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Resilient and Dynamic Modulus Testing For M-E Pavement Design

Study SD2014-21

Final Report

Prepared by

South Dakota School of Mines and Technology

Rapid City, SD 57701 **July 2020**

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15. Supplementary Notes

This project was originally funded with Principle Investigator (PI) Dr. Soonkie Nam, with Dr. Bret Lingwall as co-PI serving in a support role. The project began in late 2015, and the project was turned over to Dr. Lingwall as PI when Dr. Nam left SDSMT in August of 2017.

Due to insurmountable equipment malfunctions, none of the dynamic modulus or flow number tests performed by the research team are reliable for use by SDDOT. The results are skewed by large temperature swings in the equipment. Despite many attempts to repair, the device continuous to pump heat into test specimens. As a result, we have agreed that the project be terminated.

This report serves, by the mutual agreement reached on December 20th, 2019 at our in-person meeting in the Geotechnical Engineering Laboratory at The South Dakota School of Mines and Technology (SDSMT) (and confirmed in our follow-up communications) to summarize the work performed and close-out the research project SDDOT 2014-21.

16. Abstract

Since the development of the American Association of State Highway and Transportation Officials (AASHTO)'s empirical pavement design guide in 1972, this methodology has become the standard in pavement design, updated with only a few revisions. These design guides were simple with relatively few design inputs and have been used for decades by state and local agencies alike. However, over time it has become clear that the several factors that affect pavement performance such as climate, mix design, traffic volume, vehicle loads, and vehicle specifications are not well constrained in these methods, as the performance of the designed pavement systems no longer meet users' expectations. The need to develop a new design guide better suited to the requirements of today's transportation network resulted in a new concept of pavement design developed under the National Cooperative Highway Research Program (NCHRP) Project 1-37A (2004), known as the Mechanical Empirical Pavement Design Guide (MEPDG). This new framework includes both mechanistic and empirical analyses and incorporates significant improvements, providing more accurate evaluation of pavement performance and supporting more economical combinations of pavement materials. However, due to the complex calculations in the MEPDG methodology, which takes into account both mechanistic and empirical components, new test methods and equipment are required, as well as new software for the associated analyses. This software is an essential element of all pavement performance evaluations performed using MEPDG methodology. It consists of a set of hierarchical input systems with three levels based on the accuracy of the input parameters; these input parameters are essential and key factors that affect the reliability of the analysis. Among these, dynamic modulus and flow number are critical in terms of the material properties of the asphalt mixtures used to predict permanent deformation. Therefore, in order to design and predict pavement systems according to this new design methodology, obtaining reliable data for these input parameters is the most critical part of the entire process. In this study, the research team obtained representative asphalt mixtures from the South Dakota Department of Transportation (SDDOT), prepared compacted specimens using a Superpave gyratory compactor and conducted a series of dynamic modulus tests and repeated load triaxial tests using a Simple Performance Tester (SPT). The results of these tests were analyzed to determine the essential properties, specifically the dynamic modulus and flow number, of asphalt mixtures with SD design specifications. In addition, statistical analyses were performed with the ultimate goal of developing a South Dakota Asphalt Material Database (SDAMD) for future MEPDG applications. Unfortunately, mechanical and instrument errors with the SPT were revealed near the end of testing that brought the results of all tested specimens into question. Therefore, no productive or usable data was developed by this project despite vast amounts of time and effort expended.

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Acronym	Definition
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway Transportation Officials
FS-CH	Frequency Sweep at Constant Height
FHWA	Federal Highway Administration
HMA	Hot Mix Asphalt
M-E	Mechanistic-Empirical
MEPDG	Mechanistic-Empirical Pavement Design Guide
NCHRP	National Cooperative Highway Research Program
RAP	Recycled Asphalt Pavement
RAS	Recycled Asphalt Shingles
SD	South Dakota
SDAMD	South Dakota Asphalt Materials Database
SDDOT	South Dakota Department of Transportation
SDSMT	South Dakota School of Mines and Technology
SMA	Stone Matrix Asphalt
SPT	Simple Performance Test
TRB	Transportation Research Board
US	United States
WMA	Warm Mix Asphalt

1.0 EXECUTIVE SUMMARY

The objective of this project was to obtain the dynamic modulus and flow number of Hot Mix Asphalt (HMA) construction materials through tests performed with the Simple Performance Tester (SPT) on HMA paving material types from around the state to validate the resultant data relative to the criteria defined for Mechanistic-Empirical (M-E) pavement design processes and incorporate the data into an M-E Pavement Design database.

Since 2008, the SDSMT research team has been collaborating with SDDOT to conduct research on the dynamic modulus, resilient modulus, and flow number of different types of hot mixed and warm mixed asphalts (WMA) in order to better characterize the local materials for pavement structures. These may include Recycled Asphalt Pavements (RAP) and Recycled Asphalt Shingles (RAS). For various binders and aggregates as well as mixture types, it is recommended that SDDOT continues to add to the database of properties of materials that can be used for MEPDG and Pavement M-E Design® Software.

The research team revisited the previous data collected by the SDSMT research team since 2008 and attempted to provide an integrated database to enable SDDOT to readily and efficiently utilize the design parameters required by the Pavement ME Design® software.

Unfortunately, mechanical and instrument errors with the SPT were revealed near the end of testing that brought the results of all tested specimens into question. The temperature controls of the device were shown to be erratic, unable to maintain the prescribed temperatures during dynamic modulus ad flow number tests. Test specimens overheated to an extent that specimens began to unravel. The device was put through a series of repairs and recalibrations, but the heat generation problem could not be resolved. At the point that an additional year of effort was spent on device repairs, recalibration, and trial tests, by mutual agreement SDDOT and SDSMT terminated the project. Therefore, no productive or usable data was developed by this project despite vast amounts of time and effort expended.

1.1 Introduction

Since the development of the American Association of State Highway and Transportation Officials (AASHTO)'s empirical design guide in 1972, their design methodology has become the standard in pavement design, updated with only a few revisions (AASHTO, 1986, AASHTO, 1993). The old design guides were simple with relatively few design inputs, and have been used for decades, continually accumulating experience. However, as the factors that affect pavement systems such as climate, traffic volume, vehicle loads, and vehicle specifications become ever more challenging, the performance of the designed pavement systems no longer meet users' expectations, highlighting the need to develop a new design guide that is better suited to the requirements of today's transportation network. In 2004, a new concept of pavement design methodology was developed under the National Cooperative Highway Research Program (NCHRP) Project 1-37A (2004), known as the Mechanical Empirical Pavement Design Guide (MEPDG). This new design concept includes both mechanistic and empirical analyses and is known to incorporate significant improvements in pavement design, providing more accurate evaluation of pavement performance and supporting more economical combinations of pavement materials (Tarefder et al., 2012).

However, due to the complex calculations and structures in the MEPDG methodology, which takes into account both mechanistic and empirical components, new test methods and equipment are required, as well as new software for the associated analyses. This software, which is currently only available as a commercial version, Pavement M-E Design®, is an essential element of all pavement performance evaluations performed using MEPDG methodology. It consists of a set of hierarchical input systems with three levels based on the accuracy of the input parameters; these input parameters are essential and key factors that affect the reliability of the analysis. Among these, dynamic modulus ($E*$) and flow number (Fn) are critical in terms of the material properties of the asphalt mixtures used to predict permanent deformation. Therefore, in order to design and predict pavement systems according to this new design methodology, obtaining sufficiently accurate data for these input parameters is the most critical part of the entire process.

In this study, the research team obtained representative asphalt mixtures from SDDOT, prepared compacted specimens using a Superpave gyratory compactor and conducted a series of dynamic modulus tests and repeated load triaxial tests using a Simple Performance Tester (SPT). The results of these tests will be analyzed to determine the essential properties, specifically the dynamic modulus and flow number, of asphalt mixtures with SD design specifications. In addition, statistical analyses will be performed with the goal of developing a South Dakota Asphalt Material Database (SDAMD) for future MEPDG applications.

1.2 Objectives

The objectives of this research were:

1) Obtain the dynamic modulus and flow number of Hot Mix Asphalt (HMA) construction materials through tests performed with the Simple Performance Tester (SPT) on HMA paving

material types from around the state to validate the resultant data relative to the criteria defined for Mechanistic-Empirical (M-E) pavement design processes, and.

2) Incorporate the data into an M-E Pavement Design database.

1.3 Research Approach

Testing was performed in the Interlaken™ Simple Performance Test (SPT) device in the Geotechnical Engineering Laboratory on campus at SDSMT. Hot mix and stone matrix asphalt concrete pavement samples (HMA and SMA) with varying amounts of recycled asphalt pavement (RAP) were provided by SDDOT in the summer of 2016, 2017, and 2018. Not all samples had sufficient volumes of material for complete test suites, but sufficient material arrived for a testing program to be performed. Several samples were too small to include in the research program. If the mass of the specimen was less than 150 kg, a full test suite of 18 specimens was not able to be prepared. If the test suite was less than 90 kg, no specimens were prepared. Samples consisted of 6 to 30 bags of material. Each bag had a separate unique Quality Control number attached to it. The bags were mixed together to batch the heated HMA and SMA samples from which specimens were prepared.

Workflow on the research for each sample was established as follows: 1. Samples were received from SDDOT, weighed, and stored until needing to be heated for specimen preparation. 2. After heating to soften samples to make specimens, small portions of samples were taken at random for quality control measurements. 3. Specimens were prepared in a gyratory compactor. All the gyratory specimens were prepared targeting 7% ±0.5% air voids with a height of 7 in and a diameter of 5.9 inches using randomly combined and portioned subsets of samples. Multiple identical specimens were made from each sample. Procedures follow AASHTO Standard T312 and SDDOT Standard 318. Gyratory Specimens were weighed and measured as a quality check on compacted density from the gyratory compactor.

Gyratory Specimens were then cored down to the size required for the SPT of 100-mm diameter using a diamond coring device and trimmed to length of 150-mm with a diamond bladed saw for precision flush cuts. Attachment points for dynamic testing and flow number test strain gauges were attached with a temperature appropriate epoxy. Specimens were tested for either Dynamic Modulus or Flow Number in the SPT device at the appropriate temperature and load frequency. Tests followed the AASHTO Standard T79. No SDDOT Standard exists for these tests at this time. Testing followed a program of low, medium, and high temperatures.

The Dynamic Modulus testing program consisted of the following: dynamic modulus tests and repeated load triaxial load tests according to AASHTO TP-79-13 (2013) and AASHTO T 342-11(2011). Each dynamic modulus test was be conducted for 6 different frequencies (0.1, 0.5, 1, 5, 10, and 25 Hz) at each temperature of 4, 21, 37, and 54 ℃ , and the repeated load triaxial tests were to be conducted for a confining pressure of 170 kPa at each temperature of 34, 41, and 52 ℃. Each test would be performed for 3 replicants for further statistical analyses.

1.4 Conclusions

The Dynamic Modulus testing program began with the 4°C specimens for each HMA or SMA sample delivered to SDSMT from SDDOT. Testing then progressed through the 21° and so on. Flow Number testing also began with the coldest (34°C) and progressed to hotter. Few issues with testing were observed for the cold temperature Dynamic Modulus Tests (4 and 21°C sets). However, in the early stages of Dynamic Modulus Testing it became apparent that the SPT device was generating large amounts of heat, that often over-heated the device. Indeed, the over-heating caused two electric drive control cards to fail. These were replaced, and the SPT device was recalibrated. As testing progressed it was noted that the chiller unit was acting as a heat sink for the system, and that the cold temperature tests were not held at constant temperature in testing. In some instances, the temperatures in the specimens rose less than 5°C, but in other cases, temperature increases during testing exceeded 5°C. This temperature issue could not be remedied with maintenance on the chiller unit according to manufacturer recommendations. Testing the chiller unit showed that the unit could maintain the desired temperature for long periods when the SPT was not in test operation, but as soon as test operations began, the overheating SPT began to pump heat into the chiller unit.

As testing moved to the 37°C Dynamic Modulus tests, the SPT held at the desired temperature at the beginning of the test, and the students left the device to run over lunch. When they returned and removed the first test specimen at that temperature, the specimen was hot to the touch, enough to be painful to the touch. The data for the test showed constant temperatures, but the specimen was overheated. This was then verified in the next test with an infrared thermometer aimed at the specimen that showed increases of over 10°C in the cell during the test. Clearly outside of acceptable performance. When the first of the 41°C Flow Number tests were performed, the heat in the SPT unit increase sufficient that the sample unraveled. At this point, a critical review of all data and specimens was performed. This critical review showed that at cool and cold temperature tests, the heat of the system increased in the system per the temperature logs in most cases, but other cases showed constant temperatures of the specimens. The mid-temperature tests showed the same dichotomy, with the known test that showed constant temperature in the data but was independently measured to get quite hot. Thus, it is impossible to know which of the specimens in the testing program had acceptable temperature variations during testing, and which specimens had unacceptable temperature variations.

1.5 Recommendations

Due to the limited reliable test data from the SPT, there are only a few recommendations that can be made from this research. Some of these recommendations apply to future testing by other laboratories from the experience of the research team. Other recommendations apply to implementation of MEPDG by SDDOT as observed by the testing of this research program. The research team recommends that:

1.5.1 SDDOT evaluate if there is benefit in pursuing development of MEPDG HMA Tier I inputs, or will Tier II inputs suffice;

SDDOT should evaluate if there is benefit in pursuing the development of MEPDG HMA Tier I inputs that this project was a part of or will Tier II inputs suffice for continued implementation of MEPDG.

1.5.2 SDDOT use the remaining specimens from this research to perform Constant Height Frequency Sweep (CH-FS) tests;

One of the primary outputs of this work was a large set of prepared specimens for CH-FS testing to be performed by SDDOT in their Pierre Bituminous Materials Laboratory. Approximately ½ of these specimens were previously collected by SDDOT for testing, and the other ½ await collection. The test resultant data from the CH-FS tests will benefit SDDOT's pavement design and maintenance efforts.

1.5.3 SDDOT use the remaining specimens from this research for dynamic modulus and flow number testing at a certified laboratory outside South Dakota; and

In addition to the CH-FS specimens that await SDDOT collection, the untested specimens that were awaiting testing prior to the termination of the testing program are available for SDDOT to collect and send to a certified academic or commercial laboratory outside of South Dakota for dynamic modulus and flow number testing.

1.5.4 SDDOT obtain evidence from future MEPDG laboratories that all equipment is thermally stable through the duration of all testing prior to initiation of any testing of bituminous materials.

In this work, thermal regulation of equipment was only independently checked at the initiation of each test of an individual specimen. The internal temperature control outputs were relied on for temperature regulation during testing. In forensics of this project is was identified that the internal temperature controls were not adequate in monitoring, maintaining, or reporting specimen temperatures, whereas independent external monitors were. The failures of this research could have been avoided if SDDOT required evidence of thermal stability throughout the entirety of test duration by external measures prior to the initiation of the testing program.

2.0 PROBLEM DESCRIPTION

Data gathered during the American Association of State Highway Officials (AASHO) Road Test Project, conducted between 1958-1961, was used to create the AASHTO Guide for Design of Pavement Structures, which was initially published in 1972 with major revisions in 1986 and 1993. The resulting design method presented in the guide has served as the standard in pavement design ever since. However, the method is entirely based on an empirical methodology that does not take into account the mechanistic behaviors of pavement structures. Some of the known limitations of these design guides include deficiencies in traffic loading, rehabilitation, climatic effects, subgrade, surfacing materials, base course, truck characterization, design life, performance, and reliability (National Cooperative Highway Research Program, 2004).

To address the shortcomings of the previous design guides, the AASHTO Joint Task Force on Pavements has sponsored a research program to develop a new pavement design guide based on mechanistic-empirical principles since 1996. In 2004, the MEPDG was developed under the NCHRP Project 1-37A (National Cooperative Highway Research Program, 2004), and officially launched shortly thereafter. In this new design guide, both the principles of engineering mechanics and the empirical approaches that have traditionally been used to characterize site specific traffic, climate, and material behavior are used to evaluate pavement systems (Roberts and Nocks, 2010). As a result, a significant number of materials properties have been incorporated into the design procedure in the M-E approach.

In the MEPDG, three major design stages are provided, as shown in Figure 2.1. Most of the design parameters for asphalt pavements are required as inputs for Stage 1, with Stages 2 and 3 primarily consisting of computations and analyses in the software. The input data for Stage 1 are thus critical elements upon which all the subsequent structural/performance analyses and final decisions on the pavement design depend.

For the pertinent selection of input parameters for the MEPDG, a hierarchical approach is employed in order to provide the designers with flexibility in obtaining the design inputs based on the criticality and available resources for each project (National Cooperative Highway Research Program, 2004). Level 1 has the highest level of accuracy and the lowest level of uncertainty of error as the input parameters are provided by laboratory or field testing. Level 2 and 3 inputs provide intermediate and lowest levels of accuracy, respectively. Level 2 inputs are generally selected from an agency database, derived from a limited testing program, or estimated through correlations, whereas Level 3 inputs are typically average values for the region or default values for a given parameter. Usually, Level 1 inputs require more resources and time, and thus cost more compared to the other levels. However, they are particularly beneficial for heavy-traffic road designs or where early failure would lead to serious consequent economic or safety problems. A summary of the various hierarchical input levels used in estimating the dynamic modulus of flexible pavement materials is given as an example in Table 2.1.

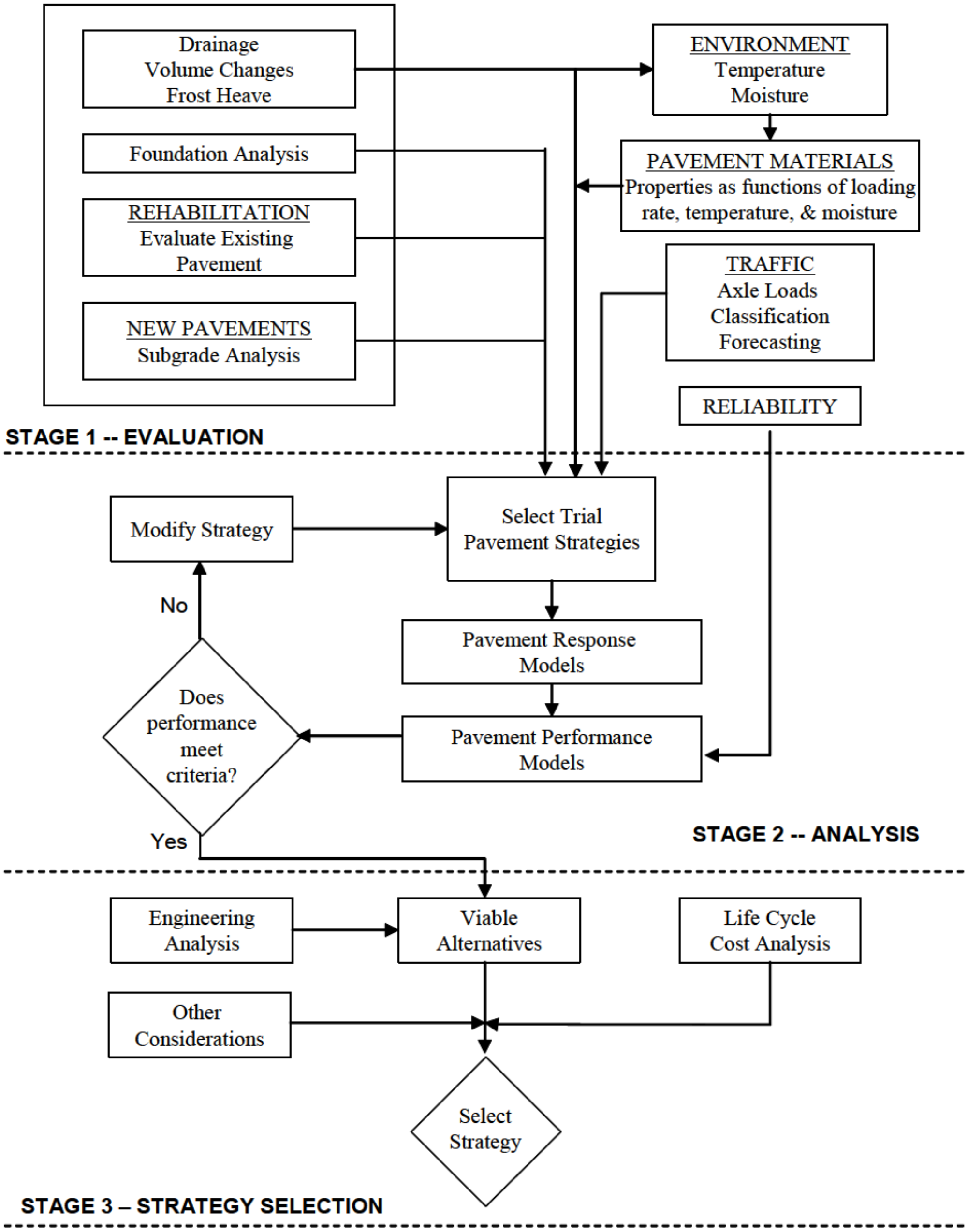

Figure 2.1 Schematic flow of the three-stage MEPDG design process (from National Cooperative Highway Research Program, 2004).

Table 2.1 Asphalt dynamic modulus (E*) estimation at various hierarchical input levels for new or reconstruction design (from NCHRP 1-37A Report (2004))

Material Group Category	Input Level	Description
Asphalt Materials	1	• Conduct E* (dynamic modulus) laboratory test (NCHRP 1-28A) at loading frequencies and temperatures of interest for the given mixture. • Conduct binder complex shear modulus (G*) and phase angle (δ) testing on the proposed asphalt binder (AASHTO T 315) at ω=1.59 Hz (10 rad/s) over a range of temperatures • From binder test data, estimate Ali-VTSi for mix-compaction temperature. • Develop a master curve for asphalt mixture that accurately defines the time-temperature dependency, including aging.
	2	• No E* laboratory test required. • Use E* predictive equation. • Conduct G*- δ on the proposed asphalt binder (AASHTO T 315) at ω=1.59 Hz (10 rad/s) over a range of temperatures. The binder viscosity of stiffness can also be estimated using conventional asphalt test data such as Ring and Ball Softening Point, absolute and kinematic viscosities, or using the Brookfield viscometer. • Develop Ai-VTSi for mix-compaction temperature. • Develop a master curve for asphalt mixture that accurately defines the time-temperature dependency including aging.
	3	• No E* laboratory test required. • Use E* predictive equation. • Use typical Ai-VTS-values provided in the *Design Guide* software based on PG, viscosity, or penetration grade of the binder. • Develop a master curve for asphalt mixture that accurately defines the time-temperature dependency, including aging.

The most important material input parameter for the structural design of flexible pavements in MEPDG is the dynamic modulus ($E*$) (Li et al., 2011). Once the dynamic modulus characteristics are obtained by experiments, they can be used 1) to develop an E* database and determine the data variability for $E*$ input Level 1, 2) to evaluate a predictive equation for $E*$ input Levels 2 and 3, and 3) to identify the appropriate $E*$ input level for initial implementation (Li et al., 2011). As temperature and loading rate are the two factors that most influence the dynamic modulus of asphalt concrete mixtures (Bonaquist, 2008); they are controlled to obtain the modulus. The AASHTO T 342 Standard test method for determining the dynamic modulus of hot mix asphalt (HMA) (2011) requires a servo hydraulic test system with an environmental chamber that can apply a sinusoidal (haversine) load for 7 different frequencies (0.1, 0.5, 1, 5, 10, and 25Hz) at temperatures of -10, 4, 21, 37, and 54 °C. Witzcak et al. (2002) noted the difficulty involved in maintaining the lowest temperature (-10 °C) in certain systems, so the temperature range requirement was revised to be from 4 to 60 °C for tests using the Asphalt Mixture Performance Tester (i.e. the SPT) (AASHTO, 2011). The standard method used to determine the dynamic modulus for pavement systems for this study follows AASHTO TP 79-11 (2011). These test environment and loading conditions can be created and applied automatically in the Simple Performance Tester manufactured by Interlaken that is available in the lab at SDSM&T. An example of an experimentally determined $E*$ at Level 1 is shown in Figure 2.2

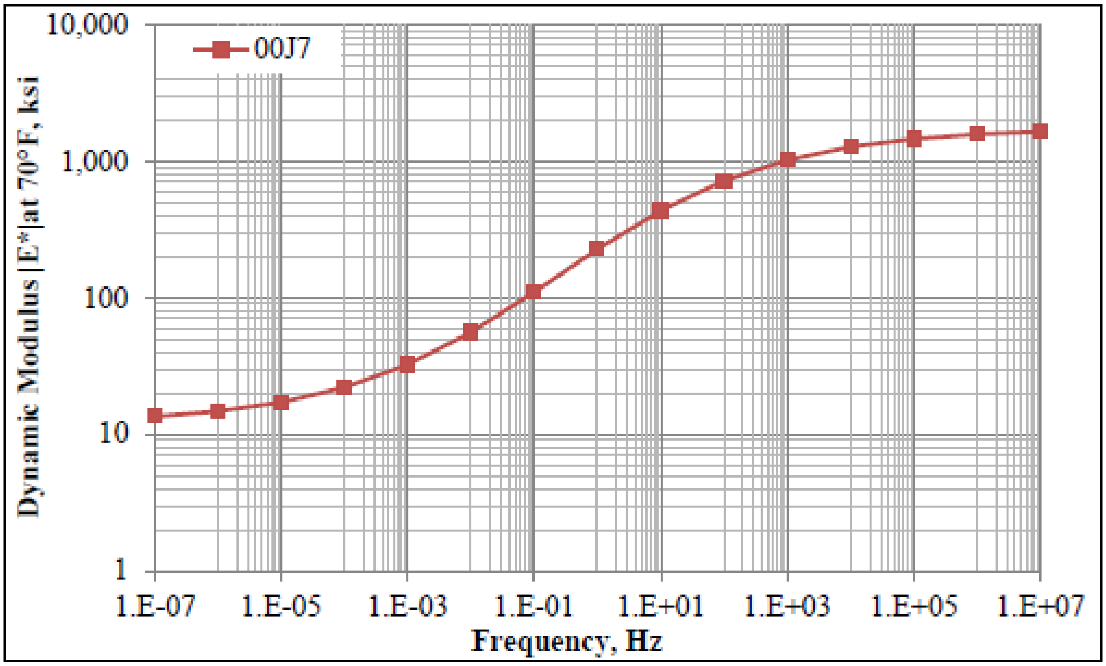

Figure 2.2 Experimentally derived dynamic modulus. (From Roberts and Nocks, 2010)

The other important input parameter is the flow number, (Fn), which is determined by a triaxial repeated load test. This is also a critical input parameter for determining the permanent deformation (rutting) characteristics of asphalt mixtures (Mohammad et al., 2014). The flow number is the number of loading cycles at which the plastic strain starts to accelerate rapidly, as shown in Figure 2.3 (Von Quintus et al., 2012). The concept of flow number has been proposed as a convenient way to characterize a mixture's resistance to plastic deformation. The test is also performed using a Simple

Performance Tester (SPT) by applying a repeated haversine load for several thousand cycles and monitoring the cumulative permanent deformation of the specimen as a function of the number of cycles.

The South Dakota Department of Transportation (SDDOT) recognizes the importance of using Level 1 inputs for certain projects and has been performing appropriate tests and collecting pertinent material properties for use in both current and future mechanistic-empirical models and design processes.

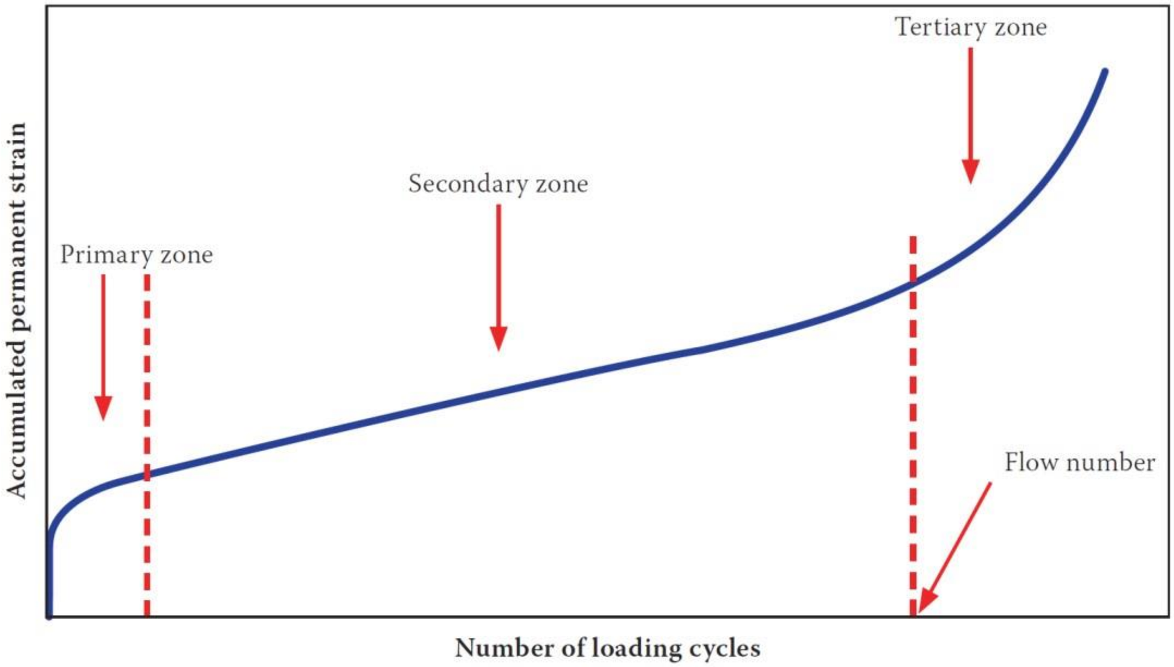

Figure 2.3 Illustration of flow number (From Walubita et al., 2013)

The primary purpose of this study is to continue to determine the dynamic modulus and flow number of the various asphalt mixtures used in South Dakota and update the database used for the implementation of Mechanistic-Empirical Pavement Design. In this study, HMA samples with varying percentages of recycled asphalt pavement (RAP) will be compacted using a Superpave gyratory compactor. The samples will then be tested for basic material properties and major MEPDG input parameters, as listed in Table 2-2, by the SDSM&T group; the remaining samples will be sent back to SDDOT for additional tests. The database of input parameters created based on these results will provide essential information for MEPDG local calibrations in the future.

Table 2.2 Soil and HMA material Test Specifications.

AASHTO Test Number	SDDOT Test Number	Test Title
T 27	**SD 202**	**Sieve analysis of fine and coarse aggregates** Standard Method of Test for Sieve Analysis of Fine and Coarse Aggregates (T 27) Method of Test for Sieve Analysis (SD 202)
T 312	**SD 318**	**Specimens using the Superpave gyratory compactor** T 312-Standard Method of Test for Preparing and Determining the Density of Hot-Mix Asphalt (HMA) Specimens by Means of the Superpave Gyratory Compactor SD 318-Method of Test for Density and Air Voids of Asphalt Concrete by the Gyratory Method
T 166	**SD 313**	**Bulk specific gravity of compacted hot mix** T 116-Bulk Specific Gravity of Compacted Hot Mix Asphalt (HMA) Using Saturated Surface-Dry Specimens SD 313-Method of Test for Density and Air Voids of Asphalt Concrete by the Marshall Method
T 209	**SD 312**	**Determining the theoretical maximum specific gravity of uncompacted hot mix.** T 209-Standard Method of Test for Theoretical Maximum Specific Gravity and Density of Hot Mix Asphalt (HMA) SD 312-Method of Test for the Theoretical Maximum Specific Gravity of Asphalt Concrete Paving Mixtures
TP 79	**N/A**	**Dynamic Modulus and Repeated Load Tests** TP 79-Standard Method of Test for Determining the Dynamic Modulus and Flow Number for Hot Mix Asphalt (HMA) Using the Asphalt Mixture Performance Tester (SPT)

3.0 RESEARCH OBJECTIVES

The objectives of the proposed research are to:

3.1 Dynamic Modulus and Flow Number Testing

Obtain the dynamic modulus and flow number of Hot Mix Asphalt (HMA) construction materials through tests performed with the Simple Performance Tester (SPT) on HMA paving material types from around the state to validate the resultant data relative to the criteria defined for Mechanistic-Empirical (M-E) pavement design processes.

The research team received bulk samples from SDDOT over a three-year period and prepared these samples into specimens for dynamic modulus and flow number testing. The research team performed quality control density and specific gravity measurements on each specimen to ensure that the correct compaction had occurred in the Superpave gyratory compactor. Specimens were trimmed to size and the placed in the SPT for testing. In the SPT, specimens are brought to temperature prior to application of cyclic or monotonic loading. During testing, the SPT device was noted to generate significant amounts of heat, that overwhelm the thermal regulatory capacity of the chiller unit on the SPT device. The device overheated to an extent that damage occurred to the unit and repairs and recalibration were initiated. Upon resumption of testing, overheating again occurred, causing a second round of repairs and recalibration. This was followed by a third round of repairs and recalibration. Test specimens also overheated and resulted in unraveling of HMA, WMA, and SMA specimens in the test chamber. A critical review of the data from all tests showed thermal regulation was insufficient for constant-temperature testing required for the conduct and interpretation of test data. A fourth round or repairs and recalibration resulted in the same outcomes. Results of all tests in the program were called into question and the project was terminated in December 2019 by mutual agreement of SDDOT and SDSMT.

3.2 Incorporate the data into an M-E Pavement Design database

Incorporate the data into an M-E Pavement Design database.

With the failure to develop any reliable test data, and the fact that previous test data is now questionable due to the identification of the thermal regulation problems with the device, no data was compiled into a database for use by SDDOT.

4.0 TASK DESCRIPTIONS

As per the SD 2014-21 Research Project Statement provided by the South Dakota Department of Transportation (SDDOT), 6 tasks were originally identified to complete this project.

However, due to the limited availability of the equipment needed to complete all the tasks, after some discussion the research team and SDDOT engineers agreed on the revised task list attached in Appendix B and described below. Specific task items shown here have been revised as per the decisions reached by the SDDOT and SDSMT in August of 2016.

The research team consisted of personnel from the South Dakota School of Mines and Technology (SDSMT), who are solely responsible for managing the project and completing the required tasks.

4.1 Task 1 Prepare six (6) gyratory HMA samples submitted by SDDOT per each construction season for a total of eighteen (18) samples.

As each HMA sample will have 3 testing iterations performed for dynamic modulus, 3 testing iterations performed for stability/flow, and 3 testing iterations performed for frequency sweep at constant height (FS-CH), a total of 18 samples is needed for each bulk sample of asphalt provided by SDDOT. All materials samples were collected and provided by the SDDOT. In each year of the three-year project, SDDOT would provide 6 different HMA materials per construction for a total of 18 materials, and the research team would prepare an adequate number of gyratory specimens following AASHTO T 312 for the property and mechanical tests. The mechanical tests include dynamic modulus tests, repeated load triaxial tests, and FS-CH tests. All the gyratory specimens would be prepared targeting 7% ±0.5% air voids with a height of 7 in and a diameter of 5.9 in.

The gyratory specimens for the FS-CH test would be delivered to SDDOT. The quantity of specimens for the FS-CH test would be determined after discussion with SDDOT, taking into account the amount of materials needed for all the property and mechanical tests as well as the amount of materials that can conveniently be provided by SDDOT.

4.2 Task 2 Perform HMA pavement materials tests with the SPT for dynamic modulus and flow numbers, whereby: Each HMA sample will have 3 testing iterations performed for dynamic modulus, and 3 testing iterations performed for stability/flow

The SDSM&T research team was to conduct dynamic modulus tests and repeated load triaxial load tests according to AASHTO TP-79-13 (2013) and AASHTO T 342-11(2011). Each dynamic modulus test would be conducted for 6 different frequencies (0.1, 0.5, 1, 5, 10, and 25 Hz) at each temperature of 4, 21, 37, and 54 ℃ , and the repeated load triaxial tests would be conducted for a confining pressure of 170 kPa at each temperature of 34, 41, and 52 ℃ . Each test was to go through 3 testing iterations for further statistical analyses.

4.3 Task 3 Perform statistical analyses to evaluate all test results obtained from the HMA pavement materials and prepare the findings for review and approval of SDDOT Project Panel members.

The research team was to perform statistical analyses for the results obtained from the current study. In addition, the team would review the results for the dynamic modulus and flow number of HMA pavement materials from the previous projects conducted by SDSMT with the support of SDDOT since 2008. Eventually, the E* master curves and permanent deformation model coefficients will be compared to characterize the permanent deformation behaviors of the tested asphalt mixtures.

4.4 Task 4 Perform comparison tests on samples submitted by SDDOT as part of the round robin testing.

The research team was to conduct the following tests required by SDDOT as part of the round robin testing. The samples would be provided by SDDOT in December of each year of the contract, and each test was to be conducted based on AASHTO and SDDOT standards. In addition to the tests listed in Table 2-2, the research team would also measure the bulk specific gravity and maximum specific gravity of the HMA samples using the Corelok® vacuum sealing device, following the T 331-Standard Method of Test for Bulk Specific Gravity and Density of Compacted Hot Mix Asphalt (HMA) Using Automatic Vacuum Sealing Method. The results of the experiments would be carefully reviewed and analyzed and will be included in an annual interim report. The report was to be submitted to SDDOT by the end of Task 4 of each round during the contract period.

Note: Round Robin Testing specimens were never delivered to SDSMT by SDDOT and this task was not initiated.

4.5 Task 5 Prepare a final report that presents the testing approaches, findings, conclusions, and recommendations, including all data resulting from the HMA pavement materials Microsoft Excel spreadsheet tables.

A draft final report was to be prepared that includes all the project's research activities, results, findings, conclusions, and recommendations to the SDDOT. In addition, all project deliverables would be provided to SDDOT and the Technical Panel. A review period was to be included so that all recommended suggested enhancements to the Draft Final Report from the panel could be incorporated in the Final Report. The revised final report would be submitted to SDDOT for publication.

4.6 Task 6 Make an executive presentation to the SDDOT Research Review Board at the conclusion of the work efforts.

The research team was to make an executive presentation to the SDDOT Research Review Board after the final report has been approved by the technical panel. The presentation would summarize all the research activities that were accomplished in this project, along with any conclusions or recommendations that resulted.

5.0 FINDINGS AND CONCLUSIONS

5.1 Testing Procedures and Protocols

Testing for dynamic modulus and flow number was performed in the Interlaken™ Simple Performance Test (SPT) device in the Geotechnical Engineering Laboratory at SDSMT. This is a first generation SPT procured in the early days of M-E testing. As a first-generation model, it was quickly supplanted by more robust devices in the manufacturer's product lineup as users identified "bugs" and deficiencies in the model. This first-generation model was repaired at least three times for electronics problems prior to PI Lingwall coming to campus. Figure 5.1 shows the SPT device. In the figure, the laptop controller is shown, along with an HMA test specimen, and compressed air supply (yellow hose). The test chamber in Figure 5.1 is open, ready for the specimen to be placed in the chamber on the small platen. Interlaken stopped providing customer support for this model in 2014.

Figure 5.1 SPT test device. Chiller unit is the grey unit on the bottom right of the image. The chiller unit operates correctly but is incapable of serving as an effective heat removal pump for the test device as the test device overheats.

Hot mix, warm mix, and stone matrix asphalt concrete pavement samples (HMA, WMA and SMA) with varying amounts of recycled asphalt pavement (RAP) and recycled asphalt shingles (RAS) were provided by SDDOT in the summer of 2016, 2017, and 2018. Not all samples had sufficient volumes of material for complete test suites, but sufficient material arrived for a testing program to be performed. Several samples were too small to include in the research program and are not listed in Table 5.1. If the mass of the specimen was less than 150 kg, a full test suite of 18 specimens was not able to be prepared. If the test suite was less than 90 kg, no specimens were prepared, and the sample is omitted from Table 5.1. The list of samples and quantities received for each year are shown in Table 5.1 by PCN number. PCN is a unique identifier for each bulk sample provided by SDDOT to SDSMT. This number is labeled on all bags of each sample. Samples consisted of 6 to 30 bags of material. Each bag had a separate unique Quality Control number attached to it. The bags were mixed together to batch the heated HMA and SMA samples from which specimens were prepared.

Table 5.1 Asphalt bulk samples received by project phase

Phase	PCN Number	Received Mass (kg)
1	037L	162
	037W	234
	026B	162
	02QU	275
2	04WM	168
	023T	620
	023Z	313
	04W9	91
	04DA	311
	026Q	136
3	00LD	143
	03T8	111
	05Q5	272
	05EG	347

Workflow on the research for each sample was established as follows:

1. Samples were received from SDDOT, weighed, and stored until needing to be heated for specimen preparation.
2. After heating to soften samples to make specimens, small portions of samples were taken at random for quality control measurements as shown in Table 5.2.

Table 5.2 Index Tests for Asphalt Concrete Bulk Samples

T 166	**SD 313**	**Bulk specific gravity of compacted hot mix** T 116-Bulk Specific Gravity of Compacted Hot Mix Asphalt (HMA) Using Saturated Surface-Dry Specimens SD 313-Method of Test for Density and Air Voids of Asphalt Concrete by the Marshall Method
T 209	**SD 312**	**Determining the theoretical maximum specific gravity of uncompacted hot mix.** T 209-Standard Method of Test for Theoretical Maximum Specific Gravity and Density of Hot Mix Asphalt (HMA) SD 312-Method of Test for the Theoretical Maximum Specific Gravity of Asphalt Concrete Paving Mixtures

In addition to the tests listed in Table 5.2, the research team also measured the bulk specific gravity and maximum specific gravity of the HMA samples using the Corelok® vacuum sealing device, following AASHTO Standard T331 - *Standard Method of Test for Bulk Specific Gravity and Density of Compacted Hot Mix Asphalt (HMA) Using Automatic Vacuum Sealing Method*.

3. Specimens were prepared in a Superpave gyratory compactor. All the gyratory specimens were prepared targeting 7% ±0.5% air voids with a height of 7 in and a diameter of 5.9 inches using randomly combined and portioned subsets of samples. Multiple identical specimens were made from each sample. Procedures follow AASHTO Standard T312 and SDDOT Standard 318. Figure 5.2 shows the gyratory specimen and the final prepared specimen.

4. Gyratory Specimens were weighed and measured as a quality check on compacted density from the gyratory compactor.

5. Gyratory Specimens were then cored down to the size required for the SPT of 100-mm diameter using a diamond coring device and trimmed to length of 150-mm with a diamond bladed saw for precision flush cuts. See Figure 5.2.

6. Attachment points for dynamic testing and flow number test strain gauges were attached with a temperature appropriate epoxy.

7. Specimens were tested for either Dynamic Modulus or Flow Number in the SPT device at the appropriate temperature and load frequency. Tests followed the AASHTO Standard T79. No SDDOT Standard exists for these tests at this time. Testing followed a program of low, medium, and high temperatures.

8. Specimens were then given to SDDOT for frequency sweep tests at the SDDOT central laboratory in Pierre, SD. About ½ of specimens have been picked-up by SDDOT to date, while the rest remain in our laboratory awaiting pickup.

Figure 5.2 Gyratory Specimen and final cored specimen comparison.

The Dynamic Modulus testing program consisted of the following: dynamic modulus tests and repeated load triaxial load tests according to AASHTO TP-79-13 (2013) and AASHTO T 342-11(2011). Each dynamic modulus test was be conducted for 6 different frequencies (0.1, 0.5, 1, 5, 10, and 25 Hz) at each temperature of 4, 21, 37, and 54 ℃ , and the repeated load triaxial tests were to be conducted for a confining pressure of 170 kPa at each temperature of 34, 41, and 52 ℃. Each test would be performed for 3 replicants for further statistical analyses.

5.2 Results of Testing Program

The Dynamic Modulus testing program began with the 4°C specimens for each HMA, WMA or SMA sample delivered to SDSMT from SDDOT. Testing then progressed through the 21° and so on. Flow Number testing also began with the coldest (34°C) and progressed to hotter. Few issues with testing were observed for the cold temperature Dynamic Modulus Tests (4 and 21°C sets). However, in the early stages of Dynamic Modulus Testing it became apparent that the SPT device was generating large amounts of heat, that often over-heated the device. Indeed, the over-heating caused two electric drive control cards to fail. These were replaced, and the SPT device was recalibrated. As testing progressed it was noted that the chiller unit was acting as a heat sink for the system, and that the cold temperature tests were not held at constant temperature in testing. In some instances, the temperatures in the specimens rose less than 5°C, but in other cases, temperature increases during testing exceeded 5°C. This temperature issue could not be remedied with maintenance on the chiller unit according to manufacturer recommendations. Testing the chiller unit showed that the unit could maintain the desired temperature for long periods when the SPT was not in test operation, but as soon as test operations began, the overheating SPT began to pump heat into the chiller unit.

As testing moved to the 37°C Dynamic Modulus tests, the SPT held at the desired temperature at the beginning of the test, and the students left the device to run over lunch. When they returned and removed the first test specimen at that temperature, the specimen was hot to the touch, enough to be painful to the touch. The data for the test showed constant temperatures, but the specimen was overheated. This was then verified in the next test with an infrared thermometer aimed at the specimen that showed increases of over 10°C in the cell during the test. Clearly outside of acceptable performance.

When the first of the 41°C Flow Number tests were performed, the heat in the SPT unit increase sufficient that the sample unraveled. At this point, a critical review of all data and specimens was performed. This critical review showed that at cool and cold temperature tests, the heat of the system increased in the system per the temperature logs in most cases, but other cases showed constant temperatures of the specimens. The mid-temperature tests showed the same dichotomy, with the known test that showed constant temperature in the data but was independently measured to get quite hot. **Thus, it is impossible to know which of the specimens in the testing program had acceptable temperature variations during testing, and which specimens had unacceptable temperature variations.**

Emergency maintenance procedures were initiated for both the chiller unit and the SPT. The chiller was demonstrated to be operating within manufacturer's specifications and tolerances. The SPT however, was shown to generate large amounts of heat whenever test operations were initiated. Indeed, the heat was sufficient to cause the electric controls of the device to become too hot to touch with the hand. During trial tests, an infrared thermometer documented that the chiller-maintained temperatures until test initiation, followed by the SPT device overheating, which caused heat to pump into the chiller, after which the chiller unit attempted to cool the device, but was unable to keep pace with the heat generation. In a high temperature Flow Number test, temperatures were shown to increase by more than 20°C during the test, which caused visible changes to the specimen's performance in the test. **No "successful" Flow Number tests were obtained, with heat visibly changing the specimen performance in each case**.

The manufacturer of the SPT unit no longer supports the device and would not provide any support for fixes. Through an investigation of the history of the device, we discovered that the device has had over-heating issues for many years, with multiple electrical control cards having "fried" over the years, the same as in this test program.

In May and June of 2019, SDDOT was alerted to these issues and additional maintenance and repairs were attempted without manufacturer aid. These attempts were to no avail, the heat generation issue was not remedied. On December 20th of 2019, at a meeting on campus at SDSMT, SDDOT and SDSMT agreed that all data was questionable to date in the SPT device, and that the device could not be repaired or reasonably replaced due to the high costs exceeding $100,000. Thus, there are no reliable results to report to SDDOT.

5.3 Remaining Specimens

Table 5.3 shows the number of test specimens sitting in the laboratory at SDSMT awaiting transfer to SDDOT for frequency sweep tests or other tests of interest to the bituminous materials engineer for the State. Table 3 is the inventory of specimens that are viable for frequency-sweep or other testing of interest to SDDOT after the work of the project. Specimens that were compromised in testing or were tested to completion are not included in Table 5.3.

Table 5.3 Asphalt specimens remaining in the SDSMT Geotechnical Laboratory

Phase	PCN Number	# of Specimens Remaining
1	037L	9
	037W	9
	026B	0
	02QU	0
2	04WM	7
	023T	10
	023Z	8
	04W9	10
	04DA	3
	026Q	11
3	00LD	5
	03T8	7
	05Q5	5
	05EG	11

5.4 Conclusions

Dozens of bituminous material specimens were prepared from bulk samples delivered by SDDOT to SDSMT. These specimens were then used in a testing program for dynamic modulus and flow number (with extra specimens prepared for use by SDDOT for frequency sweep tests). These dynamic modulus and flow number tests are constant-temperature tests where the results are sensitive to the tested temperature. Unfortunately, equipment malfunctions resulted in high heat generation in the test device that could not be arrested. These heat problems caused all tests performed to be questionable. The device could not be repaired, despite many attempts. The over-heating problems accelerated with increasing applied temperatures in the tests until specimens began to unravel in testing.

Due to insurmountable equipment malfunctions, none of the dynamic modulus or flow number tests performed by the research team are reliable for use by SDDOT. The results are skewed by large temperature swings in the equipment. Despite many attempts to repair, the device continuous to pump heat into test specimens. As a result, it was agreed that the project be terminated.

6.0 RECOMMENDATIONS

Due to the limited reliable test data from the SPT, there are only a few recommendations that can be made from this research. Some of these recommendations apply to future testing by other laboratories from the experience of the research team. Other recommendations apply to implementation of MEPDG by SDDOT as observed by the testing of this research program. The research team recommends that:

6.1 SDDOT evaluate if there is benefit in pursuing development of MEPDG HMA Tier I inputs, or will Tier II inputs suffice;

SDDOT evaluate if there is benefit in pursuing the development of MEPDG HMA Tier I inputs, will Tier II inputs suffice.

SDDOT must determine whether the benefit of continuing MEPDG implementation will justify the cost of continued materials characterization. SDDOT must decide what extent of implementation of Tier I or Tier II input parameters is most worthwhile in consideration of the benefit to be attained, possible federal mandates, increased capability that will be needed, and the amount of effort that will be required to sustain MEPDG. This is being addressed in upcoming SDDOT Research Project 2020-01.

6.2 SDDOT use the remaining specimens from this research to perform CH-FS tests;

SDDOT use the remaining specimens from this research to perform CH-FS tests.

One of the primary outputs of this work was a large set of prepared specimens for CH-FS testing to be performed by SDDOT in their Pierre Bituminous Materials Laboratory. Approximately ½ of these specimens were previously collected by SDDOT for testing, and the other ½ await collection. The test resultant data from the CH-FS tests will benefit SDDOT's pavement design and maintenance efforts.

6.3 SDDOT use the remaining specimens from this research for dynamic modulus and flow number testing at a certified laboratory outside South Dakota;

SDDOT use the remaining specimens from this research for dynamic modulus and flow number testing at a certified laboratory outside South Dakota.

In addition to the CH-FS specimens that await SDDOT collection, the untested specimens that were awaiting testing prior to the termination of the testing program are available for SDDOT to collect and send to a certified academic or commercial laboratory outside of South Dakota for dynamic modulus and flow number testing.

6.4 SDDOT obtain evidence from future MEPDG laboratories that all equipment is thermally stable through the duration of all testing prior to initiation of any testing of bituminous materials.

SDDOT obtain evidence from future MEPDG laboratories on the thermal stability of all test equipment prior to the initiation of any testing of bituminous materials.

In this work, thermal regulation of equipment was only independently checked at the initiation of each test of an individual specimen. The internal temperature control outputs were relied on for temperature regulation during testing. In forensics of this project is was identified that the internal temperature controls were not adequate in monitoring, maintaining, or reporting specimen temperatures, whereas independent external monitors were. The failures of this research could have been avoided if SDDOT required evidence of thermal stability throughout the entirety of test duration by external measures prior to the initiation of the testing program.

7.0 RESEARCH BENEFITS

SDDOT was to be able to take advantage of this by designing and evaluating pavements with MEPDG by this research. In addition, the outcomes were used to provide learning opportunities related to the newly adopted design concept to enhance the skills of local engineers and students in the state's universities and make them more competitive in the national job market. However, the failure of the project to meet the proposed technical marks limits the benefits of this project to SDDOT and SD. Despite the technical failure, four benefits were seen in this research. Benefits derived from this research as conducted are:

1. SDDOT has a large stockpile of prepared specimens of bituminous concrete for frequency-sweep tests to be carried out in Pierre by the state Bituminous Pavements Engineer. Half of the specimens were already picked-up and taken to Pierre by SDDOT. The other half of the specimens await SDDOT's dispatch of a freight carrier to SDSMT to pick-up these specimens that have been prepared. The largest tangible benefit of the project is the frequency sweep tests.
2. Testing program demonstrated the sensitivity of test chamber temperature and temperature changes to the output data. Recommendations about this factor have been provided as part of this report.
3. The funding of this research project enabled four students to complete degrees at SDSMT. MS degrees were funded for two students, while BS degrees were funded for two students. Both of the BS students have joined SDDOT and at the time of this report are in the employment of SDDOT in Pierre, SD. These students have had an in-depth exposure to asphaltic materials, bituminous materials testing, quality control and quality assurance, and the maintenance and calibration of sensitive test equipment.
4. The results of this research have shown that SDDOT should reconsider use of Tier I level inputs to M-E pavement design in the MEPDG framework. A benefit of this research is upcoming project SD2020-01 Mechanistic-Empirical Pavement Design Strategy for SDDOT.

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