AMERICAN UNIVERSITY OF BEIRUT

ASSESSMENT OF NATURAL PALM FIBERS IN ASPHALT CONCRETE MIXTURES

by

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AMERICAN UNIVERSITY OF BEIRUT

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ABSTRACT OF THE THESIS

Leticia Hassan El Zein for Master of Engineering
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Title: Assessment of Asphalt Concrete Mixtures Reinforced with Natural Palm Fibers

The asphalt paving industry is moving towards environmentally friendly practices of which the use of renewable, and recycled materials is being researched and implemented. One such practice is the use of natural fibers as reinforcement elements in asphalt concrete (AC) mixtures. Commonly used natural fibers, which can be described as threaded-like organic filaments, are preferred over of synthetic fibers because they are locally available, eco-friendly, economical, and spur economic benefits in the agricultural and industrial sectors. It has been found that the use of natural fibers often improves the mechanical behavior and performance of AC which leads to increased durability and extended service life of flexible pavements. This study investigates the effect of using palm fibers in enhancing the performance of AC mixtures. This type of fiber is specifically selected due to the widespread availability of palm trees in countries of the Middle East, Arabian Gulf, and North Africa. The conducted experimental program aims at determining the optimum content and lengths of fibers to be incorporated in the asphalt mixtures, using the results of various laboratory tests including the complex modulus test, flow number test, semi-circular bending test and Cantabro abrasion loss test on asphalt concrete samples. Finally, the effect of adding these fibers on the performance of AC is evaluated using the analysis of variance (ANOVA) statistical technique.

Keywords: Asphalt, pavement, fibers, natural, palm, sustainability, performance testing

CONTENTS

ACKNOWLEDGMENTS v

ABSTRACT vii

LIST OF ILLUSTRATIONS xi

LIST OF TABLES xiv

Chapter Page

1. INTRODUCTION 1
   - 1.1 Problem Statement 1
   - 1.2 Research Needs 2
   - 1.3 Research Objective and Significance 3
2. LITERATURE REVIEW 4
   - 2.1 The Use of Fibers in Asphalt Concrete Mixtures 4
   - 2.2 Fiber Additives Effect on Asphalt Concrete Mixture Performance 8
   - 2.3 The Use of Natural Fibers in Asphalt Concrete Mixtures 14
   - 2.4 The Use of Palm Fibers in Construction Materials 16
3. SCOPE OF RESEARCH AND PROPOSED METHODOLOGY 19
   - 3.1 Material Used 19
     - 3.1.1 Aggregates 19
     - 3.1.2 Asphalt Binder 20
     - 3.1.3 WMA Additives 21
     - 3.1.4 Palm Fibers 21
       - 3.1.4.1 Description 21
       - 3.1.4.2 Palm Fiber Lengths and Contents 22
       - 3.1.4.3 Palm Fibers Characterization Tests 23
   - 3.2 Mix Design of HMA and WMA 24

3.3 Asphalt Mixtures Preparation 25
3.3.1 Batching and Mixing 25
3.3.2 Aging and Compaction 26
3.3.3 Volumetric Samples 27
3.3.3.1 Theoretical maximum specific gravity of the loose specimens, Gmm 27
3.3.3.2 Bulk specific gravity, Gmb 28
3.3.3.3 Air Voids, AV (%) 29
3.4 Testing Program 30
3.4.1 Testing Machines 30
3.4.1.1 UTM-25: used for the Complex Modulus test and the Semi-Circular Bending test 30
3.4.1.2 AMPT: used for the Flow Number test 30
3.5 Testing Methods 31
3.5.1 Complex Modulus Test 31
3.5.2 Flow Number Test 35
3.5.3 Semi-Circular Bending Test 37
3.5.4 Cantabro Test 40
4. RESULTS AND ANALYSIS 42
4.1 Palm Fibers Characterization Tests 42
4.1.1 Scanning electron microscopy (SEM) and microscopic images 42
4.1.2 Thermogravimetric analysis 43
4.2 Performance Tests 45
4.2.1 Complex Modulus Test 45
4.2.1.1 HMA fiber reinforced mixtures versus the control HMA mix 52
4.2.1.2 Asphalt concrete mixture type mix 54
4.2.2 Statistical analysis to test effect of palm fibers on |E*| of HMA and WMA mixes 55
4.2.3 Flow Number Test 63

4.2.4 Semi- Circular Bending Test 73
4.2.5 Cantabro Loss Test 80
5. CONCLUSIONS AND FUTURE WORK 84
5.1 Conclusions 84
5.2 Future Work 85
REFERENCES 87
APPENDIX A 99

ILLUSTRATIONS

Figure Page

1. Asphalt binder basic behaviors 4
2. Coarse Gabbro aggregates 20
3. Fine Gabbro aggregates 20
4. Palm fibers extraction process 22
5. Mixing process 26
6. Compaction process 27
7. Gmm testing method 28
8. Dynamic modulus asphalt test sample 33
9. Asphalt sample under testing using 3 spring loaded linear variable differential transducers (LVDTs) 33
10. A typical plot accumulated permanent strain versus number of loading cycles. 36
11. Asphalt sample under flow number testing 37
12. Damaged asphalt samples after flow number testing 37
13. Semi-circular asphalt samples under SCB testing 38
14. Damaged semi-circular asphalt samples 38
15. A typical outcome of the SCB test illustrating the parameters derived from the load-displacement curve including peak load, critical displacement, slope at inflection point, displacement at peak load, and fracture energy 39
16. I-FIT software provided by the Illinois center of transportation 39
17. Asphalt samples before conducting Cantabro Test 41
18. Asphalt samples after conducting Cantabro Test 41
19. SEM microscopic images of palm fibers 42

20. TGA test results 44
21. E* master curves for control hot asphalt mixes- 3 replicates 47
22. E* master curves for hot asphalt mixes reinforced with 0.05% and 10mm palm fibers 47
23. E* master curves for hot asphalt mixes reinforced with 0.05% and 30mm palm fibers 48
24. E* master curves for hot asphalt mixes reinforced with 0.1% and 30mm palm fibers.. 48
25. E* master curves for hot asphalt mixes reinforced with 0.2% and 30mm palm fibers.. 49
26. E* master curves for control warm asphalt mixes 49
27. E* master curves for warm asphalt mixes reinforced with 0.1% and 30mm palm fibers 50
28. E* master curves for all mixes in a semi-log scale 50
29. E* master curves for all mixes in a log-log scale 51
30. E* master data for HMA control and fiber reinforced mixes along the HMA control mixture in a log-log scale 53
31. E* master data for HMA control and fiber reinforced mixes along the HMA control mixture in a log-log scale at low reduced frequencies 53
32. E* master data for HMA control and fiber reinforced mixes along the HMA control mixture in a log-log scale at intermediate reduced frequencies 54
33. E* master data for HMA and WMA control mixes and HMA and WMA fiber reinforced mixes along the HMA control mixture in a log-log scale 55
34. Flow number test results summary 65
35. Accumulated strain (%) versus flow number (cycles) for asphalt test sample C-H-R1 66
36. Accumulated strain (%) versus flow number (cycles) for asphalt test sample C-H-R2 67
37. Accumulated strain (%) versus flow number (cycles) for asphalt test sample C-H-R3 67
38. Accumulated strain (%) versus flow number (cycles) for asphalt test sample F-H-0.05-30-R1 68
39. Accumulated strain (%) versus flow number (cycles) for asphalt test sample F-H-0.05-30-R2 68
40. Accumulated strain (%) versus flow number (cycles) for asphalt test sample F-H-0.05-30-R3 69

41. Accumulated strain (%) versus flow number (cycles) for asphalt test sample F-H-0.1-30-R1 69
42. Accumulated strain (%) versus flow number (cycles) for asphalt test sample F-H-0.1-30-R2 70
43. Accumulated strain (%) versus flow number (cycles) for asphalt test sample F-H-0.2-30-R1 70
44. Accumulated strain (%) versus flow number (cycles) for asphalt test sample F-H-0.2-30-R2 71
45. Accumulated strain (%) versus flow number (cycles) for all tested asphalt samples.... 72
46. Average flexibility index results for HMA control and fiber reinforced mixes............ 75
47. SCB test summary output of C-H-R1........ 76
48. SCB test summary output of C-H-R2........ 76
49. SCB test summary output of F-H-0.05-10-R1 77
50. SCB test summary output of F-H-0.05-10-R2 77
51. SCB test summary output of F-H-0.05-30-R1 78
52. SCB test summary output of F-H-0.05-30-R2 78
53. SCB test summary output of F-H-0.1-30-R1 79
54. SCB test summary output of F-H-0.1-30-R2 79
55. % Cumulative weight loss of different HMA and WMA mixes at every 50 revolutions 80
56. Cantabro loss percentage for different HMA and WMA mixes at 300 revolutions 82
57. Batching sheet for asphalt mix preparation........ 99

TABLES

Table Page

1. Selected Mix Gradation 20
2. Mechanical Properties of Palm Fibers.. 22
3. Number of cycles in the dynamic modulus test for at each temperature frequency combination.. 32
4. Coefficients of sigmoidal function and time-temperature shift factors for a reference temperature of 25°C to predict |E*| of all mixes at any combination of temperature and loading frequency 46
5. TukeyHSD test results for multiple comparisons of means of |E*| mastercurves of HMA control mix and HMA reinforced with different fiber percentages at a 90% family-wise confidence level.. 57
6. TukeyHSD test results for multiple comparisons of means of |E*| mastercurves of HMA control mix and HMA reinforced with different fiber lengths at a 90% family-wise confidence level.. 59
7. Two-way ANOVA test results of means of |E*| mastercurves of both HMA and WMA control and reinforced mixes with different fiber percentage at a 90% family-wise confidence level.. 61
8. Single-Operator Precision for Unconfined Flow Number 65
9. Minimum Average FN Requirement for different traffic levels.................................. 65
10. SCB test parameters... 75
11. One-way ANOVA results of different scenarios investigating the effect of palm fiber percentage, length, and asphalt mix type on the Cantabro test results 84

This work is dedicated to my beloved country, Lebanon.

CHAPTER 1

INTRODUCTION

1.1. Problem Statement

Asphalt concrete mixture (AC), consisting of asphalt binder, aggregates, and air voids, has commonly been used to produce flexible asphalt pavement due to the strong adhesion between asphalt binder and aggregates, which provides excellent stability and enhanced mechanical properties. However, repeated traffic loading imposed to pavement cause severe distresses to the pavement, such as asphalt permanent deformation (rutting), fatigue cracks, potholes, and surface wear…and their impact considerably intensifies under the influence of climatic conditions [1].

Fatigue cracking and rutting (permanent deformation) are very well known to be the two common distresses that occur in flexible pavement. These are mainly due to the increase in vehicle numbers those with high axle loads, due to repeated traffic loading, due to the environmental conditions and /or due to construction and design errors [1]. The horizontal stresses induced between the layers soon result in crack formation and any local settlements also lead to cracking of the asphalt layers. Therefore, it can lead to significant reduction in the serviceability of flexible pavements.

Researchers are permanently trying to improve the stability and durability of asphalt mixtures by finding a solution to postpone the deterioration of AC pavements. Various researches reported that incorporating additives such as different types of polymers and fibers in either the binder or in the asphalt mixture is one way to enhance the mechanical properties of AC pavements [2].

Asphalt concrete typically exhibits adequate strength in compression but is weaker in tension. The inclusion of fibers serves as additional reinforcement that provides needed resistance to tensile stresses. Stresses can be transferred to the strong fibers, thus increasing strain energy absorption of the asphalt mix to prevent the formation and propagation of cracks that can reduce the structural integrity of the road pavement [3]. Therefore, the fibers reinforcement is one approach to improve the tensile strength of asphalt mixes and which contributes to sustainability by minimizing pavement distresses, extending its service life, and reducing road maintenance [3].

1.2. Research Needs

Both natural and synthetic fibers are used in manufacturing materials such as cement and asphalt mixtures. Fiber in asphalt concrete mixtures acts as a reinforcement. Fibrous reinforcement plays a role in ensuring material strength and improving fatigue properties while increasing ductility due to the inherent flexibility of fibers and excellent mechanical properties [3].

Over the last decades, academics and practitioners have been increasingly shifting their interest towards the use of natural fibers as an alternative to synthetic fibers. Compared to synthetic fibers, natural fibers hold numerous advantages in their use including but not limited to their high availability, low cost, light weight, high specific strength and stiffness, and low carbon footprint [4,5]. Due to the high potential to serve as alternative to synthetic fiber composites such as glass or carbon fiber composites, and the added benefit of solving global waste problems, natural fiber-reinforced composites have attracted increasing interest in research, especially as reinforcement of materials used in building structures such as beams, walls and elevated slabs [6,7], as well as in rigid and flexible pavements [2,8,9]. Different types of natural fibers, including flax, hemp, jute straw, wood, wheat, oats, rye, kenaf, ramie, oil palm, sisal, coir among others have been investigated and successfully incorporated in construction materials [10].

Biomass obtained from agricultural waste has the potential to provide a source of renewable energy, both locally and across the world. The total investment in the biomass sector is estimated to reach up to $104 billion between 2008 and 2021. Agriculture waste such as natural fibers has critical roles in engineering design that can lead to successful sustainable applications. It is estimated that the annual palm agricultural wastes are more than 20 kg of dry leaves and fibers for each palm tree. It is estimated that there are more than 120 million palm trees in different countries world-wide, two thirds of which are found in the Arabian Gulf, Middle East, and North Africa. Unfortunately, agriculture waste resulting from palm trees are not used as constituents in any applications in most of those countries [11].

Various experimental studies have been conducted to evaluate the effectiveness of incorporating palm fibers in concrete and mortar mixtures [12,13,14] In comparison, studies on the use of palm fibers in asphalt bituminous mixes are very limited. Hence an attempt is made in this study to investigate the effect of palm fibers in dense graded asphalt mixes.

1.3. Research Objective and Significance

The main purpose of this research was to introduce palm fibers as natural additives in asphalt concrete mixtures and evaluate their effect on the performance of asphalt concrete mixes. This study investigated the properties of asphalt mixes reinforced with different palm fiber percentage and length. Furthermore, the conducted experimental program aimed at determining the optimum contents and lengths of fibers incorporated in the asphalt mixtures, using the results of various laboratory tests including the complex modulus test, flow number test, semi-circular bending test and Cantabro abrasion loss test on asphalt concrete samples. Besides the potential of enhancing the service life and performance of asphalt pavements, natural palm fibers is an added benefit in rendering pavements more sustainable.

CHAPTER 2

LITERATURE REVIEW

2.1 The Use of Fibers in Asphalt Concrete Mixtures

Despite billions of dollars spent on constructing, rehabilitating, and maintaining pavements globally, many distresses such as rutting, fatigue cracking, potholes and bleeding continue to reduce the asphalt pavement serviceability life. This is due to increased traffic and axle loads, increased pressure to reduce repair costs due to global economic recession, and low maintenance in developing countries [15]. There has been an increasing interest in modifying asphalt mixtures to improve their performance and the service life of pavements.Asphalt concrete (AC), a mixture of binder and aggregates, is a sensitive material compared to other materials used in civil engineering [9]. It is due to the viscoelastic behavior of binder that causes asphalt mixtures to experience different deterioration in different weather and loading conditions. At high temperatures and low rate traffic loading, the binder shows viscous behavior and experiences deteriorations such as bleeding and rutting of asphalt pavement. However, at low temperatures and high rate traffic loading binder shows elastic behavior and it can lead to some thermal cracks and accelerate the growth of fatigue cracks in the asphalt mixture under traffic load (Figure 1) [16] [17]. Therefore, it is recommended by researches to use modifiers/additives to improve the viscoelastic behavior of asphalt concrete mixtures.

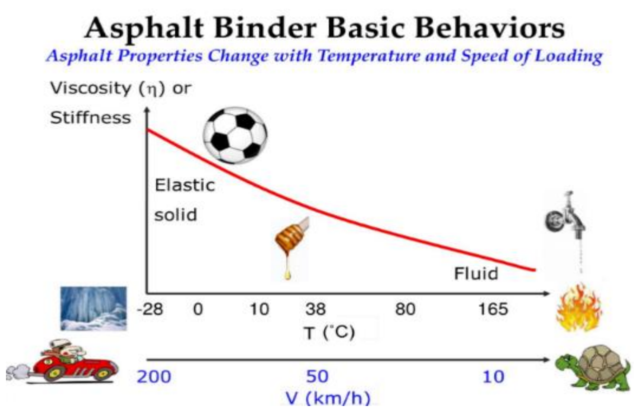

Figure 1- Asphalt binder viscosity change with temperature and speed of loading [17]

As discussed before, the increased growth of traffic and maintenance expenses requires a need for developing better, long-lasting, and more efficient roads that prevent or reduce asphalt pavement distresses. Thus, many researchers have utilized different modifiers to improve asphalt mixture service quality. Among these modifiers' different types of fibers, such as synthetic and natural. Fiber reinforcement in SMA (stone matrix asphalt mixes) was proposed as a solution in the early 1960s to avoid the binder drain down in the mixtures characterized by a high content of binder (i.e. portion of the mixture (fines and binder) separates itself from the whole sample mixture and flows downward to the bottom of the truck during mixture transportation). In the following years, this technique has enhanced, and the use of fibers is currently necessary in porous asphalt mixtures and SMA mixtures [18]. Different types of fibers can be used for this purpose, including cellulose, asbestos, rock wool, glass wool, polyester…

Stone Matrix Asphalt (SMA) is a gap graded mix, characterized by high coarse aggregates, high binder contents that is designed to maximize rutting resistance and durability by using a structural basis of stone-on-stone contact. This structure provides an efficient network for load distribution from those for previous conventional mixtures. Researches recommend these mixtures due to their high voids content; these mixtures allow the water to flow through the pores preventing its accumulation on the pavement surface. Moreover, their higher porosity allows a rougher surface texture which increases the friction between the tire and the asphalt surface, thus contributing to decrease road accidents [2].

Modification on SMA mix has been carried out by researches to prevent binder drain down from the mix. Stabilizing additives such as synthetic, mineral, and natural fibers have been tried by various researches in SMA mixtures to prevent the binder drain down problem during transport and placement of the asphalt mixture. Bindu et al. have found that the addition of fibers in the stone matrix asphalt mixture act as effective stabilizing agents. They concluded that the addition of 0.3% by mixture weight of coir, sisal, and banana fibers have stiffened the mastic and thus have decreased the drainage of the mixture at high temperatures during storage, transportation, placement, and compaction of SMA mixtures [19].

Mohammadzadeh Moghaddam et al. [20] have evaluated the effect of synthetic fibers (acrylic and polyester) and cellulosic fiber (jute) on the performance of the stone matrix asphalt (SMA) mixes containing. These fibers were also found to be effective in preventing the excessive drain down of the SMA mixtures. The findings also lead to the conclusion that the addition of acrylic fibers provides a positive contribution to the performance of asphalt pavements. SMA mixtures reinforced with acrylic fibers showed better resistance to moisture damage than control mixtures. This was attributed to the better micro-reinforcement of binder by the acrylic fibers and their better preventing of cracks propagation occurring within the mixture. Based on previous literature review, Bukowski et al. [21] observed an improvement of the service properties of SMA mixture reinforced with cellulose fibers. Cellulose fibers formed a micromesh in the SMA mixture, preventing the binder drain down while also increasing the stability and durability of the mix. Brown et al. [22] have studied the effect of different stabilizing additives such as fibers and polymers on the binder drain down. They reported that both cellulose and rock wool fibers performed better job of preventing drain down than SBS polymer.

Researchers studied the incorporation of natural cellulose fibers to SMA mixes. The results showed that fibers in such mixes act as a stabilizer thus prevent the draining down of the asphalt binder. Most studies showed that natural fibers can replace synthetic fibers in SMA mixtures as there is a good adhesion of the fibers with asphalt [3]. In practice today, all SMA mixtures overwhelmingly contain cellulose fibers.

Synthetic and natural fibers were also introduced as reinforcing materials in conventional dense asphalt mixtures. This was related to the increasing interest in modifying asphalt mixtures to improve their performance and the service life of asphalt pavements. Due to traffic growth, severe climate conditions, and heavier loads, the demand was raised to improve the mechanical properties of conventional asphalt materials by means of modification. Researches proved that fibers have the potential to achieve such modification and, thus, enhancing the mechanical properties of asphalt mixtures [23]. Studies showed that using synthetic fibers such as carbon and glass fibers to reinforce asphalt mixtures has the potential to help develop resistance to rutting and creep compliance, moisture susceptibility, stiffness modulus and freeze–thaw resistance. Also, studies on natural fibers such as cellulose, hemicelluloses, lignin, pectin and wax, which are annual renewable sources, showed that natural fibers provided certain advantages to the asphalt matrix such as high strength, acceptable thermal properties and enhanced energy recovery [24].

Yi and McDaniel studied the application of polypropylene fibers in asphalt overlays to investigate reflection cracking. Asphalt sections reinforced with polypropylene fibers were found to have less reflection cracking than unreinforced sections. Reinforced sections in which the pavement had been cracked before the overlay were found to have less reflection cracking [25]. Another study by Jenq et al. used polyester and polypropylene fibers to evaluate the effects of fiber reinforcement on crack resistance. They tested for modulus of elasticity, fracture energy and tensile strength. Fracture energy in reinforced asphalt mixtures increased by 50–100%, also toughness was increased but elasticity and tensile strength results were not significantly affected by these fibers [26]. Shaopeng et al. examined the dynamic characteristics of fiber-modified asphalt mixture. Cellulose, polyester and mineral fibers were added to asphalt mixtures, results showed that all fiber-modified asphalt mixtures have higher dynamic modulus compared with control mixture. Results also showed that the addition of cellulose fibers led to an improvement in fatigue and rutting resistance of asphalt mixtures where the rutting parameter of fiber-modified asphalt mixtures was enhanced by 1.12 times when cellulose fibers were used [27].

The modification of asphalt mixtures was also assessed by adding glass fibers which have excellent mechanical properties. It was found that adding glass fibers to asphalt mixtures enhances material strength and fatigue characteristics while increasing ductility. The use of glass fiber-reinforced asphalt mixtures can increase the construction cost; though, this can reduce and save the maintenance cost [28]. Glass fibers were also added to asphalt concrete mixtures in order to evaluate the fracture toughness. It was concluded that asphalt mixtures reinforced with glass fibers recorded higher fracture toughness than the unreinforced asphalt mixtures. This indicates that glass fibers allow a stronger resistance to crack propagation. Glass fibers can improve the stability and the ductility of the asphalt mixture without increasing bitumen content of Hot Mix Asphalt (HMA) which will be helpful to avoid rutting and bleeding in high temperature degrees during the hot season [29].

Carbon fiber can be categorized as synthetic fiber, studies on adding carbon fibers in asphalt concrete mixtures are also considered among researches. Researches showed that carbon fiber have the potential to resist structural distress in pavement, therefore enhance fatigue by increasing the resistance to cracks or rutting. Thus, it was concluded that adding carbon fiber to asphalt mixture will enhance some of the mechanical properties of the mixture such as fatigue and rutting in the asphalt pavement [30]. An interesting conclusion by Jahromi et al. and Xiaoming et al. indicated that the use of carbon fibers in asphalt mixtures also improves the electrical conductivity of the pavement and its performance is better than graphite. Hence, removing snow and ice may be possible by thermo-electrical techniques on highways in winter [28,31].

Nylon, a popular facing yarn of carpets, is used for the actual recycled carpet fibers in asphalt pavement. The effect of nylon fibers on the performance of asphalt concrete mixtures was studied using fracture energy. Joon et al. concluded that using asphalt concrete samples reinforced with nylon fibers of 1% volume and the length of 12 mm resulted in 85% higher fracture energy than non-reinforced specimens, showing improved fatigue cracking resistance [32].

This section summarized the effect of using synthetic and natural fibers in asphalt concrete mixtures. The use of fibers improves the mechanical properties and the performance of asphalt concrete mixtures. Fibers have the potential to achieve such modification in both stone matrix asphalt mixtures and conventional dense asphalt mixtures, thus increasing the asphalt pavement serviceability life. Further investigation about the effect of fibers on the main distresses that occur in pavements will be discussed in the following section.

2.2 Fiber Additives Effect on Asphalt Concrete Mixture Performance

Dynamic Modulus (|E*|) is one of the key elements for asphalt material characterization. Due to the asphalt material viscoelastic behavior, it is important to understand the stress strain responses of an asphalt pavement at different temperatures and loading conditions. The dynamic modulus test is a linear viscoelastic test used to estimate the complex dynamic modulus |E*| of asphalt mix specimens through each specimen’s stress–strain relationship at several frequencies across multiple test temperatures. The complex dynamic modulus |E*| is very important in that it is used to represent a pavement's stiffness from high to low temperatures and low to high frequencies under repeated traffic loading [33]. It is a direct input parameter in several pavement performance models to estimate the field fatigue cracking and rutting performance [34].

Researches showed in previous studies that fibers enhance the viscoelastic properties of asphalt material. Wu et al. studied the dynamic modulus of the asphalt mixtures modified with cellulose fiber, polyester fiber and mineral fiber. Dynamic modulus results showed that E* values increased with the increase of frequency at each given temperature, and the E* values of asphalt mixtures with fiber modifiers were always higher than that of the control at the highest and lowest test temperature. The test results showed that that the viscoelastic properties of asphalt mixtures could be improved by the fiber modifiers, such that fibers can enhance the viscous property of asphalt mixtures at low temperatures and the elastic property at high temperature [35]. Another study by Klinsky et al. evaluated the performance of asphalt mixtures reinforced with polypropylene and aramid fibers. This study proved that asphalt mixtures reinforced with fibers had E* values 30% higher than the control asphalt mixtures at high temperatures or low frequencies. Thus, fibers can improve the asphalt mixture behavior at higher temperatures, which contributes to a better rutting performance.

The dynamic properties of fiber-modified asphalt mixture were also assessed by Shaopeng et al. [36]. Cellulose fiber, polyester fiber and mineral fiber were used as additives to asphalt mixture. Laboratory results showed that all fiber-modified asphalt mixtures have higher dynamic modulus compared with control asphalt mixture. Khattak et al. conducted dynamic modulus test on unmodified and modified HMA specimens with carbon nanofibers. HMA specimens were tested at different frequencies under stress control mode within the linear viscoelastic stress range at 20 ℃. Asphalt mixtures modified with carbon nanofibers exhibited 35–85% higher average E* values than the control mixtures. It is considered that asphalt mixtures modified with carbon nanofibers have higher resistance to deformation [37].

Wu et al. conducted a study on the effect of polyester fibers on the rheological characteristics and fatigue properties of asphalt mixtures. The dynamic modulus test results for asphalt mixture modified with fibers indicated that the viscoelastic properties of asphalt mixtures could be changed by adding 0.3% polyester fiber. Polyester fibers can enhance the viscous property of asphalt mixtures at medium temperatures, which leads to the reduction of fatigue distress exhibit in asphalt pavements during their service life [38]. As well, Ye et al. investigated the effect of using cellulose fiber, polyester fiber and mineral fiber as modifiers for asphalt mixture. Results showed that the decrease of dynamic modulus indicates that the stiffness of asphalt mixtures can be reduced by the addition of fibers, which can enhance the resistance to fatigue damage for asphalt mixtures after several cycles loading [39].

Rutting, fatigue, low temperature cracking and raveling are well known as the most occurring asphalt distresses which usually occur due to severe weather, heavy and high-frequency loading traffic, inadequate pavement design, and poor material selection. These distresses can affect the pavement serviceability, structural capacity, and appearance [40]. Permanent deformation, mainly referring to rutting, is one of the main distress modes of asphalt pavement. Rutting usually appears in a longitudinal depression in the wheel path that can be also triggered by shear failure of the asphalt concrete layer. Slow moving traffic and high temperatures; especially at intersections, parking lots and during frequent vehiclebraking, accelerate the development of this type of deterioration [40].

Various laboratory test methods are currently used to evaluate permanent deformation resistance of HMA mixes, including the flow number test. A repeated compressive load for several thousand repetitions on a cylindrical asphalt specimen, producing permanent axial strains in it, which are recorded throughout the test [40]. Research activities in NCHRP 9-19 proposed the use of the flow number as a performance indicator of mix resistance to rutting. The test is performed at the temperature of 54.4 C and a stress level of 207 kPa. The flow number is defined as the starting point, or cycle number, at which tertiary flow occurs on a cumulative permanent strain curve obtained during the test [41].

A study by Ziari et al. showed that using up to 0.18% polyolefin-glass fiber increased the flow number value to more than twice as the control mixture [42]. A mixture of polypropylene and aramid fibers was used in this study to evaluate the performance characteristics of a modified asphalt mixture. Klinsky et al. indicated that the use of fibers in asphalt concrete could enhance the performance of asphalt pavements against common distresses as rutting, raveling, fatigue, and reflective cracking. Flow number test was applied to evaluate rutting resistance, asphalt mixtures reinforced with polypropylene and aramid fibers showed lower permanent strain accumulation compared to the control HMA and had higher flow number showing a higher rutting resistance [40]. Idaho case study evaluated the effect of fiber-reinforced asphalt mixtures used to mitigate distresses observed in the field. Control asphalt mixture test sections were constructed on US-30 in Idaho, along with fiber-reinforced asphalt mixture test sections. Three types of fibers were used in this study, Fiber 1 (i.e., aramid and polyolefin fiber), Fiber 2 (i.e., wax-treated aramid fiber), and Fiber 3 (i.e., glass fiber). Several laboratory tests including flow number test were conducted on laboratory- prepared test samples and extracted field cores. Asphalt specimens modified with fibers had higher FNs than the control asphalt mix, which meant higher resistance to rutting. Rutting resistance of asphalt modified mixtures was improved when the laboratory-produced mix had a minimum of 0.3% fiber content. Mixes that had lower fiber content did not show significant improvement. However, results indicated that the three types of fibers used in the field had no significant effect on rutting resistance [43].

Fatigue cracking is a major distress mode that causes premature failure in flexible pavements. It manifests itself in the form of cracking, and it is related with repetitive traffic loading and pavement thickness. Fatigue cracks usually initiated in the form of microcracks and proceed to macrocracks, these cracks grow due to shear and tensile stresses in road pavement [1]. Fatigue behavior of the asphalt mixtures can be characterized by the Semi-Circular Bending test. SCB test is a simple test that screen the cracking resistance of an asphalt mixture at intermediate temperature. The University of Illinois proposed a modified semicircular bending procedure, called the Illinois flexibility index test (I-FIT), which relies on three-point bending principle, where loading is applied on a semi-circular sample, to quantify the cracking potential of asphalt mixtures at intermediate temperature. The flexibility index (FI) parameter, which relates the fracture energy of the mixture and its post-peak failure behavior to determine the cracking resistance of asphalt mixtures, was introduced. Researchers have found that the FI parameter has been shown to provide a better difference between the fracture properties of mixtures than the total fracture energy parameter alone [44].

Ozer et al. used flexibility index parameter in their study to rank the potential cracking resistance of mixes. SCB test was conducted on semi-circular asphalt specimens with varying proportions of RAP and RAS and different binder type. FI index was successfully capable to discriminate the asphalt concrete mixes with respect to their overall cracking potential. It clearly showed the increase of asphalt concrete mix brittleness when RAS or RAP, or both, were added, although the impact of each is different [45]. A study by Sreedhar et al. focused on quantifying the effect of increasing the recycled asphalt content in asphalt pavement on the structural cracking resistance of the pavement in Oregon, by considering four tests commonly used to evaluate fatigue cracking resistance. SCB test was one of the chosen tests to evaluate the cracking resistance of the pavements in Oregon. Sreedhar et al. used SCB test to calculate fracture energy and flexibility index using the test outputs of the load-displacement curves. SCB results showed that the fracture energy parameter was not able to differentiate the fatigue performance of the field sections and cannot identify the sections with poor cracking performance. However, the flexibility index was successful in predicting the in-situ cracking performance. The flexibility indices of tested samples extracted from the sections with severe cracking were much lower than the samples extracted from the sections with high cracking performance. Thus, it can be concluded that the flexibility index parameter is an effective parameter in evaluating the cracking performance of asphalt concrete pavement structures [46].

Raveling has been also a challenging asphalt distress to pavement engineers. A progressive disintegration of an HMA, called raveling, might be developed from the surface downward because of the dislodgement of aggregate particles. Raveling can be related to mix material selection and to poor compacted asphalt layers. Researches have reported that raveling can be considered a significant pavement distress that affects the safety of pavement users and increases the need of regular pavement maintenance cause by pothole formation or cracking. Excessive raveling can be a threat to the pavement driver safety, aggregate particles flying into the air due to raveling can cause damage to vehicles.

Additionally, rough, and uneven pavement surfaces caused by raveling can increase pavement-tier noise and reduce the ride quality [47]. The Abrasion Resistance test, also known as Cantabro test, is used to evaluate the raveling potential of the asphalt mixture. This test is carried on by subjecting a compacted specimen to 300 revolutions (30 revolutions/minute) inside the Los Angeles machine without any steel balls. The mass loss of the specimen at the end of the test gives a measure of the Abrasion Resistance of the mixture studied, by estimating the internal cohesion between particles [48].

Sani et al. modified HMA with coir and kenaf fibers to understand the behavior and assess the performance of fiber for its potential use in HMA. Both modified asphalt mixtures with fibers recorded a lower mass loss than the control asphalt mixture. They considered that adding fibers (coir and kenaf) to the asphalt mixture increased the mixture stability [49]. Cantabro loss test was also performed on porous asphalt concrete mixtures. Slebi-Acevedo et al. evaluated the effect on the mechanical performance of using synthetic fibers (a blend of polyolefin-aramid fibers and polyacrylonitrile) in porous asphalt mixtures. The addition of fibers to PA mixture reduced the weight loss in the Cantabro test. Hence, the synthetic fibers increased the PA mixture raveling resistance [50]. Wang et al. investigated the performance of porous asphalt mixture modified with chopped basalt fibers. Chopped basalt fibers with different lengths (no-fiber, 3mm, 6mm, 9mm, and 12mm) and contents (3% and 4%) on the performance of the porous asphalt mixture. A series of tests were conducted to find the optimum fiber length and content, including drain-down test, cantabro abrasion test, freeze-thaw split tensile test, wheel tracking test, low-temperature cracking resistance test, and four-point bending beam test. Results showed that the porous asphalt mixture reinforced with chopped basalt fiber presented the lower mass loss, which means that chopped basalt fiber can improve the stability of the porous asphalt mixture. Further, results concluded that porous asphalt mixture reinforced with 9 mm length and 0.3% of basalt fibers is less prone to raveling [51].

Different literature reviews mentioned before illustrated that the use of both synthetic and natural fibers in asphalt mixtures showed a significant improvement on the asphalt mixtures viscoelastic properties and performance against common distresses as rutting, fatigue cracking and raveling.

2.3 The Use of Natural Fibers in Asphalt Concrete Mixtures

As previously mentioned, academics and practitioners have been increasingly shifting their interest towards the use of natural fibers as an alternative to synthetic fibers. Compared to synthetic fibers, natural fibers hold numerous advantages in their use including but not limited to their high availability, low cost, light weight, high specific strength and stiffness, and low carbon footprint [4,5]. Due to the sustainability benefit of using natural fibers, they are preferred over other traditional reinforcing materials. The most common use of these natural fibers in flexible pavement applications has been in specialty mixtures such as Stone-Mastic Asphalt (SMA).

Researchers studied the incorporation of natural cellulose fibers to SMA mixes. The results showed that fibers in such mixes act as a stabilizer thus preventing the draining down of the asphalt binder. Most studies showed that natural fibers can replace synthetic fibers in SMA mixtures as there is a good adhesion of the fibers with asphalt [3]. In practice today, all SMA mixtures overwhelmingly contain cellulose fibers. However, limited work has been reported on the use of natural fibers in the most used form on asphalt mixtures, namely dense-graded asphalt mixes.

A study by Abiola et al. reviewed several studies that were carried out on the application of natural fibers in modifying dense graded asphalt [3]. Results reported that reinforcement with natural fibers, provides an improvement in the fatigue life, increases the mixture's stability. A study by Shaopeng et al. [27] showed that the addition of cellulose fibers led to an improvement in fatigue and rutting resistance of asphalt mixtures where the rutting parameter of fiber-modified asphalt mixtures was enhanced by 1.12 times when cellulose fibers were used. Q. Ye et al. [39] also demonstrated in their study that the addition of cellulose fibers improves the fatigue resistance of asphalt mixtures. Gallo [52] found that asphalt mixtures reinforced with vegetable fibers achieved increased tensile strength and stiffness as well as higher resistance to permanent deformation.

Xu et al. [53] studied the reinforcing effects and mechanisms of four types of fibers for asphalt concrete (AC) mixtures: polyester, polyacrylonitrile, lignin and asbestos. Studies found that lignin fibers had a greater effect than polymer fibers on flexural strength and ultimate flexural strain. This could be due to their larger specific surface area and consequently greater absorption and stabilization of asphalt. Furthermore, all four types of fibers have significantly enhanced the rutting resistance, fatigue life and toughness of AC mixtures and improved the low-temperature flexural strength, ultimate flexural strain and split indirect tensile strength. Thulasirajan et al. [54] found that the addition of coir (coconut) fiber improved the compressibility of the mix which resulted in longer durability under moving wheel loads. Another study conducted by Bakiya et al. [55] on the use of coir fibers as reinforcement in asphalt mixtures in India. The addition of coir fibers increased the indirect tensile strength and reduced the moisture damage susceptibility of the asphalt mixtures. Another study by Hadiwardoyo et al. [56] on asphalt mixtures reinforced with coir fibers showed a high reduction in permanent deformation of the asphalt layer.

It is important to know that the suitable quantity and length of fibers required to give a reinforcement effect in asphalt concrete mixture, it depends on the type of asphalt mixture and type of fibers. If the fibers are too long, it may create the so called ‘‘balling” problem, some of the fibers may lump together, and may not blend well with the binder. Similarly, too short fibers may not give any reinforcing effect. Vale et al. conducted a study on using cellulose fibers in stone matrix asphalt mixtures. It was shown that very small amounts of cellulose fiber (about 0.3%) and 30-40mm long are needed to prevent drain down of asphalt to enhance the stability and durability of the mixture. Smaller lengths (approximately 20mm) were recommended to the difficulties in workability encountered during the production of the specimens, due to its size [57].

Concerning dense hot asphalt mixtures, Pirmohammad et al. studied the effect of both kenaf and goat wool fibers (natural fibers) on fracture strength of asphalt mixtures. Short lengths were used for both fibers (i.e., 4, 8 and 12mm) with contents (i.e., 0.1, 0.2 and 0.3% by weight of total asphalt mixture) to prepare asphalt mixtures. It was concluded that mixtures reinforced with 0.3% kenaf fibers with 8 mm in length showed the best results compared to other mixtures. Also, mixtures reinforced by 0.3% goat wool fibers with 4mm in length exhibited the best results compared to those reinforced by goat wool fibers [58]. Another study by Huang et al. stated that asphalt mixtures reinforced with 10mm polypropylene fibers reduced reflective cracking at Indiana [59]. Glass fibers of 12mm and

0.12% were found to have to a significant enhancement in resistance of all mixtures against crack initiation and propagation [60]. Coir fibers was used with different lengths (i.e., 10, 15 and 20mm) with contents (i.e., 0.3, 0.5 and 0.7%). It was observed that fiber length of 15mm with a 0.52% content provides good stability and volumetric properties [61]. It should be noted that also the maximum aggregate size may play a role in the final fiber length. Morea et al. stated that the glass macro fibers, which have a length that is longer than maximum aggregate size, is expected to influence the fracture behavior and crack propagation [62]. Wheel tracking test results showed that rutting behavior of the asphalt concretes was clearly improved by the addition of 36mm and 0.4% glass macro fibers.

2.4 The Use of Palm Fibers in Construction Materials

Agriculture waste such as natural fibers has critical roles in engineering design that can lead to successful sustainable applications. It is estimated that the annual palm agricultural wastes are more than 20 kg of dry leaves and fibers for each palm tree. This waste can be found bunches, petioles, palm trunks and leaves. It is estimated that there are more than 120 million palm trees in different countries world-wide, two thirds of which are found in the Arabian Gulf, Middle East, and North Africa [63]. Nowadays, palm fibers are used in construction fields to bring technical improvement and cost savings.

Hejazi et al. reviewed previous studies on the use of palm fibers as a soil reinforcement [64]. A study by Jamellodin et al. found that soil reinforced with palm fibers can improve the strength properties of the soil. An improvement was observed in the failure deviator stress and shear strength parameters (C and U) of the soft soil reinforced with palm fibers [65]. Ahmad et al. added palm fibers with silty sand soil to examine the increase of shear strength during triaxial compression. Palm fibers contents were added with 0.25% and 0.5% contents and different lengths (i.e. 15 mm, 30 mm, and 45 mm). Reinforced silty sand containing 0.5% coated fibers of 30 mm length exhibited approximately 25% increase in friction angle and 35% in cohesion compared to those of unreinforced silty sand [66]. Further studies on concrete mixtures reinforced with palm fibers were conducted. Machaka et al. conducted a study on the use of palm on the impact of resistance of concrete. Impact resistance test results showed that adding 1.5% and 30mm of palm fibers to concrete mixture significantly improves the impact loads up to 82% for a 30MPa compressive strength [12]. Kareche et al. proved that using palm fibers reduce drying shrinkage of concrete and cracking issues [67].

Although palm fibers are used in several construction applications, they are not yet exploited in the pavement sector. Bellatrache et al. evaluated of the physicochemical properties of palm fibers and the effect of their use on the physical, rheological and thermal properties of a 35/50 penetration grade binder. The addition of palm fibers in binder improved the binder viscosity by 50% and complex modulus norm by 40% at the service life temperatures; this increase is related to a better rutting resistance. Binder drainage test showed that palm fibers significantly reduce the binder drain down in SMA mixtures [68]. Another study by Hassan et al. investigated the effect of using palm fibers, textile fibers and SBR polymer on the properties of porous asphalt mixture. Hassan et al. pointed out that the use of 0.4% and 6mm palm fibers and 4% SBR polymer only in a mix resulted in a significant reduction in abrasion and higher raveling resistance compared with other mixes [69]. Additional studies investigated the effect of using palm fibers on asphalt binder properties. Al-Otaibi et al. preblended cellulose date palm fibers in PG 64-22 asphalt binder with various of 1.5%, 3%, 4.5%,6%, and 7.5% by weight of asphalt binder. The physical and rheological properties of asphalt binder reinforced with palm fibers were tested by using binder conventional tests. Experimental testing showed that fiber reinforced binder has a higher softening point, viscosity, and complex shear modulus, and lower penetration compared to control binder. The rheological properties were also improved since the control binder PG was raised from 64 to 70 by adding 6% palm fibers. Palm fibers improved the binder stiffness which contributes to a better pavement rutting [70]. Aziz et al. investigated the viscoelastic behavior of PG 60-70 asphalt binder modified with cellulose oil palm fiber. Experimental results indicated that the fiber modified asphalt binder had high potential to resist rutting and fatigue cracking than the control binder [71].

Literature review mentioned above reveals that natural palm fibers such as palm fibers have a great potential for replacing synthetic fibers like aramid, nylon, polypropylene, and polyester fibers due to having several advantages such as being lightweight, low-cost, low carbon footprint, etc. It was observed that palm fibers improved the physical and rheological properties of asphalt binder, also reduced the binder drain down of Sma mixtures. Further investigations will be carried out on the effect of using palm fibers reinforcement on asphalt concrete mixtures performance.

CHAPTER 3

SCOPE OF RESEARCH AND PROPOSED METHODOLOGY

The objective of this research is to investigate the effect of natural palm fibers on the asphalt concrete engineering properties and to investigate the effect of fiber lengths and contents for enhanced performance of flexible pavements. This is achieved by conducting a series of experimental laboratory investigations on unreinforced and reinforced mixes, as follows:

- Complex Modulus Test
- Flow Number Test
- Semi-Circular Bending Test, and
- Cantabro Test

Physical properties of palm fibers are determined prior to their inclusion in asphalt concrete mixtures by conducting Scanning electron microscopy (SEM) and Thermogravimetric analysis.

3.1 Material Used

The selected material in this research work, aggregates and asphalt binder, are the same material that were used in (Kassem Doctoral Dissertation) [72] which will be discussed below. The study used 19 mm nominal maximum aggregate size (NMAS) HMA and WMA mixes with the following constituent materials:

3.1.1 Aggregates

The used aggregates consist of Gabbro rock which have been imported from Fujairah in the United Arab Emirates. Gabbro is a commonly used aggregate type in asphalt pavements, especially in the Gulf region. This type of aggregates is an igneous rock that is commonly used in the asphalt pavement industry in the countries of the Arabian Gulf

Region including Qatar. The selected gradation shown in Table 1 passed the Superpave criteria and the Bailey Conformity Equations [72] (Figure2 and 3).

Table 1- Selected Mix Gradation

Sieves/mm	25	19	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.75
Passing/%	100	96	78	69	48	30	20	14	9	7	4.2

Figure 2- Coarse Gabbro aggregates

Figure 3- Fine Gabbro aggregates

3.1.2 Asphalt Binder

The asphalt used is an unmodified binder Pen 60/70 which corresponds in the Superpave Performance Grading (PG) to PG 64-16. It has been imported from BAPCO refinery in Bahrain and it is commonly used in the pavement construction industry in Qatar. The asphalt binder viscosity was measured for three replicates at temperatures higher than 135 °C in accordance to ASTM D4402. The Asphalt Institute Equi-Viscous Method was used to determine the asphalt binder mixing and compaction temperatures. The results correspond to a viscosity of 0.17±0.02 Pa.s and 0.28±0.03, respectively. Based on these results, the mixing and compaction temperatures of HMA mixes were selected to be 160˚C and 150˚C, respectively [72].

3.1.3 WMA Additives

Warm mix asphalt (WMA) are mixes that are produced and paved at lower temperatures than hot asphalt mix (HMA) while maintaining the advantages of HMA. WMA technology has many benefits compared to HMA which includes the reduction of energy consumption on the mix production, emissions from burning of fuels at the plant, fumes at the paving site, and odor. The WMA temperature reduction is the result of recently developed technologies that involve the use of organic additives, such as SonneWarmix, which is used in this study [73]. SonneWarmix is typically heated at 90-120°C before it is mixed with the binder to achieve a temperature reduction of about 30°C. A dosage of 0.5% by binder weight was added. The viscosity test was also performed on the modified asphalt binder, the mixing and compaction temperatures of WMA mixes were selected to be 125˚C and 115˚C, respectively.

3.1.4 Palm Fibers

3.1.4.1 <u>Description:</u>

Natural Palm Fibers used in this study were extracted from the leaves of Palm Trees. Leaves were air dried for a week, then split into fibers by using a handmade machine into 0.7mm to 1.0 mm width and for 30 mm length each fiber. Fibers were soaked in a 4% sodium hydroxide concentration for 24 hours to remove the weak boundary layers of the fibers. Finally, the fibers were washed with water to remove dust, waste, and any harmful materials. Fibers were dried and stored in sealed plastic bags to prevent any exposure to moisture (Figure 4). Mechanical properties of the palm fibers used in this study are listed in Table 2. This table was provided by Machaka et al. since they launched an investigation on the same natural palm fibers used in this study [74].

Table 2- Mechanical Properties of Palm Fibers

Property	**Lower-Upper**
Fiber Dimensions: Thickness (mm) Width (mm)	 0.25-0.35 0.60-0.90
Bulk Density (Kg/m3)	500-800
Modulus of elasticity (GPa)	4.5-6.5
Tensile strength (MPa)	70-120
Elongation (%)	1.5-2.0

Figure 4- Palm fibers extraction process

3.1.4.2 Palm Fiber Lengths and Contents:

As mentioned previously, it is important to know that the appropriate quantity and length of fibers required to give a reinforcement effect in asphalt concrete mixture, it depends on the type of asphalt mixture and type of fibers. Palm fibers were added to the asphalt mixtures with different lengths (10 and 30mm) and contents (0.05,0.1 and 0.2% by weight of total asphalt mixture). The selected ranges were chosen based on data reported in the available literature [57-62] that stated that the length and content of various types of fibers are optimum only in this range. The use of fibers that are longer than 30mm creates the so called ‘‘balling” problem, where the fibers lump together during mixing, and as such don’t blend well with the binder. Similarly, fibers shorter than 10mm may not give any reinforcing effect. Regarding the fiber content, SMA mixes typically require 6% asphalt binder content and the available literature review [57] showed that only 0.3% of cellulose fibers are needed to prevent drain down of asphalt to enhance the stability and durability of the mixture. Since 3.8% asphalt binder content is added to asphalt mixes in this study, hence 0.2% was found to be the maximum fiber content needed by substitution. Although dry process was used for a better distribution of fibers throughout the mixture, a “balling” problem was faced in this study when adding more than 0.2% fibers. Thus, fiber content ranged between 0.05 and 0.2%. It should be noted that cellulose fibers in specific have problems with dispersion in the mixture, resulting in clumping.

3.1.4.3 Palm Fibers Characterization Tests:

a. Scanning electron microscopy (SEM) and microscopic images

In order to characterize the microstructure and morphology of the palm fibers, SEM analysis was conducted using an a TESCAN MIRA3 LMU with an accelerating voltage of 20 kV. Before SEM observations, palm fibers samples were dried, glued directly into a carbon film sample holder and then coated with a thin layer of metal, using a vacuum sputter coater, to improve visibility.

b. Thermogravimetric analysis

Thermogravimetric analysis (TGA) was performed to evaluate the thermal stability of fibers at temperatures experienced during the mixing, paving and compaction of the asphalt mixture. About 10 mg of the dried palm fibers were then heated from 30 to 600 °C at a heating rate of 10 °C/min under a nitrogen environment in a “NETZSCH TG 209F1 Libra” thermogravimetric analyzer.

3.2 Mix Design of HMA and WMA

Control and asphalt mixtures reinforced with fibers samples (HMA and WMA) were prepared by using the preselected aggregates, asphalt binder PG 64-16, palm fibers and SonneWarmix additive (in case of WMA samples). These mixes are designated as the following:

- C-H: HMA mix without adding palm fibers
- C-W: WMA mix without adding palm fibers
- F-H-x-y: HMA mix reinforced with palm fibers
- F-W-x-y: WMA mix reinforced with palm fibers

where x stands for fiber percentage and y stands for fiber length

The mix design of the control HMA mix was first conducted to determine the optimum asphalt binder content that yields a design air void level of 4.0% for a preselected aggregate gradation. Then, the corresponding designs of the WMA mix and palm fibers reinforced asphalt mix for each category was determined based on that of the control HMA. The mix design results showed that HMA mixes require an optimum asphalt binder content of 3.7% to achieve 4.0% air voids. In comparison with the HMA mix with the same gradation and asphalt binder but with palm fibers, a 0.1% addition by weigh of asphalt binder was needed due to the addition of natural palm fibers based on mix design calculations. The use of Sonnewarmix as a WMA additive has no effect on the optimum asphalt binder content. Moreover, the mixes passed Superpave criteria, namely the required density at Nini, Ndes, Nmax, Voids in mineral aggregates (VMA), and Voids filled with asphalt (VFA) [72].

3.3 Asphalt Mixtures Preparation

3.3.1 Batching and Mixing

Aggregates were totally dried, sieved, and stored in closed barrels ready to be batched. The needed amount of sieved aggregates was added of each aggregate size as shown on the batching sheet (Appendix A). The bowl was the covered by aluminum foil and labeled, then placed with the mixing bowl, mixer, and spoons in the oven over night at a temperature 10^{o}C higher than mixing temperature (170^{o}C). Before 2 hours from the beginning of mixing, required asphalt binder cans were also placed in the oven. After 2 hours of placing the binder can, the required amount of asphalt binder was added by forming a donut shape was formed in the middle of the aggregates. For the mixes with fibers, dry blending method was used in which the palm fibers are homogenously dispersed with hot aggregates before the asphalt binder was added. Then, the aggregates, fibers and the added asphalt binder were blended properly by the heated spoon and transferred to the mixing bowl (Figure 5). The mixer was turned until the aggregates are completely coated with asphalt binder. After mixing, all the mixing equipment were scrapped well to make sure of not losing the fibers. A 135˚C mixing temperature was used for WMA mixes preparation, following the same procedures as HMA mixes. WMA binders were prepared by pre-blending the required dosages of WMA additives with the virgin asphalt binders using a laboratory mechanic stirrer at the mixing temperature prior to mixing it with aggregates. The asphalt binder was placed on a heating plate to preserve the temperature of the sample during mixing [72]. Batches were returned to the oven at the compaction temperature. Short-term aging was simulated by mixing the batches after 1 hour of mixing. A 135˚C mixing temperature was used for WMA mixes preparation, following the same procedures as HMA mixes. WMA binders were prepared by pre-blending the required dosages of WMA additives with the virgin asphalt binders using a laboratory mechanic stirrer at the mixing temperature prior to mixing it with aggregates. The asphalt binder was placed on a heating plate in order to preserve the temperature of the sample during mixing [72]. Batches were returned to the oven at the compaction temperature. Short-term aging was simulated by mixing the batches after 1 hour of mixing.

Figure 5- Mixing process

3.3.2 Aging and Compaction

The asphalt mixture was then placed in an oven at a temperature higher by 5 degrees than the compaction temperature for 2 hours. 160 ˚C and 125 ˚C compaction temperatures were used for HMA and WMA mixtures, respectively. Specimens were prepared using a Superpave Gyratory Compactor (Rainhart Cat. No. 144 Gyratory Compactor). All the specimens were compacted in a mold of 150.0 mm diameter with a height of 110.0-120.0 mm and 175.0 mm for mix design and dynamic modulus testing specimens, respectively (Figure 6). The volumetric samples are compacted to Ndes = 100, and dynamic modulus test samples were compacted to a height = 175 mm. All mixtures in this study were designed using the Superpave Mix Design method with a compaction effort equivalent to medium to high traffic (3 to 30 million ESALs) [72]. To obtain the required geometry, cores of were carefully sawed and polished from the compacted specimens.

Figure 6- Compaction process

3.3.3 Volumetric Samples

3.3.3.1 <u>Theoretical maximum specific gravity of the loose specimens, Gmm:</u>

The theoretical maximum specific gravity (Gmm) of a HMA mixture is the specific gravity excluding air voids. Thus, by eliminating all the air voids from an HMA sample, the combined specific gravity of the remaining aggregate and asphalt binder would be the theoretical maximum specific gravity [75]. The mixture should be loose and broken up so that the fine aggregate was separated into particles smaller than 6.25 mm taking care not to fracture aggregates. The loose sample was placed at room temperature into a vacuum container, then dry mass was recorded (A). A flask was filled with water after adding the loose sample, the entrapped air was removed from the sample. The filled flask mass was determined (C). Theoretical maximum specific gravity "Rice" density was measured using the flask method as per ASTM D2041 (Figure 7).

$$Gmm = K*\left(\frac{A}{A+B-C}\right)$$

A= mass of dry sample in air (g)

B= mass of flask filled with water and cover plate at 25°C (g)

C=mass of flask filled with sample, cover plate, and water (g)

K= correction factor for water temperature

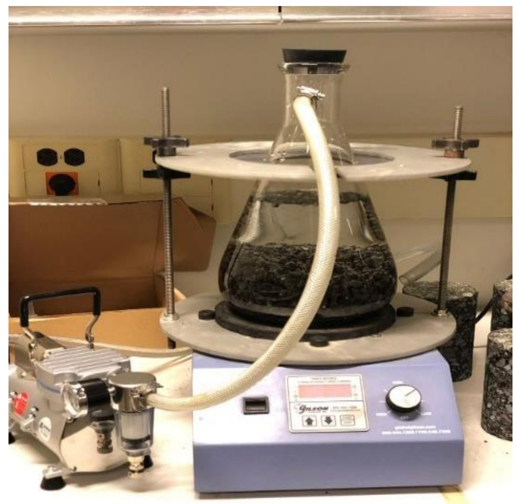

Figure 7- Gmm testing method

3.3.3.2 <u>Bulk specific gravity, Gmb:</u>

The bulk specific gravity test was used to determine the specific gravity of a compacted HMA sample by determining the ratio of its weight to the weight of an equal volume of water [76]. For the mix design purposes, and Gmb is measured using the commonly used saturated surface-dry (SSD) technique as per ASTM D2726 which is valid for specimens that do not absorb more than 2.0% of water by volumes. Volumetric specimens were dried to a constant mass and cooled to room temperature. The dry mass (A) was recorded, then specimens were completely submerged in the water bath at 25°C for 4 mins. Then, the mass (C) was determined by weighing in water using basket suspended in water under a scale. Weigh the saturated-dry specimen mass (B) surface after properly damping the specimen using a cloth towel. The acceptability of bulk specific gravity test results were checked based on the acceptable range between the samples obtained by this test method.

For the mechanical testing specimens, the Gmb of these specimens was measured using the Parafilm Method as per ASTM D1188. This technique was selected rather than the SSD method due to the high level of targeted %AV which makes the specimen's absorption of water exceeds 2.0% and thus ASTM D2041 is not applicable [72]. The specimens were dried using a 30-psi air pressure gun before measuring the Gmb, dry mass was recorded (A). Specimens were firmly wrapped in parafilm (a stretchable, waterproof membrane), mass was recorded (B). Then, the mass (C) was determined by weighing in water using basket suspended in water under a scale.

$$Gmb=(\frac{A}{B-C})$$

Where

A=mass of the dry specimen in air (g)

B= mass of the saturated surface-dry specimen in air (g)

C= mass of the specimen in water (g)

3.3.3.3 <u>Air Voids, AV (%):</u>

The calculation of %AV of the AC specimens was calculated based on ASTM D3203 as:

$$\%AV= 100(1-\frac{Gmb}{Gmm})$$

where: Gmb = the bulk specific gravity of the compacted specimens, and

and Gmm= the theoretical maximum specific gravity of the loose specimens.

3.4 Testing Program

The following sections present the corresponding testing machines used to conduct the testing program. Furthermore, an overview of the conducted test methods will be presented.

3.4.1 Testing Machines

3.4.1.1 UTM-25: used for the Complex Modulus test and the Semi-Circular Bending test

A Universal Testing Machine (UTM-25) servo-hydraulic universal testing machine was used for the tests listed above. It has a 25 kN capacity and is manufactured by Industrial Process Controls (IPC) from Australia. This closed loop machine can apply static and dynamic loads at a wide range of temperatures and loading rates/frequencies. The UTM-25 is equipped with an environmental chamber for controlling the temperature during testing. The temperature control system is refrigeration based with a heating element for achieving high temperatures. It has the capability of temperature control in the range of -15˚C to 60˚C which falls within the requirements of the mechanical tests required in this study [72].

3.4.1.2 AMPT: used for the Flow Number test

The Asphalt Mixture Performance Tester (AMPT) is a small servo-hydraulic testing device developed specifically for testing asphalt concrete mixtures. The AMPT was originally called the Simple Performance Test System when it was developed in National Cooperative Highway Research Program (NCHRP) Project 9-19 and 9-29. It is designed to perform the three asphalt tests: Dynamic Modulus, Flow Number and Flow Time. It is also the prescribed equipment in AASHTO T378-17 Standard Method Test for determining the Dynamic Modulus and Flow Number for Hot Mix Asphalt (HMA) using the Asphalt Mixture Performance Tester (AMPT) [77].

3.5 Testing Methods

3.5.1 Complex Modulus Test

The complex modulus (E*) test was conducted in the stress control mode to determine the linear viscoelastic properties and the time-temperature shift factors of all the mixes in the study. It involved the application of a uniaxial sinusoidal/haversine stress to an unconfined asphalt concrete sample and determining the response strains in order to compute the dynamic modulus (|E*|) [72]. The load amplitude for each combination of testing frequency and temperature was adjusted based on the material's stiffness and testing conditions such that the 75 micro-strains limit was not exceeded to ensure that the sample is undamaged during testing. The loading at each temperature and frequency was previously determined to provide a strain of 60-70 micro-strains a range that provides linear viscoelastic response, the micro-strains should not exceed 100 to ensure that the sample was not subjected to damage [78]. Seven frequencies ranging from 0.01 Hz to 20 Hz and four temperatures (-5°C, 10°C, 25°C and 38°C) were selected in the test procedure. A thermocouple was embedded inside a prepared replicate in order to monitor the temperature of the sample to be tested and it is used as the control temperature reading. The sample was conditioned similarly to the sample to be tested. Specimens were tested in an order of increasing temperatures and of decreasing frequency. Complex modulus tests was performed under frequency sweep mode in an order of reduced frequency at each test temperature. Asphalt samples having a diameter of 100 mm, height of 150 mm and a 7±0.5% target air voids were tested (Figure 8) and for each mix at 24 combinations of temperature and frequency mentioned below. For each temperature, preconditioning loading cycles were applied before applying the testing frequencies to obtain better quality of loading and displacement data during testing (Table 3). A temperature asphalt dummy specimen for each mix is placed in the conditioning chamber during testing to reach equilibrium after reaching the required testing temperature. The dummy sample is embedded with two k-type thermocouples at the center and mounted on the surface of the specimen, to ensure that the temperature is homogeneous between the specimen's surface and its center [72].

Table 3- Number of cycles in the dynamic modulus test for at each temperature frequency combination

Frequency (Hz)	**Temperature (℃)**			
	-5	10	25	38
20-Preconditioning	X	X	100	100
20	X	X	200	200
10-Preconditioning	100	100	100	100
10	100	100	100	100
5	100	100	100	100
1	20	20	20	20
0.5	15	15	15	15
0.1	15	15	15	15
0.01	10	10	X	X

During the test, the raw data of the applied load and the measured axial deformation of each of the 3 LVDTs was recorded through an IMACS at a rate of 50 points per cycle. This data was then analyzed by considering the last 5 cycles of each temperature frequency combination. The axial deformations were measured using 3 spring loaded linear variable differential transducers (LVDTs) that were mounted at 120 degrees apart along the circumference of the sample with a gage length of 100 mm (Figure 9). The stress and strain data was fitted to cosine functions shown in Equation 1 and Equation 2 using the least square method. The dynamic modulus is defined as the average peak stress divided by the average peak strain as shown in Equation 3 while the phase angle is the difference between the phase angle of the stress and the strain Equation 4.

$$\sigma = \sigma_0 \cos(2\pi f t + \phi_1) + \sigma_1$$ **Equation 1**

$$\varepsilon = \varepsilon_0 \cos(2\pi f t + \phi_2) + \varepsilon_1 t + \varepsilon_2$$ **Equation 2**

where

σ: stress

ε: strain

t: time in sec

f: frequency in Hz

σ0, σ1, and ϕ1 = linear regression constants for stress equation

ε0, ε1, ε2, and ϕ2 = linear regression constants for strain equation

$$|E^*| = \frac{\sigma_0}{\varepsilon_0} \qquad \textbf{Equation 3}$$

$$\phi = \phi_2 - \phi_1 \qquad \textbf{Equation 4}$$

where

|E*|: dynamic modulus

ϕ: phase angle

Figure 8- Dynamic modulus asphalt test sample

Figure 9- Asphalt sample under testing using 3 spring loaded linear variable differential transducers (LVDTs)

Comparing dynamic modulus results across different test temperatures and frequencies is very difficult. To make meaningful comparisons possible, master curves were developed. Master curves provide a means to achieve a visual representation of the dynamic modulus (E*) results determined at different temperatures and loading frequencies. For this study, all |E*| master curves were constructed using the time–temperature superposition (TTS) principle. The TTS principle addresses how the material response under different temperatures and frequencies can be shifted to construct the dynamic modulus master curve at a reference temperature, 25°C is selected in this study. This principle makes it possible that a certain dynamic modulus value at a reference temperature can be measured either at a higher temperature and high frequency, or at a lower temperature and a lower frequency. Dynamic modulus values were then shifted by the shift factor aT that is multiplied by the testing frequency to obtain the reduced frequency at the reference temperature (Equation 5) and thus construct the |E*| master curve of each replicate. The shift factors, aT, were used to shift the dynamic modulus versus frequency curves at -5, 10, and 38˚C along the frequency axis to form a continuous master curve at 25˚C are defined as the following:

$$\log(f_R) = \log(f) + \log(aT) \qquad \textbf{Equation 5}$$

where:

f_R = reduced frequency at the reference temperature (25˚C)

f = frequency at a given temperature T before shifting, and

aT = shift factor for temperature T

A log-sigmoid function is fitted to the shifted data to produce the E* master curve using the least squares technique to minimize the error between actual and predicted |E*| values (Equation 6). Also, the shift factor as a function of temperature is fitted as presented in (Equation 7).

$$\log(|E^*|) = a + \frac{b}{c + \left(\frac{f}{exp(d + e * \log(fr))}\right)} \qquad \textbf{Equation 6}$$

where:

a, b, c, d, e, and f: fitting coefficients

$$\log(aT) = a_1T^2 + a_2T + a_3 \qquad \textbf{Equation 7}$$

where:

a_1, a_2 and a_3: regression coefficients

3.5.2 Flow Number Test

The FN test is a permanent deformation test that has been introduced and used by researchers since the 1970's to measure the rutting potential of asphalt concrete mixtures. Haversine axial compressive-load pulses are applied to specimens having a diameter of 100 mm, height of 150 mm and 7±0.5% target air voids (Figure 11). The cycle duration of the load pulse is 0.1 sec followed by a rest period of 0.9 sec. This test was conducted to measure vertical accumulated permanent strains as a function of loading cycles [79]. In order to be consistent with the critical rutting temperature and closely simulate the pavement surface temperatures encountered during high summer pavement surface temperatures in State of Qatar [72], the FN test was conducted at 54°C. The deviator stress used in this study was 206 kPa as recommended in other studies. The test was set to terminate at 10,000 loading cycles or accumulated 50,000 micro-strains, whichever came first (Figure 12). Figure 10 presents a typical plot of accumulated permanent strain versus the number of loading cycles on a log–log scale. Three basic zones are identified: primary, secondary, and tertiary zones: (1) the primary zone in which the deformation rate decreases with loading cycles; (2) the secondary zone in which the deformation rate is constant with loading cycles; and (3) the tertiary zone in which the deformation rate increases with loading cycles.[79]

The output data obtained from the FN test include:

- Flow number (FN), in cycles, is the number of load cycles at which the HMA mix enters the tertiary zone, the tertiary zone in which the deformation rate increases with loading cycles, under vertical repeated loading, which corresponds to the minimum value of the strain rate.

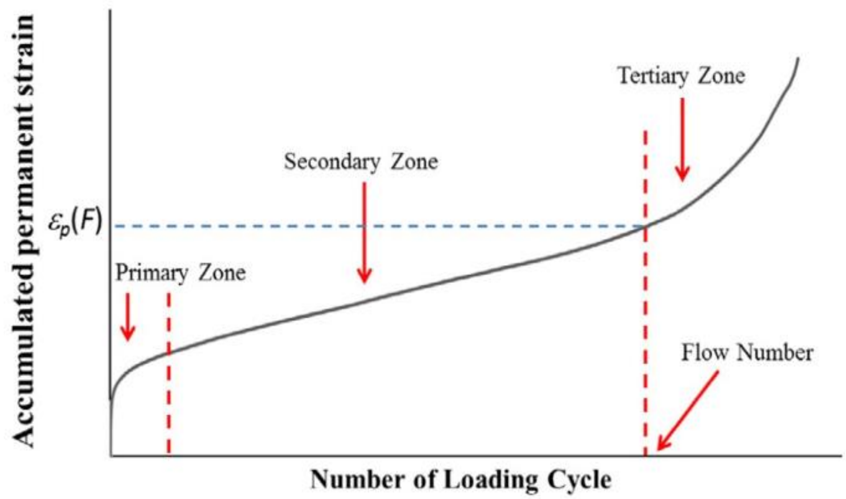

Figure 10- A typical plot accumulated permanent strain versus number of loading cycles.

Flow number can be defined analytically by finding the cycle where the 2nd derivative of the function changes from positive to negative. The raw permanent strain versus load cycle curve was fitted using Francken's model. Francken's model was selected to calculate FN due to its consistency in fitting experimental data. The fitting coefficients are determined by numerical optimization. Once fitted, the first and second derivatives of the Francken's model were easily determined analytically (Equation 8,9 and 10) [80]:

Permanent axial strain rate:

$\mathcal{E}p = AN^{B} + C(e^{DN} - 1)$ Equation 8

where:

$\mathcal{E}p$ = permanent axial strain;

N= number of cycles; and

A, B, C, and D = fitting coefficients.

First derivative of permanent axial strain rate:

$$\frac{d\mathcal{E}p}{dN} = ABN^{B-1} + CDe^{DN}$$ **Equation 9**

Second derivative of permanent axial strain rate:

$$\frac{d^2\varepsilon_p}{dN^2} = AB(B-1)N^{B-2} + CD^2e^{DN} \qquad \textbf{Equation 10}$$

Figure 11- Asphalt sample under flow number testing

Figure 12- Damaged asphalt samples after flow number testing

3.5.3 Semi-Circular Bending Test

This test method covers the determination of cracking resistance properties of asphalt mixtures at intermediate test temperatures using the Flexibility Index Test (FIT). Tested samples were obtained from prepared laboratory compacted specimens with a minimum of 160 ± 1 mm compaction height, to achieve the target 7.0 ± 1.0 percent air voids. From the middle of each 160 ± 1 mm tall specimen, two cylindrical 50 ± 1 mm thick discs were trimmed and cut in half to create semicircular test specimens. The air voids for each disc were 7.0 ± 1.0 percent. Each disc were cut into two identical halves resulting in four individual FIT specimens. A minimum of three individual test specimens were required for one FIT result. A notch of 30± 0.5 mm was sawn in the flat side of the semicircular specimen opposite the curved edge, parallel to the direction of load application. Specimens were conditioned 2 hours before testing and maintained through testing at 25 ± 0.5°C. The specimen was positioned in the fixture with the notched side down centered on two rollers. A load was applied along the vertical radius of the specimen and the load and load line displacement (LLD) were measured during the entire duration of the test. The load was applied such that a constant LLD rate of 50 mm/min is obtained and maintained for the duration of the test (Figure 13 &14) [81].

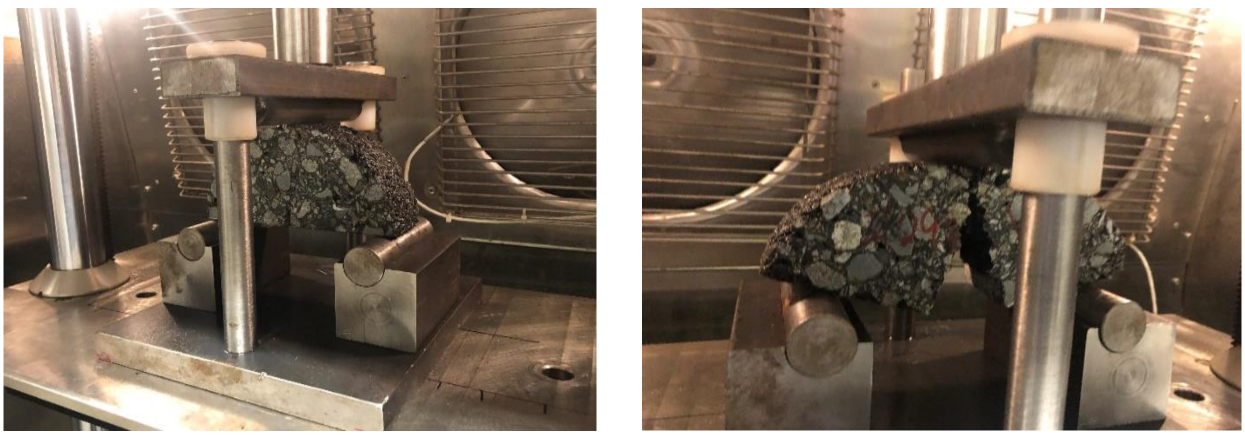

Figure 13- Semi-circular asphalt samples under SCB testing

Figure 14- Damaged semi-circular asphalt samples

Ozer et al. introduced a flexibility index (FI) that determines fracture potential parameters for asphalt concrete mixtures using the same SCB specimen geometry mentioned previously [82]. During each test, the load versus displacement curve was recorded. The data analysis procedure related to this test determines the fracture energy (Gf) and post peak slope (m) of the load–load line displacement (LLD) curve (Figure 17). Work of fracture (Wf) is defined as the area under the displacement-load curve. The facture energy (Gf) was then calculated as the work of fracture divided by ligament area (Equation 11). The flexibility index was then calculated as the fracture energy divided by the absolute value of the slope at the inflection point on the post-peak curve and then multiplied by a constant 0.01 for scaling (Equation 12). The Illinois Center of Transportation (ICT) developed the I-FIT software that uses an exponential-based equation to fit the post-peak curve and to calculate he flexibility index (FI) [83] (Figure 18). Detailed numerical integration techniques and regression functions can be found in the cited AASHTO standard [81].

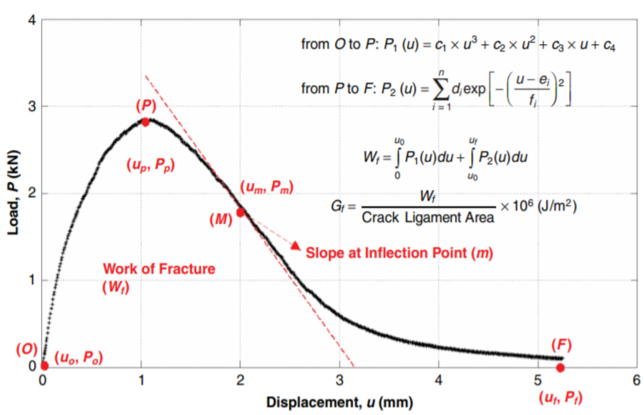

Figure 15- A typical outcome of the SCB test illustrating the parameters derived from the load-displacement curve including peak load, critical displacement, slope at inflection point, displacement at peak load, and fracture energy [82].

Figure 16- I-FIT software provided by the Illinois center of transportation [83]

$$\mathbf{Gf} = \frac{Wf}{\text{Area lig}} \times 10^{6} \qquad \textbf{Equation 11}$$

where;

Gf=fracture energy (Joules),

W_f= work of fracture (Joules), and

$Area_{lig}$ = ligament area = (r – a) × t, (mm^2)
where r=specimen radium (mm), a=notch length (mm) and t= specimen thickness (mm)

$$\mathbf{FI}=\frac{Gf}{|m|}\times A \qquad \textbf{Equation 12}$$

where;

FI= flexibility index

A= conversion factor (assume 0.01),

m= absolute value of post-peak load slope m (kN/mm)

3.5.4 Cantabro Test

This test method determines the abrasion loss of asphalt concrete specimens. It is a good indication of the bonding properties between the fibers and asphalt mixture. Cantabro test is usually used for the OGFC (Open-Graded Friction Courses) mixtures such as porous asphalt. However, there are numerous studies in the literature which are related to usage of this test method for dense gradations [84]. In this test, asphalt mixture specimens of 100 mm diameter by 150 mm height were used having 7.0 ± 1.0 percent air voids. The specimens were placed long enough to ensure a consistent temperature of 25 ± 1°C before testing. The sample mass (A) was recorded before testing. The specimens were then placed in the Los Angeles machine, without the steel balls used in the LA abrasion test, at a speed of 30–33 rpm (300 revolutions). The test takes approximately 10 minutes min to complete and during that time, the sample was subjected to impact and frictional forces, causing the specimen to disintegrate. After every 50 revolutions, the sample mass (B) was recorded to measure the extent of abrasion after removing the loose material broken off (Figure 19 and 20). Cantabro loss (%) was calculated using the below equation (Equation 13).

$$\mathbf{CL}=\frac{A-B}{A}\,\mathbf{x100} \qquad \textbf{Equation 13}$$

where;

CL= Cantabro loss, (%)

A= Initial weight of test specimen, Kg

B= Final weight of test specimen, Kg

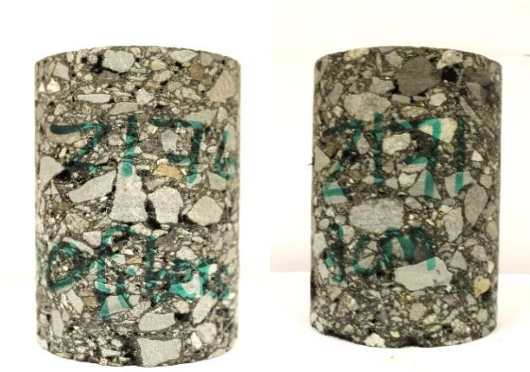

Figure 17- Asphalt samples before conducting Cantabro Test

Figure 18- Asphalt samples after conducting Cantabro Test

CHAPTER 4

RESULTS AND ANALYSIS

4.1 Palm Fibers Characterization Tests

4.1.1 Scanning electron microscopy (SEM) and microscopic images

SEM images (Figure 21) below shows the morphology and the surface of the fibers. It is a typical microstructure of a natural fiber: cylindrical, rough and full of impurities and cavities along its outer surface. The surface roughness of these natural fibers improves the interaction with the asphalt binder, thus effectively improving the interfacial adhesion between the natural palm fibers and the asphalt and improving the overall performance of the asphalt mixture subsequently. Also, the surface of the palm fiber is observed as a rough surface with irregularities, which provide good structural stability.

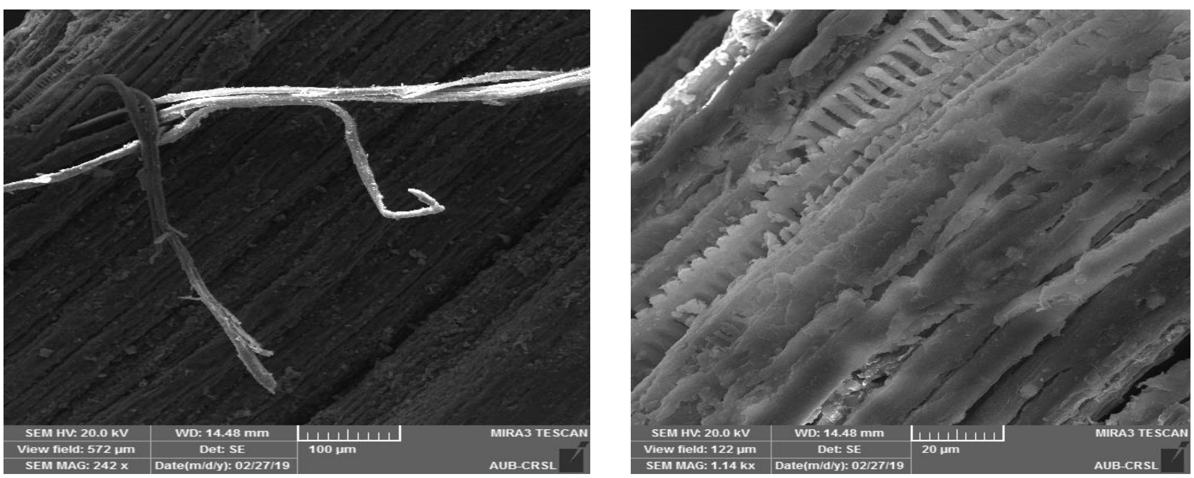

Figure 19- SEM microscopic images of palm fibers

The fiber microstructure and distribution play a significant role in the performance of fiber reinforced asphalt mixture. The interaction of fibers with other mixture material contributes significantly to their ability in spreading traffic loads [23]. Shanbara et al. examined different types of natural fibers such as jute, coir and hemp through SEM. SEM images showed that natural fibers has an uneven surface with irregularities, rough cavities on its outer surface and some voids. Images also showed that the surface has irregularities resulting in a rough surface texture that can enhance the interlock between the mixture and fibers. Moreover, these cavities could improve the surface interface between the fibers and asphalt mixture of the fibers and mixture interface [85]. Fibers also form a spatial networking to stabilize and strength mixture as approved by the micro SEM analysis. Xiong et al. analyzed synthesized basalt fiber, polyester fiber, brucite fiber and lignin fiber using SEM [86]. SEM images showed that the brucite (mineral fiber) and lignin (natural fiber) have a rougher surface than basalt fiber and polyester fiber. Experimental results of Mesh-basket drain-down test indicated that both brucite and lignin fibers recorded lower asphalt loss (%). This may be due to the fiber surface texture which is an important factor that affect the bonding strength between asphalt and fibers. It is concluded that the rougher surface texture the fiber surface is, the higher bonding strength with the asphalt will be.

4.1.2 Thermogravimetric analysis

Thermogravimetric analysis (TGA) was measured to access thermal stability of the palm fibers. According to TGA results (Figure 22), less than 10% mass loss was recorded at 160°C. This temperature represents the temperature experienced during the mixing of the asphalt mixtures. This initial mass loss is due to the dehydration process and moisture loss which will not harm the mechanical properties of test specimen. The second decrease in weight of the palm fibers was observed at 200 – 370 °C and the maximum decrease in weight loss was noticed at these temperatures. The 43% mass loss is due to the decomposition of major components of the palm fibers [87]. A 35% mass loss was recorded at 600°C at the end of this test.

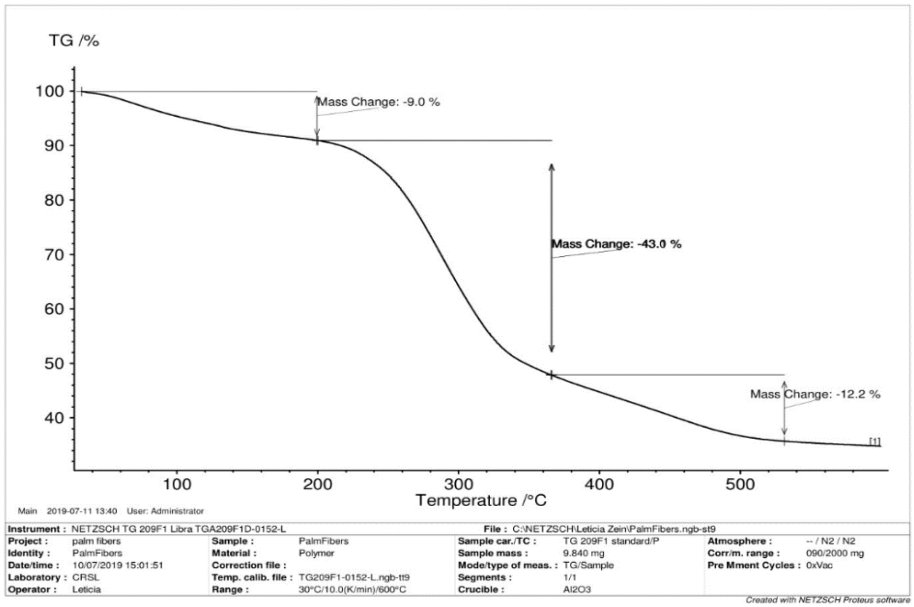

Figure 20-TGA test results

Desseaux et al. evaluated the thermal stability of microfibrillated cellulose fibers (MFCac). This test assess whether the fibers would withstand the high temperatures used during the mixing process with bitumen and the preparation of asphalt mixtures. The mass loss of microfibrillated cellulose (MFCac) was investigated during 4 h at 180 °C under air in isothermal TGA measurements. It was found that the cellulose mass loss was negligible. Thus, it was assumed that the cellulose fibers were stable under bitumen and asphalt mixing temperatures [88].

Thermogravimetric analysis was performed on the wood pulp fibers and recycled paper fibers. Common behavior observed for both fibers is the dehydration process, in which 0.55 – 1.22 % of water is removed in the temperature range between 25 °C and 127 °C. This loss mass depends on the initial moisture content of the fibers. The second decrease in weight of the cellulosic fibers was observed at 206 – 400 °C and the maximum decrease in weight loss was noticed at these temperatures. The average weight loss of wood pulp fiber and recycled paper fiber was 75.4 %, and 51.81%, respectively. It is widely accepted that the primary thermal decomposition of cellulosic materials occurs between 200 and 400 °C. The 43%

mass loss of palm fibers was recorded at 200 – 370 °C, where the maximum decrease in weight loss was observed [87].

4.2 Performance Tests

4.2.1 Complex Modulus Test

As described in the previous section, the dynamic modulus of asphalt mixture was measured at four different temperatures and at six different frequencies (for each temperature level). The dynamic modulus data collected at different test temperatures can be shifted relative to so called reduced time or frequency to form a single master curve at a reference temperature. The master curve describes the loading frequency and temperature dependent properties of asphalt mixtures under linear viscoelastic conditions. For each replicate of the mixes, the |E*| data is shifted based on the time-temperature superposition to form the master curve at a reference temperature of 25°C. The data of |E*| and the shift factors are fitted using the polynomial equation (Equation 7) and sigmoidal function (Equation 6), respectively.

For each mix, the data of the three replicates are averaged and the coefficients defining the master curve and the time-temperature shift factors are determined as shown in Table 4.

Figures 21 till 28 display the master curves for each category. Again, these mixes are designated as the following:

- C-H: HMA mix without adding palm fibers
- C-W: WMA mix without adding palm fibers
- F-H-x-y: HMA mix reinforced with palm fibers
- F-W-x-y: WMA mix reinforced with palm fibers

where x stands for fiber percentage, y stands for fiber length and R stands for replicate number

Table 4- Coefficients of sigmoidal function and time-temperature shift factors for a reference temperature of 25°C to predict |E*| of all mixes at any combination of temperature and loading frequency.

Mixture Reference	**Shift Factors Coefficients**			**Sigmoidal Coefficients**					
	a1	a2	a3	a	b	c	d	e	f
C-H-R1	4.400	2.050	-1.370	1.8465	2.6065	0.9494	0.8385	0.5640	1.5311
C-H-R2	5.200	2.050	-1.600	1.5860	1.3121	0.4444	1.8918	0.5343	1.9940
C-H-R3	5.550	2.300	-1.500	1.2776	3.7264	1.1109	1.0145	0.4972	1.6027
F-H-0.05-10-R1	5.050	2.200	-1.460	1.5080	3.8118	1.2809	1.1949	0.5094	1.9386
F-H-0.05-10-R2	4.950	2.150	-1.600	1.6653	2.1078	0.7147	1.1425	0.5298	1.3298
F-H-0.05-10-R3	4.550	2.000	-1.450	1.976	2.552	0.9902	0.7981	0.5874	1.4672
F-H-0.05-30-R1	4.500	2.000	-1.480	1.9479	3.3267	1.3567	0.7167	05904	1.7055
F-H-0.05-30-R2	4.500	2.000	-1.360	2.1233	2.4340	1.0324	0.8447	0.6173	1.7469
F-H-0.05-30-R3	4.600	2.000	-1.350	2.1901	1.3215	0.5806	0.9780	0.7056	1.0521
F-H-0.1-30-R	4.500	1.800	-1.350	1.5482	5.4489	1.8943	1.1943	0.5983	3.0311
F-H-0.1-30-R2	5.000	2.200	-1.258	1.8446	2.9372	1.0872	0.8617	0.5522	1.5756
F-H-0.1-30-R3	5.000	2.000	-1.300	1.4127	2.6020	0.8475	1.1781	0.5182	1.4207
F-H-0.2-30-R1	4.090	2.350	-1.300	2.0166	2.3840	0.9581	0.8083	0.6702	1.5129
F-H-0.2-30-R2	4.430	2.300	-1.350	1.6634	2.6907	0.9312	1.2220	0.5847	1.8085
F-H-0.2-30-R3	4.900	2.000	-1.400	1.7235	2.4564	0.9186	0.8916	0.5762	1.3087
C-W-R1	5.080	2.253	-1.800	1.9278	1.9267	0.7323	1.0233	0.5690	1.7767
C-W-R2	4.850	2.00	-12.50	2.1667	1.9316	0.8184	0.7820	0.6373	1.6358
C-W-R3	4.950	1.890	-1.400	1.2945	3.0417	0.9312	0.9800	0.5019	1.3666
F-W-0.1-30-R1	4.500	2.200	-1.400	2.2290	2.1579	0.9669	0.6479	0.6771	1.8088
F-W-0.1-30-R2	4.500	2.100	-1.600	2.2664	4.3035	2.0301	1.1127	0.7778	5.2123

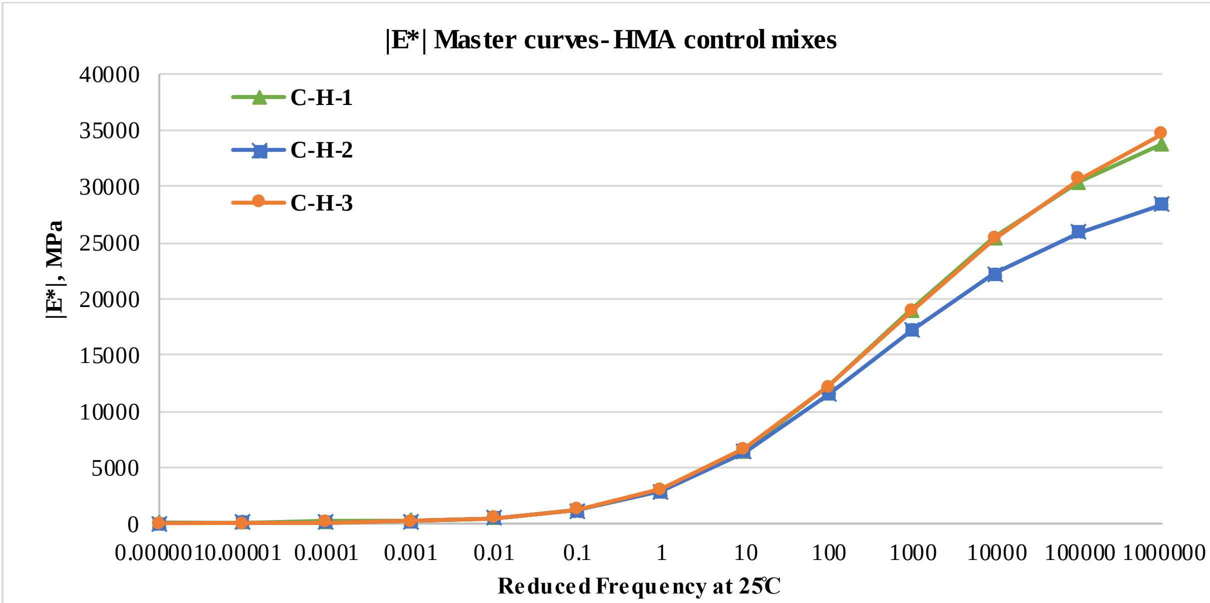

Figure 21-E* master curves for control hot asphalt mixes

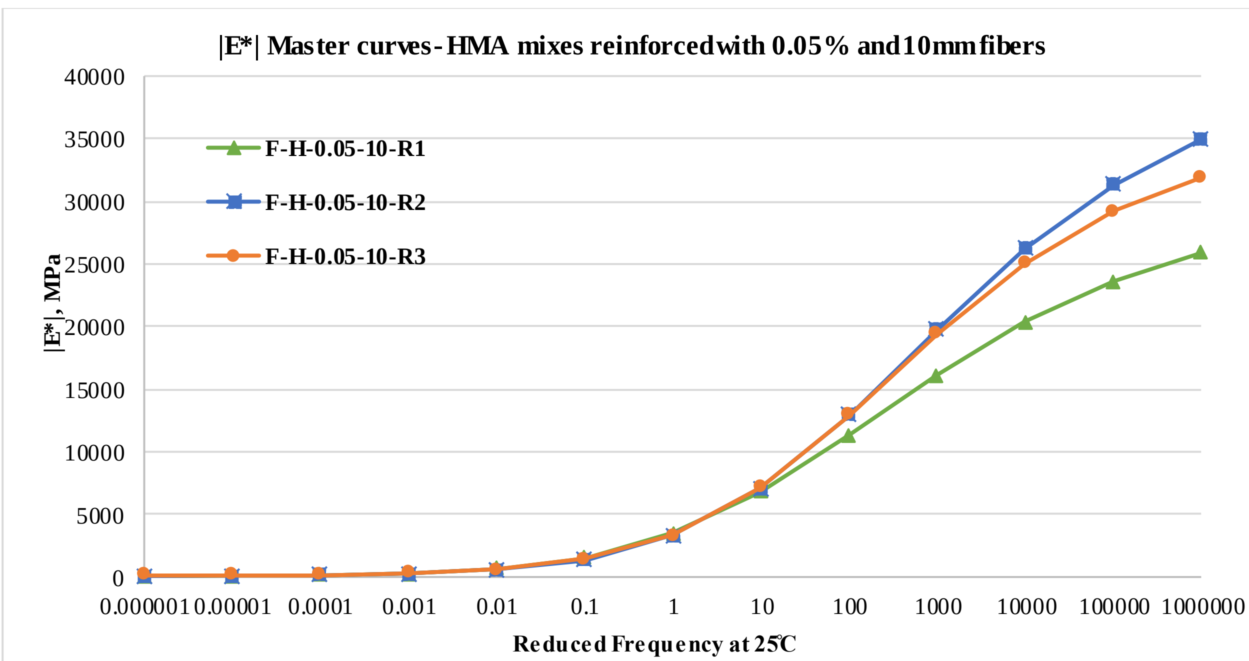

Figure 22- E* master curves for hot asphalt mixes reinforced with 0.05% and 10mm palm fibers

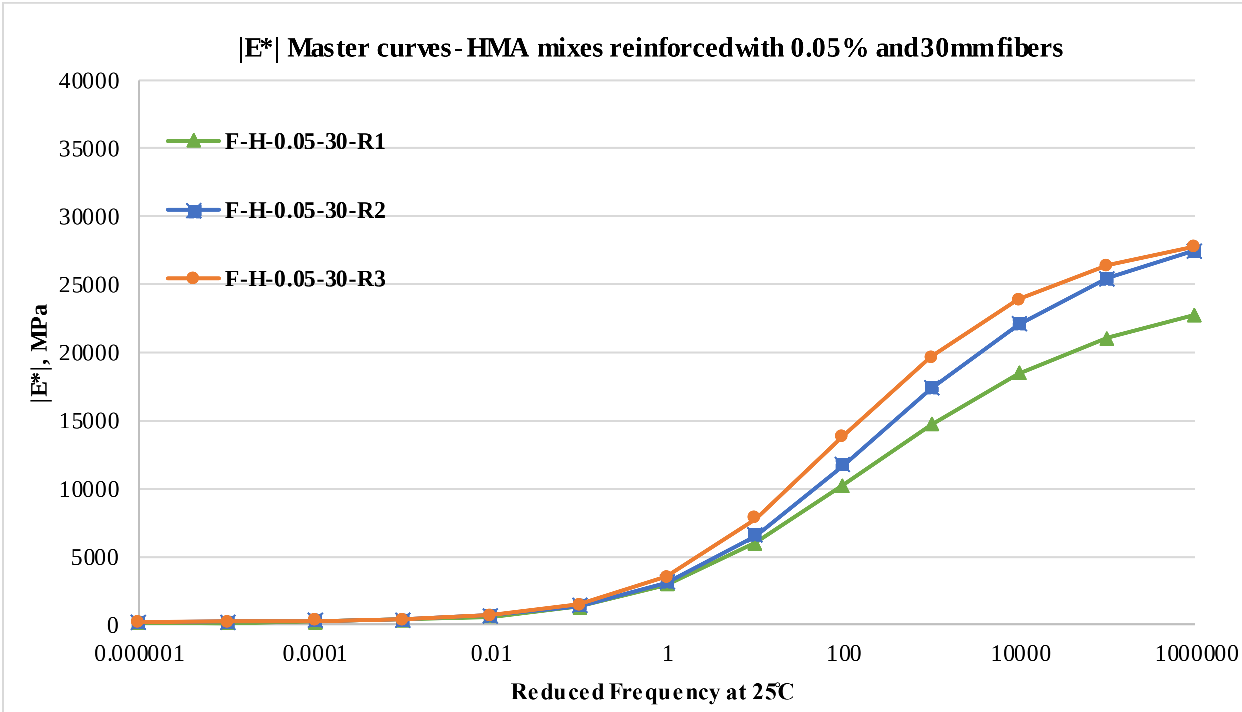

Figure 23- E* master curves for hot asphalt mixes reinforced with 0.05% and 30mm palm fibers

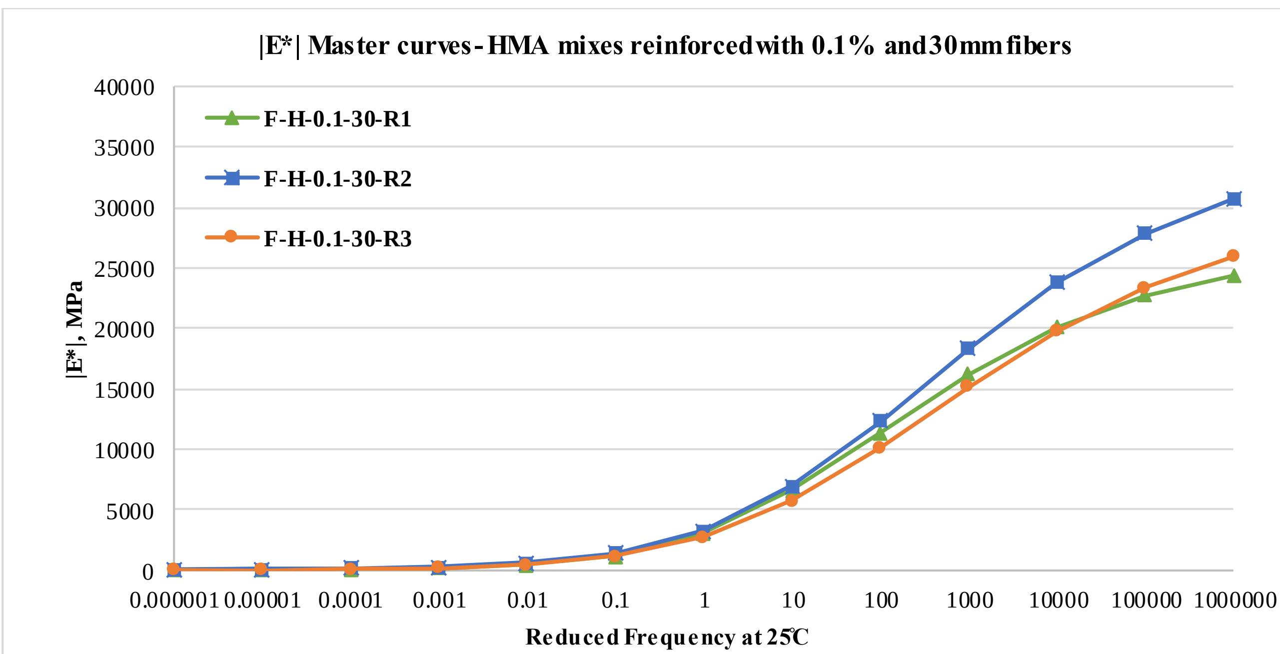

Figure 24- E* master curves for hot asphalt mixes reinforced with 0.1% and 30mm palm fibers

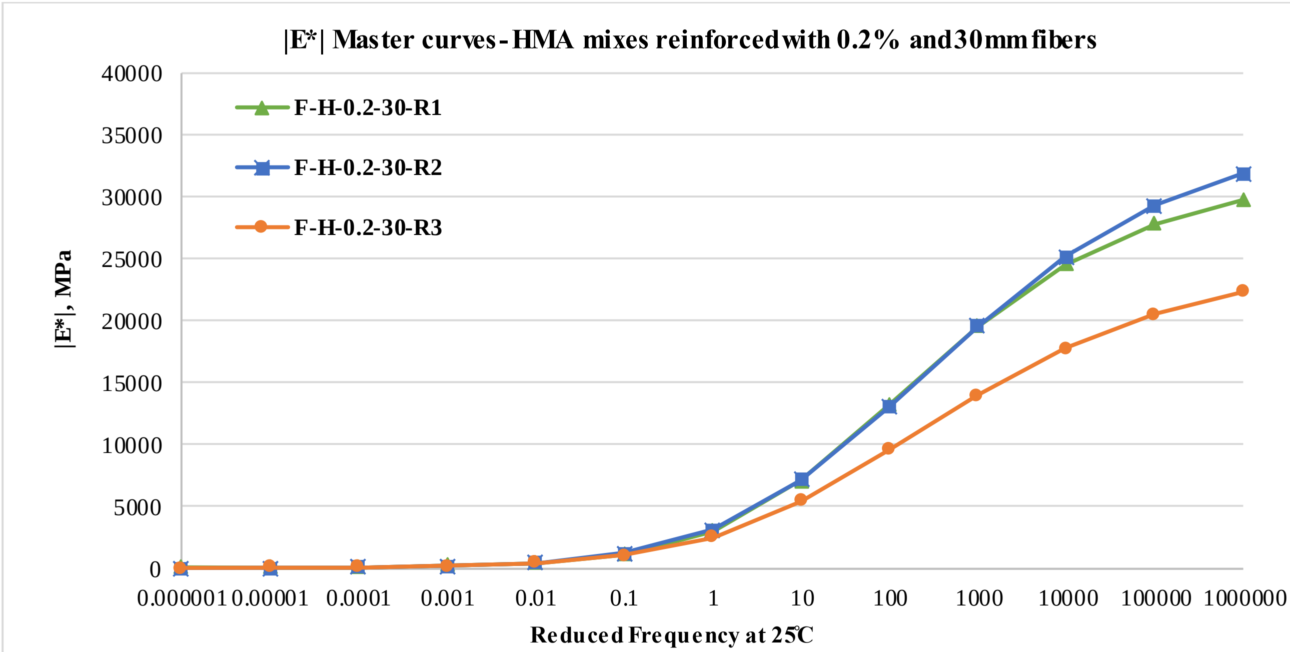

Figure 25- E* master curves for hot asphalt mixes reinforced with 0.2% and 30mm palm fibers

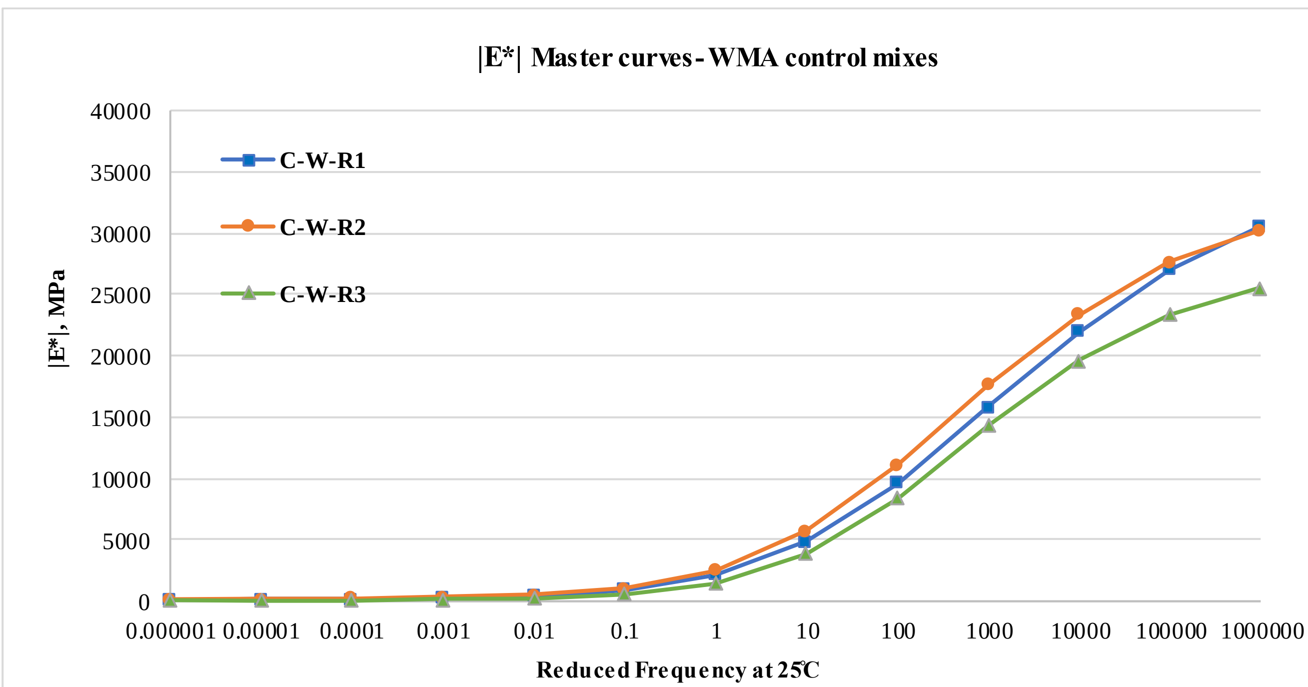

Figure 26- E* master curves for control warm asphalt mixes

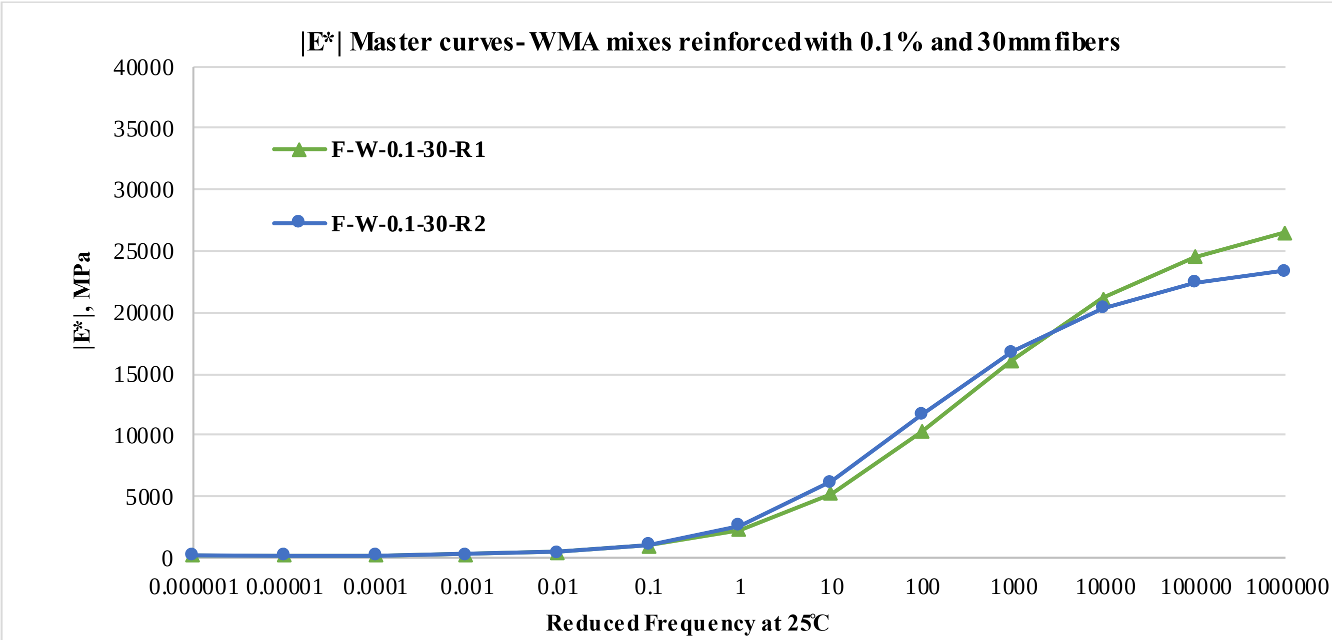

Figure 27- E* master curves for warm asphalt mixes reinforced with 0.1% and 30mm palm fibers

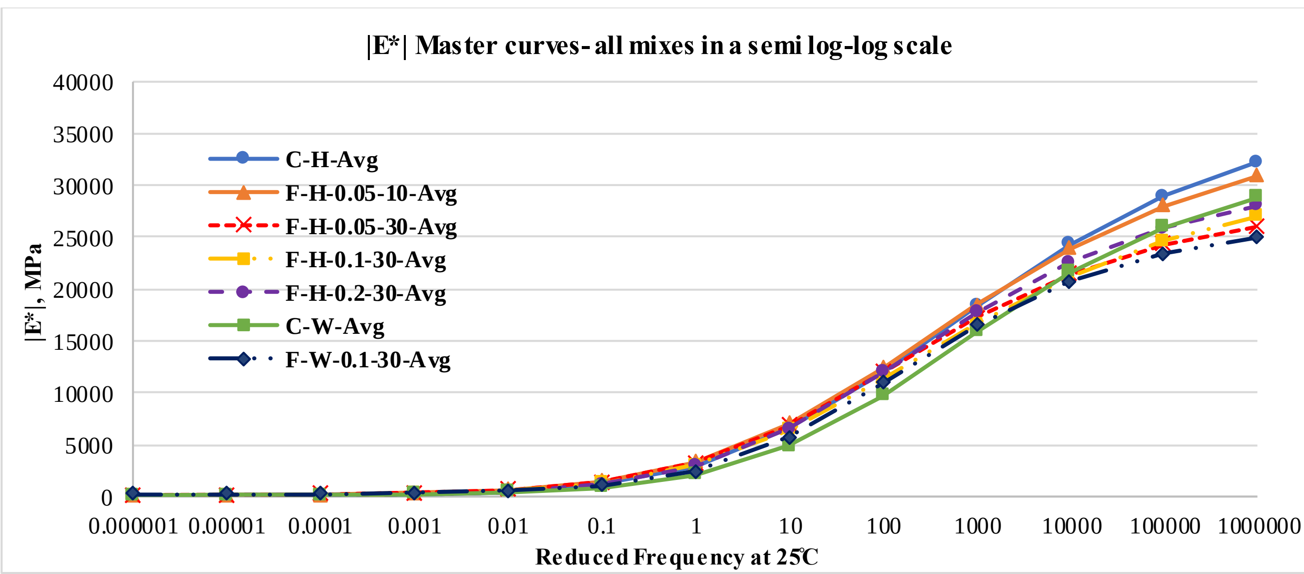

Figure 28- E* master curves for all mixes in a semi-log scale

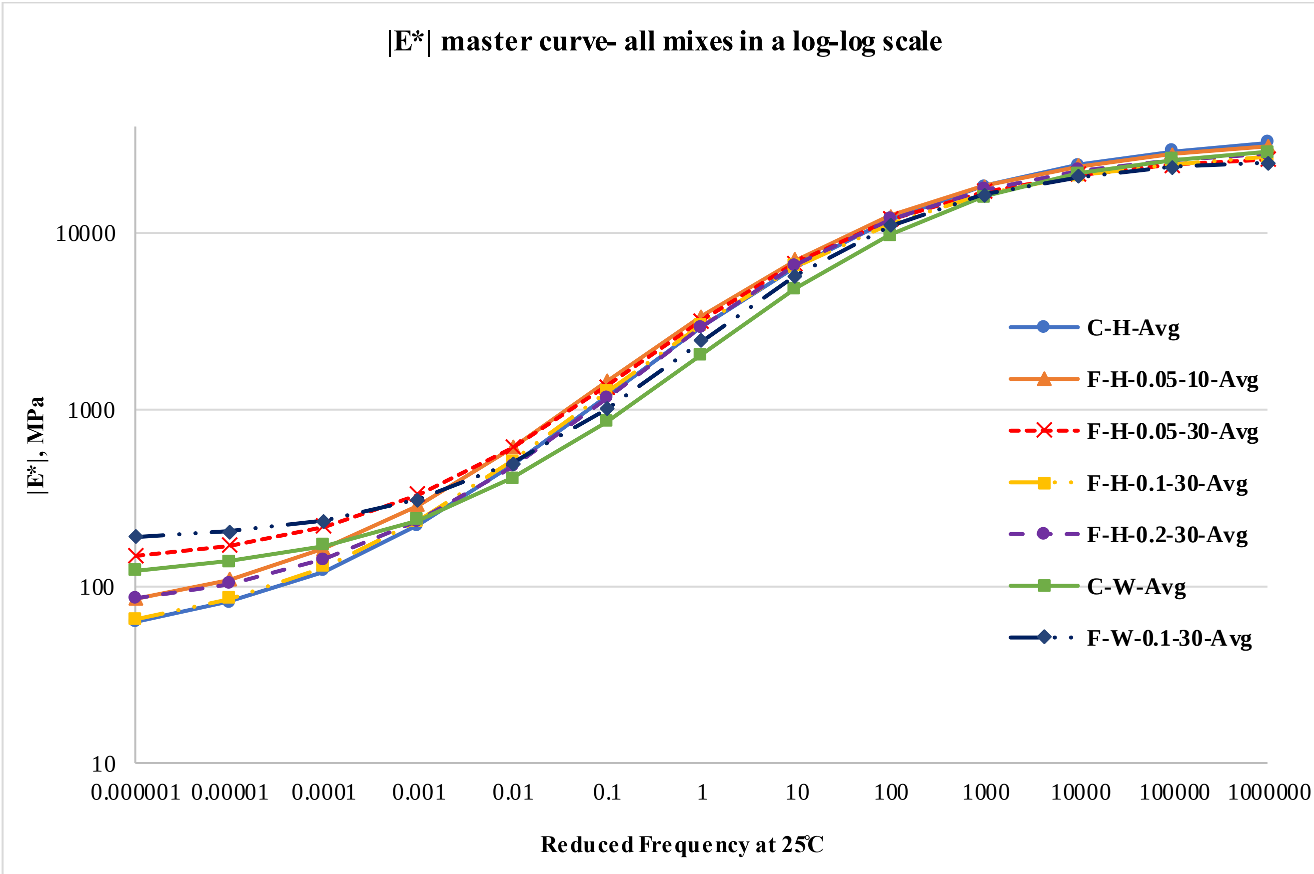

Figure 29-E* master curves for all mixes in a log-log scale

4.2.1.1 HMA fiber reinforced mixtures versus the control HMA mix:

As shown in Figure 30, that fiber addition results in a general increase in the complex dynamic modulus (E*) for all mixtures evaluated within the range of loading frequency, especially at lower frequency (Figure 31). The measured dynamic modulus E* values of F-H-0.05-30 were higher among the HMA fiber reinforced mixes. At high temperatures and low temperatures (between reduced frequencies 0.000001 and 0.001 Hz), the binder becomes softer, the aggregates dominate the elastic behavior of the asphalt mixtures, and the reinforcement effect of the fibers can enhance the modulus values at higher temperatures [89]. In other words, the palm fibers stiffens the asphalt mixture at higher temperatures and could contribute to asphalt pavements in better resisting rutting. Palm fibers support the asphalt mixture structure by holding the components together and reducing stress concentration in addition to retaining bitumen at high temperatures [2]. At high temperatures and low frequencies, HMA mixes blended with 30mm palm fibers can better enhance the interlock between the aggregate and the binder than 10mm palm fibers due to its extra length. However, it is visually observed that 10mm fiber length improved the asphalt mixture performance at intermediate temperatures and frequencies (Figure 32). The 10mm long palm fibers behaved like a stiffener inside the asphalt mixture, which provide an extra stiffening effect to the binder. Fibers increased the elastic response of the asphalt mixtures relative to that of the binder particularly at intermediate temperatures (between reduced frequencies 0.01 and 1000 Hz). Palm fibers increase the stiffness of asphalt mixtures, which results in the reduction of fatigue damage for asphalt mixtures during their serving lifespan at intermediate temperatures.It was observed that adding 0.05% palm fibers no matter what the fiber length is, was adequate to enhance the viscoelasticity properties of asphalt mixtures (Figure 30,31 and 32). It may be due to the balling effect that it is created in the asphalt mixtures when adding more than 0.05% of palm fibers.

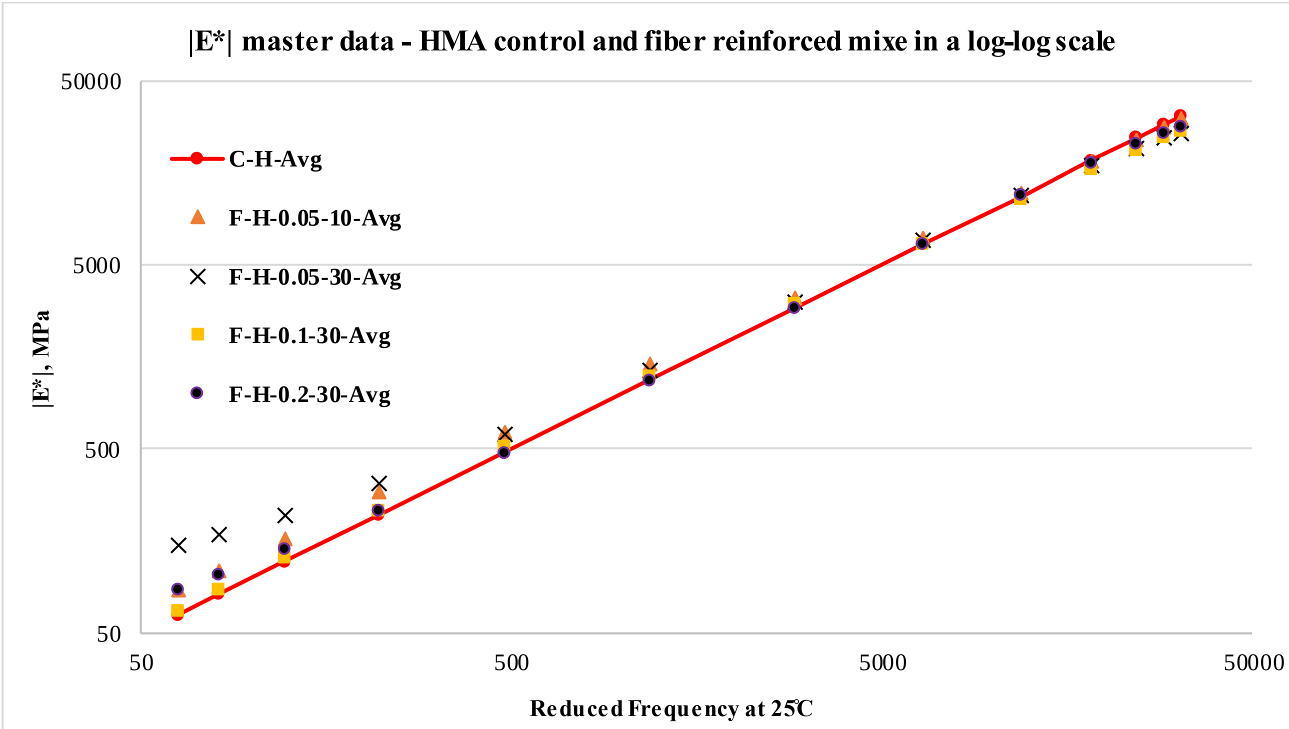

Figure 30- E* master data for HMA control and fiber reinforced mixes along the HMA control mixture in a log-log scale

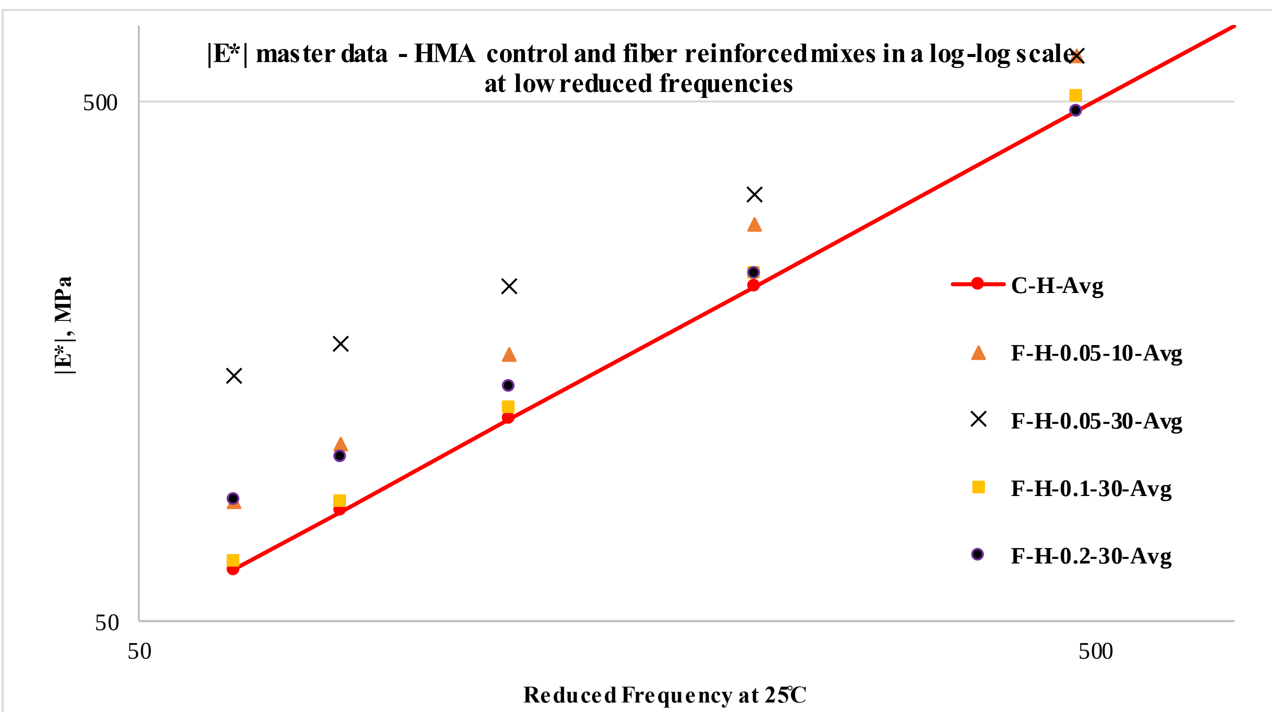

Figure 31- E* master data for HMA control and fiber reinforced mixes along the HMA control mixture in a log-log scale at low reduced frequencies

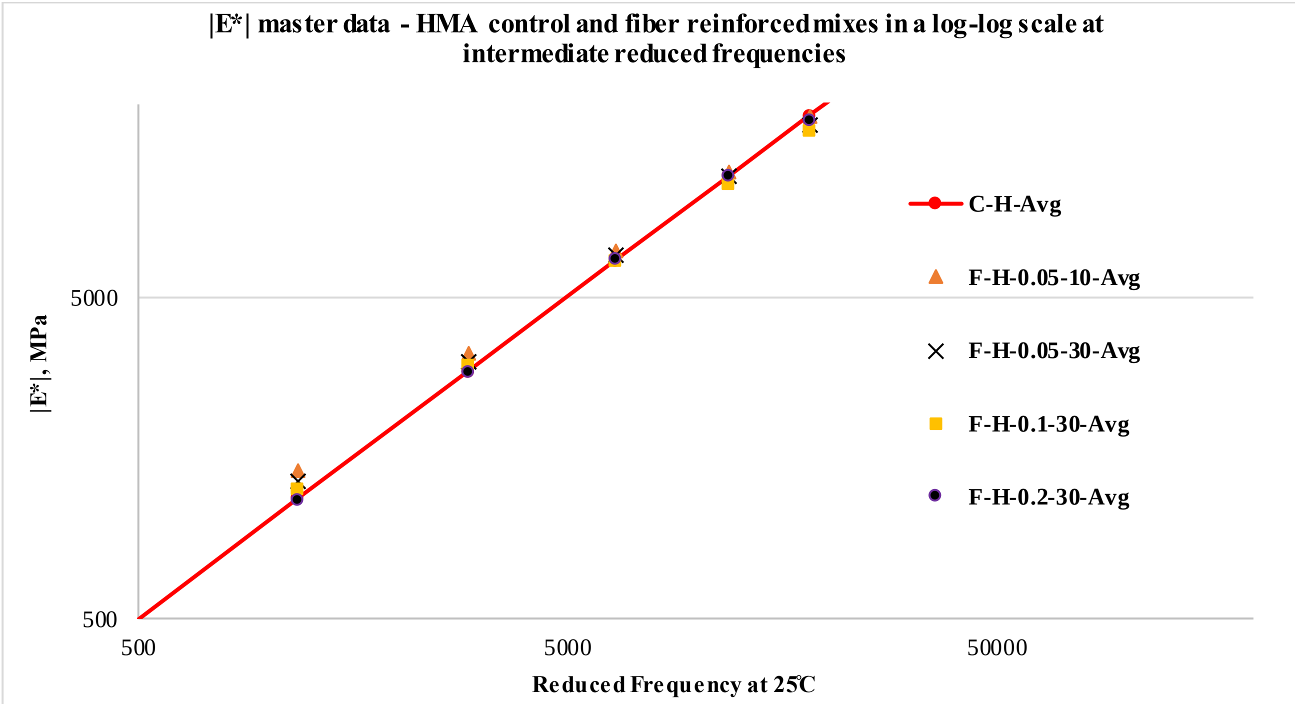

Figure 32- E* master data for HMA control and fiber reinforced mixes along the HMA control mixture in a log-log scale at intermediate reduced frequencies

4.2.1.2 Asphalt concrete mixture type:

Like other studies the overall performance of the WMA mix in terms of dynamic modulus was better as compared to the HMA mix (Figure 35) [90]. For both WMA control and fiber reinforced mixes, lower values of |E*| can be found at higher frequency (or low temperature) range when compared to their HMA mix equivalent. However, the |E*| values of both WMA mixes were significantly higher than |E*| values of both HMA mixes at the lower frequency (or high temperature) range. This means WMA mixes can be as good as or even better than HMA in terms of rutting performance.

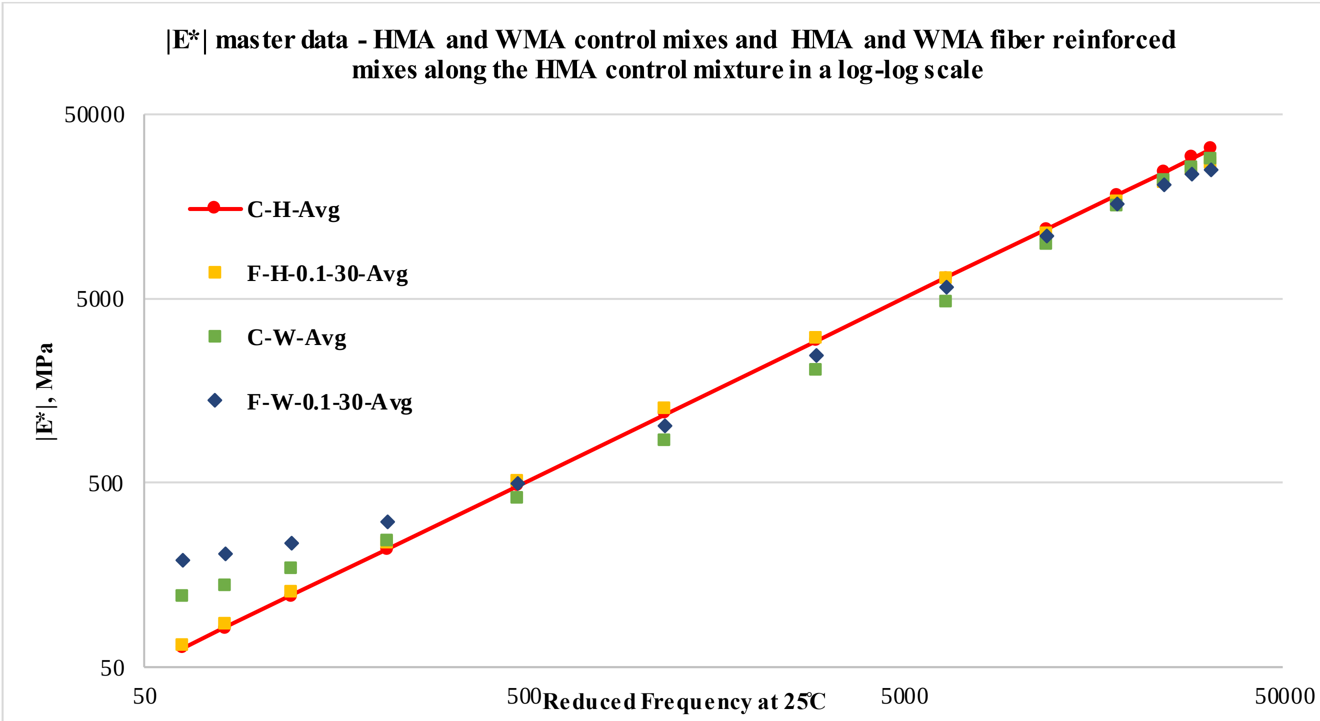

Figure 33- E* master data for HMA and WMA control mixes and HMA and WMA fiber reinforced mixes along the HMA control mixture in a log-log scale

4.2.1.3 <u>Statistical analysis to test effect of palm fibers on |E*| of HMA and WMA mixes:</u>

Using the dynamic modulus data, a statistical analysis was conducted to study the effect of the natural palm fibers on the stiffness of the asphalt mixes. This will show whether there is any significant difference between the |E*| of HMA versus those of the HMA mixes reinforced with different lengths and percentages of natural palm fibers. One-way ANOVA was conducted for each independent variable (length and percentage) by blocking on the other. Note that a two-way ANOVA was not possible since variability over length was limited. Tukey's honest (HSD) was conducted to determine which groups showed statistical differences. The predictor variable was the dynamic modulus generated from the fitted sigmoidal function for each mix at 10^-6, 10^-5, 10^-4,10^-3, 10^-2, 10^-1, 1, 10, 10^2, 10^3, 10^4, 10^5, and 10^6 Hz, which represent a wide range of frequencies that covers rutting and fatigue cracking (i.e. most frequent distresses in asphalt pavement). Two-way analysis of variance (ANOVA) was used to assess the combined effect of fiber percentage and the type of the mix. Moreover, this has been studied to check whether there is an interaction between the palm fibers percentage and WMA technology used.

a. One-way ANOVA Scenario 1:

The effect of fiber percentage using the same fiber length 30 mm on the dynamic modulus value of HMA mixes was first assessed using a one-way ANOVA. As can be seen from Figure 33, at low reduced frequencies there appears to be differences between the control hot asphalt mixture (C-H) and the asphalt mixtures reinforced with 0.05%-30mm palm fibers (F-H-0.05-30). However, at high reduced frequencies, there are no visual differences between the two groups. The results display that the natural palm fibers stiffen the dynamic modulus at high temperatures for asphalt mixtures reinforced with palm fibers against the control mixture, whereas at low temperature palm fibers soften the dynamic modulus against the control hot asphalt mixture. The One-way ANOVA results agree with these observations findings shown in the E* master curve plot in Figure 33, that the addition of 0.05% natural palm fibers have a significant effect on the dynamic modulus values from 0.000001 to 0.01 Hz reduced frequencies. Also, when looking at the p-values between groups in table 5, there is a statistical difference between F-H-0.05-30 category mix and other categories across same frequencies at a 90% confidence level (results highlighted in yellow). Rutting distress occurs at these low reduced frequencies (high temperatures and low frequencies), results show that the addition of 0.05% palm fibers induce a better rutting resistance. As stated before, the addition of only 0.05% palm fibers is adequate in enhancing the viscoelasticity properties of asphalt mixtures. It may be due to the balling effect that it is created in the asphalt mixtures when adding more than 0.05% of palm fibers. Adding 0.1 or 0.2% does not have a significant effect on the performance of asphalt concrete mixtures.

Table 5- TukeyHSD test results for multiple comparisons of means of |E*| mastercurves of HMA control mix and HMA reinforced with 30 mm fibers but at different fiber percentages. Tests conducted assuming a 90% confidence level

Predictor: |E*| of frequency	**ANOVA p-value**	**Compared Pairs of Mixes**	**p-values of TukeyHSD**
0.000001	0.0250	F-H-0.05-30 vs. C-H	0.0320675
		F-H-0.05-30 vs. F-H-0.1-30	0.0359329
		F-H-0.05-30 vs. F-H-0.2-30	0.1204429
0.00001	0.0260	F-H-0.05-30 vs. C-H	0.0328753
		F-H-0.05-30 vs. F-H-0.1-30	0.0387271
		F-H-0.05-30 vs. F-H-0.2-30	0.1085609
0.0001	0.0270	F-H-0.05-30 vs. C-H	0.0344219
		F-H-0.05-30 vs. F-H-0.1-30	0.0464185
		F-H-0.05-30 vs. F-H-0.2-30	0.0892446
0.001	0.0362	F-H-0.05-30 vs. C-H	0.0437377
		F-H-0.05-30 vs. F-H-0.1-30	0.0779288
		F-H-0.05-30 vs. F-H-0.2-30	0.0757591
0.01	0.051	F-H-0.05-30 vs. C-H	0.0689316
		F-H-0.05-30 vs. F-H-0.1-30	0.1865634
		F-H-0.05-30 vs. F-H-0.2-30	0.0652978
0.1	0.131	F-H-0.05-30 vs. C-H	0.2071818
		F-H-0.05-30 vs. F-H-0.1-30	0.6200108
		F-H-0.05-30 vs. F-H-0.2-30	0.1331021
1	0.655	F-H-0.05-30 vs. C-H	0.2576630
		F-H-0.05-30 vs. F-H-0.1-30	0.5033807
		F-H-0.05-30 vs. F-H-0.2-30	0.3188388
10	0.940	F-H-0.05-30 vs. C-H	0.9591957
		F-H-0.05-30 vs. F-H-0.1-30	0.9358594
		F-H-0.05-30 vs. F-H-0.2-30	0.9799731
100	0.930	F-H-0.05-30 vs. C-H	0.9999982

		F-H-0.05-30 vs. F-H-0.1-30	0.9483368
		F-H-0.05-30 vs. F-H-0.2-30	1.0000000
1000	0.797	F-H-0.05-30 vs. C-H	0.9249291
		F-H-0.05-30 vs. F-H-0.1-30	0.9826987
		F-H-0.05-30 vs. F-H-0.2-30	0.9928399
10000	0.562	F-H-0.05-30 vs. C-H	0.6327165
		F-H-0.05-30 vs. F-H-0.1-30	0.9994658
		F-H-0.05-30 vs. F-H-0.2-30	0.9654250
100000	0.367	F-H-0.05-30 vs. C-H	0.3778949
		F-H-0.05-30 vs. F-H-0.1-30	0.9990896
		F-H-0.05-30 vs. F-H-0.2-30	0.9332705
1000000	0.258	F-H-0.05-30 vs. C-H	0.2472636
		F-H-0.05-30 vs. F-H-0.1-30	0.9874958
		F-H-0.05-30 vs. F-H-0.2-30	0.9100738

Note: P-value > 0.1 means non-significant difference and otherwise significant difference. Significant at 90% confidence interval (P-value < 0.1).

b. One-way ANOVA scenario 2:

It was conducted to test the effect of fiber length on the dynamic modulus value of HMA mixes (variables: fiber length, predictor: dynamic modulus values at different reduced frequencies). The One-way ANOVA results agree with the findings shown in the E* master curve plot in Figure 27, whereby the use of 10 and 30mm palm fiber length had a significant effect on the dynamic modulus values from 0.000001 to 0.1 Hz reduced frequencies. However, the effect of the 10 mm length fibers was only observed across 0.001, 0.01, 0.1, and 1 Hz reduced frequencies (Figure 34) (p-value<0.1). The effect of adding 30mm palm fiber in an asphalt mixture was more effective across low reduced frequencies than adding 10mm. Adding 30mm fiber length appears to promote higher rutting resistance than 10mm. Longer palm fibers improve the interlock between the aggregate and the binder, which reduces stress concentration in addition to retaining bitumen at high temperatures. However, at intermediate temperatures (across 0.001,0.01,0.1, and 1 Hz reduced frequencies) the

10mm long palm fibers behaved like stiffeners inside the asphalt mixture, which provide an extra stiffening effect to the binder and increase the elastic response of the asphalt mixtures relative to that of the binder.

Table 6- TukeyHSD test results for multiple comparisons of means of |E*| mastercurves of HMA control mix and HMA with 5% fiber reinforced but with different fiber lengths at a 90% confidence level.

Predictor: **|E*| of frequency**	**ANOVA p-value**	**Compared Pairs of Mixes**	**p-values of TukeyHSD**
0.000001	0.0335	F-H-0.05-10 vs. C-H	0.6665580
		F-H-0.05-30 vs. C-H	0.0326122
		F-H-0.05-30 vs. F-H-0.05-10	0.0979184
0.00001	0.0302	F-H-0.05-10 vs. C-H	0.5471715
		F-H-0.05-30 vs. C-H	0.0277193
		F-H-0.05-30 vs. F-H-0.05-10	0.1078884
0.0001	0.0232	F-H-0.05-10 vs. C-H	0.3008828
		F-H-0.05-30 vs. C-H	0.0195031
		F-H-0.05-30 vs. F-H-0.05-10	0.1453614
0.001	0.0124	F-H-0.05-10 vs. C-H	0.0683903
		F-H-0.05-30 vs. C-H	0.0107829
		F-H-0.05-30 vs. F-H-0.05-10	0.3203343
0.01	0.0059	F-H-0.05-10 vs. C-H	0.0089809
		F-H-0.05-30 vs. C-H	0.0102461
		F-H-0.05-30 vs. F-H-0.05-10	0.9912639
0.1	0.0117	F-H-0.05-10 vs. C-H	0.0100841
		F-H-0.05-30 vs. C-H	0.0691734
		F-H-0.05-30 vs. F-H-0.05-10	0.2936374
1	0.080	F-H-0.05-10 vs. C-H	0.0690339
		F-H-0.05-30 vs. C-H	0.3464479
		F-H-0.05-30 vs. F-H-0.05-10	0.4516843
10	0.528	F-H-0.05-10 vs. C-H	0.4997097

		F-H-0.05-30 vs. C-H	0.7983138
		F-H-0.05-30 vs. F-H-0.05-10	0.8551756
100	0.874	F-H-0.05-10 vs. C-H	0.8989684
		F-H-0.05-30 vs. C-H	0.9997697
		F-H-0.05-30 vs. F-H-0.05-10	0.8901618
1000	0.712	F-H-0.05-10 vs. C-H	0.9991652
		F-H-0.05-30 vs. C-H	0.7649142
		F-H-0.05-30 vs. F-H-0.05-10	0.7433775
10000	0.413	F-H-0.05-10 vs. C-H	0.9754350
		F-H-0.05-30 vs. C-H	0.4288787
		F-H-0.05-30 vs. F-H-0.05-10	0.5367057
100000	0.247	F-H-0.05-10 vs. C-H	0.9298889
		F-H-0.05-30 vs. C-H	0.2520236
		F-H-0.05-30 vs. F-H-0.05-10	0.3893323
1000000	0.173	F-H-0.05-10 vs. C-H	0.8948474
		F-H-0.05-30 vs. C-H	0.1754279
		F-H-0.05-30 vs. F-H-0.05-10	0.3077346

Note: P-value > 0.1 means non-significant difference and otherwise significant difference. Significant at 90% confidence interval (P-value < 0.1).

c. Two-way ANOVA scenario 1:

It was conducted to test the effect of both fiber percentage and mix type on the dynamic modulus value of HMA and WMA mixes. (variables: fiber percentage and mix type, predictor: dynamic modulus values at different reduced frequencies). In this case, two-way ANOVA was used to test the following null hypothesis H0: Dynamic modulus means for the different fiber percentages (0 and 0.1%) are equal, H0: Dynamic modulus means for the different asphalt mix type (HMA and WMA) are equal and H0: There is no interaction between fiber percentage and the asphalt mix type. Figure 34 show the master curves of mix categories; control hot asphalt mix, hot asphalt mix reinforced with 0.1% 30mm palm fibers, control warm asphalt mixture and warm asphalt mix reinforced with 0.1% 30mm palm fibers. Therefore, in this scenario two-way ANOVA investigates the effect of both variables, asphalt mix type and percentage on the dynamic modulus values. Two-way ANOVA results agree with the findings shown in the E* master curve plot in Figure 30, that the asphalt mix type had a significant effect on the dynamic modulus values across all reduced frequencies. Compared to the traditional HMA mixes, WMA mixes induced a higher resistance to rutting due to the wax additive that stiffens the binder at in-service temperatures. Similarly, in the case of fatigue cracking or thermal cracking, the lower production temperature of WMA implies a binder that is less aged than the case of HMA [72]. The effect of using 0.1% palm fibers was also significant across 0.000001 to 10 Hz reduced frequencies (highlighted yellow values in table 7). It is showed that there was no statistically significant interaction between the palm fibers percentage and WMA technology used (p-value>0.1). Thus, it can be concluded that the relative effect of fibers was the same regardless of the asphalt mix type.

Table 7- Two-way ANOVA test results of means of |E*| mastercurves of both HMA and WMA control and reinforced mixes with different fiber percentage at a 90% family-wise confidence level.

Predictor: |E*| of frequency	**Variables**	**ANOVA p-value**
0.000001	percentage	0.11269
	type	0.00402
	Interaction	0.27843
0.00001	percentage	0.10459
	type	0.00855
	interaction	0.37401
0.0001	percentage	0.0766
	type	0.0368
	interaction	0.5974
0.001	percentage	0.0488
	type	0.5412
	interaction	0.9822
0.01	percentage	0.0325

	type	0.0817
	interaction	0.6122
0.1	percentage	0.02939
	type	0.00433
	interaction	0.58119
1	percentage	0.02813
	type	0.00163
	interaction	0.92103
10	percentage	0.04335
	type	0.00344
	interaction	0.62428
100	percentage	0.1459
	type	0.0151
	interaction	0.5432
1000	percentage	0.6050
	type	0.0447
	interaction	0.8064
10000	percentage	0.7781
	type	0.0699
	interaction	0.8601
100000	percentage	0.4853
	type	0.0747
	interaction	0.6690
1000000	percentage	0.3768
	type	0.0701
	interaction	0.5842

Note: P-value > 0.1 means non-significant difference and otherwise significant difference. Significant at 90% confidence interval (P-value < 0.1).

4.2.2 Flow Number Test

The flow number (FN) test is a performance test for evaluating rutting resistance of asphalt concrete mixtures [91]. During flow number test, a constant deviator stress is applied at each load cycle on the test sample and the permanent strain is measured at each cycle (Figure 35 till 45). The flow number is defined as the starting point, or cycle number, at which tertiary flow occurs on a cumulative permanent strain curve obtained during the test. High FN values indicate that asphalt mixtures have high rutting resistance. Francken model for triaxial and uniaxial repeated-load tests for different temperatures and stress levels [92]. Dongre et al. verified the robustness of Francken model by fitting FN data obtained from field projects. It is also used due to its consistency in fitting experimental data. Flow number can be defined analytically by finding the cycle where the 2nd derivative of the function changes from positive to negative. The raw permanent strain versus load cycle curve is fitted using Francken's model. The model shown in Equation 8 is fitted to the permanent strain versus the number of cycles for each test sample. After estimating the regression constants (A, B, C and D) to find the number of load cycles at the inflection point, FN is computed at the point which Equation 10 (second derivative of Francken model) is equal to zero. The fitting coefficients (A, B, C, and D) are determined by numerical optimization. Once fitted, FN is easily determined.Figure 35 and 45 present the FN test results for HMA control and fiber reinforced mixes. HMA reinforced with fibers could withstand a higher number of cycles, when compared to the control HMA. Although, the improvement was insignificant, but it is evident that the use of palm fibers enhance the rutting resistance of asphalt mixtures. The use of different fiber percentages recorded roughly the same recorded the same FN (Figure 34), more replicates should be tested for a conclusive comparison. The difference between each mix category replicates was checked; it shouldn't exceed the acceptable percentage average range. Table 8 below found in AASHTO T378-17 accepted bias for replicates developed by high variables.

Table 8- Single-Operator Precision for Unconfined Flow Number

NMAS, mm	**Acceptable range for n Specimens, % of Average**				
	n=2	**n=3**	**n=4**	**n=5**	**n=6**
9.5	92	109	118	128	132
12.5	121	142	155	168	172
19	164	193	211	228	234
25	192	227	247	268	275

Minimum FN values (calculated by using the Francken model) for different traffic levels recommended by AASHTO TP 79-13 are given in Table 9.

Table 9-Minimum Average FN Requirement for different traffic levels

Traffic (million ESALs)	**Minimum Average FN Requirement**
<3	Not applicable
3 to <10	50
10 to <30	190
≥30	740

Studies indicated that adding a higher fiber content and longer fibers promotes a higher rutting resistance. Ziari et al. showed that using a high percentage of polyolefin-glass fiber in HMA mixtures improved rutting resistance. Adding 0.18% polyolefin-glass fiber promotes a higher resistance to rutting with respect to lower fiber percentages [93]. Coleri et al. concluded that the longer the aramid fiber, the higher flow number [94]. Rutting performance of asphalt concrete mixtures can be characterized from the dynamic modulus test performed at high temperatures and low frequencies. Studies showed that the change in asphalt concrete mixtures viscoelastic behavior from dynamic modulus test was effective to identify rutting potential of HMA mix when tested at different range of temperatures and loading frequencies [95]. Also, studies indicated that the dynamic modulus had a good correlation with the repeated loading permanent performance test results; the flow number

(FN) [96]. In this study, dynamic modulus test results proved that palm fibers with different lengths and percentages improved resistance to rutting. It was observed that 30mm fiber length can promote higher rutting resistance than 10mm, and the effect of 10mm length is more effective at intermediate temperatures. Although flow number test included 10mm fiber length, but results weren't reliable. Further investigations could confirm the effect of short palm fibers on flow number test. The flow number appeared to be a more sensitive indicator of the rutting resistance of HMA than the dynamic modulus, since rutting is more critical at elevated temperatures. Dynamic modulus test results previously pointed out that the addition of high fiber dosage (more than 0.05%) creates a fiber balling effect, which induces a lower rutting resistance. Flow number test results showed the opposite, the higher fiber percentage the higher the flow number. This variability could be attributed to the viscoelastic nature of the asphalt binder, whose behavior tends to be more viscous at elevated temperature and therefore exhibits a variable response especially in destructive tests (flow number test). A higher concentration of palm fibers might be required to resist higher permanent deformation.

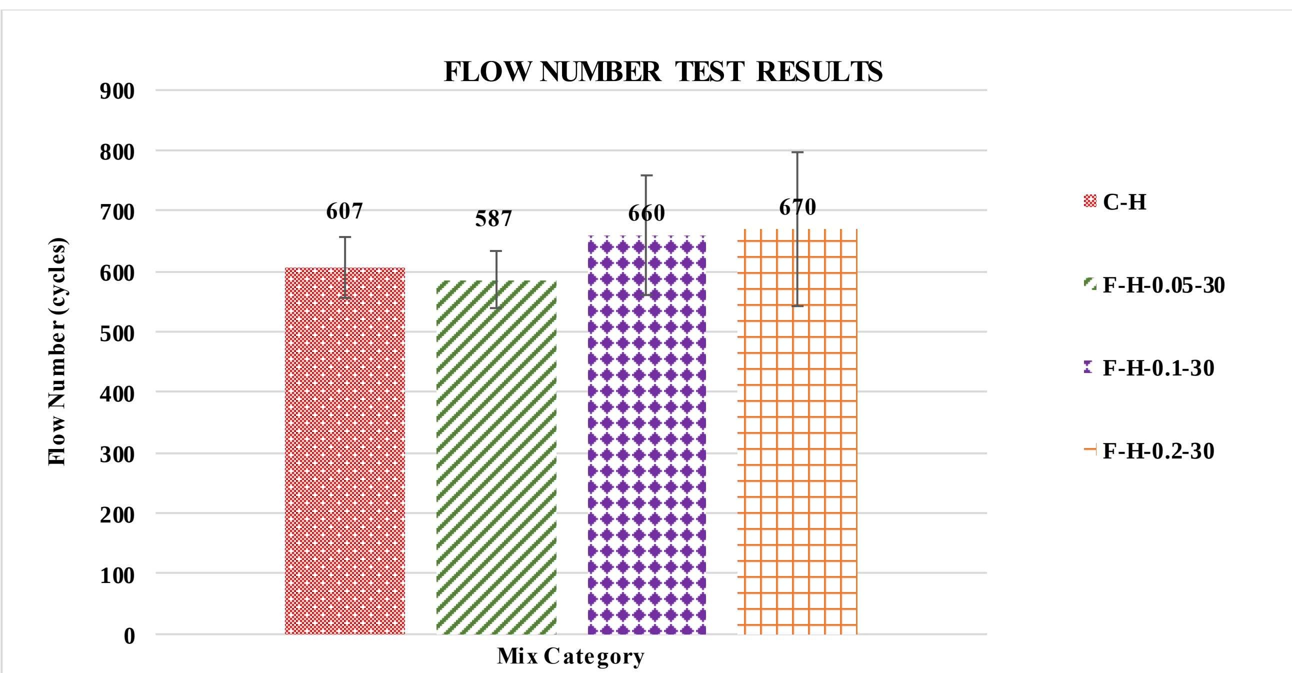

Figure 34- Flow number test results summary

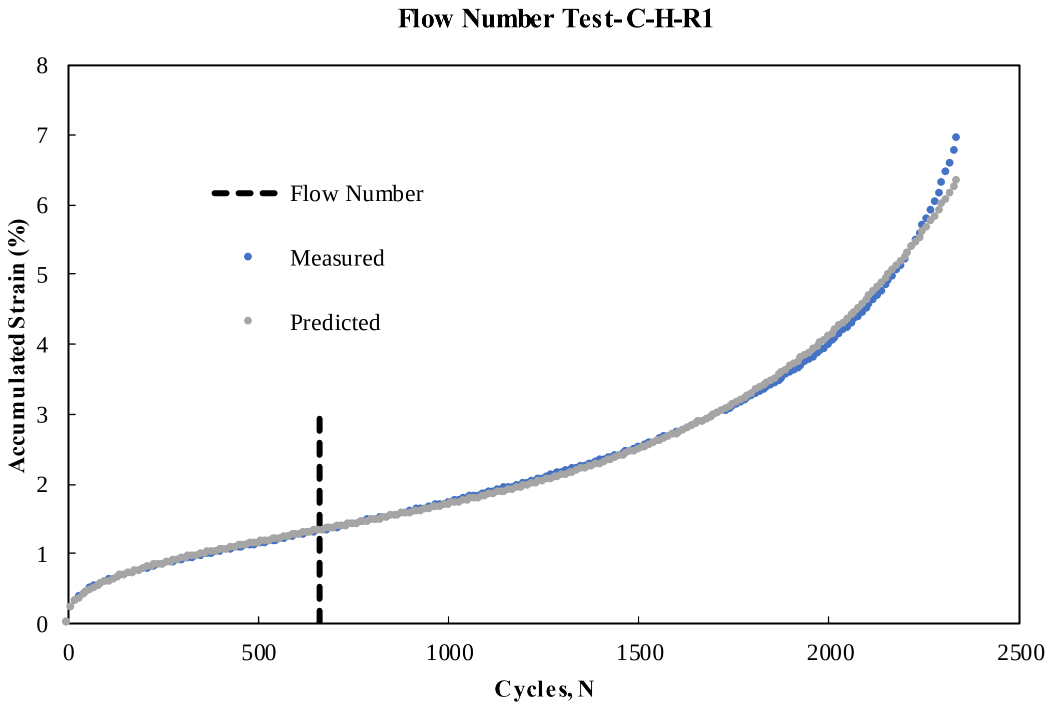

Figure 35- Accumulated strain (%) versus flow number (cycles) for asphalt test sample C-H-R1

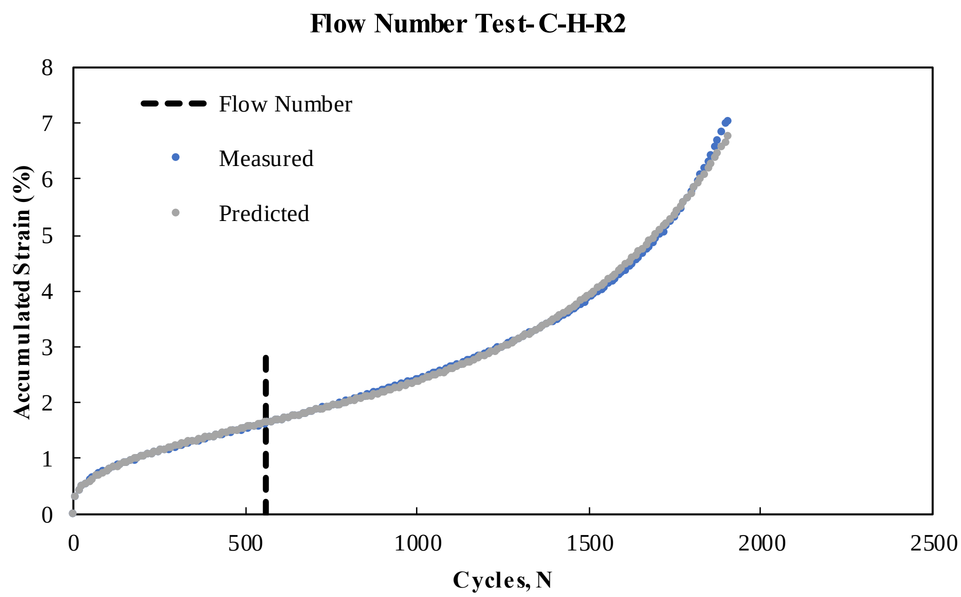

Figure 36- Accumulated strain (%) versus flow number (cycles) for asphalt test sample C-H-R2

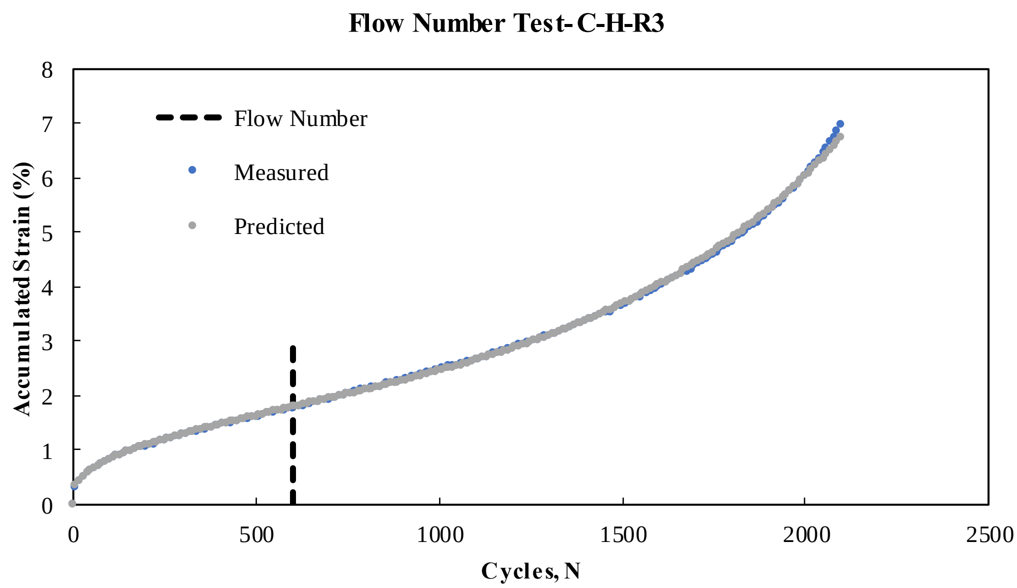

Figure 37- Accumulated strain (%) versus flow number (cycles) for asphalt test sample C-H-R3

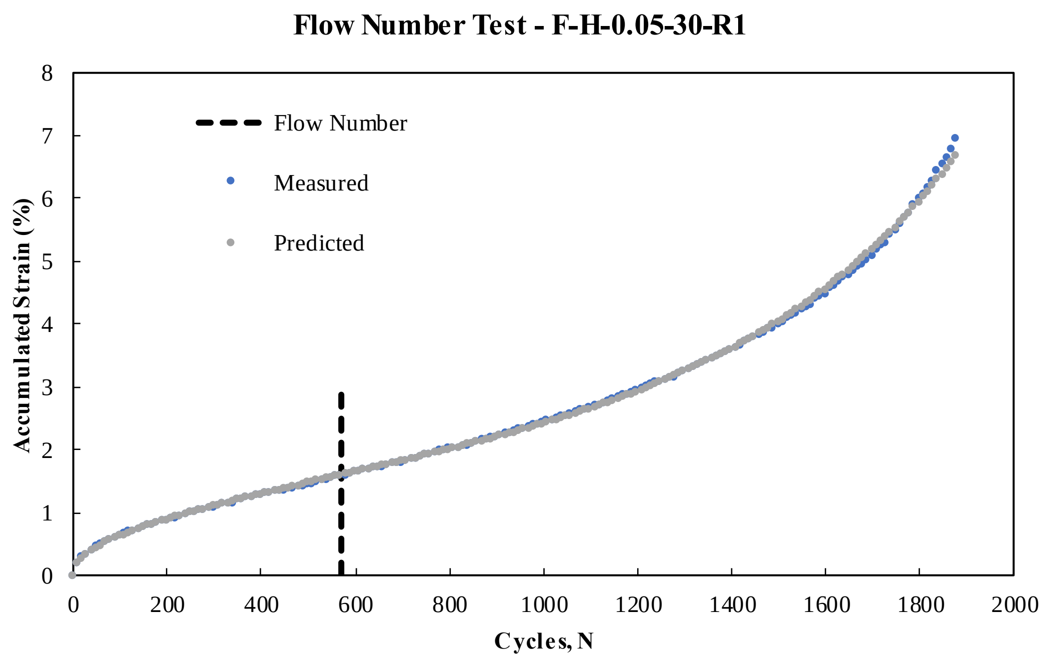

Figure 38- Accumulated strain (%) versus flow number (cycles) for asphalt test sample F-H-0.05-30-R1

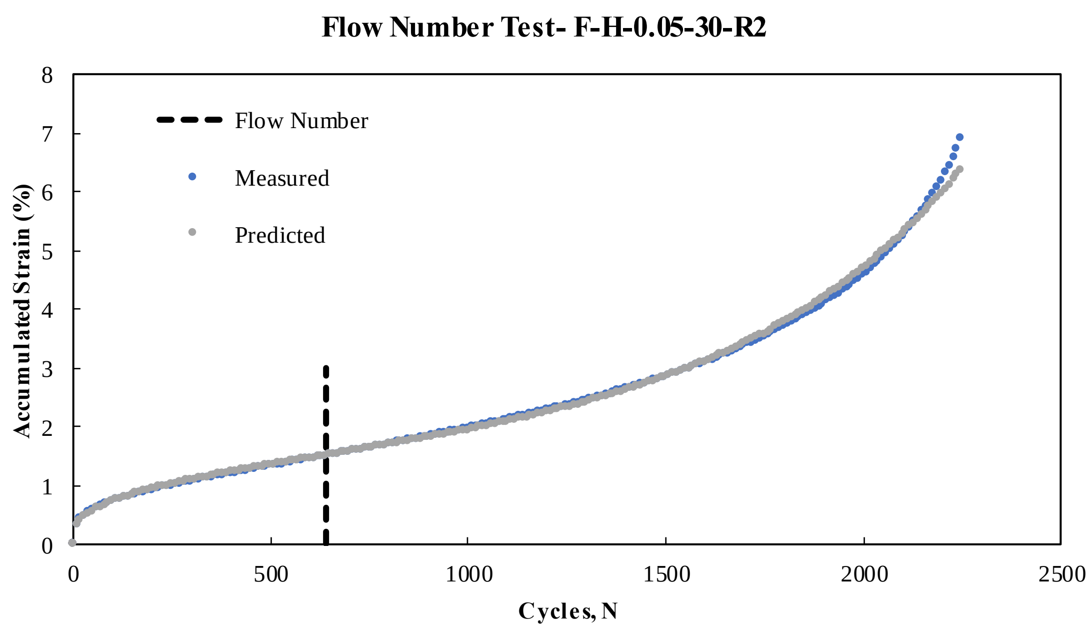

Figure 39- Accumulated strain (%) versus flow number (cycles) for asphalt test sample F-H-0.05-30-R2

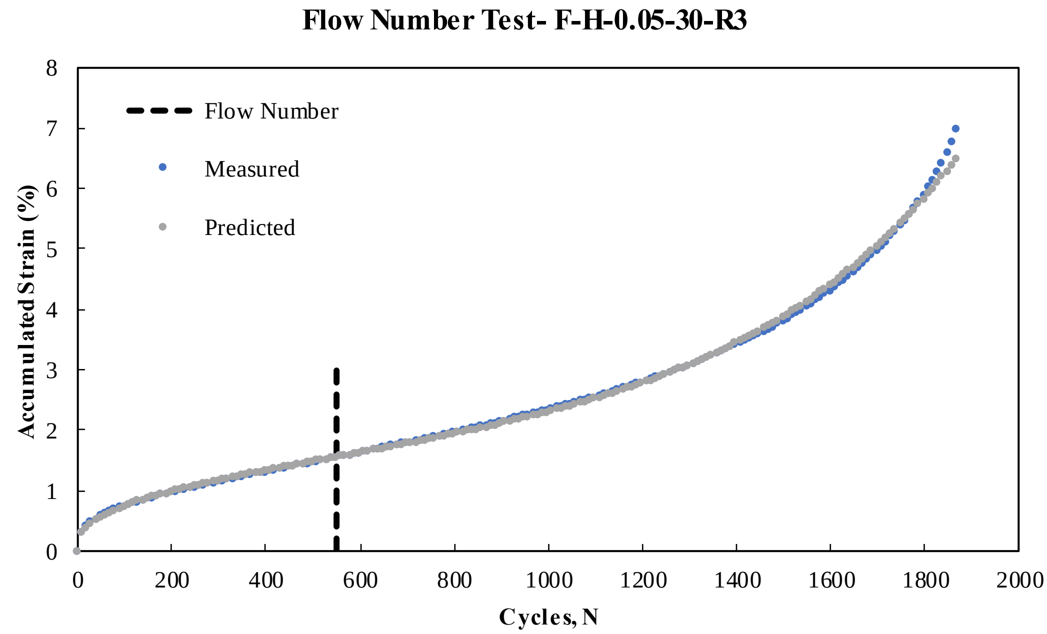

Figure 40- Accumulated strain (%) versus flow number (cycles) for asphalt test sample F-H-0.05-30-R3

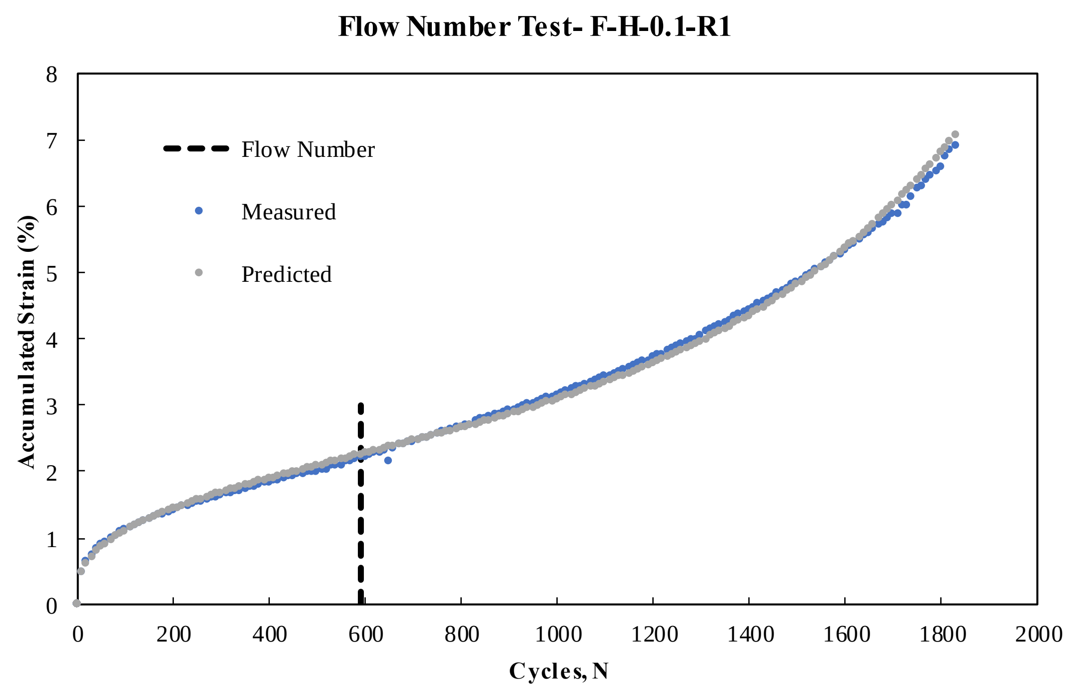

Figure 41- Accumulated strain (%) versus flow number (cycles) for asphalt test sample F-H-0.1-30-R1

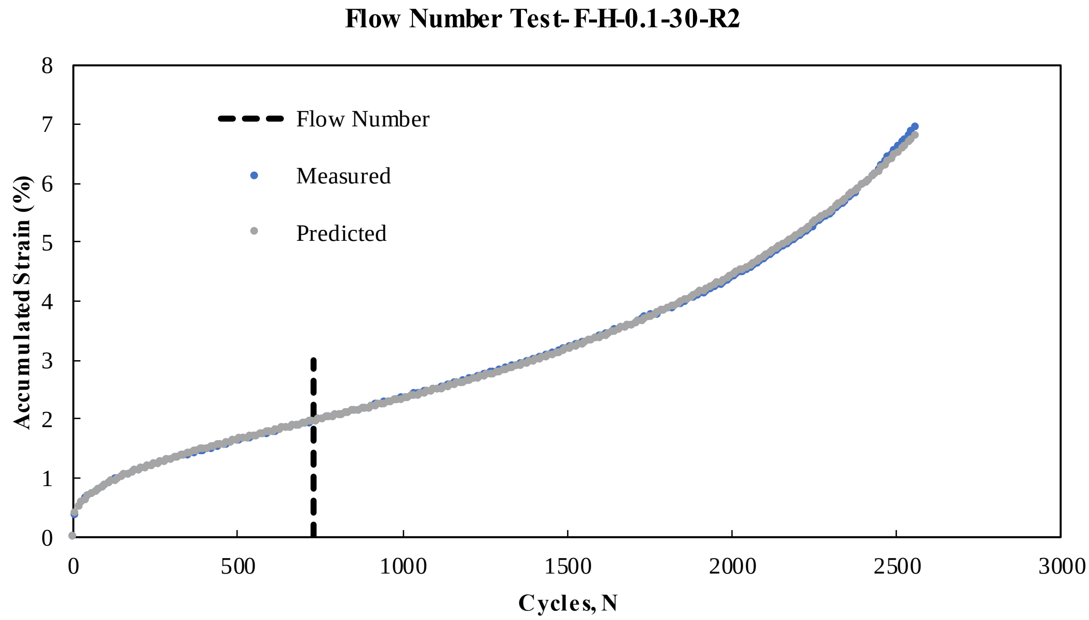

Figure 42- Accumulated strain (%) versus flow number (cycles) for asphalt test sample F-H-0.1-30-R2

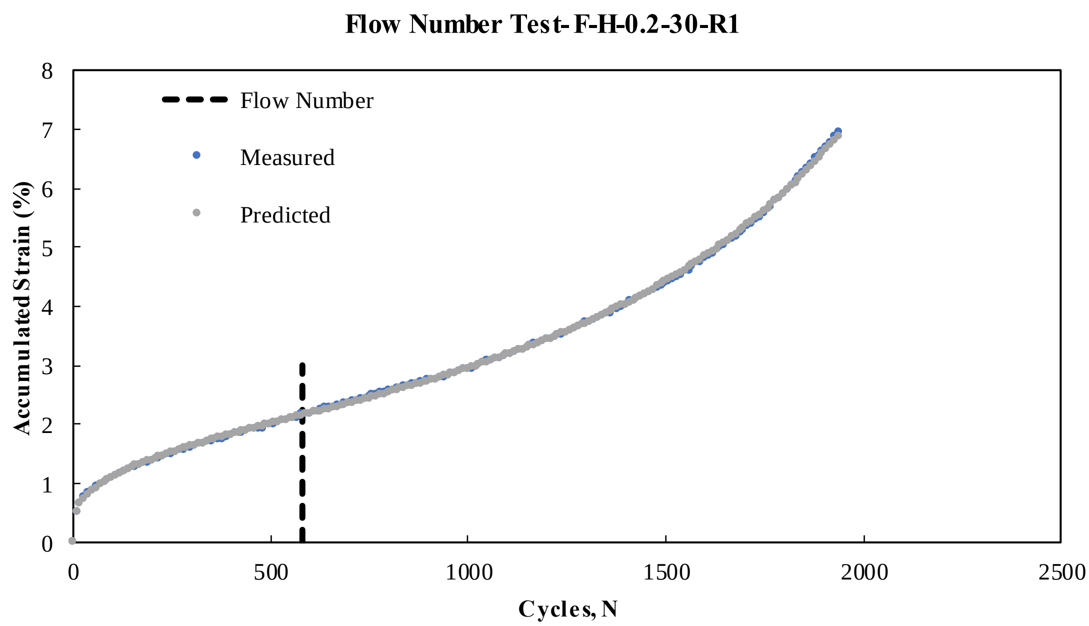

Figure 43- Accumulated strain (%) versus flow number (cycles) for asphalt test sample F-H-0.2-30-R1

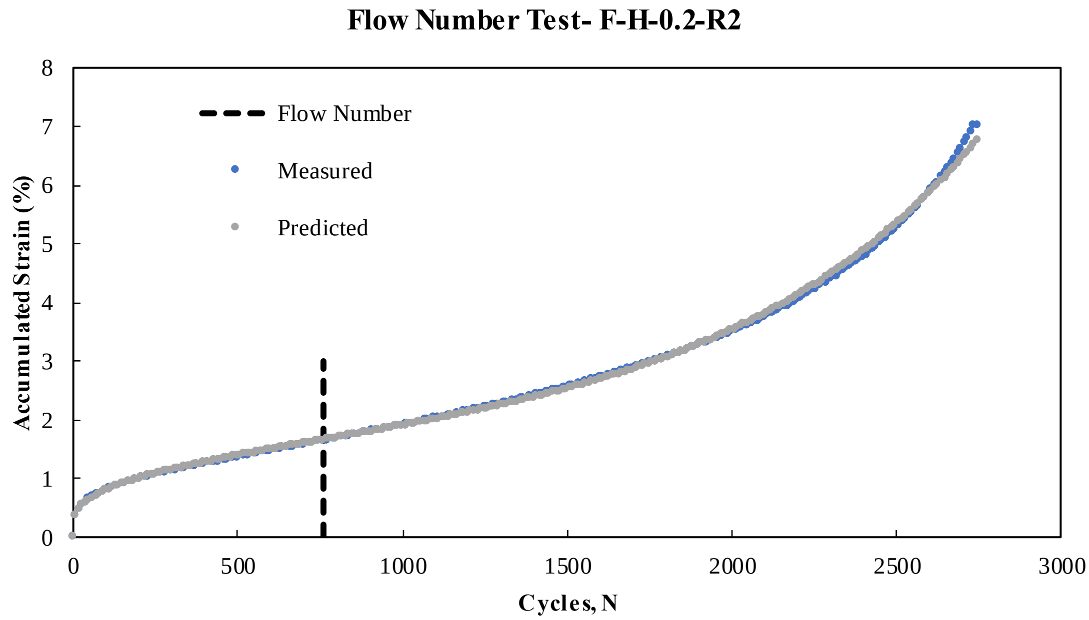

Figure 44- Accumulated strain (%) versus flow number (cycles) for asphalt test sample F-H-0.2-30-R2

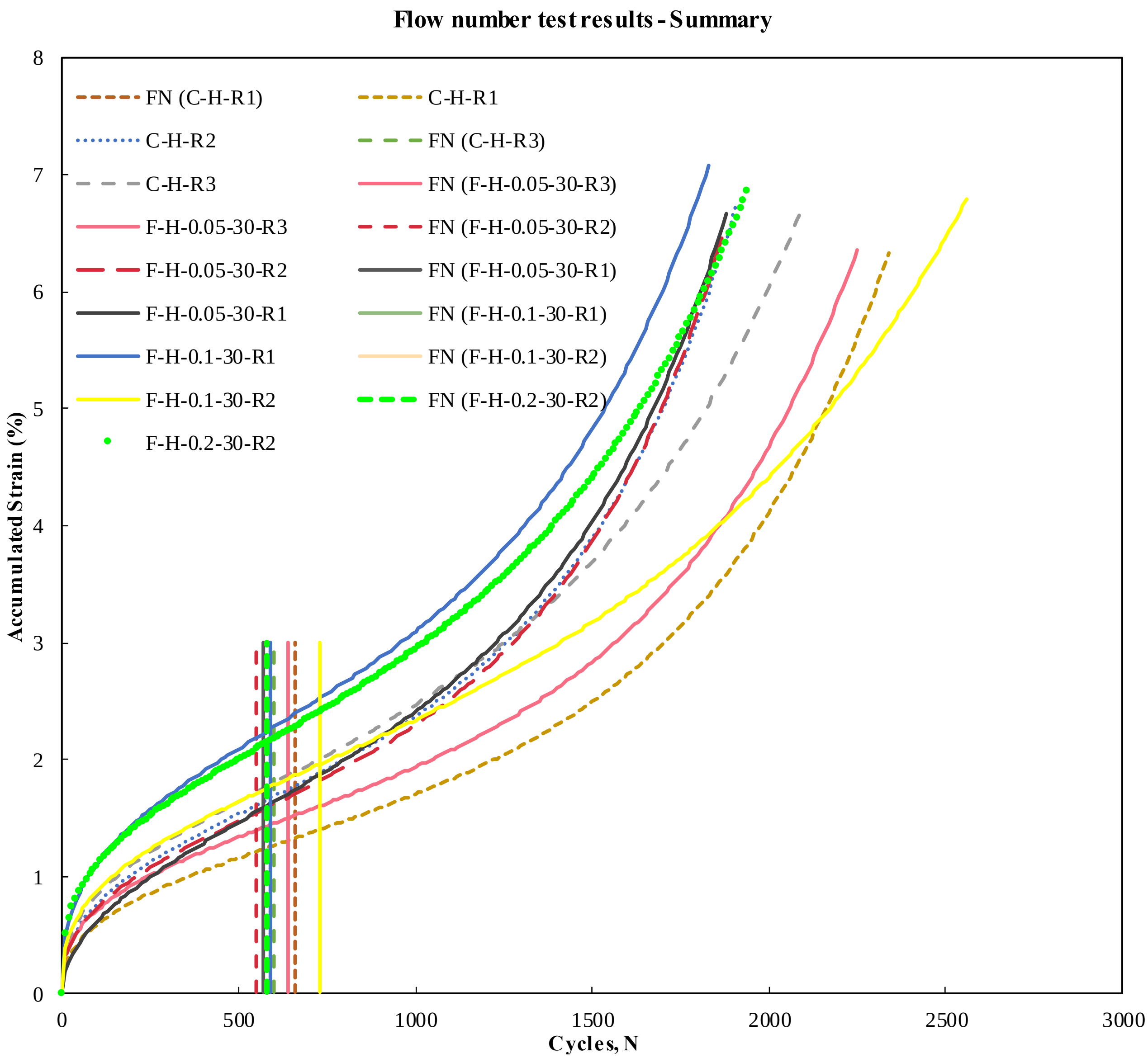

Figure 45- Accumulated strain (%) versus flow number (cycles) for all tested asphalt samples

4.2.3 Semi- Circular Bending Test

The semicircular bend (SCB) test is used to determine the flexibility index of asphalt mixtures at intermediate temperatures. Two specimens of a thickness of 50 mm and a half-diameter of 150 mm with a 3mm notch were tested. The load was applied at a constant displacement rate of 50 mm/min at the temperature of 25 ℃. Generally, a mixture with higher FI can resist crack propagation for longer time duration under tensile stress. SCB Test results are presented in Table 9. As stated in previous studies, fibers do not add an extra tensile strength to resist cracking before the initiation of the crack. Fibers behaved like any other additives inside the mix, which it was observed during all the laboratory tests that did not result in higher deformations during testing. However, when a crack started to propagate, the fibers began to absorb part of the strain energy and helped reduce crack propagation. This behavior was observed at intermediate and higher temperatures but not at low temperatures [43].

Fracture energy (Gf) is one of the main output parameters in SCB testing, it is defined as the work needed to initiate and propagate the crack in the specimen until fracture, and is represented by the area under the load versus displacement curve (Figure 46 till Figure 54). However, fracture energy is not sufficient as a single parameter to distinguish between different asphalt mixtures, due to the inability of fracture energy to distinguish between mixtures with high peak load and steep post-peak slope (brittle mixture) and mixtures with low peak load and shallow post-peak slope (more flexible mixture). To avoid misleading results, flexibility index (FI) was developed by using both fracture energy and post-peak slope parameter at the inflection point [97].

Based on the post-peak load-displacement curve, the inflection point is where the curvature changes from negative to positive and it is determined by setting the second derivative of the post-peak equation (post-peak load-displacement curve) to equal zero, and the tangential slope at the inflection point (m) represents the ability of the mixture to resist crack propagation. From Gf and m (Table 10), the FI was introduced, which is based on an empirical correlation between flexibility and crack propagation speed. Thus, flexibility index is introduced as a ranking parameter that can distinct asphalt mixtures based on cracking resistance [97].

In this study, the range of FI values for the laboratory tested mixes was in the range from 12 to 19 with an increasing crack propagation with lower FI values. FI values of HMA fiber reinforced mixes recorded a higher FI value compared to HMA control mix. F-H-0.05-10 (Hot mix asphalt reinforced with 0.05% & 10mm palm fibers) recorded the highest FI. It showed a fracture resistance improvement of 35.8% with respect of the HMA control mix. Results show that adding 10mm fibers can resist more crack propagation than 30mm fibers. This could be related to the dynamic modulus test results at intermediate temperatures, where palm fibers 10mm long helped improving the stiffness of the asphalt mixture. The fiber/binder matrix mechanism assist to dissipate a part of the crack driving force and this could lead to slow the fracture process and crack propagation.

Studies on fibers reinforced concrete mixes showed that toughness of cementitious surface could be improved by adding short fibers to the mix as reinforcement. Short fibers can bridge the cracks in the matrix and provide resistance to crack propagation before being pulled out or stressed to rupture [98]. Thus, short 10mm palm fibers (triple the 30mm palm fibers length) are found to provide a denser mesh resulting in a low stress intensity factor at the crack tip. Thus, the palm fiber-matrix bond strongly affects the ability of fibers to stabilize crack propagation in the asphalt mixture. As the fiber percentage increases, the flexibility index slightly decreases. This might be also due to the fiber clumping effect created by adding higher fiber content. Asphalt samples with 0.2% and 30mm palm fibers were also tested. Due to the high variability between the replicates, results were discarded.

As a conclusion, 0.05% and 10mm are the optimum fiber percentage and length for cracking resistance. Analysis of Variance (ANOVA) is very useful for analyzing the effect of length on the flexibility index results. It should be used to confirm the graphical conclusion that adding 10mm fiber length is statistically significant. More replicates should be tested in future work since at least three replicates for each mix category are needed for one-way ANOVA.

Table 10- SCB test parameters

Mix Reference	Peak Load, (KN)	Displacement, (mm)	Fracture Energy Gf, (J/m2)	Slope |m|, (KN/mm)	Flexibility Index FI	Average FI
C-H-R1	3.292	17.666	2141.94	1.88	11.39	12.37
C-H-R2	2.996	8.669	2336.65	1.75	13.35	
F-H-0.05-10-R1	2.485	16.674	2299.04	1.20	19.16	19.26
F-H-0.05-10-R2	2.661	19.137	2090.11	1.08	19.35	
F-H-0.05-30-R1	2.651	10.682	2116.59	1.53	13.83	13.56
F-H-0.05-30-R2	2.318	18.716	1540.95	1.16	13.28	
F-H-0.1-30-R1	2.749	17.369	1930.02	1.50	12.87	12.43
F-H-0.1-30-R2	2.907	12.463	1988.53	1.66	11.98	

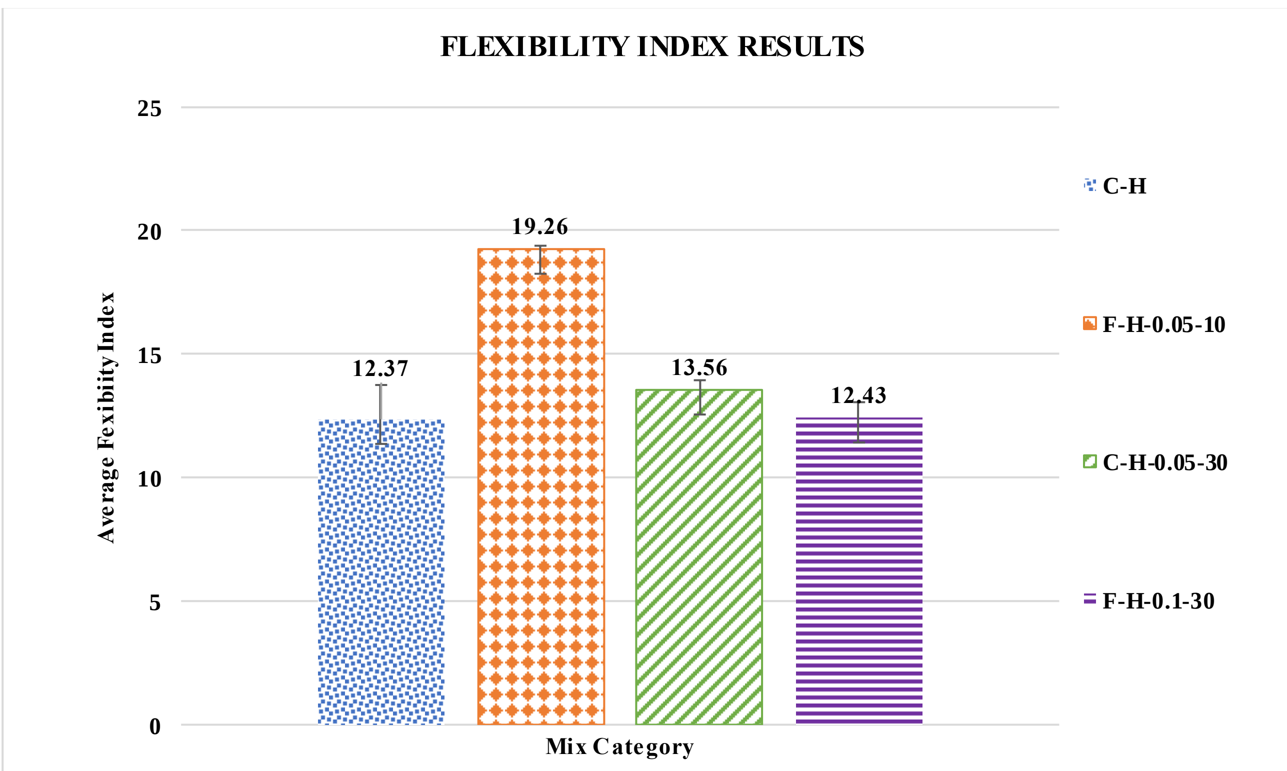

Figure 46- Average flexibility index results for HMA control and fiber reinforced mixes

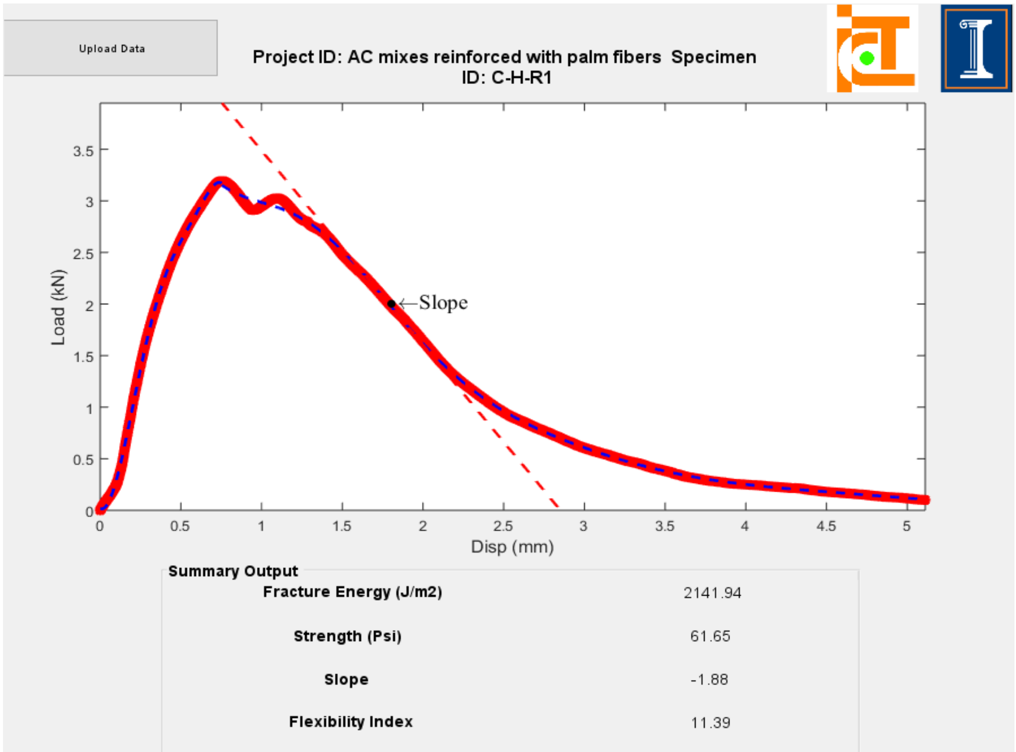

Figure 48- SCB test summary output of C-H-R1

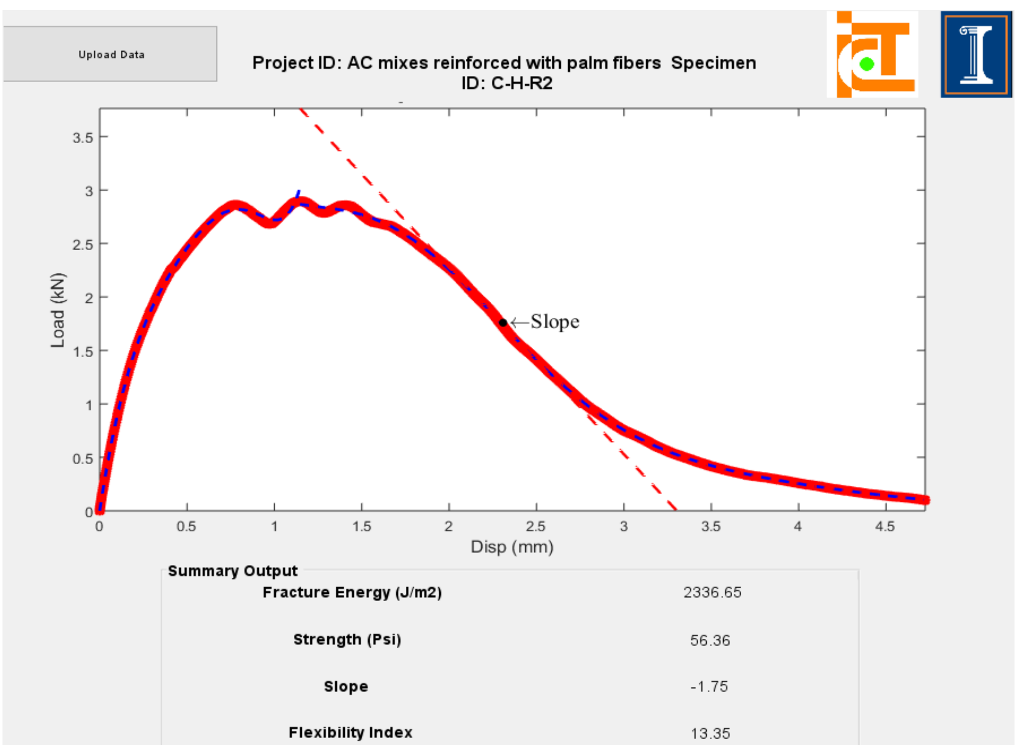

Figure 47- SCB test summary output of C-H-R2

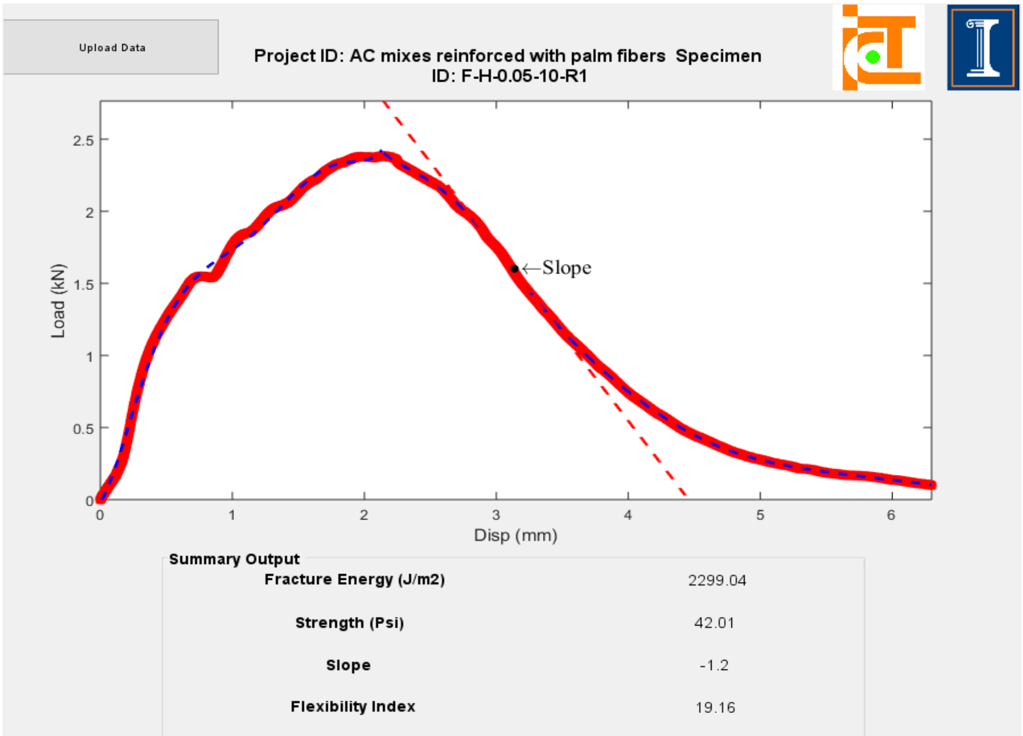

Figure 49- SCB test summary output of F-H-0.05-10-R1

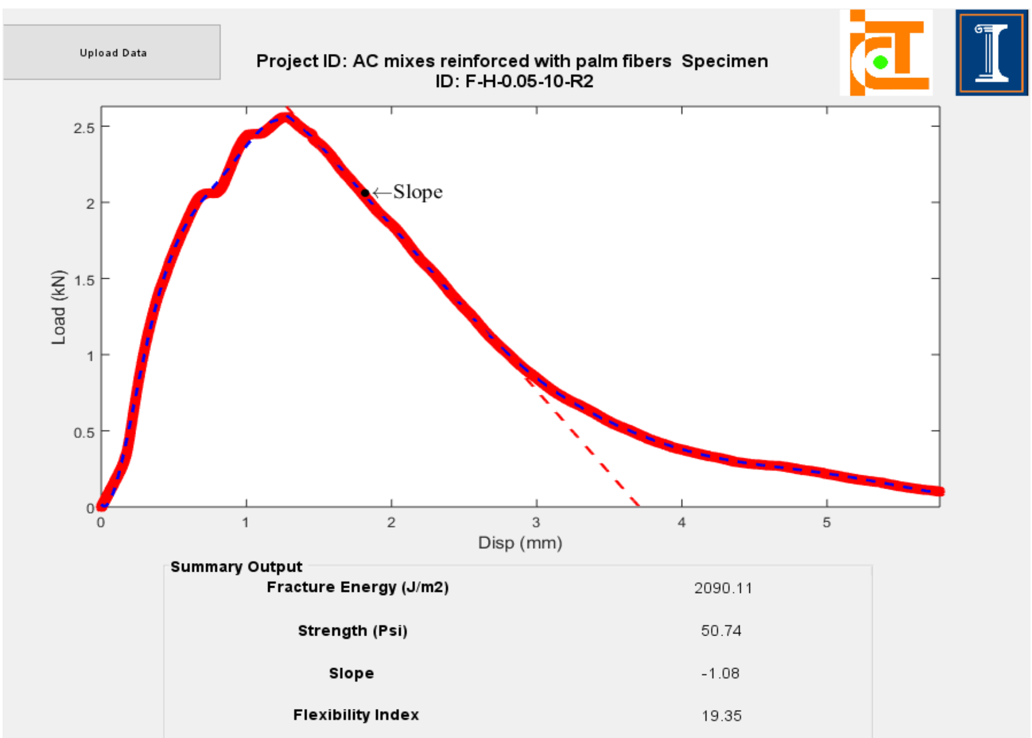

Figure 50- SCB test summary output of F-H-0.05-10-R2

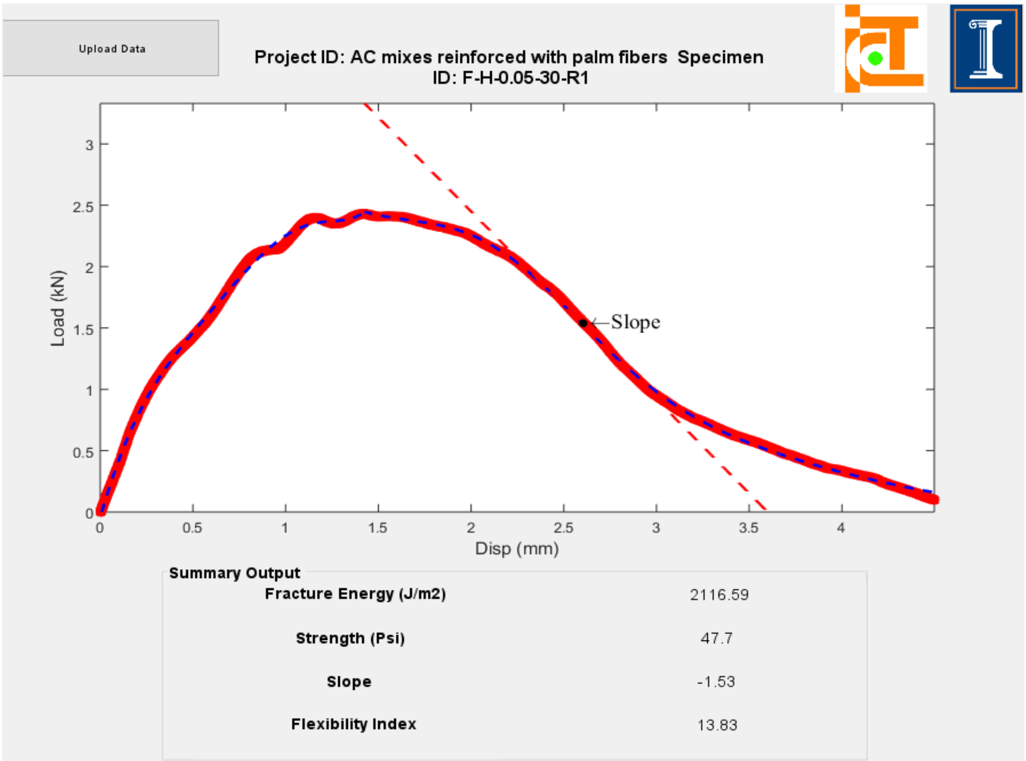

Figure 51- SCB test summary output of F-H-0.05-30-R1

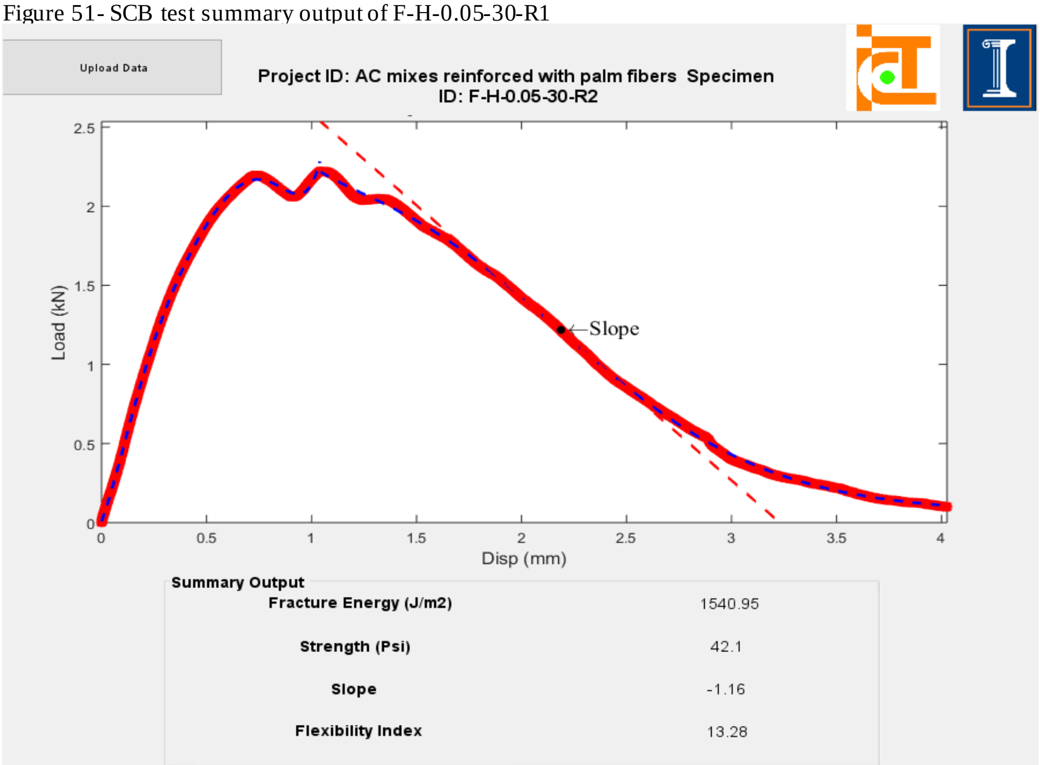

Figure 52- SCB test summary output of F-H-0.05-30-R2

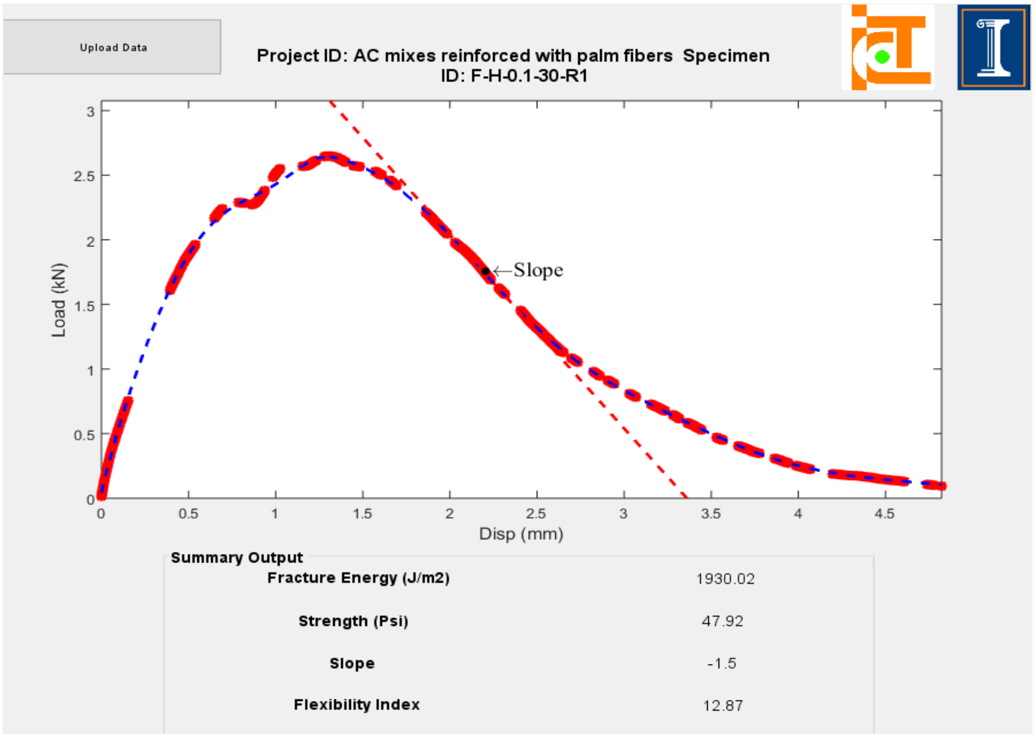

Figure 53- SCB test summary output of F-H-0.1-30-R1

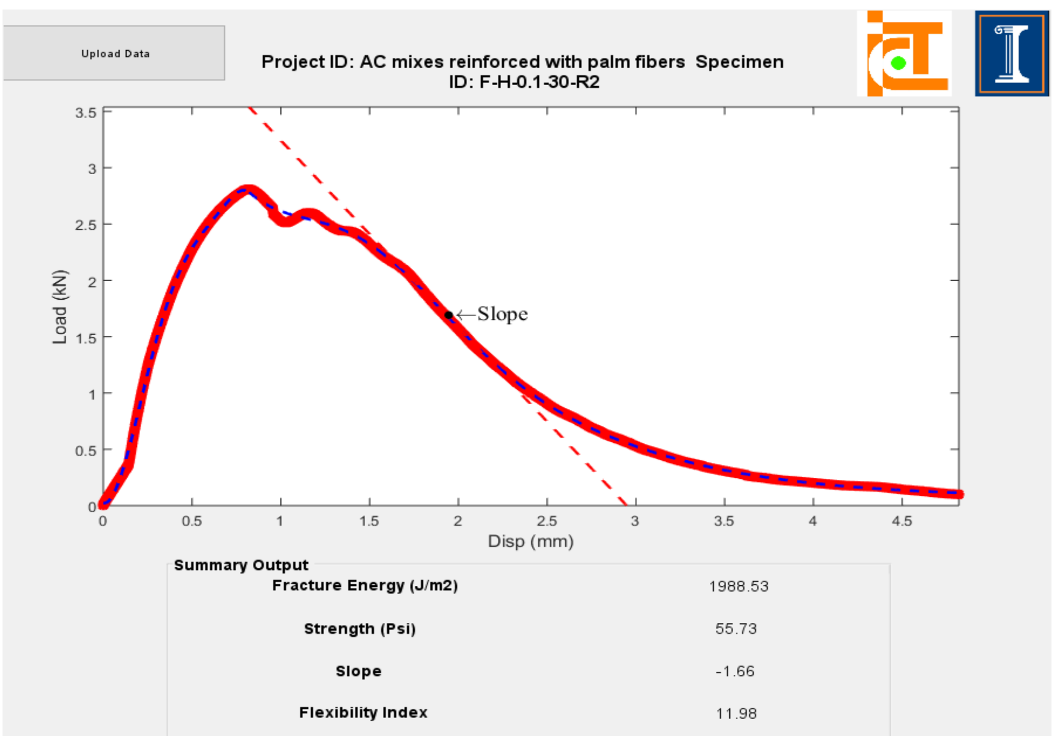

Figure 54- SCB test summary output of F-H-0.1-30-R2

4.2.4 Cantabro Loss Test

The Cantabro loss is used as an important indicator of bonding properties between aggregates and binder. This abrasion test is used to evaluate the raveling potential of the mix. This test used the LA abrasion drum without steel balls. The specimen is placed in the machine and rotated for 300 revolutions. The specimen is weighed before and after each 50 revolutions, and the weight loss taken as a percentage of the original weight defines the percentage cantabro abrasion. Figure 55 represents the percentage cumulative cantabro loss for each category mix.

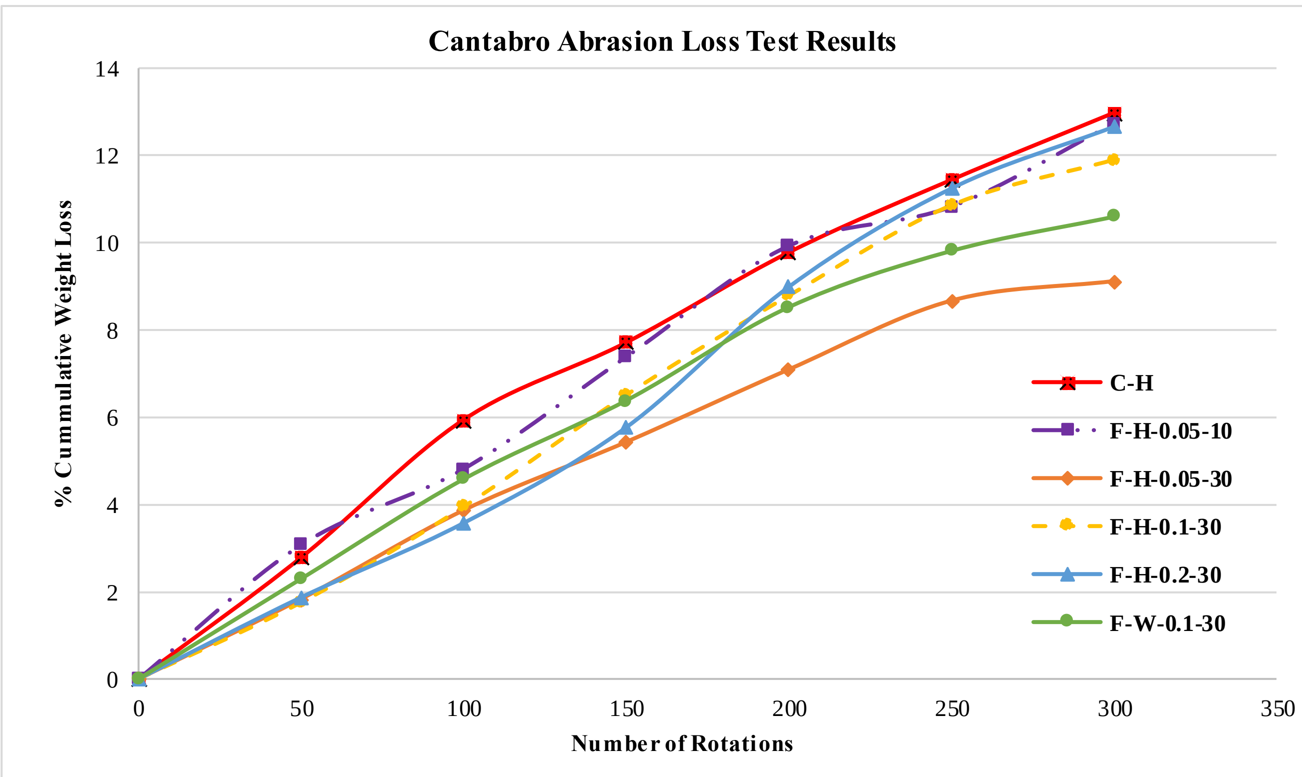

Figure 55- % Cumulative weight loss of different HMA and WMA mixes at every 50 revolutions

Palm fibers are added with different percentages and lengths to evaluate their potential to resist the separation of asphalt mastic from the coarse skeleton. WMA mix reinforced with 0.1% and 30mm palm fibers is also tested. The cantabro loss percentage at 300 revolutions for each category is shown in Figure 56. According to the results, the use of palm fibers in both HMA and WMA mixes positively affected their abrasion loss resistance. Mix reference F-H-0.05-30 (Hot mix asphalt reinforced with 0.05% & 30mm palm fibers) is the optimum mix among all mixes in terms of securing the integrity of aggregate's skeleton. It showed an abrasion loss improvement of 29.7% with respect of the control HMA mix. As the fiber percentage increases, the higher abrasion percentage mass loss. Adding only 0.05% palm fibers is enough to ensure the asphalt mix. It may be due to the same reason faced in the dynamic modulus results, that adding more than 0.05% fibers could create a balling effect which prevents the fiber interlocking networking matrix between the aggregates. Besides, palm fiber length of 10 mm presented the highest cantabro loss percentage. Thus, adding 10mm palm fibers long almost contributes with no effect on the asphalt mix stability. Fiber length plays a significant role in holding the coarse skeleton and preventing its separation from the binder. The longer the fiber, the better the asphalt mixture stability. WMA mix is also included in this test. Results of WMA reinforced with 0.1% and 30mm palm fiber mix recorded a slightly lower abrasion loss. Although SonneWarmix contributed with a higher abrasion resistance, but the addition of 0.05% rather than 0.1% palm fibers recorded a lower abrasion loss.

The experimental data were further analyzed statistically to test the effect fiber percentage, length, and asphalt mix type on the abrasion loss of the asphalt mixes. The analysis was performed for each explanatory variable using one-way Analysis of Variance (ANOVA) based on a 90% (a = 0.1) confidence level (Table 11). The effect of adding 0.05% palm fibers does not show a statistical difference in scenario 1 ANOVA results (p-value=0.26). It is due to the large variability within the group itself. This variability is larger than the variability between the groups, thus more replicates are needed for ANOVA analysis. However, based on a T-test between C-H and F-H-0.05-30, results showed a statistical effect of using palm fibers 30mm (p-value= 0.11). A slight effect is reported in scenario 2 ANOVA results, which showed that fiber length contributes the cantabro loss test results (p-value=0.143). It also validates that the longer the fiber, the lower the abrasion loss, thus the higher the stability of an asphalt mixture (p-value between 10mm-control=0.99> p-value between 30mm-control=0.17). Scenario 3 confirmed that the type of the asphalt mix does not contribute in reducing the abrasion loss of an asphalt sample (p-value=0.529<0.1).

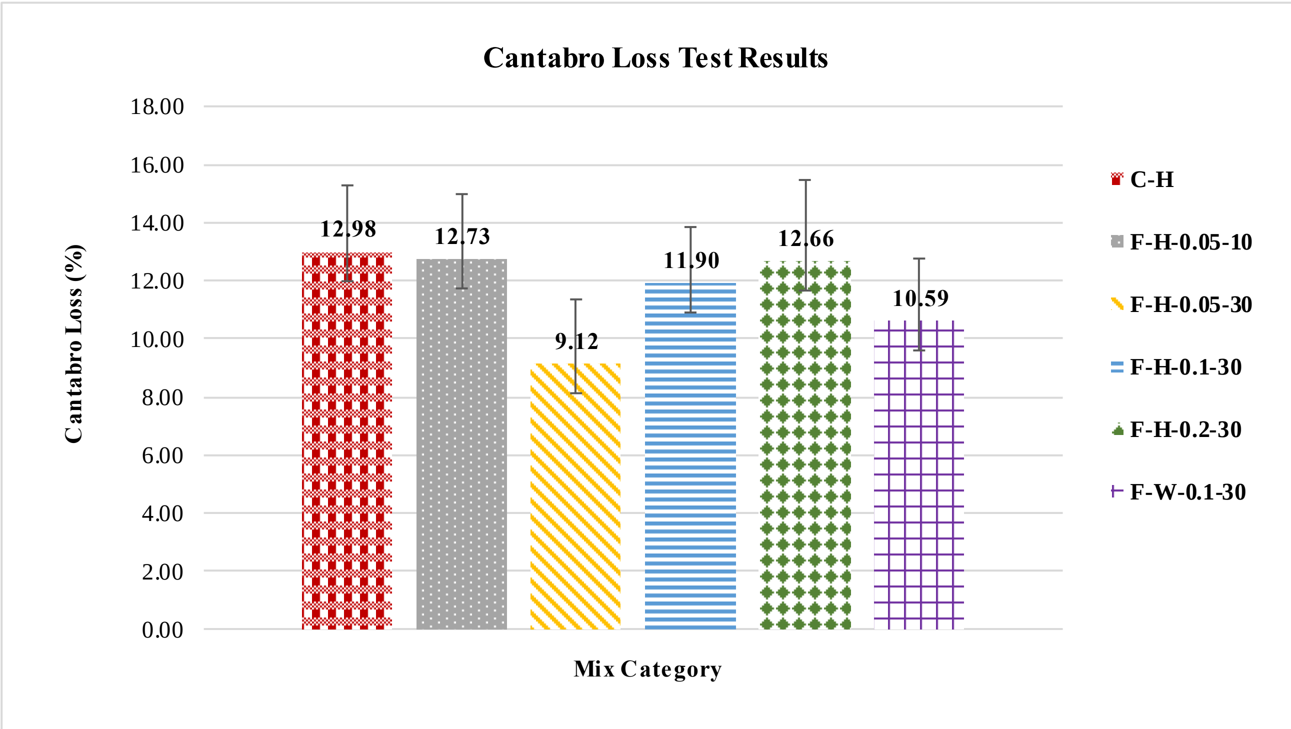

Figure 56- Cantabro loss percentage for different HMA and WMA mixes at 300 revolutions

Table 11- One-way ANOVA results of different scenarios investigating the effect of palm fiber percentage, length and asphalt mix type on the Cantabro test results

Scenario #	**ANOVA p-value**	**Compared Pairs of Mixes**	**Difference indicator**
1-Variable: Fiber percentage (control,0.05,0.1 and 0.2%)	0.246	F-H-0.05-30 vs. C-H	0.258
		F-H-0.1-30 vs. C-H	0.940
		F-H-0.2-30 vs. C-H	0.998
		F-H-0.1-30 vs. F-H-0.05-30	0.503
		F-H-0.2-30 vs. F-H-0.05-30	0.319
		F-H-0.2-30 vs. F-H-0.1-30	0.978
2- Variable: Fiber length (control, 10 and 30mm)	0.143	F-H-0.1-30 vs. C-H	0.990
		F-H-0.1-30 vs. C-H	0.172
		F-H-0.05-10 vs. F-H-0.05-30	0.204
3- Variable: asphalt mix type (HMA and WMA)	0.529	WMA vs. HMA	0.529

Note: P-value > 0.1 means non-significant difference and otherwise significant difference. Significant at 90% confidence interval (P-value < 0.1).

CHAPTER 5

CONCLUSIONS AND FUTURE WORK

5.1 Conclusions

This research study investigated the use of natural palm fibers in HMA and WMA as an additive with different percentages and lengths. The results of the laboratory tests executed in this study showed that the addition of palm fibers to AC mixes improves its performance. Below are the main conclusions of this study:

- A rough fiber surface full of impurities was observed by SEM, this is responsible for improved mechanical interlocking between the palm fibers and asphalt mixture.
- Palm fibers preserve their mechanical properties during asphalt sample preparation. Less than 10% mass loss was recorded at 160°C due to dehydration process and moisture loss.
- Dynamic modulus test results proved that the viscoelastic properties of asphalt mixtures could be improved by the palm fibers. 30 mm palm fibers support the asphalt mixture structure by holding the components together and reducing stress concentration in addition to retaining bitumen at high temperatures. At intermediate reduced frequencies, 10mm long palm fibers behaved like a stiffener inside the asphalt mixture, which provide an extra stiffening effect to the binder. This reduces fatigue damage for asphalt mixtures during their serving lifespan at intermediate temperatures.
- Flow number test appeared to be a more sensitive indicator of the rutting resistance of HMA than the dynamic modulus, since rutting is more critical at elevated temperatures. This variability could be attributed to the viscoelastic nature of the asphalt binder, whose behavior tends to be more viscous at elevated temperature and therefore exhibits a variable response especially in destructive tests (FN test). FN results show that the use of palm fibers in HMA mixes could lead to a higher

resistance to asphalt pavement rutting. A higher concentration of palm fibers might be required to resist higher permanent deformation.

- AC mixes reinforced with 10mm and 0.05% palm fibers showed a cracking resistance improvement of 35.8% with respect of the HMA control mix. This could be related to the dynamic modulus test results at intermediate temperatures, where palm fibers 10mm long helped improving the stiffness of the asphalt mixture.
- It was validated that the longer the fiber, the lower the abrasion loss, thus the higher the stability of an asphalt mixture. Mixes with 0.05% and 30mm palm fibers recorded an abrasion loss improvement of 29.7% with respect of the control HMA mix. 30mm palm fibers have the potential to resist the separation of asphalt mastic from the coarse skeleton.

  It was concluded that adding only 0.05% palm fibers is adequate in enhancing the viscoelasticity properties of asphalt mixtures. It may be due to the balling effect that it is created in the asphalt mixtures when adding more than 0.05% of palm fibers. Only in flow number test, 0.05% palm fibers recorded the lowest improvement.

5.2 Future Work

The introduction of palm fibers as a natural additive in AC mixes has shown to provide acceptable performance. Besides the potential of enhancing the service life and performance of asphalt pavements, natural palm fibers is an added benefit in producing sustainable asphalt pavements. However, several areas are still to be further investigated. The following are the recommended for future research:

- It is recommended that results of dynamic modulus test should be used as input into the MEPDG. This will predict the effect of palm fibers on field performance and evaluate its impact on varying pavement design thicknesses.
- Resistance to cracking propagation was improved using 10mm palm fibers in AC mixes. The addition of 10mm palm fibers in asphalt overlayers on cracked pavements should be considered in further studies. It could retard the development of fatigue cracking in asphalt pavement, thus extending its service life.Asphalt overlays

or localized areas with 30mm palm fibers could be a solution for raveling and abrasion pavement distresses.

- It is recommended that future investigations should be carried out by adding 30mm palm fibers to overlaying.
- It is further recommended more flow number testing to have a conclusive comparison about the optimum fiber percentage required to resist a higher permanent deformation.With the assumption of longer service life of the asphalt concrete pavements reinforced with natural palm fibers, life cycle assessment should be conducted for further understanding of the impact of their use on the environment.

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APPENDIX A

Department of Civil & Environmental Engineering
Faculty of Engineering and Architecture

AUB
American University of Beirut

Batching Sheet

Project:		**Specimen ID: Z7500-**	
Mix Type/ Description:		**Computer file:**	
		Date:	**Time:**
Specimen Type:		**Aggregate Type(s):**	
% AC:	**Weight & Type of Binder: 277.5g U**	**Specimen weight:**	

Balance	**Capacity:** ________ **Sensitivity:** ________ **Leveled:** ________ **Fans affecting reading are off:** _____	**Bowl**	**Clean and dry:** ________ **Weight Empty:** ________

	Mix Gradation of aggregates			
	Sieve Size	% Cumulative Retained Mass	Cumulative Retained Mass	Batched Cumulative Retained Mass
Coarse	**1"**	0.0	0.0000	
	3/4"	4.0	0.2889	
	1/2"	22.0	1.5890	
	3/8"	31.0	2.2390	
	# 4	52.0	3.7557	
Fine	**# 8**	70.0	5.0558	
	# 16	80.0	5.7780	
	# 30	86.0	6.2114	
	# 50	91.0	6.5725	
	# 100	93.0	6.7169	
	# 200	95.8	6.9192	
Filler	**Pan**	100.0	7.2225	
	Total	100.0		

Final Weight of Bowl +aggregates:	
Aluminum foil placed:	**Batch labeled:**

Signature: ________________

Figure 57- Batching sheet for asphalt mix preparation