP124 is to find the Flexibility Index (FI), an effective indicator of cracking behavior at intermediate temperatures. It is calculated using Equation 9.

$$FI = \frac{G_f}{|m|} \times A \tag{9}$$

Where

G_f = Fracture Energy

m= Slope at the inflection point

A= Unit correction factor (0.01)

Standardization of this analysis is important because personal calculation methods can greatly change the results, specifically when fitting the post-peak portion of the curve. Depending on the fitting range, this method may not be able to find an inflection point. The RAAT-Pack uses an iterative process to ensure a proper fit. Then, the area under the curve is found by integration. The inflection point and slope at this point are difficult to solve and require the use of second derivatives. Much like the fitting, the software uses an iterative process to find the correct inflection point, as each curve can have several local inflection points. Should the program find the incorrect point, the user may click on a specific region of the curve to narrow the search range to find the correct point. This is shown below.

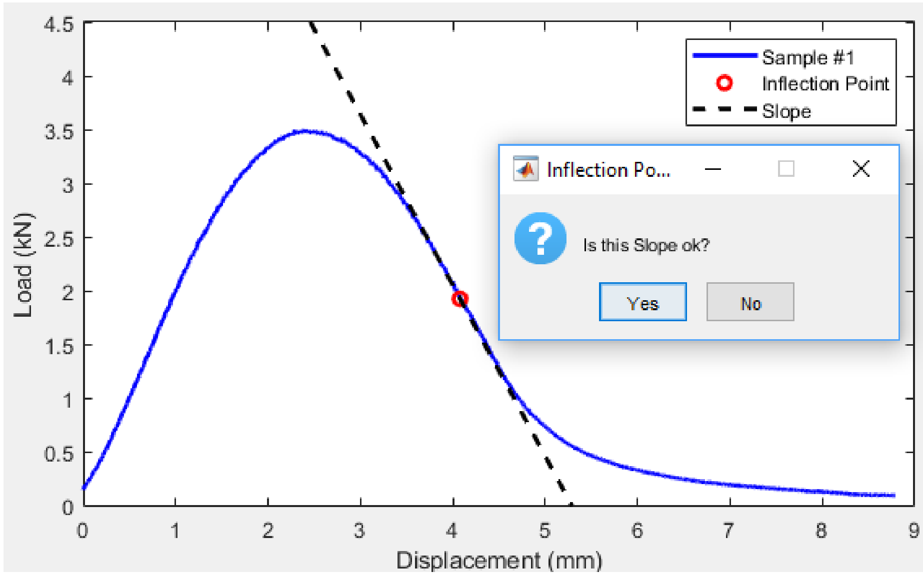


Figure 37: Verification of SBC slope is important because more than one inflection point can exist.

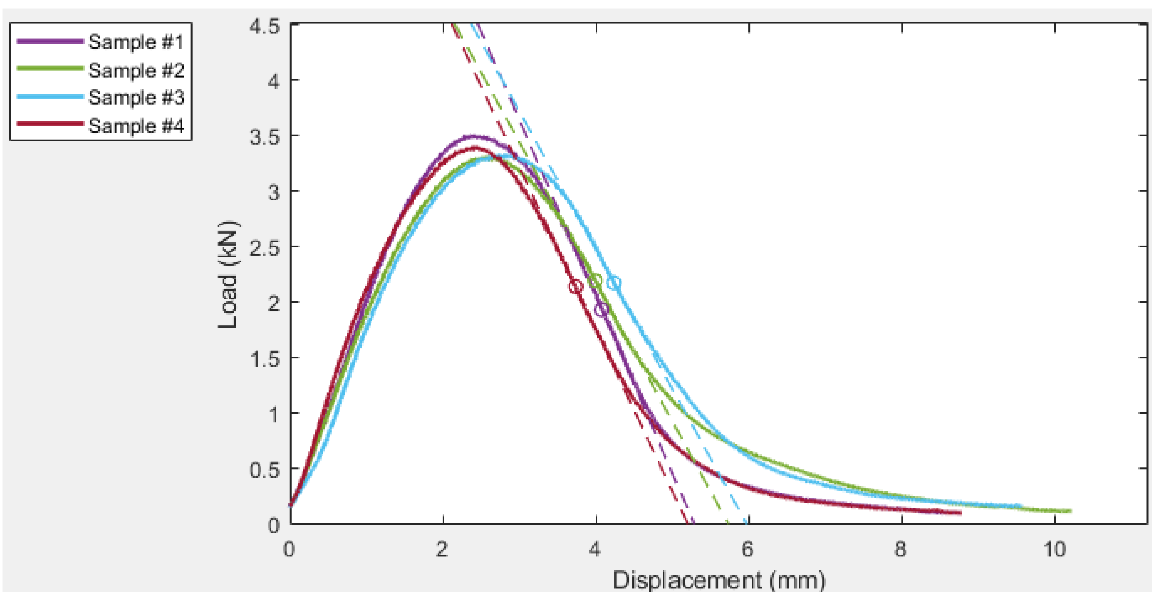


Figure 38: SCB results are plotted together to show differences in slopes, areas, and peak loads.

3.10.2 SCB Data Trimming

To improve both analysis and presentation, a data trimming feature is included in the module. This helps remove inconsistencies in the data that may impede calculations. That is, there may be leading zero values in the beginning of the data. Likewise, if the SCB sample meets the edges of the platform after breaking, there may be a spike in the end of the data. Therefore, the SCB module automatically trims the end of the data to 0.1 kN, where the test may be concluded according to TP124. Trimming of the beginning is optional, as shown below. This trimming also improves presentation of data because it removes potentially long tails from the graph.

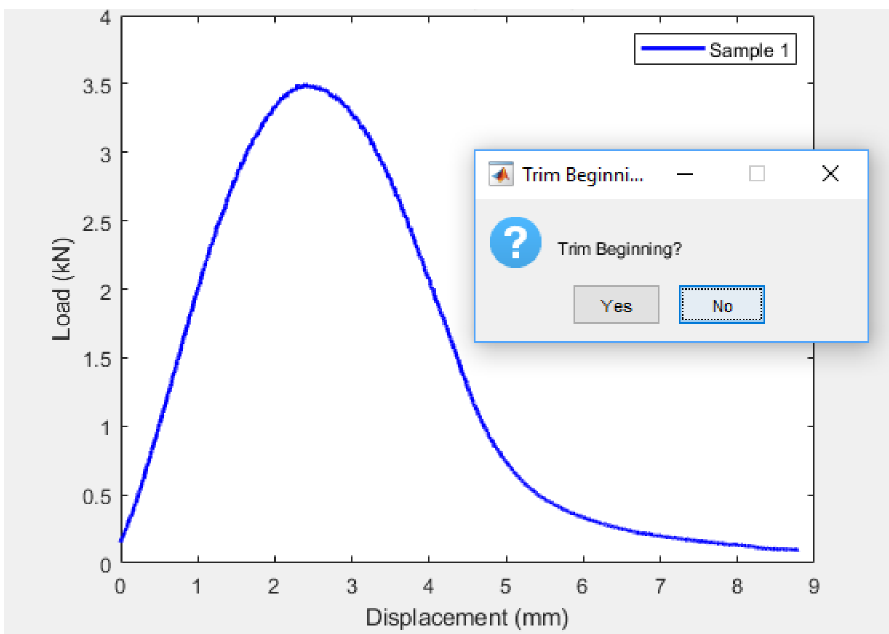


Figure 39: Beginning of SCB data may be trimmed. The end is automatically trimmed to 0.1 kN as per the specification.

3.10.2 Presentation

Intermediate temperature SCB-FI results are in Appendix A.

3.10.3 Verification

SCB-FI Results were verified using several different mixes to capture different load-displacement curves. Steeper curves are more difficult for analysis software to find the inflection point, as there are less data points. However, the RAAT-Pack procedure does this well. Some analysis software struggle to find this FI for brittle mixes, but the careful coding of the RAAT-pack ensures that a value is found. If not, the user has the option to select a region on the graph to search, and it will find a point there. Binder Rich Intermediate Course (BRIC), Recycled Asphalt Pavement (RAP), and High-Performance Thin Overlay (HPTO) mixes were tested and compared between Excel and the RAAT-Pack to provide a wide spectrum of results.

Table 13: SCB-FI Results

Mix	Excel	RAAT-Pack
9.5M64 30% RAP	0.13	0.14
9.5M64 30% RAP	0.25	0.27
9.5M64 30% RAP	0.25	0.18
9.5M64 30% RAP	0.37	0.35
BRIC	7.69	7.75
BRIC	8.53	8.48
BRIC	8.79	8.76
BRIC	10.23	10.23
HPTO	7.07	7.02
HPTO	8.46	8.44
HPTO	10.81	10.88
HPTO	10.89	10.80

Table 14: SCB-FI Result Comparison

Mix	Excel	RAAT-PACK	Std Dev (Excel)	Std Dev (RAAT-PACK)
9.5M64 30% RAP	0.25	0.23	0.10	0.09
BRIC	8.81	8.80	1.06	1.04
HPTO	9.31	9.29	1.87	1.89

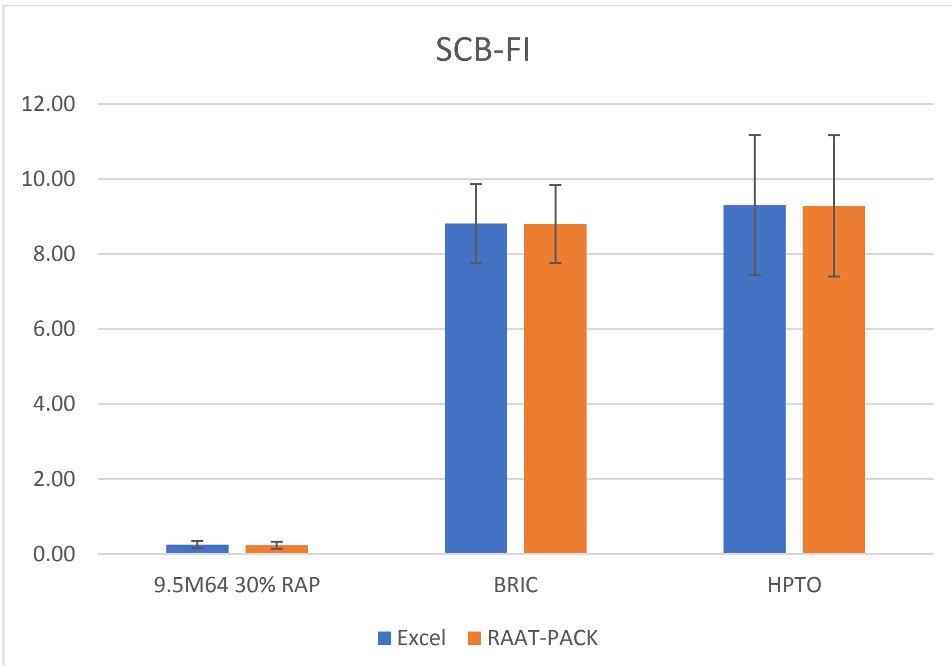


Figure 40: Intermediate Temperature SCB-FI Results Comparison

Chapter 4: Deliverables

Working closely with the Rutgers Office of Research Commercialization, a website was created to host the software. Interested users may apply for a free license. This will allow Rutgers to keep track of existing users and to distribute updates. Two installers are provided for the RAAT-Pack. Each one is an individual executable file. One provides the MATLAB Runtime, and the other automatically downloads the MATLAB Runtime from the MathWorks website. Both versions are given as an option in case strict firewall rules prevent downloading from the MathWorks website. Written and video instructions are also provided with the software on the website. The written instructions detail every module together, whereas each video is tailored to an individual module. Several demo files are included with the installer package to give the user an idea of how the data should be normalized for analysis.

Chapter 5: Conclusions

The asphalt industry is shifting toward simpler and faster tests for QA/QC work, so analyzing performance data should be as efficient and as accurate as the test procedures themselves. This is easier said than done, and it often requires heavy knowledge of spreadsheets or coding languages like MATLAB. The RAAT-Pack removes the need for coding, alleviating this burden from technicians. It should be considered by QA/QC laboratories across the nation due to its simplicity and uniform formatting. Offering a suite of analyses, it is the first of its kind in terms of analyzing multiple performance tests together. Ultimately, the software offers a standardized method of analyzing performance test data and promotes the use of BMD by contractors and state agencies.

5.1 Unique Features

The RAAT-Pack breaks ground with several unique features to make it stand out from traditional spreadsheets or analysis software. They are summarized below.

1. **Multiple Tests-** Ten tests are contained in one software. This promotes BMD, which is a balance between several performance criteria.
2. **Batch analysis-** Many files can be analyzed at once. This is not possible when using a spreadsheet, as data must be entered and analyzed manually.
3. **Automated data normalization-** This unique feature allows users to format their data automatically. Given the variability of test data across laboratories, this makes the analysis more universal and makes inter-laboratory comparisons easier.
4. **GUI:** Analyses are performed using buttons and charts, so users are not required to know any coding.

5. **Uniform summary sheets:** Uniform summary sheets were created to provide useful information after testing.

5.2 Reduction of Error

The RAAT-Pack has huge potential to reduce both user error and software error. It effectively addresses the following sources of error: data normalization, personal calculation methods, repetitive calculations, and formatting. These processes become automated when using the software, but user input is still required to ensure the accuracy of the results. In this way, the most egregious mistakes in data analysis are removed without adding bias from the software.

5.3 Verification

The RAAT-Pack results were proven to be statistically no different from results in Excel if the analysis is performed the same way. Each of the ten tests were verified against Excel, and the results were identical. Certain tests always yield the same result between software due to the simplicity of the analysis: APA, Bond Strength, and HT-IDT. The math involved is just simple averaging, which may be done by hand. The other seven tests require the use of spreadsheets or analysis software. They require calculus, but as evidenced by the RAAT-Pack, they do not require knowledge of coding. Different mixes were taken for each test, to ensure that the analyses were correct for materials that may exhibit different behavior. There may be differences in the way MATLAB and Excel calculate area, slope, model coefficients, etc. However, these differences are statistically negligible.

5.4 Recommendations

Performance data may contain a high level of variability due to machine error, user bias, and errors in calculations, making it difficult to analyze. As such, it is recommended that black box systems be avoided, as they do not show the technician what calculations are being performed and do not always give accurate results. The RAAT-Pack prompts the user during certain difficult analyses to verify the calculated parameters. Therefore, technicians should explore MATLAB, Excel, and other software designed for analysis. Results can be expedited with an analysis software instead of a typical spreadsheet, and this can lead to cost savings in the long run. Agencies should consider using the RAAT-Pack as a QA/QC tool to promote the use of performance testing and BMD.

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Appendix A- Summary Sheets

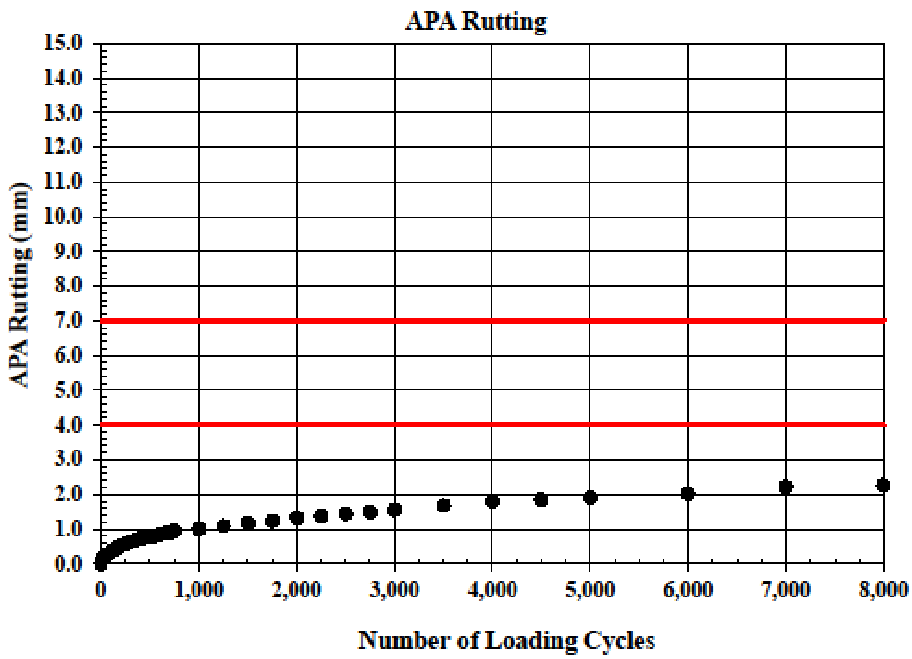
AASHTO T340-10: Standard Method of Test for Determining Rutting Susceptibility of Hot Mix Asphalt (HMA) Using the Asphalt Pavement Analyzer (APA)

Project Name:		**Institution:**	
Mix Type:		**Date Tested:**	
Test Temperature (C):		**Technician:**	

Sample	Air Voids (%)	Left Rut Depth (mm)	Middle Rut Depth (mm)	Right Rut Depth (mm)	Average Rut Depth (mm)	Standard Deviation	COV (%)
Sample #1		2.26	2.25		2.26	0.01	0.30

APA Intermediate Course (PG64-22) Criteria ≤	7	mm Rutting
APA Surface Course (PG76-22) Criteria ≤	4	mm Rutting

64C Test Temp.; psi Hose Pressure; lb Load Load

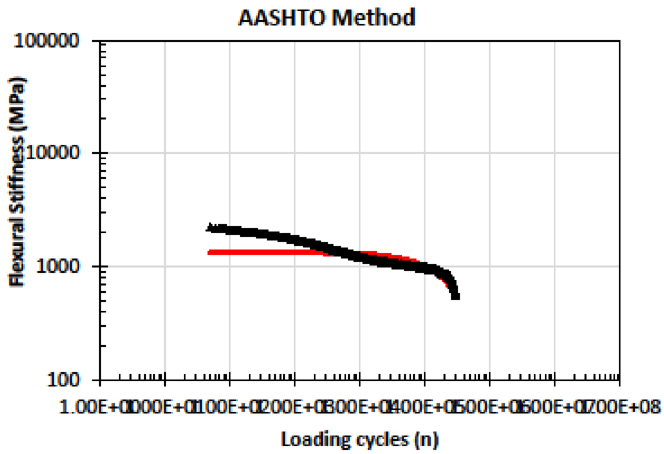


This report was developed using the Rutgers Asphalt Analysis Tool-Pack (RAAT-Pack)

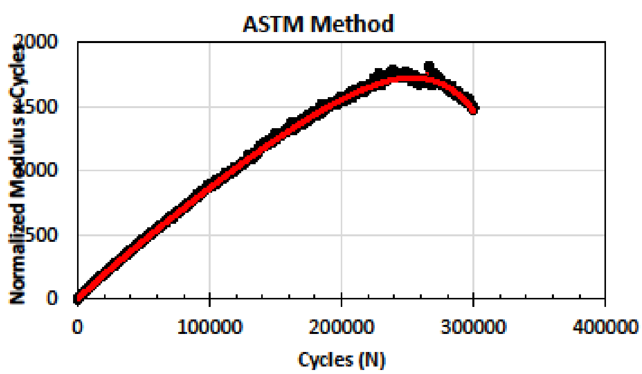
AASHTO T321: Standard Method of Test for Determining the Fatigue Life of Compacted Asphalt Mixtures Subjected to Repeated Flexural Bending

Project Name:		Institution:	
Mix Type:		Date Tested:	
Test Temperature:		Technician:	

Specimen ID	Air Voids (%)	Width (mm)	Height (mm)	Length (mm)	AASHTO nf,50	ASTM nf,50
Sample #1		100	100	100	248502	253987



AASHTO Trendline	
A	1.33E+03
b	-2.79E-06
Stiffness, Measured at nf,50	2222
Elastic Modulus, Measured at nf,50 (psi)	2363



ASTM Trendline	
-1.23E-29	x^6
9.03E-24	x^5
-2.80E-18	x^4
4.34E-13	x^3
-4.02E-08	x^2
1.04E-02	x^1
n at max	266070

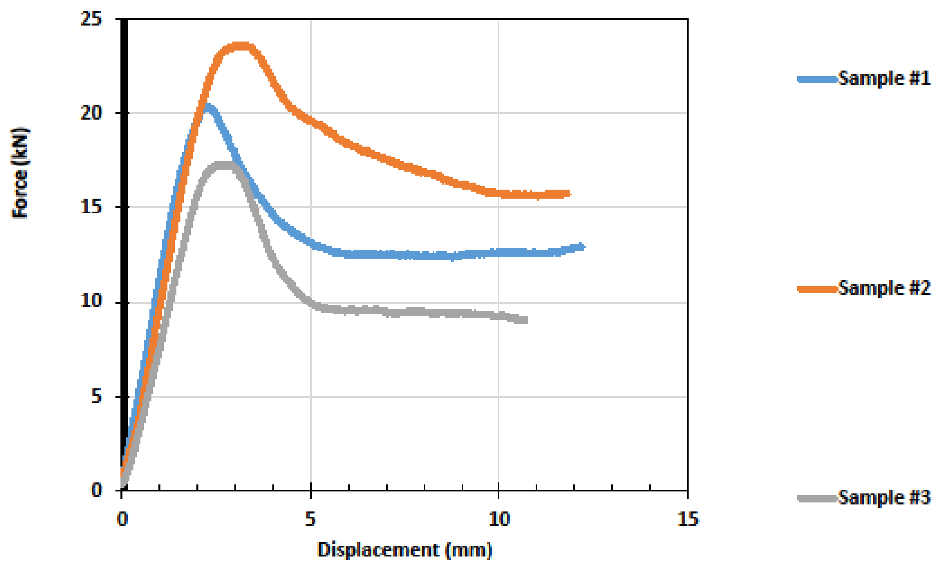
This report was developed using the Rutgers Asphalt Analysis Tool-Pack (RAAT-Pack)

AASHTO TP 114-17: Standard Method of Test for Determining the Interlayer Shear Strength (ISS) of Asphalt Pavement Layers

Project Name:		**Institution:**	
Mix Type:		**Date Tested:**	
Test Temperature:	**25C**	**Technician:**	

Specimen ID	Air Voids (%)	Length (in)	Diameter (in)	Peak Load (kN)	Displacement at Peak (mm)	Bond Strength (psi)
Sample #1		5.9	5.9	20.3	2.2	166.9
Sample #2		5.9	5.9	23.6	3.1	194.1
Sample #3		5.9	5.9	17.3	2.8	142.2
Average		**5.9**	**5.9**	**20.4**	**2.7**	**167.7**
Std Dev		**0.0**	**0.0**	**3.2**	**0.5**	**26.0**
COV (%)		**0.0**	**0.0**	**15.5**	**16.6**	**15.5**

Bond Strength



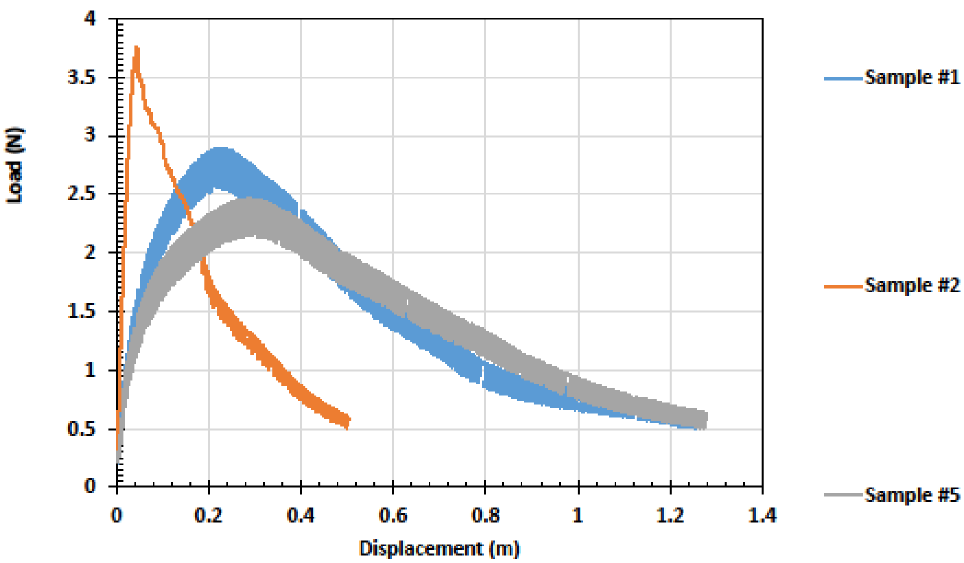
This report was developed using the Rutgers Asphalt Analysis Tool-Pack (RAAT-Pack)

AASHTO TP 105-13: Standard Method of Test for Determining the Fracture Energy of Asphalt Mixtures Using the Semicircular Bend Geometry (SCB)

Project Name:		**Institution:**	
Mix Type:		**Date Tested:**	
Test Temperature:		**Technician:**	

Specimen ID	Air Voids (%)	Thickness (mm)	Radius (mm)	Notch Length (mm)	Peak Load (kN)	Time At Peak (s)	Uc (mm)	Stiffness (kN/m)	K_{IC} ($MPa*m^{.5}$)	Fracture Energy (J/m^2)	CMOD Slope (mm/s)
Sample #1		25.0	75.0	15.0	2.9	452.1	1.286	2889.4	0.885	1385	5.00E-04
Sample #2		25.0	75.0	15.0	3.8	123.9	1.177	2967.7	1.148	1355	4.93E-04
Sample #5		25.0	75.0	15.0	2.5	570.1	1.151	2793.3	0.752	1152	5.00E-04
Average		**25.0**	**75.0**	**15.0**	**3.0**	**382.1**	**1.205**	**2883.5**	**0.928**	**1297**	**4.98E-04**
Std Dev		**0.0**	**0.0**	**0.0**	**0.7**	**231.2**	**0.072**	**87.3**	**0.201**	**127**	**3.95E-06**
COV (%)		**0.0**	**0.0**	**0.0**	**21.7**	**60.5**	**6.0**	**3.0**	**21.7**	**9.8**	**0.8**

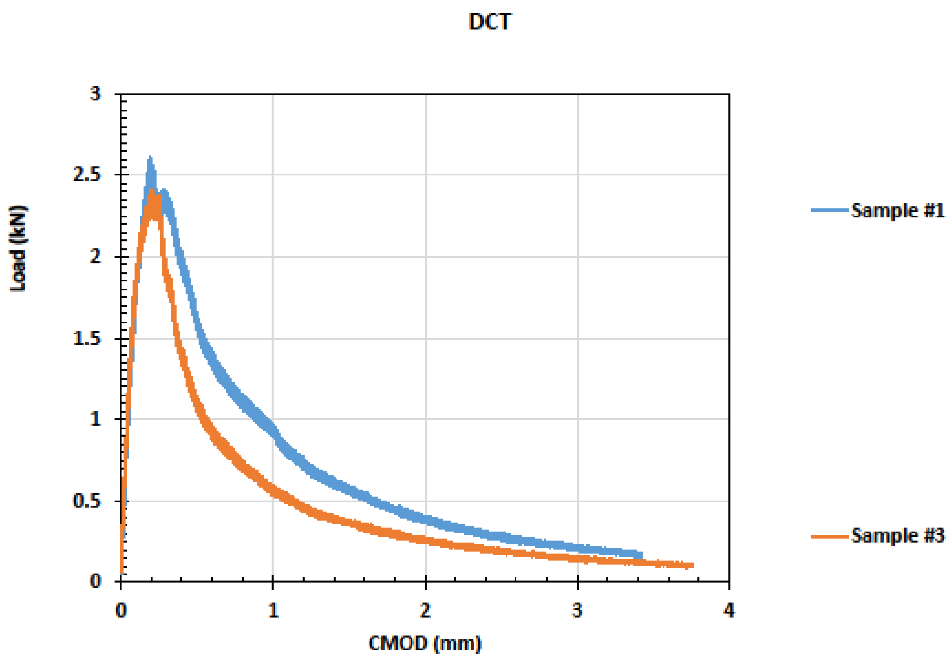
Cold SCB



ASTM D7313-13: Standard Test Method for Determining Fracture Energy of Asphalt-Aggregate Mixture Using the Disk-Shaped Compact Tension Geometry

Project Name:		**Institution:**	
Mix Type:		**Date Tested:**	
Test Temperature:		**Technician:**	

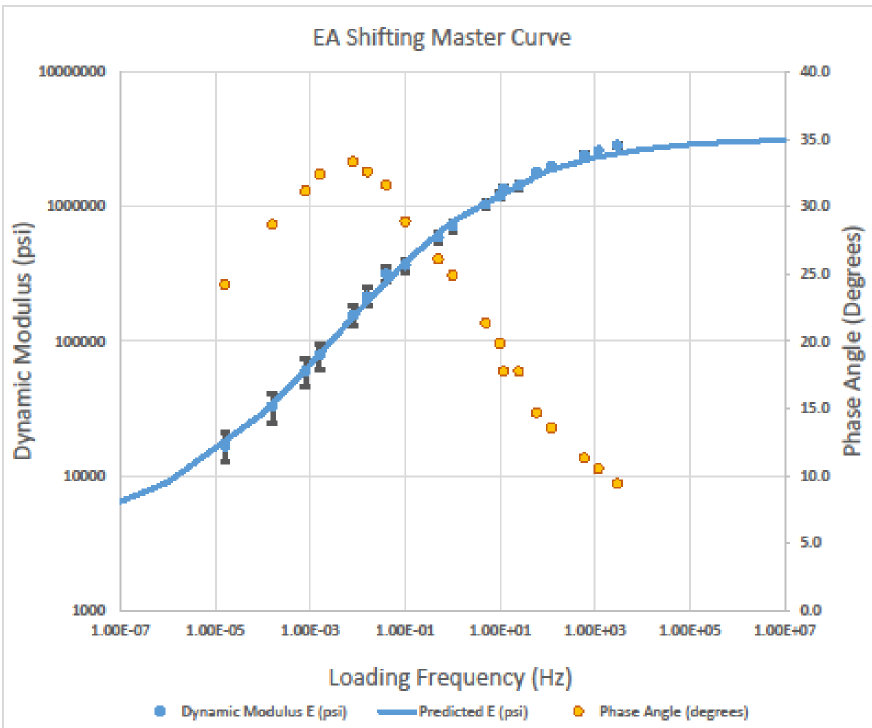
Specimen ID	Air Voids (%)	Diameter (mm)	Thickness (mm)	Ligament (mm)	Peak Load (kN)	Displacement at Peak (mm)	Time at Peak Load (sec)	Fracture Energy (J/m²)	CMOD Slope (mm/s)
Sample #1		150.00	50.00	83.00	2.606	0.194	11.40	601.1	0.0170
Sample #3		150.00	50.00	83.00	2.410	0.197	11.60	452.8	0.0170
Average		**150.00**	**50.00**	**83.00**	**2.508**	**0.196**	**11.50**	**526.9**	**0.017**
Std Dev		**0.00**	**0.00**	**0.00**	**0.139**	**0.002**	**0.14**	**104.9**	**0.000**
COV (%)		**0.0**	**0.0**	**0.0**	**5.5**	**1.2**	**1.2**	**19.9**	**0.0**



This report was developed using the Rutgers Asphalt Analysis Tool-Pack (RAAT-Pack)

AASHTO T342: Standard Method of Test for Determining Dynamic Modulus of Hot Mix Asphalt (HMA)

Project Name:	**Institution:**
Mix Type:	**Date Tested:**
	Technician:

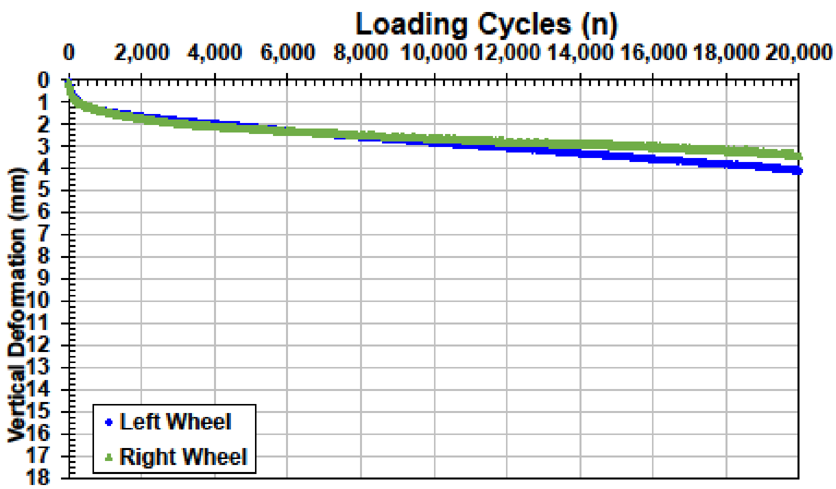


This report was developed using the Rutgers Asphalt Analysis Tool-Pack (RAAT-Pack)

AASHTO T324-17: Standard Method of Test for Hamburg Wheel-Track Testing of Compacted Asphalt Mixtures

Project Name:		Institution:	
Mix Type:		Date:	
Test Temp:		Technician:	

Wheel	Average Rutting at 20,000 cycles (mm):	Average Creep Slope (mm/cycle):	Average Stripping Slope (mm/cycle):	Stripping Inflection Point (cycles):
Left	4.03	1.08E-04	1.46E-04	
Right	3.38	4.92E-05	1.02E-04	16197
Average	**3.7**	**7.84E-05**	**1.24E-04**	**16197**
Std Dev	**0.5**	**4.13E-05**	**3.10E-05**	
COV (%)	**12.5**	**52.7**	**25.1**	

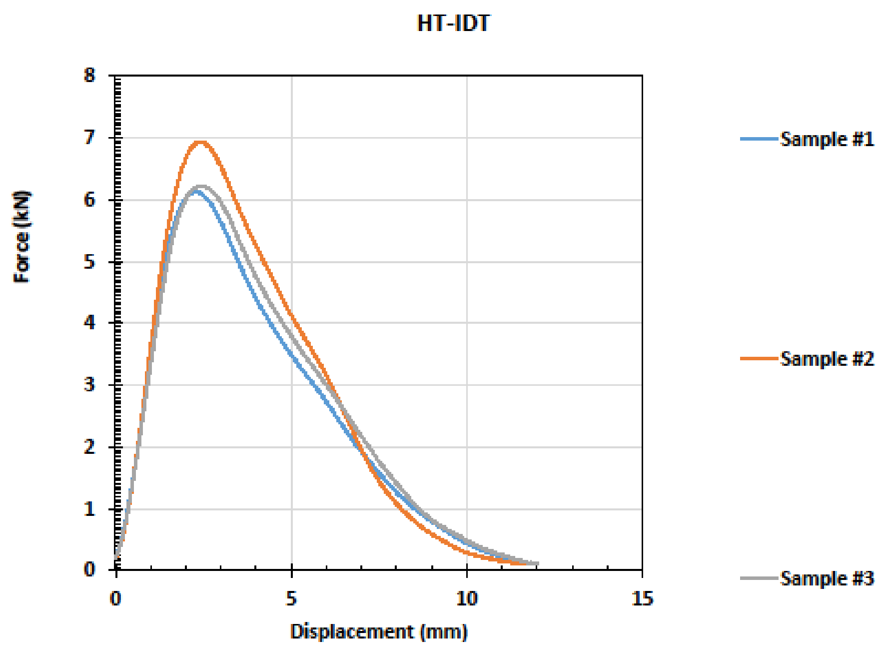


This report was developed using the Rutgers Asphalt Analysis Tool-Pack (RAAT-Pack)

ASTM D6931 (Modified, High Temperature): HT-IDT

Project Name:		**Institution:**	
Mix Type:		**Date Tested:**	
Test Temperature:	44C	**Technician:**	

Specimen ID	Air Voids (%)	Thickness (mm)	Diameter (mm)	Peak Load (N)	IDT Strength (kPa)
Sample #1		95.0	150.0	6130.0	273.9
Sample #2		95.0	150.0	6940.0	310.0
Sample #3		95.0	150.0	6220.0	277.9
Average		**95.0**	**150.0**	**6430.0**	**287.3**
Std Dev		**0.0**	**0.0**	**444.0**	**19.8**
COV (%)		**0.0**	**0.0**	**6.9**	**6.9**

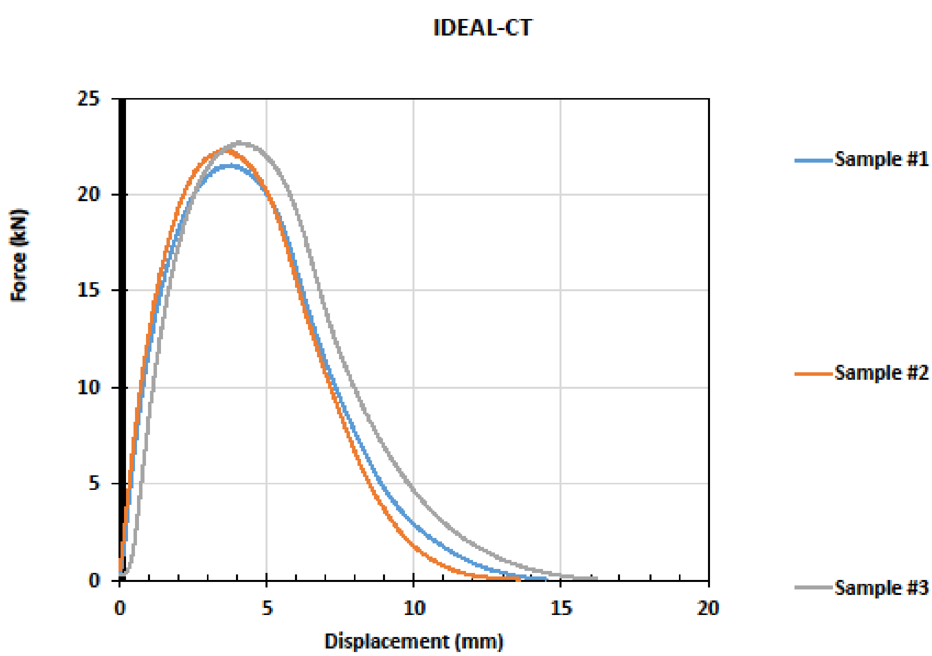


This report was developed using the Rutgers Asphalt Analysis Tool-Pack (RAAT-Pack)

IDEAL-CT: Proposed Cracking Test

Project Name:		**Institution:**	
Mix Type:		**Date Tested:**	
Test Temperature:	25C	**Technician:**	

Specimen ID	Air Voids (%)	Thickness (mm)	Diameter (mm)	Peak Load (kN)	(L) (mm)	Tensile Strength (kPa)	Fracture Energy (Gf) (LLD)	Slope (S)	Gf/S	Gf/S * (L/D)^2	CT Index
Sample #1		62.0	150.0	21.5	6.0	1474.8	15028.0	5.16	2915.2	4.7	116.5
Sample #2		62.0	150.0	22.3	5.8	1526.9	14747.5	5.21	2832.6	4.2	109.0
Sample #3		62.0	150.0	22.7	6.4	1554.0	16460.6	5.26	3128.7	5.7	134.0
Average		**62.0**	**150.0**	**22.2**	**6.1**	**1518.6**	**15412.0**	**5.21**	**2958.8**	**4.9**	**119.8**
Std Dev		**0.0**	**0.0**	**0.6**	**0.3**	**40.3**	**918.9**	**0.05**	**152.8**	**0.8**	**12.8**
COV (%)		**0.0**	**0.0**	**2.7**	**5.5**	**2.7**	**6.0**	**1.0**	**5.2**	**16.3**	**10.7**



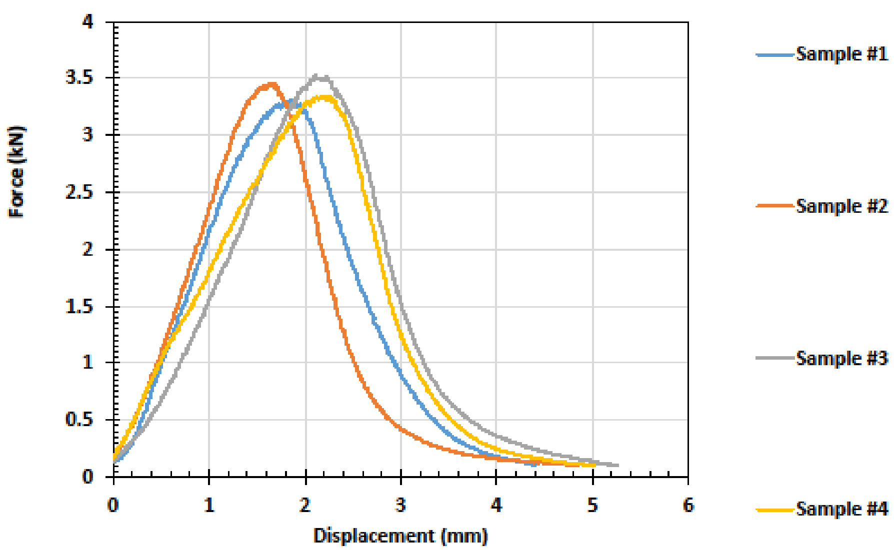
This report was developed using the Rutgers Asphalt Analysis Tool-Pack (RAAT-Pack)

AASHTO TP 124: Standard Method of Test for Determining the Fracture Potential of Asphalt Mixtures Using Semicircular Bend Geometry (SCB) at Intermediate Temperatures

Project Name:	**Institution:**
Mix Type:	**Date Tested:**
Test Temperature: 25C	**Technician:**

Specimen ID	Air Voids (%)	Thickness (mm)	Ligament Length (mm)	Max Load (kN)	Fracture Energy, G_f (J/m^2)	Slope (kN/mm)	Flexibility Index (FI)
Sample #1		50.00	59.00	3.31	2164.3	-3.02	7.17
Sample #2		50.00	59.00	3.46	1975.4	-3.76	5.25
Sample #3		50.00	59.00	3.52	2431.6	-3.41	7.13
Sample #4		50.00	59.00	3.34	2372.3	-3.68	6.45
Average		**50.00**	**59.00**	**3.41**	**2235.9**	**-3.47**	**6.5**
Std Dev		**0.0**	**0.0**	**0.1**	**208.1**	**0.3**	**0.9**
COV (%)		**0.0**	**0.0**	**3.0**	**9.3**	**-9.7**	**13.8**

Intermediate Temperature SCB



This report was developed using the Rutgers Asphalt Analysis Tool-Pack (RAAT-Pack)