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Preliminary Laboratory Evaluation of Fiber Reinforced Asphalt Concrete Pavement

Study SD2009-10

Final Report

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DISCLAIMER

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EXECUTIVE SUMMARY

INTRODUCTION

The use of conventional hot mix asphalt (HMA) concrete pavement is relatively widespread throughout South Dakota. HMA pavement mixtures produced using locally available aggregate sources and asphalt binders should be highly resistant to the failure modes that are commonly encountered in South Dakota, including moisture damage, thermal and fatigue cracking, and permanent deformation. Recently, a laboratory and field study was conducted by Arizona State University where synthetic fibers, comprising a blend of aramid and polypropylene, were added to an HMA pavement mixture to demonstrate the potential improved performance against these types of failure modes. The study proved that the addition of the fibers did indeed provide an improvement within the performance of the HMA pavement laboratory data, which indicated either longer pavement life or decreased pavement thickness, and thus significant economic benefit. In order to validate and quantify the potential performance benefits of utilizing fiber reinforced HMA pavements in South Dakota, a preliminary laboratory experimental program was conducted to assess the applicability of the technology under South Dakota's traffic and climatic conditions and using typical aggregate sources and asphalt binder materials. Utilizing advanced material characterization tests, the laboratory experimental program evaluated the mechanical properties of fiber reinforced HMA. The verification of improved pavement performance through this preliminary laboratory experimental program described herein could lead to subsequent detailed analysis in South Dakota focused on further evaluation of fiber reinforcement in typical asphalt mixes and characterization of these mixes with respect to the Mechanistic-Empirical Pavement Design Guide (M-EPDG) principles. Subsequent analysis that demonstrates an increase in pavement performance and an economic benefit with using fiber reinforced asphalt may eventually lead to future incorporation of the material within the asphalt highways and roadways of South Dakota.

At the time of this study, the approximate cost increase to incorporate fibers into an HMA mix is 10 to 15% per ton. This cost increase includes the raw material cost for the fibers, in addition to the labor cost to incorporate the fibers as described within this report. However, as reported in Kaloush et al. (2008), for the rutting distress criteria, a reduced AC layer thickness of between 30 and 40% can be achieved with the inclusion of fibers to an HMA mix. To that end, subsequent analyses that demonstrate an increase in pavement performance and an economic benefit with using fiber reinforced asphalt may eventually lead to future incorporation of the material within the asphalt highways and roadways of South Dakota.

OBJECTIVES

The objectives of this research were the following:

1) Observe and document the field placement of fiber reinforced hot mix asphalt (HMA) material on a pavement project coordinated with the City of Rapid City and the South Dakota Department of Transportation (SDDOT). During the time of construction, samples of the fiber reinforced HMA, along with samples of a conventional (control) HMA mix, were collected for laboratory testing.

2) Conduct preliminary laboratory experimental testing of four different fiber reinforced HMA mixes, along with complementary conventional (control) HMA mixes, in order to develop a preliminary characterization of various mechanical and performance properties of each mix. For this project, HMA mixes from Rapid City, South Dakota, Sioux Falls, South Dakota, Taylors Falls, Minnesota, and Box Elder, South Dakota were tested in the laboratory.

3) Determine if further investigation of fiber reinforced HMA was warranted. The goal of the preliminary laboratory experimental program was to demonstrate the feasibility and potential improvement in pavement performance with using fiber reinforced HMA based on the material properties, which may lead to the need for further detailed analysis of the technology within South Dakota.

RESEARCH APPROACH

The research objectives were accomplished through a research plan, which was comprised of the following four tasks:

Task 1 – Observe and document the construction of a fiber reinforced HMA test section and a conventional (control) HMA test section coordinated with the City of Rapid City and the South Dakota Department of Transportation.

Observe and document the placement of fiber reinforced HMA material on a pavement project coordinated with the City of Rapid City and the South Dakota Department of Transportation (SDDOT). The research team at SDSM&T documented the construction process via field notes and photographs. During construction, the research team obtained adequate samples of the fiber reinforced HMA mix and the control HMA mix (i.e. non-reinforced HMA mix that was placed on the same paving project) for use in the laboratory testing. The location of the test section was selected to coincide with the City of Rapid City's and SDDOT's current HMA projects and included mill and overlay projects.

Task 2 – Perform laboratory testing of the fiber reinforced HMA mix and control HMA mix.

Perform laboratory testing of a fiber reinforced HMA mix and a control HMA mix obtained during Task 1 from Rapid City, South Dakota and Box Elder, South Dakota, along with material obtained from a pavement project in Sioux Falls, South Dakota and Taylors Falls, Minnesota. This task also included the data analysis computations related to the laboratory experimental program to compare the performance of the fiber reinforced and control HMA mixes. The laboratory experimental program included the following testing protocol:

Dynamic modulus testing (E*)

Dynamic modulus testing was performed on a minimum of three (3) specimens each of the fiber reinforced HMA and control HMA mix. For this project, the material from Taylors Falls, Minnesota and Box Elder, South Dakota was tested for dynamic modulus. The specimens were prepared using a Superpave gyratory compactor at a target air void content of 7.0% ± 0.5%. The Corelok® device was utilized to determine the maximum and bulk specific gravity. Each specimen was tested at a temperature of 40°, 70°, 100° and 130°F (4.4°, 21.1°, 37.8° and 54.0ºC) and at a frequency of 25, 10, 5, 1, 0.5, and 0.1 Hz. The dynamic modulus testing criteria and specimen preparation process followed the guidelines established in NCHRP Report 547, NCHRP Report 580, NHCRP Project 9-29 proposed standard test methods, and AASHTO TP62. E* Master Curves for both the fiber reinforced and control HMA mix at reference temperatures of 45°F, 70°F, and 100°F were generated using the results of the dynamic modulus test.

Indirect-tensile strength (ITS)

Indirect-tensile strength (ITS) testing was performed on a minimum of two (2) sets of three (3) specimens each of the fiber reinforced HMA and the control HMA mix. One set of specimens was prepared and tested in dry conditions for indirect-tensile strength (unconditioned). The other set was subjected to vacuum saturation and a freeze cycle, followed by a warm-water soaking cycle, before testing for indirect-tensile strength (conditioned). The retained indirect-tensile strength was computed using the two sets: unconditioned and conditioned. The indirect-tensile strength testing and specimen preparation protocol followed AASHTO T 283. The specimens were prepared using a Superpave gyratory compactor at a target air void content of 7.0% ± 0.5%. Bulk specific gravity of the specimens was determined using the Corelok® device.

C* energy measurement

The C* energy measurement test was performed on a minimum of three (3) sets of three (3) specimens each of the fiber reinforced HMA and the control HMA mix. The test was performed on disc specimens prepared using a Superpave gyratory compactor at a target air void content of

7.0% ± 0.5%, similar to the ITS specimens. The specimens were loaded using the Lottman-type loading device within a load testing frame with displacement control. Each set of specimens were loaded at three specified displacement rates: 0.05, 0.1, and 0.2 in/min. Load and displacement measurements were recorded at specific intervals in order to compute the magnitude of energy required to initiate an indirect tensile crack along with the energy required to propagate the crack until specimen failure.

Task 3 – Prepare a final report and executive summary of project findings.

The research team at SDSM&T prepared a final report that included a comprehensive summary of the project and documented the project results, findings, and conclusions related to the field placement and laboratory testing of the fiber reinforced HMA and control HMA mix. A draft final report was submitted to the Project Technical Panel for comment and review prior to submission of the final report.

Task 4 – Make an executive presentation to the SDDOT Research Review Board at the conclusion of the project and after acceptance of the final report.

The research team at SDSM&T made an executive presentation to the SDDOT Research Review Board and Project Technical Panel that summarized all research activities and presented any conclusions and recommendations that resulted from the research.

CONCLUSIONS

The HMA mixes tested in the laboratory for this project consisted of a relatively wide array of aggregate types, liquid asphalt cement (AC) binder types, liquid AC binder content, and RAP percentages, which was beneficial to examine the broader performance of fiber reinforced HMA mixes. It was observed that for the Sioux Falls and Minnesota HMA mixes tested for this project, the fiber reinforced HMA mixes possessed greater indirect-tensile strength and greater pre-crack and post-crack energy absorption when compared to the control HMA mixes:

- The increase in the indirect-tensile strength (ITS) was observed to be approximately 43% and 16% for the unconditioned samples of the Sioux Falls and Minnesota fiber reinforced HMA mixes, respectively. For the conditioned samples, the increase in indirect-tensile strength was observed to be approximately 98% and 15% for the Sioux Falls and Minnesota fiber reinforced HMA mixes, respectively.
- For the Minnesota fiber reinforced HMA mix, the increase in the pre-crack energy absorption was observed to be between 21% and 52%. The increase in the post-crack energy absorption was observed to be between 9% and 43%. The percentage increase for both the pre-crack and post-crack energy absorption magnitudes is dependent upon the loading speed of the C* energy measurement test.

These general strength characterization tests provide evidence that the introduction of the fibers into a conventional HMA mix can increase the basic strength performance of the material. This increase in laboratory performance relates to increased resistance to tensile cracking in the field and thus fewer pavement distresses, longer design life, and decreased maintenance. The introduction of fibers into the Rapid City and Box Elder HMA mixes did not always result in an increase in the indirect-tensile strength or pre and post-crack energies, which may be related to the tight gradation, and thus high quality, of these mixes, along with the low asphalt content of these mixes. Further examination as to the cause of this lack of increase should be conducted.

In the case of the dynamic modulus testing, the following was observed:

- For the Minnesota site, the fiber reinforced HMA possessed a lower dynamic modulus and increased phase angle at all testing temperatures when compared to the conventional HMA mix. This indicates an overall reduction in the stiffness of the mix and increased viscous behavior with the addition of the fiber.
- For the Box Elder site, the fiber reinforced HMA possessed a higher dynamic modulus and decreased phase angle at the lower testing temperatures and a lower dynamic modulus and increased phase angle at the higher testing temperatures when compared to the conventional HMA mix. This indicates decreased and increased viscous behavior at lower and higher temperatures, respectively, with the addition of the fiber.

The dynamic modulus testing results for both sites were utilized to develop a series of E* Master Curves at different pavement temperatures. The results of the E* Master Curves indicate slight variations within the magnitude of the dynamic modulus between the control and fiber reinforced HMA mix over the range of frequencies. Overall, the greatest variation within the magnitude of E* between the conventional and fiber reinforced HMA mixes occurs at very low frequencies. It is important to note that the magnitude of E* is a general indication of the quality of the HMA mix, and a lower value of E* is not necessarily indicative of an inferior material. In fact, too high of an E* value represents a brittle mix which may suffer extensive cracking, while too low of an E* value represents a soft mix which may suffer extensive rutting. However, it is the combination of the E* value, along with a number of other parameters, that are utilized to predict the performance of the pavement using a mechanistic-empirical design approach.

Visual surveys of all test section locations to date indicate that no visible distresses have been observed in the fiber reinforced HMA. At the test site in Sioux Falls, minor rutting has been observed in the conventional HMA test section, with no rutting in the fiber reinforced HMA test section. At the test site in Rapid City, minor transverse cracking was noted in a non-reinforced HMA test section, with no transverse cracking in the fiber reinforced HMA test section. No substantial distresses have been noted in the test sections at the Minnesota or Box Elder test sites.

RECOMMENDATIONS

The purpose of this research project was to perform a preliminary laboratory evaluation of fiber reinforced asphalt concrete pavement materials. To that end, the laboratory testing program was rather limited in scope and focused predominately on strength, toughness, and stiffness characterization tests. The following recommendations are made based on the results of the preliminary laboratory testing program:

1. Although an observable increase in the strength and energy absorption within two of the fiber reinforced HMA mixes was realized, it is recommended to expand the laboratory testing program to include the following tests that may better characterize the potential improvement in performance of fiber reinforced HMA materials:

    - Resistance of fiber reinforced HMA mixes to permanent deformation using the repeated load triaxial (RLT) test. This test can provide an indication of the rutting potential of the fiber reinforced HMA mix compared to a conventional HMA mix.
    - Resistance of fiber reinforced HMA mixes to fatigue cracking using the flexural beam fatigue test. This test can provide an indication of the fatigue life of the fiber reinforced HMA mix, which is defined as the number of loading cycles to achieve fatigue damage (i.e. 50% reduction in the initial stiffness).
    - Resistance of fiber reinforced HMA mixes to thermal cracking using the thermal stress restrained specimen test (TSRST) or a similar test. This test can measure the field temperature at which the fiber reinforced HMA pavement will experience thermal cracking (i.e. "fracture temperature"). The measurement of thermal cracking performance is particularly beneficial in colder climates, like South Dakota, where thermal effects may be the predominant cause of HMA pavement distresses.

    These laboratory tests have been specifically recommended for further investigation because it is theorized that the addition of fibers to a conventional HMA mix should improve the rutting, fatigue, and thermal performance of the mix due to the increase in the tensile strength and improved fracture behavior within the liquid asphalt matrix. These properties, in addition to the dynamic modulus, are important for pavement design using the Mechanistic-Empirical Pavement Design Guide (M-EPDG) approach. It is likely that the M-EPDG approach will be required for all HMA pavement designs in lieu of the current AASHTO *Guide for Design of Pavement Structures* (AASHTO 1993). Comparative pavement designs that examine pavement life or pavement thickness can be conducted using the M-EPDG approach for a conventional and fiber reinforced HMA mix, which can provide a direct indication of the potential economic benefits of using fiber reinforced asphalt in paving projects based on the goals of the agency.

2. Construction and long-term monitoring of field test sections consisting of both conventional and fiber reinforced HMA materials is recommended. Obviously, a side-by-side comparison of long-term performance of conventional and fiber reinforced HMA pavements can provide direct evidence of the potential reduction in distress and maintenance achieved using fiber reinforcing in HMA mixes and can provide basic design correlations to the laboratory testing results, such as those obtained in this project. A long-term pavement monitoring program will also allow for development of transfer functions that can also be utilized directly in the M-EPDG approach. Transfer functions are empirically derived mathematical relationships that relate the critical pavement response parameter to pavement distress. The default transfer functions that are currently used in the M-EPDG approach to predict pavement distress may not be representative of the behavior of a fiber reinforced asphalt mix and thus significant benefit in design should be realized by developing these functions independently for these types of HMA mixes. In addition, long-term pavement monitoring that includes International Roughness Index (IRI) measurements, along with Falling Weight Deflectometer (FWD) measurements and back-calculation of dynamic modulus can provide insight into the performance of fiber reinforced asphalt pavement materials in the field over time.

3. Since two of the HMA mixes tested for this project did not possess an increase in strength or toughness with the addition of the fibers, it is recommended that the mix characteristics, such as aggregate composite gradation, aggregate type, liquid AC binder quantity, and liquid AC binder type be investigated in order to identify possible reasons why certain mixes may not benefit from the fibers. For example, it is theorized that a minimum amount of liquid AC binder must be available in order to coat and properly bond the fibers into the asphalt matrix. In addition, the aggregate composite gradation of the mix may be such that the fibers are not able to properly disperse into the available pore space of the mix without an extended mixing time or without thorough mixing of the fibers into the dry components of the mix prior to deposition into the drum.

4. Investigate the use of a mobile automated system to introduce the fibers into the HMA mix. This could increase the reliability and consistency of the mix (i.e. quality control), as well as ensure proper dispersion of the fibers within the pore space of the mixture. This would also eliminate the need to station plant personnel at the RAP port on a larger fiber reinforced asphalt project and would reduce human error that is inherent with manual introduction of the fibers. This investigation should also include methods to add the fibers into the aggregate components of the mix, such as in a pugmill mixer, prior to the deposition into the drum. The addition and mixing of the fibers in this manner may further ensure proper dispersion of the fibers into a mix with a tight gradation due to the relatively low shear mixing behavior of most typical drum plants.

CHAPTER 1 INTRODUCTION

1.1 Problem Statement

The use of conventional hot mix asphalt (HMA) concrete pavement is relatively widespread throughout South Dakota. HMA pavement mixtures produced using locally available aggregate sources and asphalt binders should be highly resistant to the failure modes that are commonly encountered in South Dakota, including moisture damage, thermal and fatigue cracking, and permanent deformation. Recently, a laboratory and field study was conducted by Arizona State University where synthetic fibers, comprising a blend of aramid and polypropylene, were added to an HMA pavement mixture to demonstrate the potential improved performance against these types of failure modes. The study proved that the addition of the fibers did indeed provide an improvement within the performance of the HMA pavement laboratory data, which indicated either longer pavement life or decreased pavement thickness, and thus significant economic benefit (Kaloush et al. 2008). In order to validate and quantify the potential performance benefits of utilizing fiber reinforced HMA pavements in South Dakota, a preliminary laboratory experimental program was conducted to assess the applicability of the technology under South Dakota's traffic and climatic conditions and using typical aggregate sources and asphalt binder materials. Utilizing advanced material characterization tests, the laboratory experimental program evaluated the mechanical properties of fiber reinforced HMA. The verification of improved pavement performance through the preliminary laboratory experimental program described herein could lead to subsequent detailed analysis in South Dakota focused on further evaluation of fiber reinforcement in typical asphalt mixes and characterization of these mixes with respect to the Mechanistic-Empirical Pavement Design Guide (M-EPDG) principles.

At the time of this study, the approximate cost increase to incorporate fibers into an HMA mix is 10 to 15% per ton. This cost increase includes the raw material cost for the fibers, in addition to the labor cost to incorporate the fibers as described within this report. However, as reported in Kaloush et al. (2008), for the rutting distress criteria, a reduced AC layer thickness of between 30 and 40% can be achieved with the inclusion of fibers to an HMA mix. To that end, subsequent analyses that demonstrate an increase in pavement performance and an economic benefit with using fiber reinforced asphalt may eventually lead to future incorporation of the material within the asphalt highways and roadways of South Dakota.

1.2 Objectives

The objectives of this research were the following:

1) Observe and document the field placement of fiber reinforced hot mix asphalt (HMA) material on a pavement project coordinated with the City of Rapid City and the South Dakota

Department of Transportation. During the time of construction, samples of the fiber reinforced HMA, along with samples of a conventional (control) HMA mix, were collected for laboratory testing.

2) Conduct preliminary laboratory experimental testing of four different fiber reinforced HMA mixes, along with complementary conventional (control) HMA mixes, in order to develop a preliminary characterization of various mechanical and performance properties of each mix. For this project, HMA mixes from Rapid City, South Dakota, Sioux Falls, South Dakota, Taylors Falls, Minnesota, and Box Elder, South Dakota were tested in the laboratory.

3) Determine if further investigation of fiber reinforced HMA was warranted. The goal of the preliminary laboratory experimental program was to demonstrate the feasibility and potential improvement in pavement performance with using fiber reinforced HMA based on the material properties, which may lead to the need for further detailed analysis of the technology within South Dakota.

1.3 Research Plan

The research plan identified four tasks required to accomplish the objectives of this research project. The following sections briefly describe the approach to accomplish the objectives.

Task 1 –Observe and document the construction of a fiber reinforced HMA test section and a conventional (control) HMA test section coordinated with the City of Rapid City and the South Dakota Department of Transportation.

Observe and document the placement of fiber reinforced HMA material on a pavement project coordinated with the City of Rapid City and the South Dakota Department of Transportation (SDDOT). The research team at SDSM&T documented the construction process via field notes and photographs. During construction, the research team obtained adequate samples of the fiber reinforced HMA mix and the control HMA mix (i.e. non-reinforced HMA mix that was placed on the same paving project) for use in the laboratory testing. The location of the test section was selected to coincide with the City of Rapid City's and SDDOT's current HMA projects and included a mill and overlay project.

Task 2 – Perform laboratory testing of the fiber reinforced HMA mix and control HMA mix.

Perform laboratory testing of a fiber reinforced HMA mix and a control HMA mix obtained during Task 1 from Rapid City, South Dakota and Box Elder, South Dakota, along with material obtained from a pavement project in Sioux Falls, South Dakota, and Taylors Falls, Minnesota. This task also included the data analysis computations related to the laboratory experimental program in order to compare the performance of the fiber reinforced and conventional HMA mixes. The laboratory experimental program included the indirect tensile strength (ITS) test, dynamic modulus (E*) test, and C* energy measurement test. The details of these tests are provided in Chapter 3.

Task 3 – Prepare a final report and executive summary of project findings.

The research team at SDSM&T prepared a final report that included a comprehensive summary of the project and documented the project results, findings, and conclusions related to the field placement and laboratory testing of the fiber reinforced HMA and control HMA mix. A draft final report was submitted to the Project Technical Panel for comment and review prior to submission of the final report.

Task 4 – Make an executive presentation to the SDDOT Research Review Board at the conclusion of the project and after acceptance of the final report.

The research team at SDSM&T made an executive presentation to the SDDOT Research Review Board and Project Technical Panel that summarized all research activities and presented any conclusions and recommendations that resulted from the research.

CHAPTER 2 TEST SECTION CONSTRUCTION

2.1 Introduction

The construction of test sections consisting of fiber reinforced and conventional (control) hot mix asphalt (HMA) was completed at four sites: (1) Rapid City, South Dakota; (2) Sioux Falls, South Dakota; (3) Taylors Falls, Minnesota; and (4) Box Elder, South Dakota. The location of each test site is shown on the map in Figure 2-1. Specific construction details for each test section location are provided in the succeeding sections.

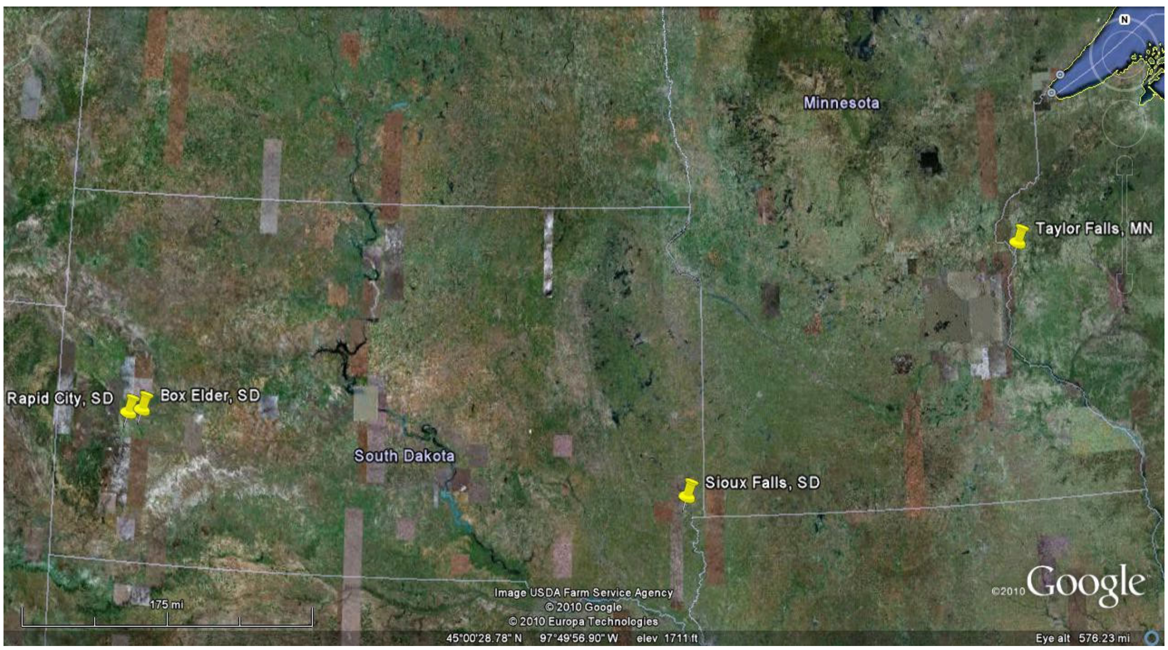

Figure 2-1: Location of fiber reinforced asphalt test sites (adapted from Google).

2.2 Rapid City Test Section Construction

The fiber reinforced and control asphalt test sections were constructed on St. Cloud Street between 7th Street and Mt. Rushmore Road in Rapid City, South Dakota in October 2009. The project was administered by the City of Rapid City Public Works Department and was characterized as a street rehabilitation project that consisted of milling two-inches of the existing asphalt, performing full-depth repairs in several locations along St. Cloud Street, and placing two-inches of new asphalt between the existing curbs. The average daily traffic (ADT) for St. Cloud Street is 444 vehicles for the eastbound lane and 420 vehicles for the westbound lane. The percentage of trucks is low with most of the traffic being local residential. The map shown in Figure 2-2 shows the approximate location of the test section construction.

Figure 2-2: Approximate location of fiber reinforced HMA test sections in Rapid City, South Dakota (adapted from Google).

The sketch in Figure 2-3 shows the general layout and composition of the various test sections placed along St. Cloud Street and 7th Street. As observed from Figure 2-3, the test sections were comprised of both an HMA and warm mix asphalt (WMA) section with fibers, along with a control HMA and WMA. A warm mix asphalt section with recycled manufactured shingles was also constructed at the site, but was not part of this study. All asphalt mixes contained 15% recycled asphalt pavement (RAP). The job mix formula (JMF) for the HMA and WMA mix is provided in Section 2.6.

After the milling of St. Cloud Street and prior to placement of the new asphalt, a crack and distress survey was conducted to assess the condition of the road below the new overlay for possible future analysis. During the condition survey, the location of all cracks and other distresses were photographed, measured, and noted on a drawing. A typical crack observed during the survey is shown in Figure 2-4. The results of the condition/crack survey are provided in Appendix A.

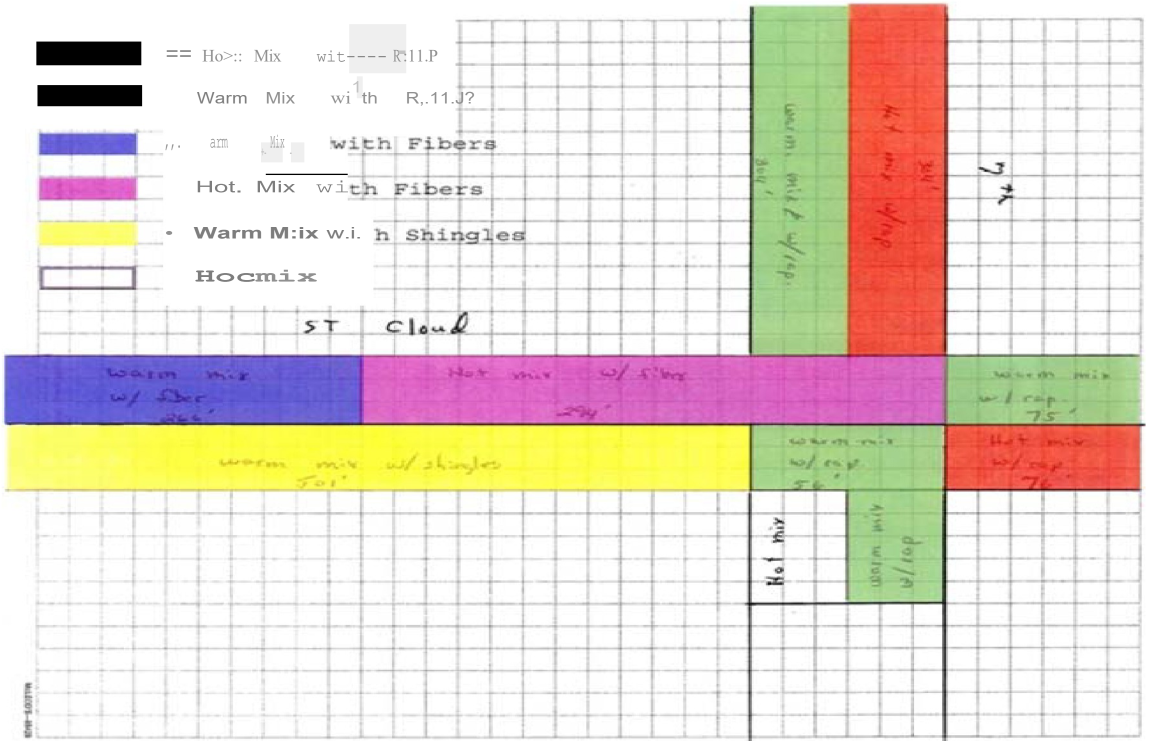

Figure 2-3: Rapid City test section layout and composition.

Figure 2-4: Conducting the distress survey with typical crack.

The test section construction began at the asphalt plant managed by Hills Materials Company of Rapid City. The overall production process for the WMA and HMA material was typical for these types of materials. However, during the production of the fiber reinforced asphalt, the addition of the aramid and polypropylene fibers required the placement of 1 lb. bags of fibers onto the recycled asphalt pavement (RAP) conveyor as shown in Figure 2-5. The addition rate of the fibers is typically 1 lb. of fibers (i.e. one bag) per 1 ton of asphalt. Therefore, the addition of the fibers into the process must be accomplished at a rate that matches the production rate of the plant. In this project, a single bag of fibers was introduced onto the RAP conveyor approximately every 12-15 seconds to target the aforementioned dosage rate. The total amount of fiber reinforced asphalt produced was approximately 45 tons. Since the total quantity of fiber reinforced asphalt was relatively small, adding the bags to the RAP conveyor by hand was not an issue. On larger projects with higher tonnages, the introduction of the fibers into the HMA or WMA mix can be accomplished with the use of pneumatic and vibratory systems, as well as cleated conveyors that can all be slaved into the production rate of the plant allowing for almost total automation. No other changes in the production process are necessary.

Figure 2-5: Adding the fibers onto the RAP conveyor during asphalt production.

After production, the asphalt was placed into silos to ensure no mixing between the various types of asphalt that were to be placed at the test section location. Dump trucks were loaded from each silo and hauled the asphalt to the test site, where it was dumped into a conventional paving machine as shown in Figure 2-6.

No modifications to the paving process were required for placement of the fiber reinforced asphalt. Following the placement of the asphalt with the paving machine, the asphalt was compacted as shown in Figure 2-7. Again, no modifications were required during the compaction process. Field density testing was performed by FMG Consultants, Inc. using a nuclear density gauge in general accordance with ASTM D2950 (2007). The target field densities were 92% of the maximum density (Rice) results provided by Hills Materials Company. It was observed that the fiber reinforced asphalt test sections did tend to require fewer passes of the vibratory compactor in order to achieve the target density as compared to the conventional (control) asphalt sections.

Figure 2-6: Placement of fiber reinforced HMA with conventional paving equipment.

Figure 2-7: Compaction of fiber reinforced HMA with conventional paving equipment.

The samples for the laboratory testing were obtained from the second or third truck for each type of asphalt to be tested in the laboratory. The second or third trucks were sampled in order to avoid sample contamination between the various types of asphalt mixes that were placed at the test site. The asphalt samples were removed by shovel directly from the paving machine and placed in paper bags by the SDSM&T researchers. The sampling process is shown in Figure 2-8.

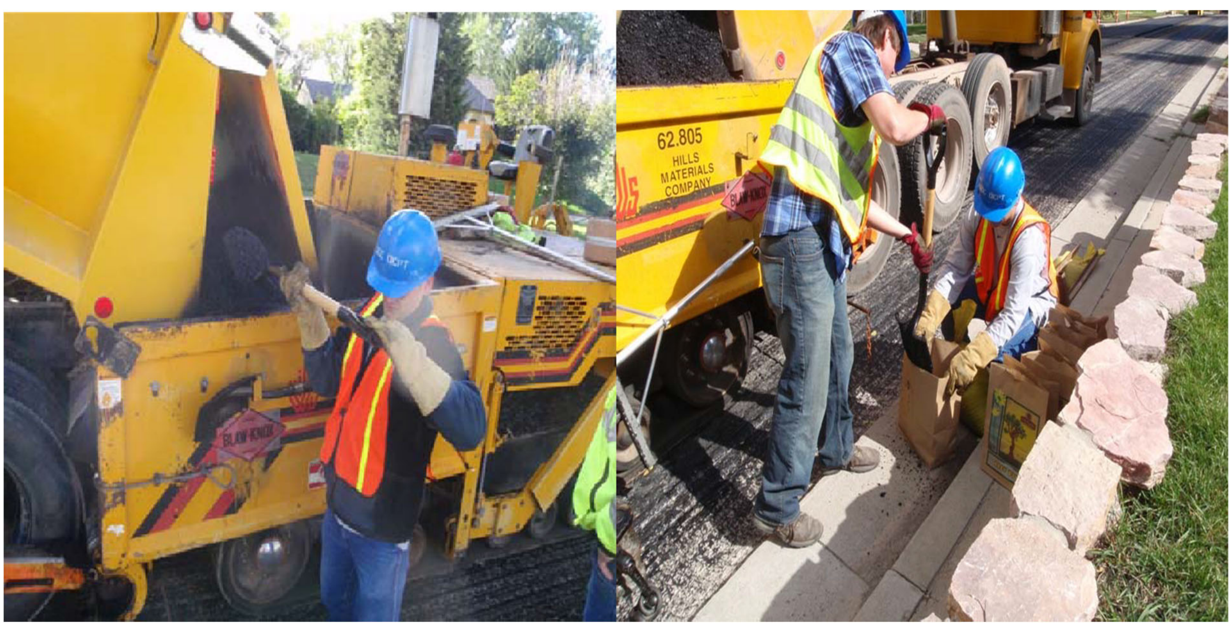

Figure 2-8: Sampling of fiber reinforced HMA material at test section site.

All test sections were constructed within the period of one day. A final inspection of the test sections by the research team located a fresh crack in the newly placed asphalt within the WMA with shingles test section. The area of the crack was within the limits of a full-depth repair that was located along the centerline of St. Cloud Street. However, as shown in Figure 2-9, the crack appeared to be arrested within the fiber reinforced HMA section that was also located above the full-depth repair. No additional cracks were visible immediately after construction. Subsequent inspections conducted six months after the construction reveal no additional cracking as well.

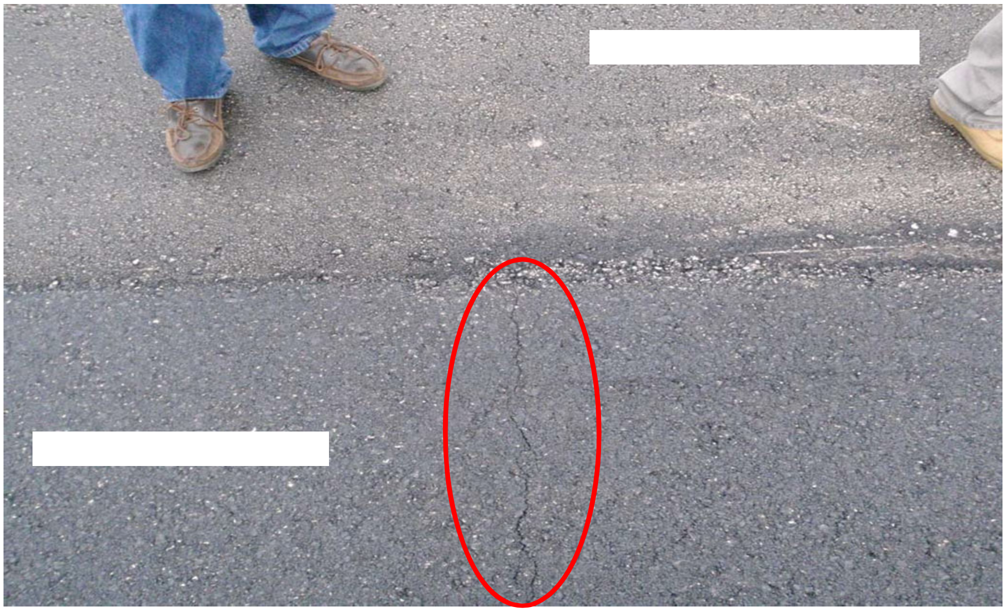

Figure 2-9: Transverse crack in the new asphalt overlay between the WMA with shingles and fiber reinforced HMA test sections.

2.3 Sioux Falls Test Section Construction

The fiber reinforced and control asphalt test sections were constructed on E. Chambers Street near the intersection with E. Ash Street in Sioux Falls, South Dakota in August 2009. The project was administered by the City of Sioux Falls Public Works Department and was characterized as a street rehabilitation project that consisted of milling two-inches of the existing asphalt and placing two-inches of new asphalt. The map in Figure 2-10 provides the approximate location and length of the fiber reinforced HMA test section. The ADT for E. Chamber Street is 4,300 with an estimated 75% trucks due to the location of the site to the Sioux Falls Street Department complex. The job mix formula for the HMA mix is provided in Section 2.6. As observed from the JMF, the Sioux Falls mix contained 20% RAP.

The test section construction began at the asphalt plant managed by Myrl & Roy's Paving Inc. of Sioux Falls. The production of the fiber reinforced asphalt required the addition of the 1 lb. bag of aramid and polypropylene fibers onto the recycled asphalt pavement conveyor. The addition rate of the fibers was targeted at 1 lb. of fibers per 1 ton of asphalt and thus the addition of the fibers matched the production rate of the plant. The batched materials were delivered, placed, and compacted at the paving site by City of Sioux Falls personnel and equipment. Samples of the control and fiber reinforced HMA mixes were collected by representatives of FORTA Corporation and delivered to SDSM&T by the South Dakota Department of Transportation. Figure 2-11 shows the test section near completion.

Figure 2-10: Approximate location of fiber reinforced HMA test sections in Sioux Falls, South Dakota (adapted from Google).

Figure 2-11: Completing test section construction at Sioux Falls site.

2.4 Minnesota Test Section Construction

Fiber reinforced and control asphalt test sections were constructed on (1) CSAH 20 and (2) CSAH 37 near Taylors Falls, Minnesota in October 2009. The project was administered by the Chisago County Engineer/Public Works Department in conjunction with the Minnesota Department of Transportation (MnDOT). At each location, the project consisted of milling two-inches of the existing asphalt and placing two-inches of new asphalt. The map in Figure 2-12 provides the approximate location of the fiber reinforced HMA test sections. The ADT for CSAH 20 was 1,150 vehicles in 2009, while the ADT for CSAH 37 was 1,450 vehicles in 2009. Both roads have an estimated percentage of trucks between 7% and 11%. The job mix formula for the HMA mix is provided in Section 2.6. The Minnesota mix contained 30% RAP.

The test section construction began at the asphalt plant managed by Knife River of Harris, Minnesota. The production of the fiber reinforced asphalt required the addition of the 1 lb. bag of aramid and polypropylene fibers onto the recycled asphalt pavement (RAP) conveyor. The addition rate of the fibers was targeted at 1 lb. of fibers (i.e. one bag) per 1 ton of asphalt and thus the addition of the fibers into the process matched the production rate of the plant. The batched materials were delivered, placed, and compacted at the paving site by Knife River personnel and equipment. Samples of both the control and fiber reinforced HMA mixes were collected by representatives of FORTA Corporation and delivered to the research team at SDSM&T by Federal Express. Figure 2-13 shows the test section near completion.

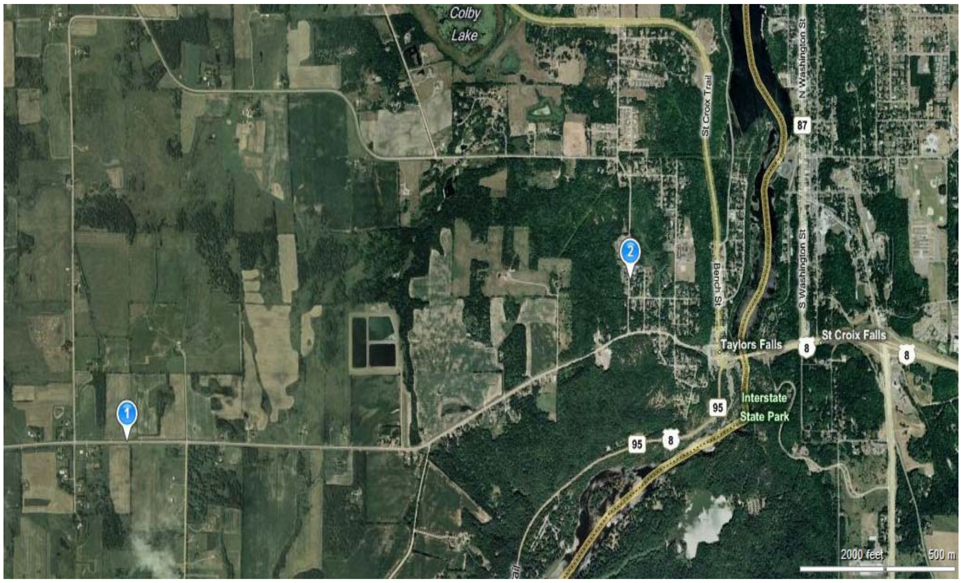

Figure 2-12: Approximate location of fiber reinforced HMA test sections in Taylors Falls, Minnesota (adapted from Bing).

Figure 2-13: Completing test section construction at Minnesota site.

2.5 Box Elder Test Section Construction

Per the Project Technical Panel recommendations, it was determined to test two fiber reinforced HMA mixes from the West River area of South Dakota. Hot mix asphalt mixes in this area of the state generally contain crushed limestone as the predominant aggregate and therefore tend to generate a large magnitude of fines and require relatively low liquid asphalt cement contents. These properties could lead to challenges with the introduction and mixing of the fibers in these types of mixes. Because of the small dosage rate of fibers within the HMA mix (1 lb. per 1 ton of HMA), it was ideal to obtain the material directly from a batch plant rather than produce the mix in the laboratory. This would ensure that the material proportions are correct. As a result, it was possible to construct additional fiber reinforced HMA test sections for this project. The South Dakota Department of Transportation (SDDOT) agreed to place the fiber reinforced HMA during the construction of a small paving project in Box Elder, South Dakota, in September 2010. The site consisted of a frontage road between the Exit 61 and Exit 63 interchanges of I-90 as shown in Figure 2-14. Prior to the placement of the new HMA, the existing road was milled to a depth of two-inches. Unfortunately, no ADT data exists for the frontage road. The job mix formula for the HMA mix is provided in Section 2.6.

The fiber reinforced HMA material was prepared at the Hills Material plant in Rapid City in a similar manner as the Rapid City test section material. The addition of the fibers into the mix is shown in Figure 2-15. The fibers were introduced in to the mix using the RAP conveyor although the Box Elder mix did not contain any RAP. The batched materials were delivered, placed, and compacted at the paving site by Hills Materials personnel and equipment. The total amount of fiber reinforced asphalt produced was approximately 60 tons. Samples of both the control and fiber reinforced HMA mixes were collected by the research team at SDSM&T. Figure 2-16 shows the completion of the eastbound lane of the test section.

Figure 2-14: Approximate location of fiber reinforced HMA test sections in Box Elder, South Dakota (adapted from Bing).

Figure 2-15: Adding the fibers onto the RAP conveyor during asphalt production.

Figure 2-16: Completed test section construction of eastbound lane at Box Elder site.

2.6 Job Mix Formula for HMA Mixes

The job mix formulas (JMF) for the HMA mixes at each of the sampling/test sites are provided in Tables 2-1 through 2-4. The JMF reports the components of each HMA mix, along with the proportions of each component. The type of liquid asphalt cement binder, supplier of the binder, and amount of virgin binder added to the mix, by percentage of weight, are also reported. As discussed in the previous sections, the Rapid City, Sioux Falls and Minnesota HMA mixes contained various percentages of recycled asphalt pavement (RAP), while the Box Elder HMA mix did not contain any RAP. The aggregate composite gradations of each HMA mix are provided in Chapter 4.

Table 2-1: Job Mix Formula for Rapid City HMA mix.

Mix:	Rapid City	
Mix Type:	Class E/G, Type 1	
AC Type	Percentage	Source
PG 64-28	4.1	Exxon Mobil
Aggregate Type	Percentage	Source
3/4" Rock	27%	Hills Materials RC Quarry
ASF	44%	Hills Materials RC Quarry
BF Ash	9%	Ben French
3/8" chips	5%	Hills Materials RC Quarry
RAP	15%	Various Projects

Table 2-2: Job Mix Formula for Sioux Falls HMA mix.

Mix:	Sioux Falls	
Mix Type:	Class G, Type 2	
AC Type	Percentage	Source
PG 58-28	5.7	Jebro
Aggregate Type	Percentage	Source
1/2" x 4	15%	East Sioux Quarry
3/8" down	35%	East Sioux Quarry
AC sand	30%	Anderson Pit
RAP	20%	Various Projects

Table 2-3: Job Mix Formula for Minnesota HMA mix.

Mix:	Minnesota	
Mix Type:	MVWE45030/MVNW45030	
AC Type	Percentage	Source
PG 58-28	4.3	Superior
Aggregate Type	Percentage	Source
1/2" x 4	18%	Tiller/Sunrise
Man. sand	20%	Tiller/Sunrise
Washed man. sand	12%	Tiller/Sunrise
Fines	20%	Ramberg
RAP	30%	Various

Table 2-4: Job Mix Formula for Box Elder HMA mix.

Mix:	Box Elder	
Mix Type:	Class E, Type 1	
AC Type	Percentage	Source
PG 64-22	4.9	Exxon Mobil
Aggregate Type	Percentage	Source
3/4" RX	32%	Hills Materials RC Quarry
3/8 " chips	6%	Hills Materials RC Quarry
PLS Creston	10%	BSG Creston
ASF	52%	Hills Materials RC Quarry

CHAPTER 3 LABORATORY TEST METHODS

3.1 Introduction

This chapter provides a description of each laboratory test performed during the course of the research project. In general, the laboratory testing protocol focused on establishing performance differences between the fiber reinforced HMA and conventional (control) HMA mixes.

3.2 Gradations

The job mix formula for the Rapid City HMA mix, Sioux Falls HMA mix, Minnesota HMA mix and Box Elder HMA mix were received by the research team and provided the composite gradation of the aggregates used in each respective mix. The composite gradations of each mix are provided in Chapter 4.

3.3 Indirect-Tensile Strength (ITS) Test

Indirect-tensile strength (ITS) test was performed on a minimum of two (2) sets of three (3) specimens each of the fiber reinforced HMA and the control HMA mix, each. The ITS testing was conducted on material from all four sampling sites. The fiber reinforced WMA mix from Rapid City was not tested. One set of specimens was prepared and tested in dry conditions for indirect-tensile strength (unconditioned). The other set was subjected to vacuum saturation and a freeze cycle, followed by a warm-water soaking cycle, before testing for indirect-tensile strength (conditioned). The retained indirect-tensile strength was computed using the two sets: unconditioned and conditioned. The indirect-tensile strength testing and specimen preparation protocol followed AASHTO T283 (2009). The specimens were prepared using a Superpave gyratory compactor at a target air void content of 7.0% ± 0.5%. Bulk specific gravity of the specimens was determined using the Corelok® device. The ITS testing setup and the testing apparatus are shown in Figure 3-1. Per AASHTO T283 (2009), the standard displacement rate for the loading ram used in the ITS test was 2 in/min. A maximum displacement value was read from a calibrated load ring on the testing apparatus. A calibration factor was employed to convert the displacement reading into a maximum sustained loading on the specimen prior to indirect tensile failure. The maximum sustained load was converted to the maximum indirect tensile stress using Eq. 3-1.

$$S_t = \frac{2 * P}{\pi * t * D} \qquad (3\text{-}1)$$

where, S_t is the indirect-tensile strength (psi), P is the maximum recorded load (lbs), t is the specimen thickness (in), and D is the average specimen diameter (in). After subjecting the second set of specimens to a single freeze-thaw cycle, along with a period of drying, the same test was repeated. The tensile stress ratio (TSR) can be expressed using the following equation:

$$TSR = \frac{S_c}{S_u} \tag{3-2}$$

where, S_c is the indirect-tensile stress for the conditioned specimen and S_u is the indirect-tensile stress for the unconditioned specimen.

Figure 3-17: Indirect-tensile strength (ITS) testing setup.

3.4 C* Energy Measurement Test

The C* energy measurement test was performed on a minimum of three (3) sets of three (3) specimens each of the fiber reinforced HMA and the control HMA mix. Only material from the Rapid City, Minnesota, and Box Elder sampling sites was subjected to the C* energy measurement test due to an inadequate quantity of material from the Sioux Falls site. The test was performed on disc specimens prepared using a Superpave gyratory compactor at a target air void content of 7.0% ± 0.5%, similar to the ITS specimens. The specimens were loaded using the Lottman-type loading device within a load testing frame with displacement control. Each set of specimens were loaded at three specified displacement rates: 0.05, 0.1, and 0.2 in/min. Load and displacement measurements were recorded at one second intervals in order to compute the magnitude of energy required to initiate an indirect tensile crack along with the energy required to propagate the tensile crack until specimen failure. The curves created to compute the energies are shown in Figure 3-2. After recording the complete load-displacement curve during the test, the energy is computed as the area under the curve. A "pre-crack" energy was computed from the start of the test to the peak of the load-displacement curve, denoted as AREA 1 in Figure 3-2, while a "post-crack" energy was computed from the peak to the end of the test, denoted as AREA 2 in Figure 3-2. The C* energy measurement testing apparatus and testing setup are shown in Figure 3-3. The image on the right is the computer program used to record the data.

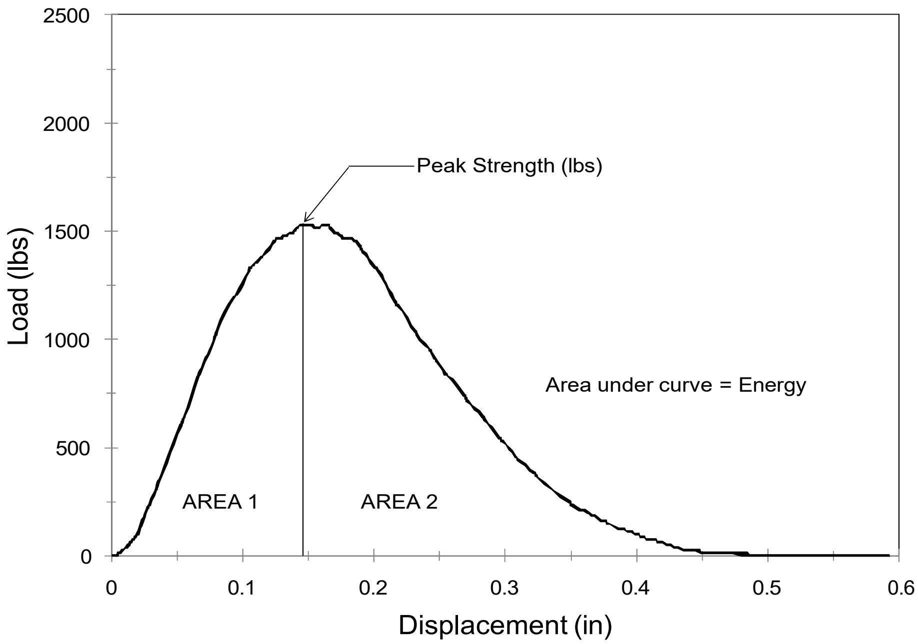

Figure 3-18: Measurement of pre-crack and post-crack energy from C* test.

Figure 3-19: C* energy measurement testing setup.

3.5 Dynamic Modulus Specimen Preparation

In order to prepare the samples for the dynamic modulus test, the HMA material was heated between 230ºF to 275ºF (110°C to 135°C) long enough to make the material pliable, which was typically one to two hours. Approximately 1000-grams of material were removed from the oven to perform a maximum theoretical specific gravity test (density of HMA excluding air voids). This test was conducted according to the CoreLok Operator's Guide developed by InstroTek Incorporated (2003). The 1000-gram sample was broken apart, cooled, placed inside vacuum bags, and sealed within the CoreLok vacuum chamber as shown in Figure 3-4. The bags were cut open under water and a submerged weight was recorded. The weight of the sample in air and the submerged weight were used to calculate the maximum specific gravity, G_{mm}, of the asphalt mixture. The target specimen size was 7-inches (177.8-mm) in height, 5.9-inches (150-mm) in diameter with an air void content of 7% ± 0.5%. The weight of material required for compaction was computed by:

$$\text{Weight} = \frac{G_{mm} \cdot \%G_{mm} \cdot \text{Volume}_{specimen} \cdot \gamma_{water}}{\text{Correction Factor}} \quad (3\text{-}3)$$

where, $\%G_{mm}$ is assumed to be equal to 93% (to obtain 7% air voids), $Volume_{specimen}$ is the volume of the specimen, and γ_{water} is the unit weight of water.

The correction factor was computed as:

$$\text{Correction Factor} = \frac{\text{Bulk Specific Gravity (measured)}}{\text{Bulk Specific Gravity (estimated based on sample height and weight)}} \quad (3\text{-}4)$$

The material and compaction mold were heated to compaction temperature of 300°F (150ºC) for two hours. Specimens were prepared by gyratory compaction according to AASHTO T312-04 (2009). Figure 3-5 shows the loose HMA in the gyratory mold before compaction.

Figure 3-20: Maximum theoretical specific gravity sample in CoreLok device.

Figure 3-21: HMA in gyratory compaction mold.

After the sample cooled, a 4-inch diameter specimen was cored from the middle of the 5.9-inch diameter sample as shown in Figure 3-6. Each end of the sample was trimmed with a concrete saw, as shown in Figure 3-7, so that the final specimen height was 6-inches.

Figure 3-22: HMA coring operation.

Figure 3-23: Sawing the ends of the HMA sample.

After the sample had surface dried, a bulk specific gravity test was performed using the CoreLok. The air void content (%AV) was computed using Eq. 3-5. The submerged HMA sample during a bulk specific gravity test is shown in Figure 3-8.

$$\%AV = 100 \cdot \frac{G_{mm} - G_{mb}}{G_{mm}} \tag{3-5}$$

where, G_{mb} is the bulk specific gravity of the HMA specimen.

Figure 3-24: Submerged HMA sample for bulk specific gravity determination.

The sample was air dried completely for approximately two days. After drying, the sample was subjected to a number of critical measurements. Sample specifications are outlined in Table 3-1.

Table 3-5: HMA sample specifications per NCHRP 9-29.

Item	Specification
Average Diameter from 6 measurements	100 mm to 104 mm
Standard Deviation of Diameter	1.0 mm
Height	147.5 to 152.5
End Flatness	0.3 mm
End Parallelism	1 degree

3.6 Dynamic Modulus (E*) Test

The time-temperature dependent dynamic modulus (E*) is the primary stiffness property of interest for asphalt materials. Dynamic modulus testing was performed on a minimum of three (3) specimens comprised of the fiber reinforced HMA and control HMA mix, each. The specimens were prepared using a Superpave gyratory compactor and the procedure described in the previous section of this report to a target air void content of 7.0% ± 0.5%. After allowing the specimen to dry, a gage point glue fixture was used to glue the gage points onto the HMA specimens for the magnetic extensometers. A quick setting epoxy was used to glue the gage points to the specimen as shown in Figure 3-9.

Figure 3-25: Gage points placed on HMA sample.

Once the gage points were affixed, the samples were temperature conditioned according to Table 3-2 prior to testing. The conditioning requirements are per AASHTO TP62-07 (2007).

Table 3-6: Temperature conditioning for dynamic modulus specimens.

Specimen Temperature (°C)	Time from Room Temperature (hrs)	Time from Previous Test (hrs)
4.4	Overnight	Overnight
21.1	1	3
37.8	2	2
54	3	1

Friction-reducing end treatments made from Teflon® were placed on the top and bottom of the sample and the sample was placed between two platens. The sample was placed in the Simple Performance Tester (SPT) machine and extensometers were attached as shown in Figure 3-10.

Figure 3-26: Dynamic modulus specimen assembled in SPT machine.

The test consisted of applying a haversine axial compressive stress to the specimen at a given temperature and loading frequency as given in Table 3-3. The applied dynamic stress and the resulting recoverable axial strain response of the HMA specimen was measured and used to calculate the dynamic modulus and the phase angle.

Table 3-7: Dynamic modulus loading and temperature sequences.

Temperature (°C)	Typical Dynamic Stress Level (psi)
4.4	100-200
21.1	15-100
37.8	20-50
54	5-10
Frequency* (Hz)	**Number of Cycles**
25**	200
25	200
10	200
5	100
1	20
0.5	15
0.1	15

The test series was conducted at 40°, 70°, 100° and 130°F (4.4°, 21.1°, 37.8° and 54.0°C) and at loading frequencies of 0.1, 0.5, 1, 5, 10, and 25 Hz at each temperature. Testing began at the coldest temperature and the highest frequency. AASHTO TP62-07 (2007) mandated a preconditioning phase that consisted of 200 cycles at 25 Hz. All samples were unconfined during testing. A contact load equal to 5% of the dynamic load was applied to the sample prior to the application of the haversine loading. The dynamic stress was adjusted to obtain axial strains between 50 and 150 microstrain. The applied dynamic stress is a function of the sample stiffness; thus a higher stress was required at colder temperatures to reach the target axial strains.

Vertical deformation measurements were performed with two Epsilon Strain Gaged Extensometers (model 3909 Axial Asphalt Extensometer) placed 180° apart on the sample. The extensometers have independent outputs capable of measuring specimen deformations in two locations. Magnets at each end of the extensometer snap in place onto steel gage points glued to the test sample. During the course of the dynamic modulus testing, if the cumulative unrecovered permanent strain of the sample exceeded 1500 microstrain, the sample was discarded and a new sample was used for the remaining temperatures.

For each frequency, 500 data points were recorded over 10 complete loading cycles. Data included vertical displacement, vertical load, extensometer readings, and the command load. Displacement data was corrected for drift by determining the average slope of local minima and maxima in the data and subtracting this slope from the original data. This eliminated mechanical and electrical drift from the analysis and resulted in more accurate analyses. Both load and displacement data were centered prior to analysis by subtracting the applicable average value.

After testing, the data quality indicators were reviewed for each test frequency and compared to the recommended values listed in Table 3-4.

Table 3-8: Maximum values for data quality indicators.

Data Quality Indicator	Allowable Maximum Value
Load Standard Error	10%
Deformation Standard Error	10%
Load Drift	3%
Deformation Drift	400%
Deformation Uniformity	20%
Phase Uniformity	3^{o}

The dynamic modulus is the average result obtained from three test specimens.

An E* Master Curve for both the fiber reinforced HMA and the control HMA mix was generated using the results of the dynamic modulus test. The E* Master Curves are constructed using the principle of time-temperature superposition. First, a standard reference temperature is selected and data at various temperatures are shifted with respect to time until the curves merge into a single smooth function. The reference temperature selected for this project was 70°F and curves were generated by shifting to temperatures of 45°F and 100°F. The master curve of dynamic modulus as a function of time formed in this manner describes the time dependency of the material. The amount of shifting at each temperature required to form the master curve describes the temperature dependency of the material. Thus, both the master curve and the shift factors are needed for a complete description of the rate and temperature effects.

3.7 Asphalt Burn-off Test

All HMA samples that were obtained for the project were subjected to a "burn-off" test using an NCAT asphalt content furnace which is capable of igniting and burning off the asphalt binder. The weight change is utilized in order to determine the percentage of asphalt binder in the final mix. The burn-off tests were completed by the SDDOT. No correction factors were applied for the aggregate in the calculations and therefore the burn-off quantities are provided for information only due to the potential of some error within the calculations. The burn-off test was conducted on one specimen of fiber reinforced and one control mixture for each of the sample test sites. It should be noted that the burn-off testing is conducted at a temperature of approximately 1000°F (538°C), which is high enough to melt the polypropylene fibers within the fiber reinforced HMA mixes. In general, most literature reports that the aramid fibers do not possess a defined melting point (Dupont 2010); however, the aramid fibers will begin to degrade at approximately 930°F (500°C) and thus the weight measurements for the fiber specimens taken before and after the burn-off process will include both AC oil and fibers.

CHAPTER 4 LABORATORY TEST RESULTS AND ANALYSIS

4.1 Introduction

The laboratory test results and analyses presented in this chapter are from the fiber reinforced HMA and control HMA materials tested for this research project. These materials consisted of HMA samples obtained from Rapid City, South Dakota (RC), Sioux Falls, South Dakota (SF), Taylors Falls, Minnesota (MN), and Box Elder, South Dakota (BE).

4.2 Gradation and Particle Size

The results of the composite particle size analysis testing conducted on the four HMA materials are reported in Table 4-1, with gradation curves illustrated in Figure 4-1. As observed from Figure 4-1, the gradations between the aggregates within the four HMA mixes are relatively similar. The aggregate within the Minnesota HMA mix does appear to be more gap-graded than the Sioux Falls HMA, Rapid City HMA, and Box Elder HMA aggregates; however, this difference in the gradation is not significant enough to warrant any discussion. It should be noted the Sioux Falls material was a crushed quartzite and the Rapid City and Box Elder materials were a crushed limestone. The Minnesota material was a river run aggregate that was processed through a crusher, which resulted in the crushing of all aggregate greater than a ½" nominal size. To that end, the aggregate within the Minnesota HMA mix was much more rounded, while the aggregate within the Sioux Falls, Rapid City and Box Elder HMA mixes contained multiple jagged fractured faces.

Table 4-9: Composite particle size distributions for aggregate in each HMA mix.

Sieve Size		Percent Passing			
No.	mm	RC	SF	MN	BE
1"	25.4	100	100	100	100
3/4"	19.1	99.5	100	100	99.4
5/8"	15.88	95.8	100	100	95.2
1/2"	12.7	88.7	99.6	100	88.2
3/8"	9.51	80.5	94.3	94	78.9
#4	4.76	63.8	72	71	62.3
#8	2.36	46.1	53.7	58	43.5
#16	1.19	28.3	39.2	47	28.1
#30	0.595	-	-	26	-
#40	0.42	13.9	19.2	-	14.2
#50	0.3	-	-	17	-
#100	0.149	-	-	8	-
#200	0.074	5	5.2	4.8	4.5

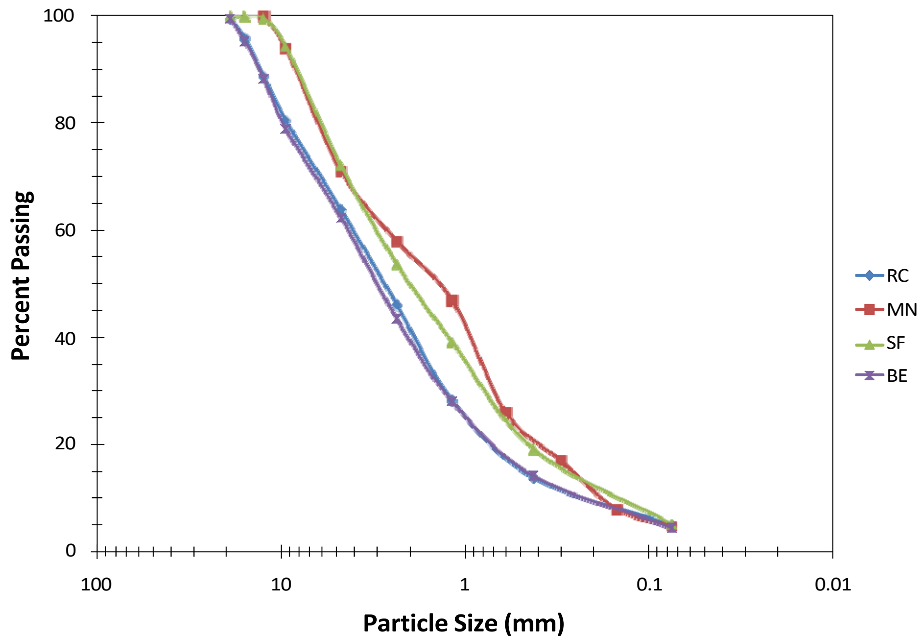

Figure 4-27: Composite particle size distribution curves.

4.3 Indirect-Tensile Strength (ITS) Test

The results of the indirect-tensile strength (ITS) test are reported in Table 4-2 for all four asphalt test sites. The difference in the magnitude of the average ITS value between the fiber reinforced and control HMA samples is reported as the change in stress (Δ Stress) in Table 4-2 for both the unconditioned and conditioned samples, respectively. As observed in Table 4-2, the addition of the fibers into the HMA mixes generally increased the magnitude of the ITS for both the unconditioned and conditioned specimens when compared to the control (unreinforced) mix. In the case of the Sioux Falls and Minnesota fiber reinforced HMA mixes, it was observed that the indirect-tensile strength increased by 43% and 16%, respectively, for the unconditioned samples and 98% and 16%, respectively, for the conditioned samples. An exception to this increase in indirect-tensile strength is observed within the unconditioned Rapid City fiber reinforced HMA mix and the conditioned Box Elder fiber reinforced HMA mix. In both of these cases, it was observed that the indirect-tensile strength decreased by approximately 10%. At this time, it is not known why these mixes contained lower indirect-tensile strengths, although it is possible that distribution of the fibers throughout the asphalt matrix could be the issue. For example, Figure 4-2 provides an indication that clumping of the fibers was observed in the Rapid City mix. The distribution of the fibers throughout the asphalt matrix could be affected by the percentage of AC binder content in the mix, the aggregate composite gradation, or mixing time. These factors were not examined directly within this project. Table 4-2 also reports the tensile strength ratio (TSR) between the conditioned and unconditioned samples. The TSR is often used as one criterion to accept or reject a particular HMA mix during the design phase of paving projects.

Table 4-10: Results of the indirect-tensile strength (ITS) test.

	Rapid City Fiber	Rapid City Control	Sioux Falls Fiber	Sioux Falls Control	Minnesota Fiber	Minnesota Control	Box Elder Fiber	Box Elder Control
Unconditioned (psi)	149	161	363	297	128	112	137	134
	146	174	312	214	136	113	139	129
	156	161	440	269	129	113	136	126
Average	150	165	372	260	131	113	137	130
COV	3.4%	4.5%	17.3%	16.2%	3.3%	0.5%	1.1%	3.1%
Δ Stress	-9.98%		42.95%		16.27%		5.91%	
1 Cycle Conditioned (psi)	100	82	264	111	84	75	125	135
	108	107	256	175	94	76	121	144
	101	107	234	95	92	82	126	132
Average	103	99	251	127	90	78	124	137
COV	4.2%	14.6%	6.2%	33.3%	5.9%	4.9%	2.1%	4.6%
Δ Stress	4.39%		97.90%		15.88%		-9.49%	
TSR	69%	60%	68%	49%	69%	69%	90%	100%

Figure 4-28: Indication of fiber clumping in Rapid City HMA mix.

4.4 C* Energy Measurement Test

The C* energy measurement test was only conducted on the Rapid City HMA, Minnesota HMA and Box Elder HMA mixes due to inadequate sample quantity with the Sioux Falls HMA mix. The results of the C* energy measurement test are shown in Table 4-3, Table 4-4 and Table 4-5 for the Minnesota, Box Elder, and Rapid City mixes, respectively. Tables 4-3 to 4-5 provide the magnitude of energy absorbed by each specimen prior to indirect-tensile cracking of the specimens ("pre-crack") and after indirect-tensile cracking until full specimen failure ("post-crack"). Figures 4-3 to 4-11 provide a comparison of the load versus displacement at the various loading rates for the fiber reinforced and control HMA specimens for the three mixes. Full specimen failure occurred when the specimen separated into two pieces. The average absorbed energy has been computed from the three specimens tested for each mix, along with the standard deviation and coefficient of variation (COV) within the testing results. The difference in the average absorbed energy between the control HMA specimens and the fiber reinforced HMA specimens is reported at the bottom of Tables 4-3 to 4-5 as the "Energy Differential".

As expected, the magnitude of energy absorbed by the specimens increased as the loading speed increased. This was observed for both the fiber reinforced and control HMA mixes. For the Minnesota fiber reinforced HMA mix, the magnitude of the energy absorbed by the fiber reinforced specimens is greater than the energy absorbed by the control specimens. This can be visually observed in Figures 4-3 to 4-5 and is reported in Table 4-3. The addition of the fibers increased the pre-crack absorbed energy in the Minnesota fiber reinforced HMA mix by as much as 50%. The post-crack absorbed energy in the Minnesota fiber reinforced HMA mix was increased by nearly 40%. Interestingly, the Box Elder fiber reinforced HMA mix displayed a general decrease of between 5% and 12% in the pre-crack absorbed energy when compared to the control HMA mix. However, the post-crack absorbed energy for the Box Elder reinforced HMA mix displayed a general increase of between 1% and 7% versus the control HMA mix. This can be visually observed in Figures 4-6 to 4-8 and is reported in Table 4-4. Lastly, the Rapid City fiber reinforced HMA mix displayed a decrease in both the pre-crack and post-crack absorbed energies compared to the control HMA mix. The decrease in the absorbed energy was as high as 32%. This can be visually observed in Figure 4-9 to 4-11 and is reported in Table 4-5.

As with the indirect-tensile strength testing, it is not entirely known why some of the fiber reinforced mixes possessed lower absorbed energy magnitudes when compared to the conventional mixes, although fiber distribution within the mix is suspected. For the Minnesota mix, however, an increase in the magnitude of energy absorption prior to crack initiation and after cracking is indicative of the increase in the cracking resistance within the fiber reinforced HMA. An increase in cracking resistance is beneficial for HMA as mechanical and thermal cracking is a common distress in these types of roadways and can result in significant spending for state, county, and city agencies in order to maintain and repair these problems.

Table 4-11: C* energy measurement results for Minnesota HMA mixes (lbf-in).

Minnesota Control HMA Mix						
	0.2 in/min		0.1 in/min		0.05 in/min	
Sample	Pre	Post	Pre	Post	Pre	Post
1	114	178	95	154	59	112
2	114	175	97	144	70	102
3	116	192	93	158	58	108
Average	**115**	**182**	**95**	**152**	**62**	**107**
Std. Dev.	1	9	2	7	7	5
COV	1%	5%	2%	5%	11%	5%
Minnesota Fiber Reinforced HMA Mix						
	0.2 in/min		0.1 in/min		0.05 in/min	
Sample	Pre	Post	Pre	Post	Pre	Post
1	185	205	110	149	97	153
2	145	195	122	182	101	147
3	134	200	113	167	87	161
Average	**155**	**200**	**115**	**166**	**95**	**154**
Std. Dev.	27	5	6	17	7	7
COV	17%	3%	5%	10%	8%	5%
	Energy Differential Between FB and CM Mix					
	35%	10%	21%	9%	52%	43%

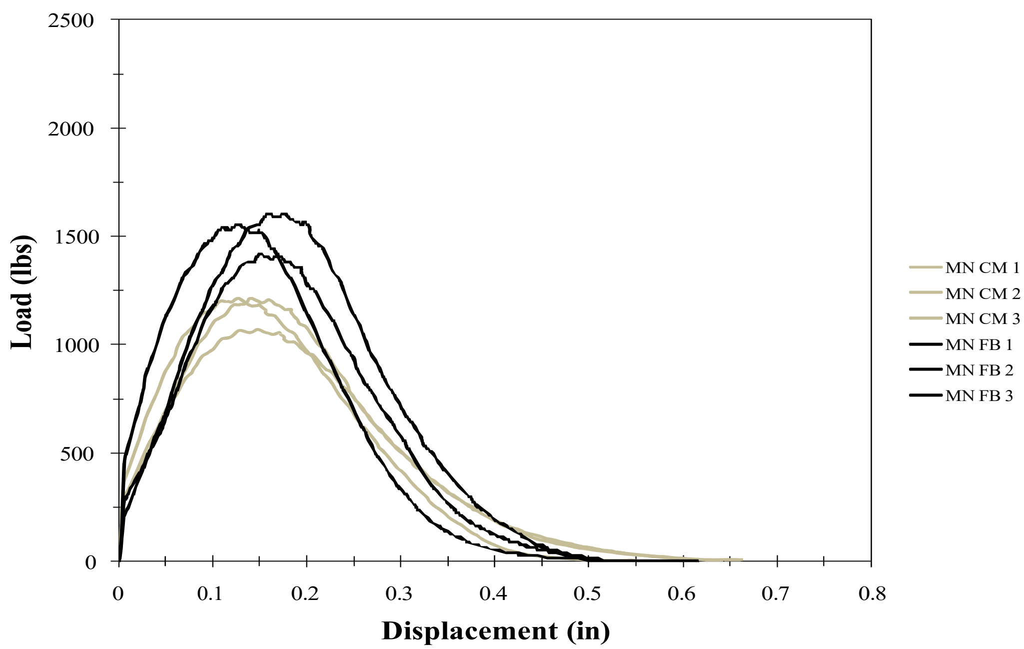

Figure 4-29: Load versus displacement for Minnesota HMA mix at 0.2 in/min loading rate.

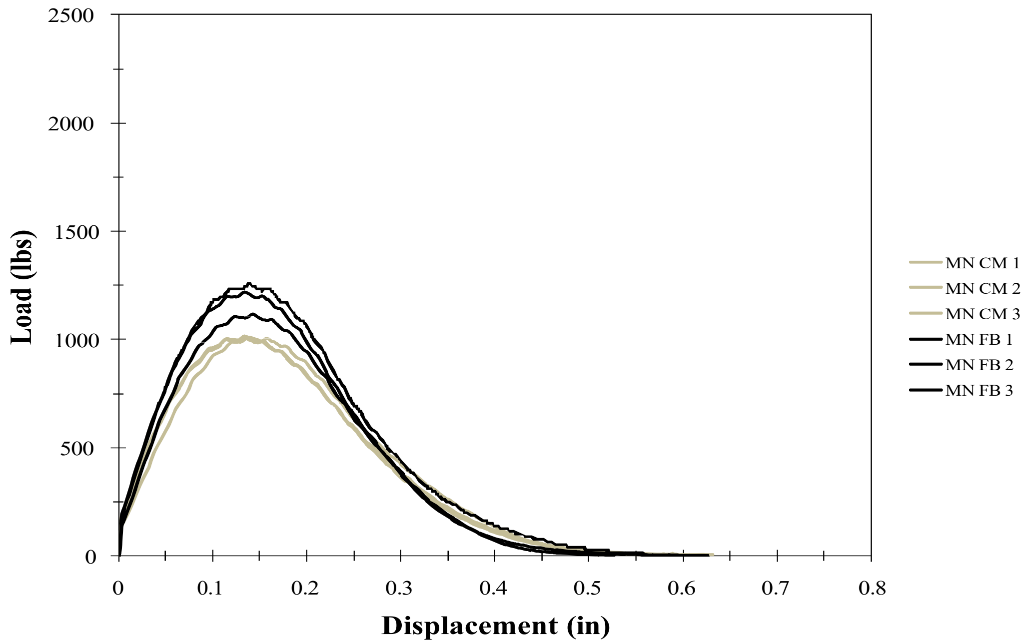

Figure 4-30: Load versus displacement for Minnesota HMA mix at 0.1 in/min loading rate.

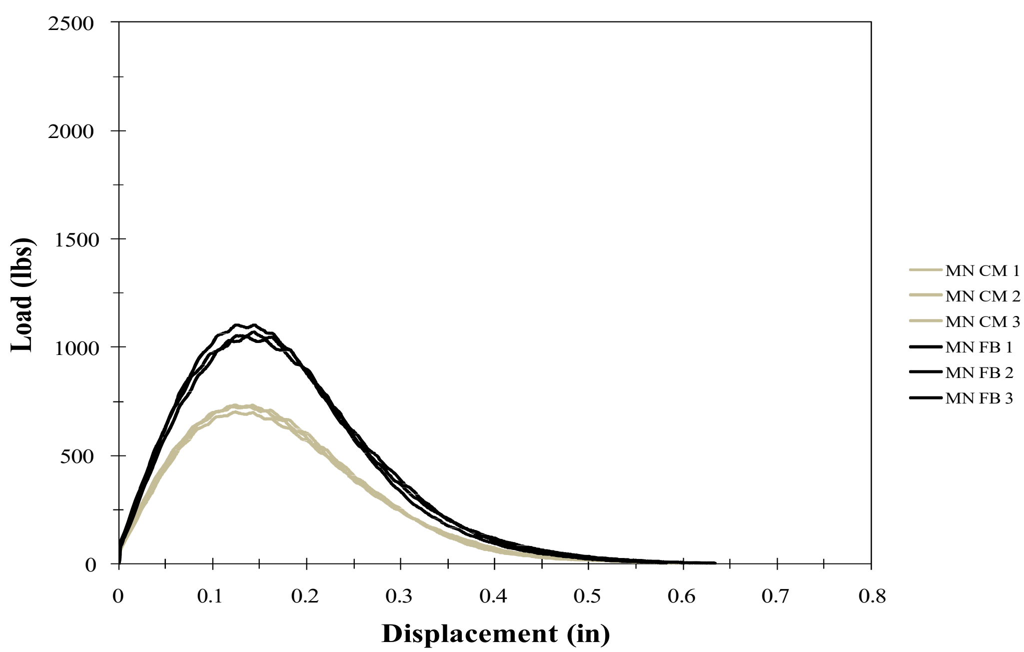

Figure 4-31: Load versus displacement for Minnesota HMA mix at 0.05 in/min loading rate.

Table 4-12: C* energy measurement results for Box Elder HMA mixes (lbf-in).

Box Elder Control HMA Mix						
	0.2 in/min		0.1 in/min		0.05 in/min	
Sample	Pre	Post	Pre	Post	Pre	Post
1	164	290	141	228	118	180
2	157	261	131	231	102	199
3	161	240	134	220	80	133
Average	**161**	**264**	**135**	**226**	**100**	**171**
Std. Dev.	4	25	5	6	19	34
COV	2%	10%	4%	3%	19%	20%
Box Elder Fiber Reinforced HMA Mix						
	0.2 in/min		0.1 in/min		0.05 in/min	
Sample	Pre	Post	Pre	Post	Pre	Post
1	135	262	127	240	99	216
2	152	275	124	205	100	175
3	139	252	116	238	87	157
Average	**142**	**263**	**122**	**228**	**95**	**183**
Std. Dev.	9	12	6	20	7	30
COV	6%	4%	5%	9%	8%	17%
	Energy Differential Between FB and CM Mix					
	-12%	0%	-10%	1%	-5%	7%

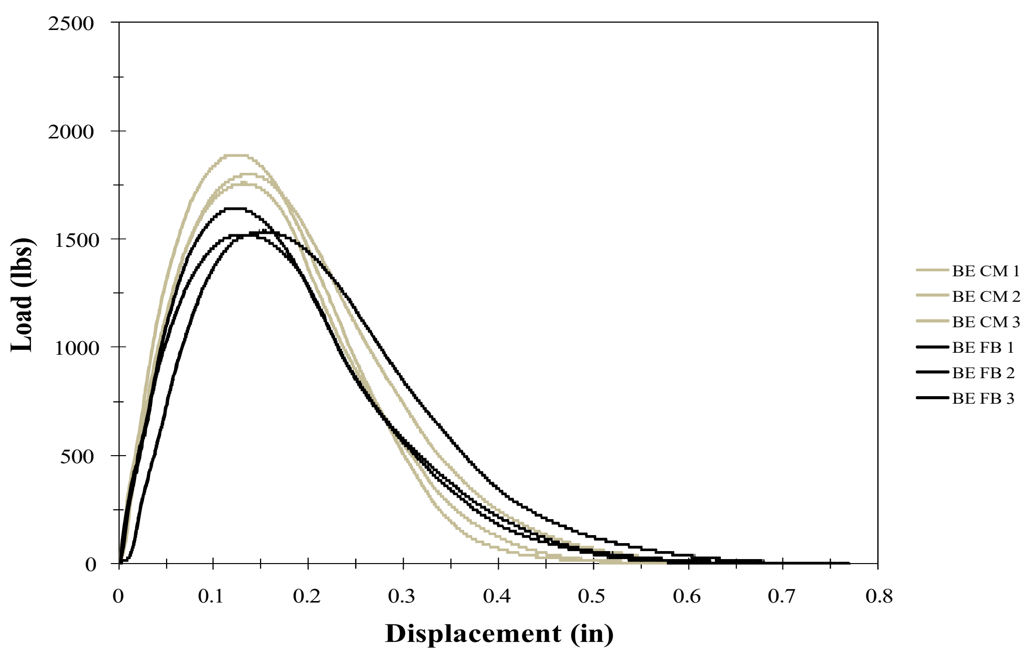

Figure 4-32: Load versus displacement for Box Elder HMA mix at 0.2 in/min loading rate.

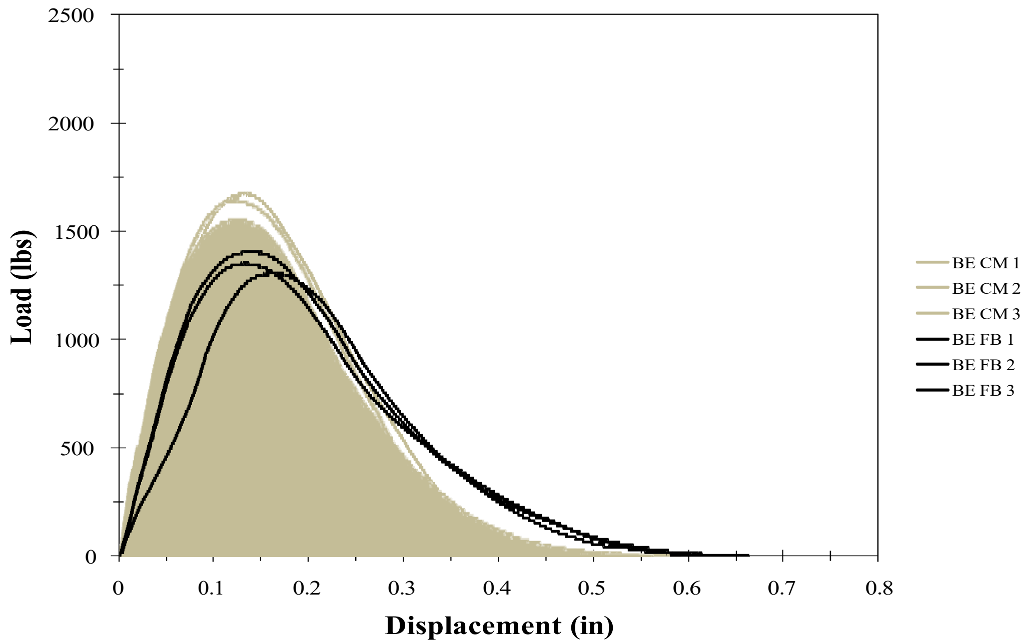

Figure 4-33: Load versus displacement for Box Elder HMA mix at 0.1 in/min loading rate.

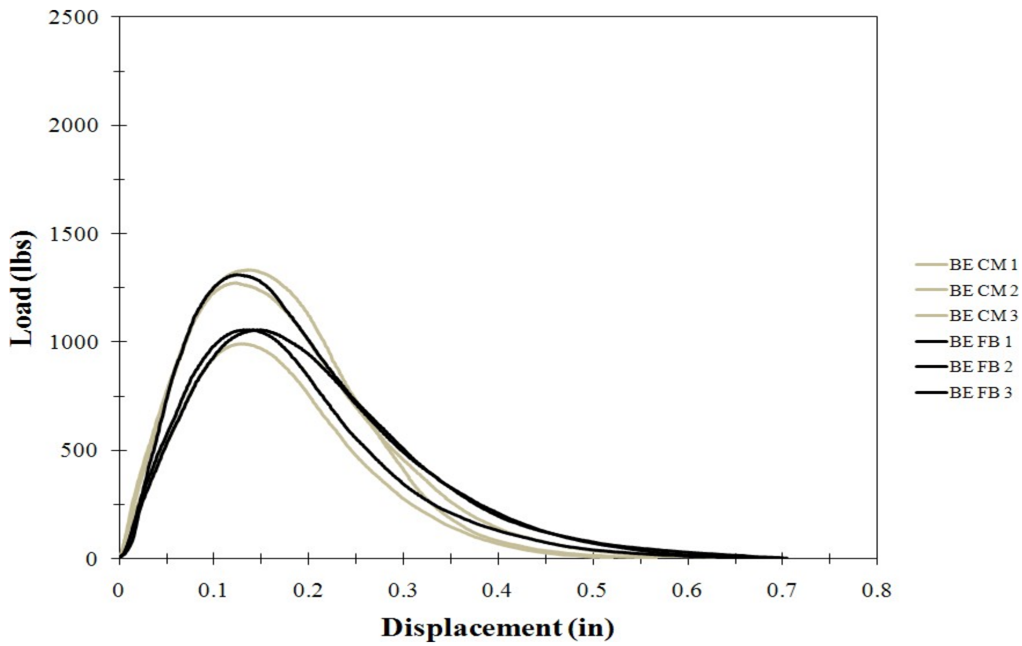

Figure 4-34: Load versus displacement for Box Elder HMA mix at 0.05 in/min loading rate.

Table 4-13: C* energy measurement results for Rapid City HMA mixes (lbf-in).

Rapid City Control HMA Mix						
	0.2 in/min		0.1 in/min		0.05 in/min	
Sample	Pre	Post	Pre	Post	Pre	Post
1	202	260	157	254	130	166
2	181	280	171	249	116	189
3	177	308	150	224	113	167
Average	**187**	**283**	**159**	**242**	**120**	**174**
Std. Dev.	13	24	11	16	9	13
COV	7%	9%	7%	7%	8%	7%
Rapid City Fiber Reinforced HMA Mix						
	0.2 in/min		0.1 in/min		0.05 in/min	
Sample	Pre	Post	Pre	Post	Pre	Post
1	199	268	124	202	102	134
2	200	277	122	204	105	171
3	163	229	117	216	36	113
Average	**187**	**258**	**121**	**207**	**81**	**139**
Std. Dev.	21	26	4	8	39	29
COV	11%	10%	3%	4%	48%	21%
	Energy Differential Between FB and CM Mix					
	0%	-9%	-24%	-14%	-32%	-20%

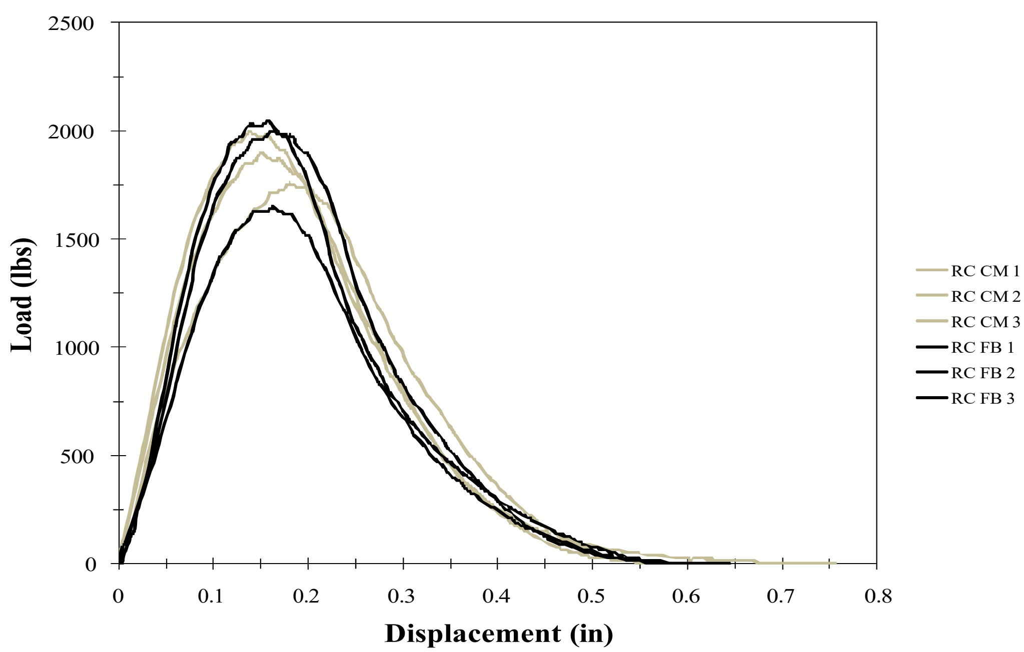

Figure 4-35: Load versus displacement for Rapid City HMA mix at 0.2 in/min loading rate.

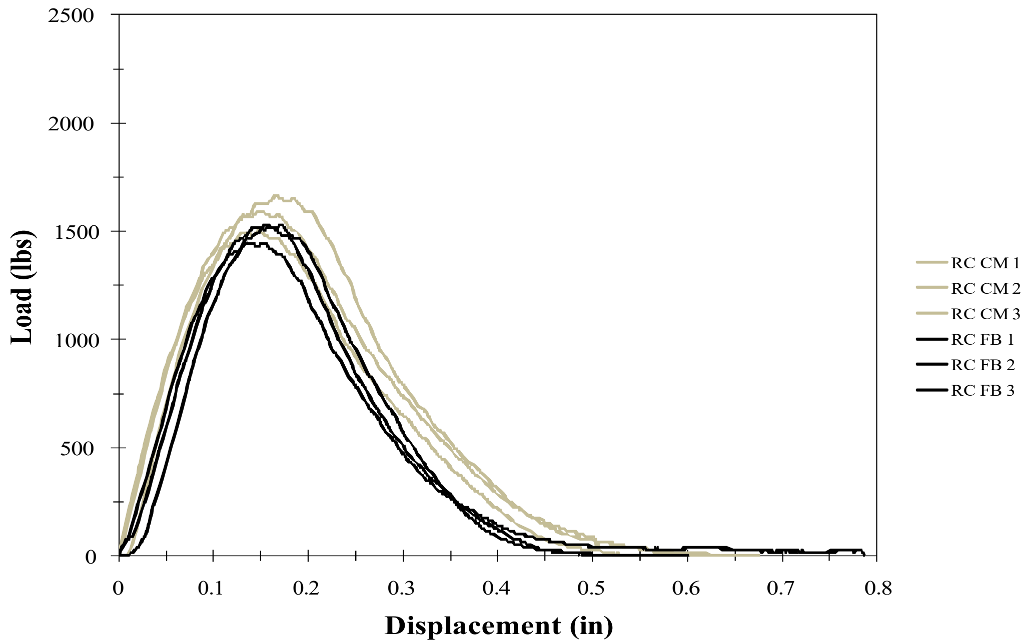

Figure 4-36: Load versus displacement for Rapid City HMA mix at 0.1 in/min loading rate.

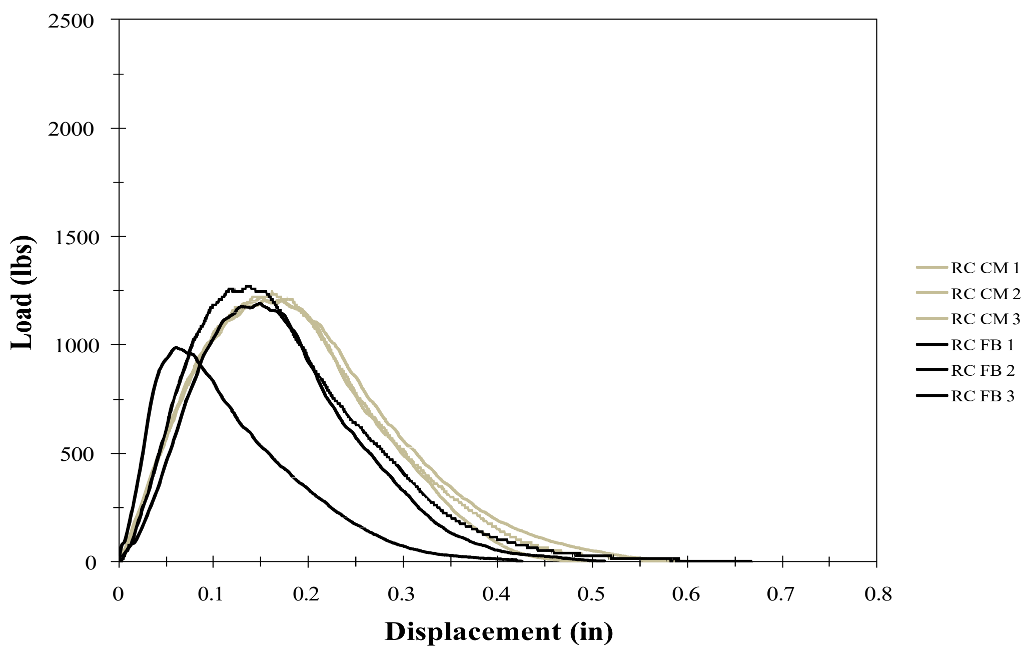

Figure 4-37: Load versus displacement for Rapid City HMA mix at 0.05 in/min loading rate.

4.5 Dynamic Modulus Test

The dynamic modulus testing was conducted on the Minnesota and Box Elder control and fiber reinforced HMA mixes. The fabrication of the dynamic modulus specimens is discussed in detail in Chapter 3. The target air void for the specimens was selected as 7% ± 0.5%. Therefore, after coring, sawing, and drying of the fabricated specimens, it was necessary to measure the percentage of air voids via the bulk specific gravity test. Three specimens each of the control and fiber reinforced HMA mixes were fabricated for the dynamic modulus testing. For the Minnesota material, the average air void percentage within the three specimens was determined to be 7.5% and 7.1% for the control and fiber reinforced HMA mixes, respectively. For the Box Elder material, the average air void percentage within the three specimens was determined to be 6.6% and 7.1% for the control and fiber reinforced HMA mixes, respectively. It should be noted that one of the control HMA specimens from the Minnesota mix contained an air void content slightly greater than the tolerance (7.7%), yet it was determined by the research team to proceed with the testing of that specimen.

The dynamic modulus testing was conducted as described in Chapter 3. The results of the dynamic modulus testing, which include the dynamic modulus and phase angle values for each specimen at each temperature and frequency, are provided in Appendix B. Using those results, the averaged dynamic modulus values (i.e. mean) for the three specimens at each testing temperature and frequency are provided in Table 4-6 and Table 4-7 for the Minnesota control and fiber reinforced HMA mix, respectively, and Table 4-10 and Table 4-11 for the Box Elder control and fiber reinforced HMA mix, respectively. The averaged phase angle values for the three specimens at each testing temperature and frequency are provided in Table 4-8 and Table 4-9 for the Minnesota control mix and fiber reinforced HMA mix, respectively, and Table 4-12 and Table 4-13 for the Box Elder control and fiber reinforced HMA mix, respectively. Each of these tables also provides the standard deviation and coefficient of variation (COV) within the testing results, which serve as data quality indicators. For example, as observed from Table 4-6 and Table 4-7, the COV within the test results for the Minnesota control HMA and fiber reinforced HMA mixes are less than 30%, with most of the COV values less than 20%. This is indicative of relative repeatability and consistency within the testing. The COV values within the phase angle test results for both the control and fiber reinforced HMA mixes from Minnesota are generally less than 10% as observed in Table 4-8 and 4-9, respectively. Similarly, as observed in Table 4-10 and Table 4-11, the COV within the test results for the Box Elder control HMA and fiber reinforced HMA mixes is generally less than 30%; however, several frequency and temperature combinations for the control HMA mix contain COV magnitudes greater than 30%, thereby indicating less confidence in the repeatability and consistency within the testing. In addition, the COV values within the phase angle test results for both the control and fiber reinforced HMA mixes from Box Elder are generally less than 20% as observed in Table 4-12 and 4-13, respectively.

Table 4-14: Dynamic modulus statistical data for Minnesota control HMA mix.

Dynamic Modulus (psi)							
Temperature (°C)		Frequency (Hz)					
		25	10	5	1	0.5	0.1
4.4	Mean	1,200,049	1,041,012	923,662	682,554	577,370	378,467
	Std. Dev.	305,202	253,347	217,676	170,414	141,261	84,353
	COV	25%	24%	24%	25%	24%	22%
21.1	Mean	578,314	456,909	376,340	202,391	160,900	100,433
	Std. Dev.	79,439	59,158	52,156	12,584	7,488	10,977
	COV	14%	13%	14%	6%	5%	11%
37.8	Mean	182,286	128,373	98,991	55,069	47,102	32,274
	Std. Dev.	15,571	11,454	8,429	5,124	3,162	1,703
	COV	9%	9%	9%	9%	7%	5%
54.0	Mean	77,396	52,668	40,202	24,848	20,637	14,982
	Std. Dev.	13,947	9,191	6,753	3,360	2,407	1,126
	COV	18%	17%	17%	14%	12%	8%

Table 4-15: Dynamic modulus statistical data for Minnesota fiber reinforced HMA mix.

Dynamic Modulus (psi)							
Temperature (°C)		Frequency (Hz)					
		25	10	5	1	0.5	0.1
4.4	Mean	1,126,789	958,482	842,652	579,017	479,410	299,668
	Std. Dev.	158,755	117,822	99,212	90,814	58,866	31,382
	COV	14%	12%	12%	16%	12%	10%
21.1	Mean	595,505	459,164	368,097	188,407	146,235	85,644
	Std. Dev.	47,514	31,013	21,461	22,395	19,042	6,289
	COV	8%	7%	6%	12%	13%	7%
37.8	Mean	149,340	102,028	77,675	43,647	38,608	27,191
	Std. Dev.	543	518	1,322	453	722	1,461
	COV	0.40%	1%	2%	1%	2%	5%
54.0	Mean	64,810	44,082	34,196	23,253	19,056	14,850
	Std. Dev.	15,403	10,888	8,525	6,387	4,976	4,308
	COV	24%	25%	25%	27%	26%	29%

Table 4-16: Phase angle statistical data for Minnesota control HMA mix.

Phase Angle (deg)							
Temperature (°C)		Frequency (Hz)					
		25	10	5	1	0.5	0.1
4.4	Mean	13.9	15.5	16.7	20.5	22.7	27.1
	Std. Dev.	1.9	1.5	1.3	1.2	0.8	0.8
	COV	14%	9%	8%	6%	4%	3%
21.1	Mean	24.4	26.4	28.0	31.8	32.0	32.3
	Std. Dev.	1.8	1.4	1.5	1.2	0.5	2.2
	COV	7%	5%	5%	4%	2%	7%
37.8	Mean	31.5	31.5	30.9	29.2	27.4	23.4
	Std. Dev.	0.3	0.6	0.7	1.0	1.2	1.3
	COV	1%	2%	2%	3%	4%	5%
54.0	Mean	33.5	31.8	30.2	25.2	23.0	17.7
	Std. Dev.	0.3	0.3	0.6	1.6	1.7	1.6
	COV	1%	1%	2%	6%	7%	9%

Table 4-17: Phase angle statistical data for Minnesota fiber reinforced HMA mix.

Phase Angle (deg)							
Temperature (°C)		Frequency (Hz)					
		25	10	5	1	0.5	0.1
4.4	Mean	14.7	16.6	18.4	23.0	25.4	30.1
	Std. Dev.	1.0	0.7	0.8	1.5	1.2	1.2
	COV	7%	4%	5%	6%	5%	4%
21.1	Mean	26.7	28.4	30.5	33.5	33.3	32.4
	Std. Dev.	1.5	1.0	0.8	0.4	0.4	1.3
	COV	6%	4%	3%	1%	1%	4%
37.8	Mean	32.8	32.4	31.5	28.3	26.3	21.9
	Std. Dev.	0.7	0.6	0.6	1.1	1.4	2.0
	COV	2%	2%	2%	4%	6%	9%
54.0	Mean	34.0	31.2	28.6	23.2	19.9	16.1
	Std. Dev.	0.8	0.9	1.3	1.4	2.3	1.4
	COV	2%	3%	4%	6%	12%	9%

Table 4-18: Dynamic modulus statistical data for Box Elder control HMA mix.

Temperature (°C)		Dynamic Modulus (psi) Frequency (Hz) 25	10	5	1	0.5	0.1
4.4	Mean	2,538,759	2,202,207	1,988,059	1,648,534	1,454,229	969,875
	Std. Dev.	226,229	220,347	207,093	234,725	224,473	177,750
	COV	9%	10%	10%	14%	15%	18%
21.1	Mean	924,018	706,383	575,091	329,403	262,377	158,529
	Std. Dev.	101,317	96,962	92,897	67,174	53,433	32,925
	COV	11%	14%	16%	20%	20%	21%
37.8	Mean	347,665	242,413	184,731	98,428	96,599	69,375
	Std. Dev.	117,509	89,929	70,859	36,832	28,488	16,042
	COV	34%	37%	38%	37%	29%	23%
54.0	Mean	125,711	88,163	68,255	42,472	52,933	41,983
	Std. Dev.	46,681	28,866	20,391	8,297	7,996	5,411
	COV	37%	33%	30%	20%	15%	13%

Table 4-19: Dynamic modulus statistical data for Box Elder fiber reinforced HMA mix.

Temperature (°C)		Dynamic Modulus (psi) Frequency (Hz) 25	10	5	1	0.5	0.1
4.4	Mean	2,338,231	2,168,939	2,005,763	1,699,643	1,535,303	1,134,978
	Std. Dev.	470,779	363,813	308,664	435,236	411,210	210,511
	COV	20%	17%	15%	26%	27%	19%
21.1	Mean	983,132	797,877	669,808	403,007	321,517	192,258
	Std. Dev.	74,674	68,028	68,161	64,695	57,551	43,974
	COV	8%	9%	10%	16%	18%	23%
37.8	Mean	347,930	244,029	187,882	100,204	96,022	68,099
	Std. Dev.	58,477	50,269	43,458	24,990	18,154	7,638
	COV	17%	21%	23%	25%	19%	11%
54.0	Mean	105,684	74,197	58,765	35,532	47,010	36,897
	Std. Dev.	28,262	18,229	14,158	6,345	4,843	3,158
	COV	27%	25%	24%	18%	10%	9%

Table 4-20: Phase angle statistical data for Box Elder control HMA mix.

Phase Angle (deg)							
Temperature (°C)		Frequency (Hz) 25	10	5	1	0.5	0.1
4.4	Mean	10.9	12.3	13.5	17.9	19.9	24.5
	Std. Dev.	1.9	1.4	1.5	2.2	2.6	2.6
	COV	18%	12%	11%	12%	13%	11%
21.1	Mean	23.5	25.8	27.5	31.5	31.5	30.4
	Std. Dev.	1.5	2.3	2.3	1.6	0.4	1.6
	COV	7%	9%	8%	5%	1%	5%
37.8	Mean	31.9	32.2	31.9	31.2	26.1	21.4
	Std. Dev.	2.9	2.3	1.4	0.5	2.0	2.5
	COV	9%	7%	5%	2%	8%	12%
54.0	Mean	32.1	29.4	27.8	24.0	18.5	15.6
	Std. Dev.	1.6	3.0	3.5	4.7	1.8	1.0
	COV	5%	10%	13%	20%	10%	6%

Table 4-21: Phase angle statistical data for Box Elder fiber reinforced HMA mix.

Phase Angle (deg)							
Temperature (°C)		Frequency (Hz) 25	10	5	1	0.5	0.1
4.4	Mean	8.6	9.4	10.5	12.9	14.4	18.1
	Std. Dev.	0.3	1.3	1.3	2.5	2.9	4.1
	COV	3%	14%	13%	19%	20%	22%
21.1	Mean	20.9	22.8	24.7	29.9	31.0	32.2
	Std. Dev.	2.1	2.5	2.7	3.3	2.9	1.9
	COV	10%	11%	11%	11%	9%	6%
37.8	Mean	31.0	31.5	31.3	31.2	27.8	23.1
	Std. Dev.	2.7	2.2	1.4	0.6	2.9	4.5
	COV	9%	7%	5%	2%	11%	20%
54.0	Mean	31.9	29.0	27.1	23.9	19.2	16.8
	Std. Dev.	0.6	1.8	2.1	3.4	3.0	2.6
	COV	2%	6%	8%	14%	15%	15%

The dynamic modulus and phase angle test data reported in Tables 4-6 to 4-13 was utilized to develop Table 4-14 and Table 4-15 in order to determine the difference (i.e. either an increase or decrease) within the dynamic modulus and phase angle results between the control HMA mix (CM) and fiber reinforced HMA mix (FB) for the Minnesota and Box Elder sites, respectively. As observed from Table 4-14 for the Minnesota site, the magnitude of the dynamic modulus tended to decrease with the addition of the fibers to the HMA mix, while the phase angle tended to increase. A decrease in the dynamic modulus with a corresponding increase in the phase angle is indicative of a shift from a purely elastic response of the material to a more viscous response. Interestingly, as observed from Table 4-15 for the Box Elder site, the magnitude of the dynamic modulus tended to increase with the addition of the fibers at the lower temperatures and decrease at the higher temperatures. In addition, the magnitude of the phase angle tended to decrease with the addition of the fibers at the lower temperatures and slightly increase (or remain relatively constant) at the higher temperatures. Therefore, the Box Elder fiber reinforced HMA mix tended to respond more elastically at the lower testing temperatures and more viscously at the higher testing temperatures. It is important to note that the magnitude of the dynamic modulus of the Box Elder control mix is nearly two times greater than the Minnesota control mix. Therefore, the stiffness and dynamic response of the two mixes is obviously significantly different and is likely a considerable contributor to the observed results of the dynamic modulus testing. For example, based on the results of the dynamic modulus testing for this project, it is not known if either greater elastic or viscous behavior within the HMA mixes would lead to greater distress within an in-situ pavement structure without testing the same materials for rutting potential or fatigue. In addition, although not directly examined in this project, it is theorized that the addition of fibers would ultimately reduce load-related cracking (i.e. tensile failure) of the pavement. To that end, further research that includes an expanded laboratory testing matrix that includes dynamic modulus, repeated load triaxial, and fatigue testing, along with monitoring of field test sections, will allow for development of improved transfer functions that would properly reflect the observed distress behavior of the fiber reinforced HMA material, which is critical to the M-EPDG design approach. For completeness, the dynamic modulus results from the control and fiber reinforced HMA mixes have been plotted as a series of E* Master Curves at various pavement temperatures in Figure 4-12 and Figure 4-13 for the Minnesota and Box Elder sites, respectively. The E* Master Curves were developed using the principle of time-temperature superposition and are plotted at a temperature of 45°F, 70°F, and 100°F. As observed from Figure 4-12 and Figure 4-13, the difference in the E* Master Curves between the control and fiber reinforced HMA mixes for both the Minnesota and Box Elder site does not appear to be significant at the three selected temperatures. Although some deviation between the curves is noted at very low frequencies within the mixes at both sites, the results of the E* Master Curves provide further support that additional investigation into the performance of fiber reinforced HMA (and WMA) mixes is warranted in order to obtain maximum benefits.

Table 4-22: Comparison of average dynamic modulus and phase angle values for control and fiber reinforced HMA mixes from Minnesota.

Temperature (°C)	Frequency (Hz)	Control (CM)		Fiber Reinforced (FB)		Change from CM to FB	
		Dynamic Modulus	Phase Angle	Dynamic Modulus	Phase Angle	Dynamic Modulus	Phase Angle
4.4	25	1,200,049	13.94	1,126,789	14.7	-6.50%	5.10%
	10	1,041,012	15.48	958,482	16.59	-8.60%	6.70%
	5	923,662	16.74	842,652	18.37	-9.60%	8.90%
	1	682,554	20.47	579,017	22.97	-17.90%	10.90%
	0.5	577,370	22.71	479,410	25.43	-20.40%	10.70%
	0.1	378,467	27.14	299,668	30.08	-26.30%	9.80%
21.1	25	578,314	24.4	595,505	26.66	2.90%	8.50%
	10	456,909	26.43	459,164	28.43	0.50%	7.00%
	5	376,340	27.96	368,097	30.54	-2.20%	8.50%
	1	202,391	31.8	188,407	33.52	-7.40%	5.10%
	0.5	160,900	31.96	146,235	33.28	-10.00%	4.00%
	0.1	100,433	32.25	85,644	32.38	-17.30%	0.40%
37.8	25	182,286	31.45	149,340	32.81	-22.10%	4.10%
	10	128,373	31.46	102,028	32.44	-25.80%	3.00%
	5	98,991	30.88	77,675	31.53	-27.40%	2.10%
	1	55,069	29.15	43,647	28.29	-26.20%	-3.00%
	0.5	47,102	27.42	38,608	26.29	-22.00%	-4.30%
	0.1	32,274	23.43	27,191	21.89	-18.70%	-7.00%
54.0	25	77,396	33.46	64,810	34.02	-19.40%	1.60%
	10	52,668	31.76	44,082	31.19	-19.50%	-1.80%
	5	40,202	30.21	34,196	28.58	-17.60%	-5.70%
	1	24,848	25.23	23,253	23.19	-6.90%	-8.80%
	0.5	20,637	23.04	19,056	19.93	-8.30%	-15.60%
	0.1	14,982	17.7	14,850	16.14	-0.90%	-9.70%
					Average	-14.10%	1.70%

Table 4-23: Comparison of average dynamic modulus and phase angle values for control and fiber reinforced HMA mixes from Box Elder.

Temperature (°C)	Frequency (Hz)	Control (CM) Dynamic Modulus	Control (CM) Phase Angle	Fiber Reinforced (FB) Dynamic Modulus	Fiber Reinforced (FB) Phase Angle	Change from CM to FB Dynamic Modulus	Change from CM to FB Phase Angle
4.4	25	2,538,759	10.9	2,338,231	8.6	-8.6%	-27.0%
	10	2,202,207	12.3	2,168,939	9.4	-1.5%	-31.2%
	5	1,988,059	13.5	2,005,763	10.5	0.9%	-29.1%
	1	1,648,534	17.9	1,699,643	12.9	3.0%	-38.6%
	0.5	1,454,229	19.9	1,535,303	14.4	5.3%	-38.0%
	0.1	969,875	24.5	1,134,978	18.1	14.5%	-35.0%
21.1	25	924,018	23.5	983,132	20.9	6.0%	-12.6%
	10	706,383	25.8	797,877	22.8	11.5%	-13.2%
	5	575,091	27.5	669,808	24.7	14.1%	-11.2%
	1	329,403	31.5	403,007	29.9	18.3%	-5.4%
	0.5	262,377	31.5	321,517	31.0	18.4%	-1.4%
	0.1	158,529	30.4	192,258	32.2	17.5%	5.7%
37.8	25	347,665	31.9	347,930	31.0	0.1%	-2.9%
	10	242,413	32.2	244,029	31.5	0.7%	-2.1%
	5	184,731	31.9	187,882	31.3	1.7%	-1.9%
	1	98,428	31.2	100,204	31.2	1.8%	0.2%
	0.5	96,599	26.1	96,022	27.8	-0.6%	6.1%
	0.1	69,375	21.4	68,099	23.1	-1.9%	7.1%
54.0	25	125,711	32.1	105,684	31.9	-18.9%	-0.7%
	10	88,163	29.4	74,197	28.9	-18.8%	-1.6%
	5	68,255	27.8	58,765	27.1	-16.1%	-2.8%
	1	42,472	24.0	35,532	23.9	-19.5%	-0.4%
	0.5	52,933	18.5	47,010	19.2	-12.6%	4.0%
	0.1	41,983	15.6	36,897	16.8	-13.8%	6.9%
					Average	0.1%	-9.4%

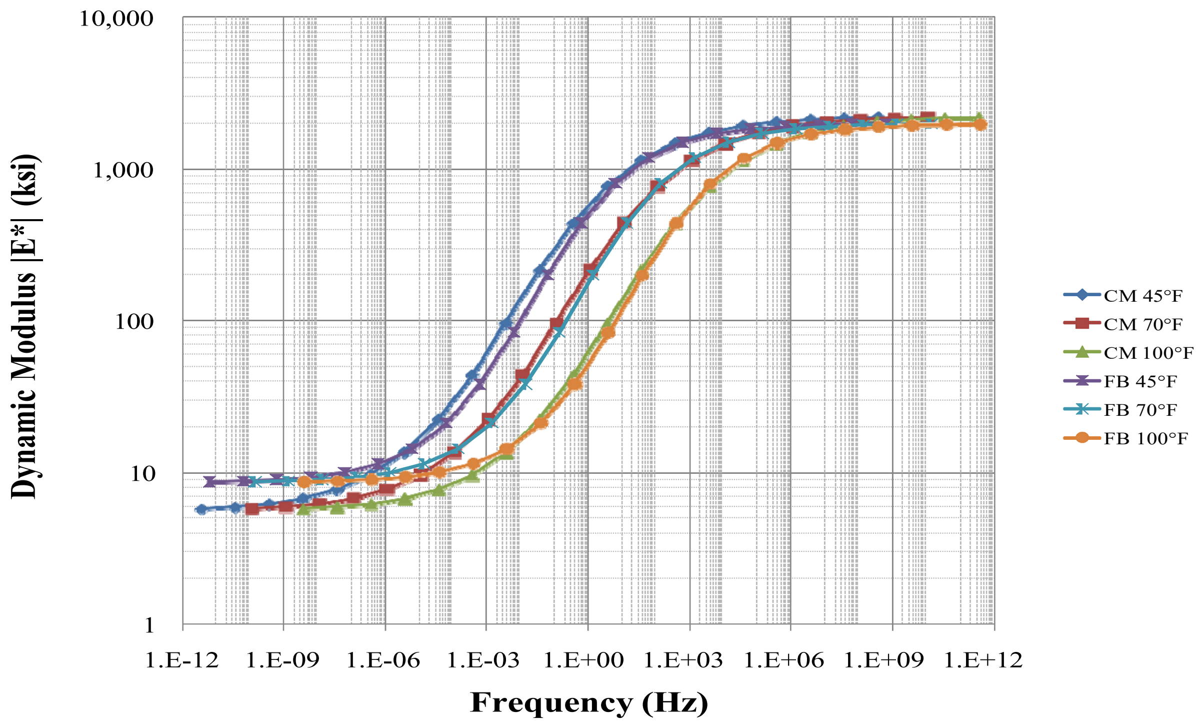

Figure 4-38: E* Master Curves for control and fiber reinforced HMA mixes from Minnesota site at various pavement temperatures.

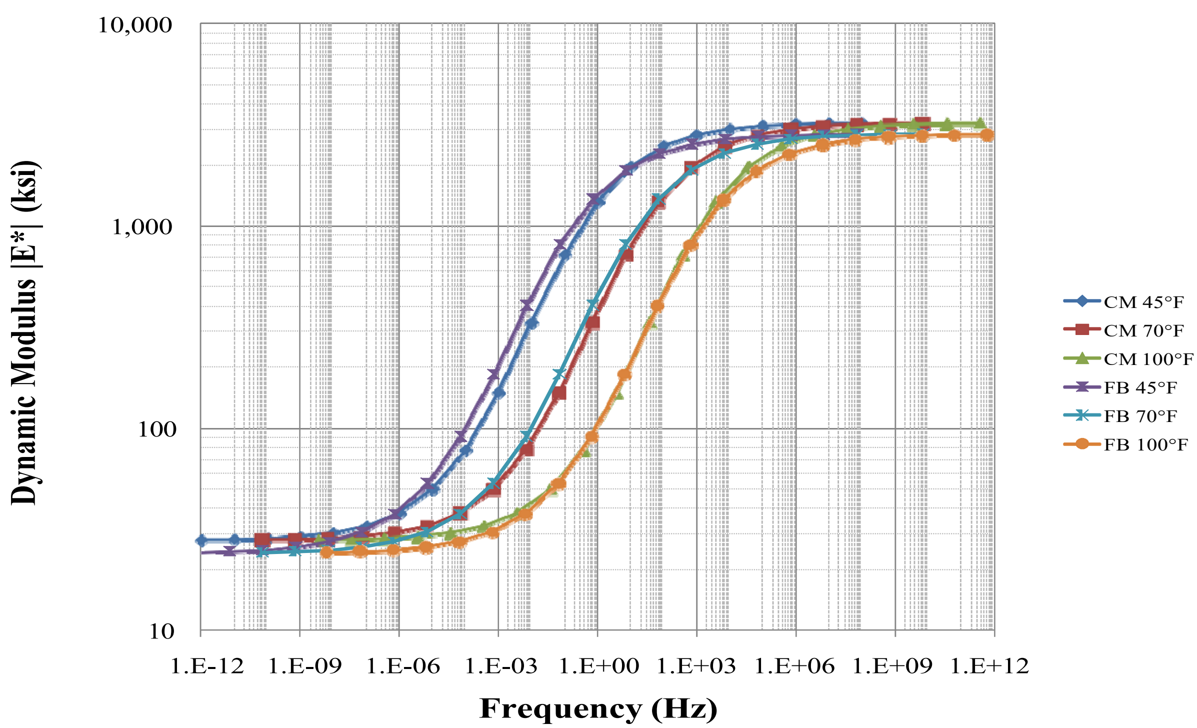

Figure 4-39: E* Master Curves for control and fiber reinforced HMA mixes from Box Elder site at various pavement temperatures.

4.6 Asphalt Burn-off Results

The results of the asphalt burn-off on laboratory specimens for all HMA materials tested for this project are provided in Table 4-16. These results are presented for information only as no correction factors for the aggregates were applied to the burn-off computations. Ideally, chemical extraction should be conducted in order to properly assess the liquid AC content. However, as observed from Table 4-16, it is likely that the range of the liquid AC content between the four mixes tested for this project is significant. It is theorized that the percentage of liquid AC in the HMA mix may contribute significantly to the behavior of the fiber reinforced mixes as the mixes with higher liquid AC content should have the ability to more easily coat and properly bond the fibers into the asphalt matrix. In general, the reported liquid AC content of the fiber reinforced mixes is higher than the conventional mixes, which is likely the result of the weight loss calculations including the loss of the liquid oil and fibers during the burning process.

Table 4-24: Asphalt binder percentage based on burn-off tests.

	Rapid City		Sioux Falls		Minnesota		Box Elder	
	CM	FB	CM	FB	CM	FB	CM	FB
Sample Weight (gram)	1205	1218	1247	1237	1209	1368	1448	1237
Weight Loss (gram)	54.5	58.2	76.2	84.2	80.7	97.7	73.7	61.6
Weight Loss (%)	4.52%	4.78%	6.11%	6.81%	6.67%	7.14%	5.09%	4.98%
Temp. Comp.	0.22%	0.25%	0.24%	0.21%	0.25%	0.22%	0.21%	0.23%
Bitumen Ratio	4.52%	4.77%	6.27%	7.09%	6.90%	7.47%	5.16%	5.01%
Calibrated AC Content	4.31%	4.53%	5.87%	6.60%	6.43%	6.92%	4.88%	4.75%

CHAPTER 5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Introduction

The purpose of this research project was to perform a preliminary laboratory evaluation of fiber reinforced asphalt concrete pavement materials. Fiber reinforced and conventional HMA mixes were obtained from project sites in Rapid City, South Dakota, Sioux Falls, South Dakota, Taylors Falls, Minnesota, and Box Elder, South Dakota. The details related to the HMA mixes and the construction at each of the test sites was provided in Chapter 2. In Chapter 3, the various laboratory testing procedures were outlined in order to ensure consistency within the testing protocol. The preliminary laboratory evaluation included indirect-tensile strength (ITS) testing, C* energy measurement testing, and dynamic modulus testing. Supplementary analyses, such as gradation and in-place asphalt content, were also conducted for completeness within the project. The results of the preliminary laboratory testing program were presented in Chapter 4. This chapter will provide the final conclusions based on the preliminary laboratory investigation program and will also provide recommendations for future research involving fiber reinforced asphalt materials.

5.2 Conclusions

The HMA mixes tested in the laboratory for this project consisted of a relatively wide array of aggregate types, liquid asphalt cement (AC) binder types, liquid AC binder content, and RAP percentages, which was beneficial in order to examine the broader performance of fiber reinforced HMA mixes. From the laboratory testing results presented in Chapter 4, it was observed that for the Sioux Falls and Minnesota HMA mixes tested for this project, the fiber reinforced HMA mixes possessed greater indirect-tensile strength and greater pre-crack and post-crack energy absorption when compared to the conventional HMA mixes. The results are summarized as follows:

- The increase in the indirect-tensile strength (ITS) was observed to be approximately 43% and 16% for the unconditioned samples of the Sioux Falls and Minnesota fiber reinforced HMA mixes, respectively. For the conditioned samples, the increase in indirect-tensile strength was observed to be approximately 98% and 15% for the Sioux Falls and Minnesota fiber reinforced HMA mixes, respectively.
- For the Minnesota fiber reinforced HMA mix, the increase in the pre-crack energy absorption was observed to be between 21% and 52%. The increase in the post-crack energy absorption was observed to be between 9% and 43%. The percentage increase for both the pre-crack and post-crack energy absorption magnitudes is dependent upon the loading speed of the C* energy measurement test.

These general strength characterization tests provide evidence that the introduction of the fibers into a conventional HMA mix can increase the basic strength performance of the material. This increase in laboratory performance relates to increased resistance to tensile cracking in the field and thus fewer pavement distresses, longer design life, and decreased maintenance. The introduction of fibers into the Rapid City and Box Elder HMA mixes did not always result in an increase in the indirect-tensile strength or pre and post-crack energies, which may be related to the tight gradation, and thus high quality, of these mixes, along with the low asphalt content of these mixes. Further examination as to the cause of this lack of increase should be conducted.

In the case of the dynamic modulus testing, the following was observed:

- For the Minnesota site, the fiber reinforced HMA possessed a lower dynamic modulus and increased phase angle at all testing temperatures when compared to the conventional HMA mix. This indicates an overall reduction in the stiffness of the mix and increased viscous behavior with the addition of the fiber.
- For the Box Elder site, the fiber reinforced HMA possessed a higher dynamic modulus and decreased phase angle at the lower testing temperatures, and a lower dynamic modulus and increased phase angle at the higher testing temperatures when compared to the conventional HMA mix. This indicates decreased viscous behavior at lower temperatures and increased viscous behavior at higher temperatures with the addition of the fiber.

The dynamic modulus testing results for both sites were utilized to develop a series of E* Master Curves at different pavement temperatures. The results of the E* Master Curves indicate slight variations within the magnitude of the dynamic modulus between the control and fiber reinforced HMA mix over the range of frequencies. Overall, the greatest variation within the magnitude of E* between the conventional and fiber reinforced HMA mixes occurs at very low frequencies. It is important to note that the magnitude of E* is a general indication of the quality of the HMA mix, and a lower value of E* is not necessarily indicative of an inferior material. In fact, too high of an E* value represents a brittle mix which may suffer extensive cracking, while too low of an E* value represents a soft mix which may suffer extensive rutting. However, it is the combination of the E* value, along with a number of other parameters, that are utilized to predict the performance of the pavement using a mechanistic-empirical design approach.

Visual surveys of all test section locations indicate that no visible distresses have been observed in the fiber reinforced HMA. At the test site in Sioux Falls, minor rutting has been observed in the conventional HMA test section, with no rutting in the fiber reinforced HMA test section. At the test site in Rapid City, minor transverse cracking was noted in a non-reinforced HMA test section, with no transverse cracking in the fiber reinforced HMA test section. No substantial distresses have been noted in any of the fiber reinforced test sections at the Minnesota or Box Elder test sites.

5.3 Recommendations

The purpose of this research project was to perform a preliminary laboratory evaluation of fiber reinforced asphalt concrete pavement materials. To that end, the laboratory testing program was rather limited in scope and focused predominately on strength, toughness, and stiffness characterization tests. The following recommendations are made based on the results of the laboratory testing program:

1. Although an observable increase in the strength and energy absorption within two of the fiber reinforced HMA mixes was realized, it is recommended to expand the laboratory testing program to include the following tests that may better characterize the potential improvement in performance of fiber reinforced HMA materials as follows:

    - Resistance of fiber reinforced HMA mixes to permanent deformation using the repeated load triaxial (RLT) test. This test can provide an indication of the rutting potential of the fiber reinforced HMA mix compared to a conventional HMA mix.
    - Resistance of fiber reinforced HMA mixes to fatigue cracking using the flexural beam fatigue test. This test can provide an indication of the fatigue life of the fiber reinforced HMA mix, which is defined as the number of loading cycles to achieve fatigue damage (i.e. 50% reduction in the initial stiffness).
    - Resistance of fiber reinforced HMA mixes to thermal cracking using the thermal stress restrained specimen test (TSRST) or a similar test. This test can measure the field temperature at which the fiber reinforced HMA pavement will experience thermal cracking (i.e. "fracture temperature"). The measurement of thermal cracking performance is particularly beneficial in colder climates, like South Dakota, where thermal effects may be the predominant cause of HMA pavement distresses.

    These laboratory tests have been specifically recommended for further investigation because it is theorized that the addition of fibers to a conventional HMA mix should improve the rutting, fatigue, and thermal performance of the mix due to the increase in the tensile strength and improved fracture behavior within the liquid asphalt matrix. These properties, in addition to the dynamic modulus, are important for pavement design using the Mechanistic-Empirical Pavement Design Guide (M-EPDG) approach. It is likely that the M-EPDG approach will be required for all HMA pavement designs in lieu of the current AASHTO *Guide for Design of Pavement Structures* (AASHTO 1993). Comparative pavement designs that examine pavement life or pavement thickness can be conducted using the M-EPDG approach for a conventional and fiber reinforced HMA mix, which can provide a direct indication of the potential economic benefits of using fiber reinforced asphalt in paving projects based on the goals of the transportation agency.

2. Construction and long-term monitoring of field test sections consisting of both conventional and fiber reinforced HMA materials is recommended. Obviously, a side-by-side comparison of long-term performance of conventional and fiber reinforced HMA pavements can provide direct evidence of the potential reduction in distress and maintenance achieved using fiber reinforcing in HMA mixes and can provide basic design correlations to the laboratory testing results, such as those obtained in this project. A long-term pavement monitoring program will also allow for development of transfer functions that can also be utilized directly in the M-EPDG approach. Transfer functions are empirically derived mathematical relationships that relate the critical pavement response parameter to pavement distress. The default transfer functions that are currently used in the M-EPDG approach to predict pavement distress may not be representative of the behavior of a fiber reinforced asphalt mix and thus significant benefit in design should be realized by developing these functions independently for these types of HMA mixes. In addition, long-term pavement monitoring that includes International Roughness Index (IRI) measurements, along with Falling Weight Deflectometer (FWD) measurements and back-calculation of dynamic modulus can provide insight into the performance of fiber reinforced asphalt pavement materials in the field over time.

3. Since two of the HMA mixes tested for this project did not possess an increase in strength or toughness with the addition of the fibers, it is recommended that the mix characteristics, such as aggregate composite gradation, aggregate type, liquid AC binder quantity, and liquid AC binder type be investigated in order to identify possible reasons why certain mixes may not benefit from the fibers. For example, it is theorized that a minimum amount of liquid AC binder must be available in order to coat and properly bond the fibers into the asphalt matrix. In addition, the aggregate composite gradation of the mix may be such that the fibers are not able to properly disperse into the available pore space of the mix without an extended mixing time or without thorough mixing of the fibers into the dry components of the mix prior to deposition into the drum.

4. Investigate the use of a mobile automated system to introduce the fibers into the HMA mix. This could increase the reliability and consistency of the mix (i.e. quality control), as well as ensure proper dispersion of the fibers within the pore space of the mixture. This would also eliminate the need to station plant personnel at the RAP port on a larger fiber reinforced asphalt project and would reduce human error that is inherent with manual introduction of the fibers. This investigation should also include methods to add the fibers into the aggregate components of the mix, such as in a pugmill mixer, prior to the deposition into the drum. The addition and mixing of the fibers in this manner may further ensure proper dispersion of the fibers into a mix with a tight gradation due to the relatively low shear mixing behavior of most typical drum plants.

REFERENCES

AASHTO. (1993). *Guide for Design of Pavement Structures*. AASHTO, Washington, D.C.

AASHTO TP 62-07. (2007). "Standard Method of Test for Determining Dynamic Modulus of HMA". AASHTO, Washington, D.C.

AASHTO. (2009). *Standard Specifications for Transportation and Methods of Sampling and Testing*. 29th edition, Washington, D.C.

ASTM International. (2007). *Annual Book of ASTM Standards, Section Four, Construction*. Volume 04.08, Soil and Rock (I): D420-D5611, West Conshohocken, PA.

DuPont. (2010). *Technical Guide: KEVLAR Aramid Fiber*. DuPont Advanced Fiber Systems, www.dupont.com.

InstroTek Incorporated. (2003). *CoreLok Operator's Guide*. Version 20.

Kaloush, K.E., Biligiri, K.P., Zeiada, W.A., Rodezno, C., Dwivedi, S., Reed, J. and Cary, C. (2008). *Evaluation of FORTA Fiber-Reinforced Asphalt Mixtures Using Advanced Material Characterization Tests – Evergreen Drive, Tempe, Arizona*. Report No. 200903AT101, Ira A. Fulton School of Engineering, Arizona State University, Tempe, September 2008.

APPENDIX A

Rapid City Test Section Condition/Crack Survey

Survey date: 10-6-09			
Starting from the East side of the sidewalk on 8th Street			
11' 2" to start of milling			
Distance to crack		Length of crack	Transverse or longitudinal
(feet)	(inches)		
29	6	length 11' from N side	T
45	1	extends from curb across	T
95	3	3'6" from curb ends 118'10"	L
113	2	extends from curb across	T
118	10	Extends from curb 4'6"	L
122	2	Extends from curb 4'6"	T
115	8	6'6" from curb ends 126'7"	L
129	4	extends from curb across	T
133	6	extends from curb across	T
133	6	3'6" from curb ends 150'5"	L
142	8	extends from curb across	T
170	0	7' from curb ends 178'10"	L
182	10	extends from curb across	T
186	6	extends from curb across	T
206	10	extends from curb across	T
216	4	extends from curb across	T
222	10	extends from curb across	T
226	6	extends from curb across	T
261	8	extends from curb across	T
263	7	extends from curb across	T
267	0	extends from curb across	T
283	3	extends from curb across	T
288	0	extends from curb across	T
306	9	extends from curb across	T
312	2	extends from curb across	T
358	7	extends from curb across	T
366	4	extends from curb across	T
372	2	extends from curb across	T
375	0	12' from curb patch	Patch
401	10	extends from curb across	T
411	10	Patch start 11'3" NW corner and is 7'x12'	Patch
417	0	extends from curb across	T
422	2	extends from curb across	T
430	5	extends from curb across	T
441	0	Patch start 9'4" NW corner and 8'6"x23'	Patch
463	5	extends from curb across	T
472	2	extends from curb across	T
498	11	extends from curb across	T
527	0	zig zag crack	zig zag
590	10	extends from patch across	T
602	6	extends from patch across	T
609	1	extends from curb across	T
619	0	Patch 8'x4'6" NW corner	Patch
626	3	extends from curb across	T
636	9	extends from curb across	T
648	9	Pavement begins milling ends	
7th Street south side of sidewalk south side of intersection			
4	3	End of asphalt	
2	4	All the way across	T
15	10	All the way across	T
26	7	All the way across	T
68	1	All the way across begin side patchwork	
187	10	end of asphalt beginning of just subgrade	
378	5	Beginning of asphalt end of project 1.5" of asphalt at CL	
7' on either side of 7th street full depth patch			

APPENDIX B

Dynamic Modulus Test Data

Minnesota Control HMA Mix

		Sample 1		Sample 2		Sample 3		Average		CV	
Temp (°C)	Frequency (Hz)	Dynamic Modulus (psi)	Phase Angle (deg)	Dynamic Modulus (psi)	Phase Angle (deg)	Dynamic Modulus (psi)	Phase Angle (deg)	Dynamic Modulus (psi)	Phase Angle (deg)	Dynamic Modulus	Phase Angle
4.4	25	1,028,579	13.44	1,552,424	16.09	1,019,144	12.3	1,200,049	13.94	25.43%	13.95%
	10	885,509	15.2	1,333,353	17.05	904,174	14.18	1,041,012	15.48	24.34%	9.40%
	5	784,882	16.61	1,174,540	18.09	811,564	15.53	923,662	16.74	23.57%	7.68%
	1	567,134	20.59	878,285	21.57	602,243	19.26	682,554	20.47	24.97%	5.66%
	0.5	482,279	22.57	739,689	23.62	510,143	21.94	577,370	22.71	24.47%	3.74%
	0.1	319,009	27.03	475,009	28.02	341,383	26.37	378,467	27.14	22.29%	3.06%
21.1	25	595,501	23.4	647,753	23.37	491,689	26.43	578,314	24.40	13.74%	7.21%
	10	466,564	25.52	510,646	25.67	393,518	28.1	456,909	26.43	12.95%	5.48%
	5	386,932	27.18	422,387	27.02	319,702	29.67	376,340	27.96	13.86%	5.32%
	1	198,524	30.86	216,455	31.34	192,194	33.21	202,391	31.80	6.22%	3.90%
	0.5	156,609	31.4	169,546	32.3	156,545	32.19	160,900	31.96	4.65%	1.54%
	0.1	105,034	30.34	108,361	31.79	87,905	34.61	100,433	32.25	10.93%	6.73%
37.8	25	197,238	31.19	183,458	31.82	166,162	31.34	182,286	31.45	8.54%	1.05%
	10	140,051	31.53	127,910	31.98	117,157	30.87	128,373	31.46	8.92%	1.77%
	5	107,649	31.33	98,514	31.17	90,810	30.13	98,991	30.88	8.52%	2.11%
	1	60,985	29.84	52,226	29.63	51,997	27.99	55,069	29.15	9.31%	3.47%
	0.5	50,753	28.74	45,243	26.93	45,310	26.58	47,102	27.42	6.71%	4.23%
	0.1	34,212	24.9	31,019	22.59	31,590	22.81	32,274	23.43	5.28%	5.44%
54	25	91,688	33.24	76,679	33.31	63,822	33.84	77,396	33.46	18.02%	0.98%
	10	62,505	31.99	51,197	31.88	44,302	31.41	52,668	31.76	17.45%	0.97%
	5	47,319	30.9	39,403	29.95	33,884	29.78	40,202	30.21	16.80%	2.00%
	1	28,727	26.39	22,939	25.84	22,876	23.47	24,848	25.23	13.52%	6.15%
	0.5	23,179	24.89	20,340	22.72	18,392	21.51	20,637	23.04	11.66%	7.43%
	0.1	16,201	19.42	14,765	17.35	13,980	16.33	14,982	17.70	7.52%	8.90%

Minnesota Fiber Reinforced HMA Mix

		Sample 1		Sample 2		Sample 3		Average		CV	
Temp (°C)	Frequency (Hz)	Dynamic Modulus (psi)	Phase Angle (deg)	Dynamic Modulus (psi)	Phase Angle (deg)	Dynamic Modulus (psi)	Phase Angle (deg)	Dynamic Modulus (psi)	Phase Angle (deg)	Dynamic Modulus	Phase Angle
4.4	25	1,272,883	15.42	957,849	13.61	1,149,635	15.07	1,126,789	14.70	14.09%	6.53%
	10	1,066,889	16.39	833,089	16.03	975,467	17.35	958,482	16.59	12.29%	4.11%
	5	928,093	18.1	733,842	17.7	866,020	19.31	842,652	18.37	11.77%	4.56%
	1	661,167	22.85	481,500	21.58	594,383	24.48	579,017	22.97	15.68%	6.33%
	0.5	533,125	25.44	416,480	24.24	488,626	26.61	479,410	25.43	12.28%	4.66%
	0.1	328,676	30.01	266,356	28.93	303,972	31.31	299,668	30.08	10.47%	3.96%
21.1	25	618,655	25.82	540,853	25.76	627,007	28.39	595,505	26.66	7.98%	5.63%
	10	479,132	28.08	423,435	27.62	474,924	29.59	459,164	28.43	6.75%	3.62%
	5	382,424	30.12	343,422	30.04	378,443	31.47	368,097	30.54	5.83%	2.63%
	1	212,830	33.91	183,553	33.2	168,837	33.46	188,407	33.52	11.89%	1.07%
	0.5	166,252	33.47	144,104	32.81	128,348	33.57	146,235	33.28	13.02%	1.24%
	0.1	92,906	32.99	82,029	33.21	81,996	30.94	85,644	32.38	7.34%	3.87%
37.8	25	149,967	33.42	149,014	32.08	149,040	32.93	149,340	32.81	0.36%	2.07%
	10	102,507	33.16	102,098	31.97	101,479	32.2	102,028	32.44	0.51%	1.95%
	5	78,058	32.22	78,764	31.2	76,204	31.18	77,675	31.53	1.70%	1.89%
	1	43,924	29.06	43,124	28.79	43,894	27.03	43,647	28.29	1.04%	3.90%
	0.5	38,093	27.22	38,298	27.03	39,434	24.62	38,608	26.29	1.87%	5.51%
	0.1	26,676	22.79	26,057	23.34	28,840	19.55	27,191	21.89	5.37%	9.35%
54	25	55,168	34.03	56,689	34.83	82,574	33.21	64,810	34.02	23.77%	2.38%
	10	38,074	30.81	37,522	32.25	56,650	30.5	44,082	31.19	24.70%	2.99%
	5	28,845	28.79	29,715	29.75	44,027	27.21	34,196	28.58	24.93%	4.49%
	1	20,592	21.62	18,626	24.16	30,540	23.8	23,253	23.19	27.47%	5.93%
	0.5	16,687	19.62	15,708	22.39	24,774	17.78	19,056	19.93	26.11%	11.64%
	0.1	13,144	14.57	11,656	17.31	19,750	16.54	14,850	16.14	29.01%	8.76%

Box Elder Control HMA Mix

		Sample 1		Sample 2		Sample 3		Average		CV	
Temp (°C)	Frequency (Hz)	Dynamic Modulus (psi)	Phase Angle (deg)	Dynamic Modulus (psi)	Phase Angle (deg)	Dynamic Modulus (psi)	Phase Angle (deg)	Dynamic Modulus (psi)	Phase Angle (deg)	Dynamic Modulus	Phase Angle
	25	2,798,670	8.77	2,431,482	11.29	2,386,125	12.55	2,538,759	10.87	8.91%	17.71%
	10	2,455,205	10.6	2,099,095	12.99	2,052,322	13.2	2,202,207	12.26	10.01%	11.78%
	5	2,225,743	11.77	1,891,964	14.3	1,846,471	14.48	1,988,059	13.52	10.42%	11.21%
	1	1,915,487	15.44	1,474,464	18.5	1,555,650	19.62	1,648,534	17.85	14.24%	12.12%
	0.5	1,707,310	17.04	1,279,206	20.38	1,376,171	22.14	1,454,229	19.85	15.44%	13.05%
4.4	0.1	1,175,109	21.6	869,325	25.28	865,190	26.55	969,875	24.48	18.33%	10.50%
	25	998,323	22.34	965,124	22.95	808,608	25.24	924,018	23.51	10.96%	6.50%
	10	769,058	24.35	755,391	24.59	594,700	28.49	706,383	25.81	13.73%	9.00%
	5	634,502	26.01	622,733	26.28	468,038	30.08	575,091	27.46	16.15%	8.29%
	1	370,675	30.46	365,642	30.7	251,892	33.31	329,403	31.49	20.39%	5.02%
	0.5	295,461	31.07	290,938	31.44	200,734	31.91	262,377	31.47	20.36%	1.34%
21.1	0.1	177,898	31.41	177,177	31.25	120,512	28.53	158,529	30.40	20.77%	5.32%
	25	308,617	31.56	479,728	29.2	254,651	34.92	347,665	31.89	33.80%	9.01%
	10	212,294	32.07	343,535	29.96	171,409	34.49	242,413	32.17	37.10%	7.05%
	5	161,482	31.55	264,294	30.7	128,416	33.51	184,731	31.92	38.36%	4.51%
	1	87,677	30.69	139,438	31.63	68,167	31.18	98,428	31.17	37.42%	1.51%
	0.5	87,029	26.37	128,640	27.92	74,129	23.93	96,599	26.07	29.49%	7.71%
37.8	0.1	63,150	22.04	87,597	23.62	57,379	18.67	69,375	21.44	23.12%	11.79%
	25	109,763	32.5	178,276	33.52	89,093	30.33	125,711	32.12	37.13%	5.07%
	10	78,086	29.54	120,716	32.33	65,685	26.37	88,163	29.41	32.74%	10.14%
	5	60,376	28.05	91,410	31.22	52,980	24.15	68,255	27.81	29.87%	12.74%
	1	41,650	22.75	51,149	29.28	34,616	20.07	42,472	24.03	19.54%	19.71%
	0.5	47,278	18.89	62,082	20.01	49,440	16.47	52,933	18.46	15.11%	9.80%
54	0.1	37,284	16.3	47,898	15.99	40,765	14.49	41,983	15.59	12.89%	6.21%

Box Elder Fiber Reinforced HMA Mix

		Sample 1		Sample 2		Sample 3		Average		CV	
Temp (ºC)	Frequency (Hz)	Dynamic Modulus (psi)	Phase Angle (deg)	Dynamic Modulus (psi)	Phase Angle (deg)	Dynamic Modulus (psi)	Phase Angle (deg)	Dynamic Modulus (psi)	Phase Angle (deg)	Dynamic Modulus	Phase Angle
4.4	25	2,190,476	8.23	1,959,052	8.73	2,865,164	8.71	2,338,231	8.56	20.13%	3.31%
	10	2,043,907	9.88	1,884,130	7.86	2,578,781	10.31	2,168,939	9.35	16.77%	13.99%
	5	1,895,613	11.05	1,767,285	8.94	2,354,392	11.43	2,005,763	10.47	15.39%	12.81%
	1	1,422,674	13.74	1,474,951	10.09	2,201,303	14.82	1,699,643	12.88	25.61%	19.24%
	0.5	1,254,213	15.35	1,344,434	11.11	2,007,261	16.69	1,535,303	14.38	26.78%	20.25%
	0.1	958,637	19.45	1,078,260	13.58	1,368,038	21.36	1,134,978	18.13	18.55%	22.36%
21.1	25	899,685	22.07	1,006,050	18.47	1,043,662	22.08	983,132	20.87	7.60%	9.97%
	10	719,662	24.3	843,284	19.87	830,683	24.24	797,877	22.80	8.53%	11.14%
	5	595,439	26.22	729,305	21.55	684,679	26.32	669,808	24.70	10.18%	11.04%
	1	340,690	30.95	469,842	26.15	398,490	32.51	403,007	29.87	16.05%	11.10%
	0.5	269,497	31.73	383,340	27.83	311,715	33.57	321,517	31.04	17.90%	9.44%
	0.1	158,776	31.34	242,059	30.97	175,940	34.41	192,258	32.24	22.87%	5.86%
37.8	25	329,155	32.05	413,489	27.9	301,147	33	347,930	30.98	16.81%	8.75%
	10	222,845	32.41	301,423	29.03	207,818	33.09	244,029	31.51	20.60%	6.90%
	5	167,130	31.98	237,826	29.71	158,690	32.33	187,882	31.34	23.13%	4.54%
	1	87,287	30.55	129,008	31.65	84,316	31.5	100,204	31.23	24.94%	1.91%
	0.5	89,772	24.87	116,476	30.71	81,819	27.68	96,022	27.75	18.91%	10.52%
	0.1	65,823	19.16	76,616	28.03	61,857	22.02	68,099	23.07	11.22%	19.62%
54	25	85,204	31.24	137,928	32.05	93,921	32.36	105,684	31.88	26.74%	1.81%
	10	61,985	27.06	95,151	30.54	65,456	29.24	74,197	28.95	24.57%	6.07%
	5	48,959	24.84	74,997	28.93	52,340	27.4	58,765	27.06	24.09%	7.64%
	1	31,622	20.55	42,853	27.41	32,121	23.87	35,532	23.94	17.86%	14.33%
	0.5	45,414	16.26	52,450	22.18	43,166	19.23	47,010	19.22	10.30%	15.40%
	0.1	37,670	14.14	39,597	19.31	33,425	16.82	36,897	16.76	8.56%	15.43%