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Design and Evaluation of FORTA FI Fiber-Reinforced Asphalt Mixtures ACWC 14 and ACBC 28

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SCOPE:

This report presents a laboratory investigation into the effects of fiber-reinforced (polypropylene and aramid fibers) HMA mixtures (ACWC14 and ACBC28). The aggregate and asphalt binder physical properties were characterized using traditional mechanical testing. Four Hot Mix Asphalt types were used namely; Asphalt Concrete Wearing Course (ACWC14), Asphalt Concrete Binder Course (ACBC28) without fiber reinforcement as control samples and Asphalt Concrete Wearing Course (ACWC14), Asphalt Concrete Binder Course (ACBC28) with fiber reinforcement that contained 0.5% of reinforcing FORTA FI (synthetic) fiber by weight of aggregate for this design and evaluation work. The Marshall Mix design procedure was used in accordance with ASTM D 1559 to determine the Optimum Asphalt Content (OAC) and to measure volumetric the mechanical properties of the four HMA mixtures. Performance characteristics tests were also conducted to examine the moisture susceptibility, fatigue cracking, and Permanent Deformation (Rutting) resistance.

The properties of the four HMA mixtures evaluated included Optimum Asphalt Content (OAC), Volumetric Properties, Stability and Flow, Resilient (Stiffness) Modulus. The performance laboratory experimental program included: Static Load Unconfined Permanent Deformation in accordance with the Public Works Department (JKR) Malaysia and BS-EN 12697-25 Standards. The Indirect Tensile Fatigue Test (ITFT) was carried out in accordance with the BS DD213 ABF British Standard Draft, and Tensile Strength Ratio (TSR) tests was carried out in accordance with the Modified Lottman Test AASHTO T 283 using the Marshall Apparatus. The test results were used to compare the performance of the fiber modified mixtures against the control mixtures.

The fiber showed a significant influence on volumetric and mechanical properties of HMA mixtures such as the optimum asphalt content, volumetric properties, Marshall stability, resilient modulus and permanent deformation and fatigue characteristics of the asphalt mixtures.

1. INTRODUCTION

The FORTA FI fibers were submitted to the Highway Engineering Laboratory, Department of Civil Engineering, Universiti Putra Malaysia (UPM) by Magna Effort Sdh Bhd to carry out laboratory investigations on FORTA FI fiber reinforced Asphalt Concrete Wearing Course (ACWC14) and Asphalt Concrete Binder Course (ACBC28) in accordance with Jabatan Kerja Raya (JKR) specifications. This laboratory investigation report describes and summarizes the test results.

2. OBJECTIVE

The objectives of this investigation were to design and evaluate the material properties of conventional (control) ACWC14 and ACBC28 and fiber-reinforced ACWC14 and ACBC28 asphalt mixtures using the most current laboratory tests adopted in the pavement community. The goal was to assess how the material properties for the modified fiber-reinforced mixture differ in volumetric properties, stiffness, permanent deformation, strength, and cracking characteristics.

3. DESIGN and EVALUATION APPROACH

3.1 Materials

3.1.1 FORTA FI Synthetic Fiber

The fibers used in this work were a blend of synthetic fibers designed for use in Hot Mix Asphalt (HMA) applications. The blend consisted of a proprietary blend of polypropylene and aramid fibers. Figure 1 (a) shows typical fibers contained in one-lb bag (approximately 445.0 g), of the aramid and polypropylene. Figure 1 (b) shows a close up of a loose asphalt mixture that was spread on the table for preparation of the Rice specific Gravity test (Theoretical Maximum Density, TMD). Fibers were seen by the naked eye with very good distribution throughout the mix (See Appendix). Table 1 shows the main physical properties of fiber supplied by Magna Effort Sdh Bhd.

Table 1: Physical Characteristics of Fiber

Materials	Properties
Form	Multifilament Fiber
Specific Gravity	Not tested
Tensile Strength (MPa)	Not tested
Length (mm)	19 mm/0.5KG
Color	Yellow, Grey, and Black
Acid/Alkali Resistance	Not tested
Decomposition Temperature (°C)	Not tested

(a) (b)

Figure 1: (**a**) Close up of Reinforced Fibers **(b)** A Close-Up of the Fiber-Reinforced Asphalt Mixture.

3.1.2 Asphalt Binder

Most agencies would normally specify a higher PG grade, such as a PG 76-22 instead of the 80/100 penetration grade for highway construction projects. Since the performance of the fibers were of concern in this study, the commonly used 80/100 penetration grade soft binder was intentionally selected. This is to make sure there are no additional properties derived from additives if modified binders such as 60/70 and PG 76-22 were used. The Traditional (empirical) rheological tests performed to evaluate the asphalt properties included the Penetration at 25°C, Ring and Ball (R&B) Softening Point, Specific Gravity, Viscosity at 135 and165°C using Brookfield Rotational Viscometer (RV), Flash Point, and Ductility tests.

The rutting resistance parameter (G*/sin δ) of the un-aged asphalt binder was measured at 64, 58, 52°C, in control stress mode using Dynamic Shear Rheometer (DSR). The physical properties and the standard used are summarized and presented in Table 2.

Table 2: Fundamental Properties of Asphalt Binder and Standard used

Parameter measured	Test method	Specification	Results
Specific gravity at 25°C, (g/cm³)	AASHTO T228	-	1.03
Penetration at 25°C, (0.1mm), 100 g, 5s	AASHTO T49	80 - 100	84
Softening point (R&B), °C	AASHTO T53	45 - 52	48
Viscosity at 135°C, Pa.s	AASHTO T201	3 maximum	0.413
Viscosity at 165°C, Pa.s	AASHTO T201	-	0.100
Ductility at 25°C, (cm)	AASHTO T51	100 minimum	>100
Flash Point, °C	AASHTO T48	219 minimum	230°C
Dynamic Shear, Rutting Parameter (G*/sin δ), Temperature52°C @ 10 red/sec, 1.59Hz (kPa)	AASHTO TP5	1 kPa minimum	1.15

3.1.3 Aggregate Properties

To accomplish the most realistic simulation of HMA mixtures paved in Malaysia, common local aggregate was selected for fabricating laboratory samples. Crushed granite aggregate was selected because siliceous gravel is very hard materials while limestone is very soft. Granite aggregate is somewhere between these two extremes and provides excellent qualities. The cubical shape of granite aggregate provides unique properties to contribute to an HMA mixture and it is the most widely used aggregate on the Malaysian roads. The laboratory tests performed to evaluate the properties of coarse aggregates are presented in Table 3 and gradation used in accordance with the JKR specification is presented in Table 4 and depicted in Figures 2 and 3.

Table 3: Physical Properties of the Granite Aggregate

Test	Standard used	Specification	Results
Los Angeles Abrasion (%)	ASTM C 131	30 Max.	22.3%
Aggregate Impact Value	BS 812: Part 3	15% Max.	7.84%
Flakiness Index	ASTM D 4791	20 Max.	14.89%
Elongation Index	ASTM D 4791	5 Max.	1.55%
Coarse aggregate Angularity One or more fractured face Two or more fractured face	AASHTOTP61/ ASTM D5821	 95 Min. 90 Min.	 97% 93%
Fine aggregate Angularity, Air voids % (loose)	AASHTO TP33/ ASTM C1252	45% Min.	53%
Water absorption (%)	AASHTO T 85	2% Max.	0.5
Specific Gravity of Aggregate	ASTM C 127	-	2.60

Table 4: JKR Gradation Limits for Asphalt Concrete and Percent Used

Mix Type	Wearing Course	Binder Course	Wearing Course	Binder Course
Mix Designation	**ACWC 14**	**ACBC 28**	**ACWC 14**	**ACBC 28**
BS Sieve Size (mm)	Percent Passing by Weight		Percent Passing by Weight Used Mean values	
28.0	-	100	-	100
20.0	100	72 – 90	100	81
14.0	90 -100	58 – 76	95	67
10.0	76 – 86	48 – 64	81	56
5.0	50 – 62	30 – 46	56	38
3.35	40 – 54	24 – 40	47	32
1.18	18 – 34	14 – 28	26	21
0.425	12 – 24	8 – 20	18	14
0.150	6 – 14	4 – 10	10	7
0.075	4 - 8	3 - 7	6	5

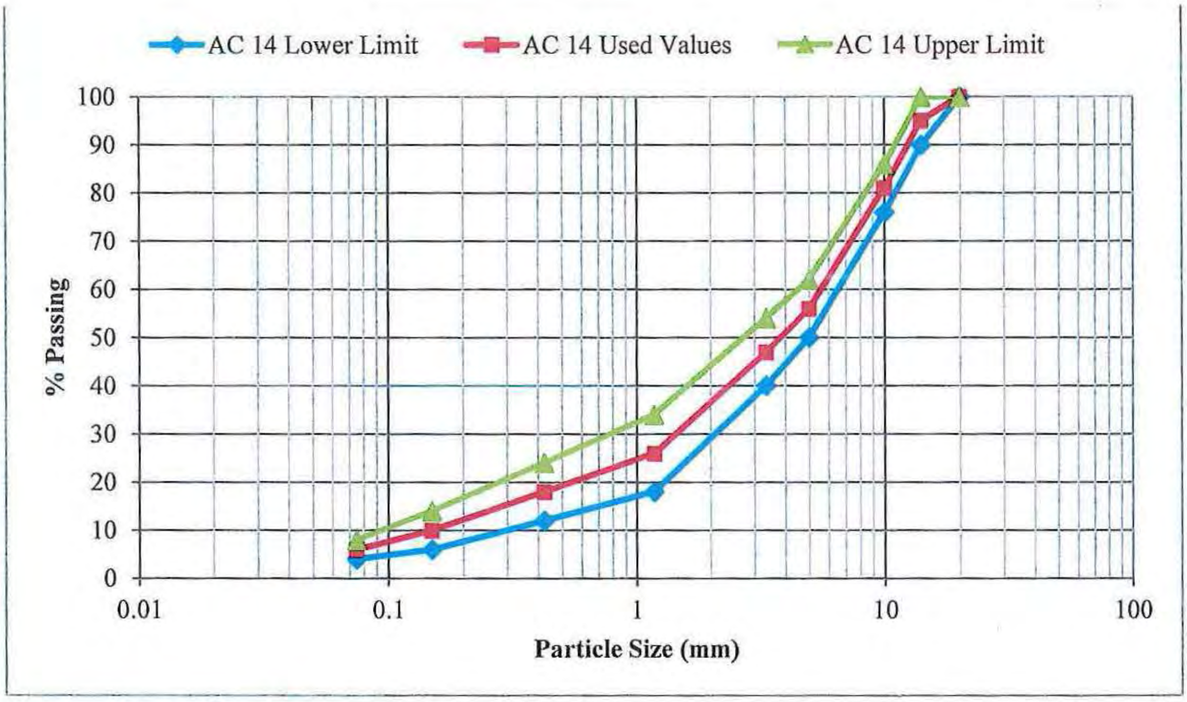

Figure 2: Gradation curve for asphalt concrete ACWC 14 mixtures

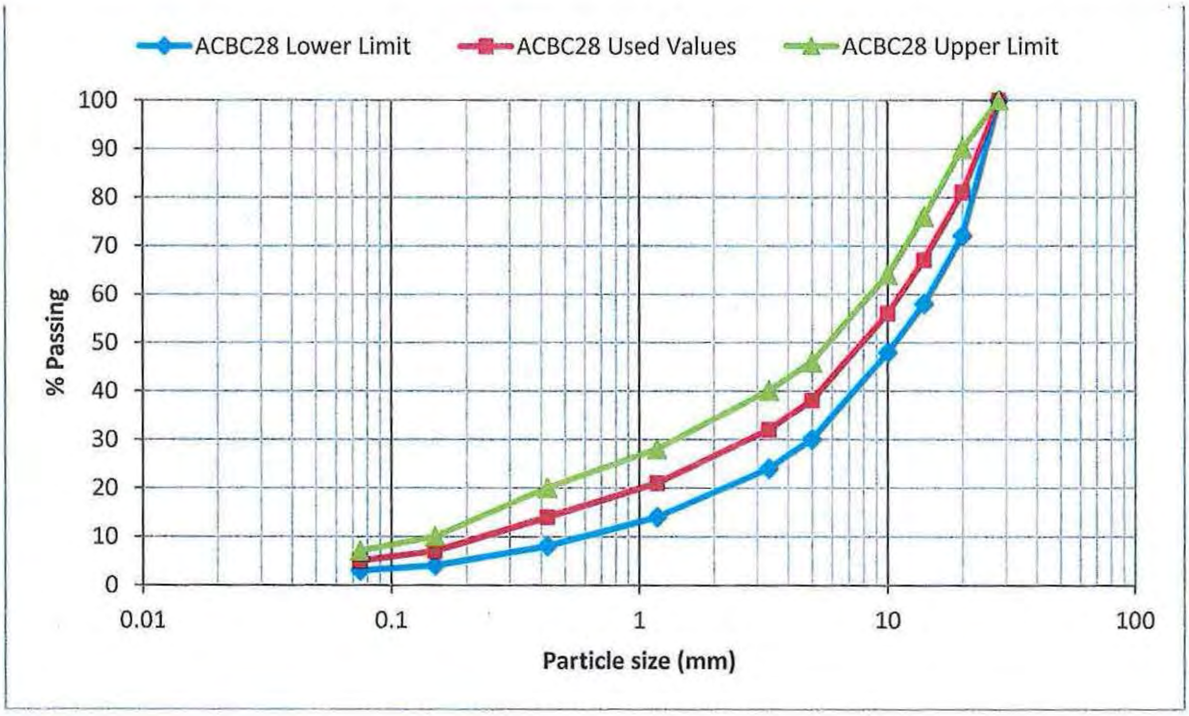

Figure 3: Gradation curve for asphalt concrete ACBC 28 mixtures

3.1.4 Asphalt mixture

The aggregate gradation for ACWC14 and ACBC28 mixtures – a frequently used mixture in Malaysia – is designed following the Jabatan Kerja Raya (JKR) specification, as detailed in Table 4. The manufacturers have recommended the fiber contents (by mass of aggregate) for mixture design, as 0.5%, which have been used in the ACWC14 and ACBC28 mixtures. However, in order to study the influence of fiber on the volumetric and engineering properties of asphalt mixture, two different asphalt mixture (ACWC14 and ACBC28) and one fiber content (0.5%) were used in comparison with the two controlled mixtures (without fiber) ACWC14 and ACBC 28. The optimum asphalt contents for the four different type mixtures were determined using the Marshall Mix Design method in accordance with ASTM D1559. In this method, the asphalt contents at the maximum density, 4% air void, and maximum Marshall Stability are determined, and the average value is used as the Optimum Asphalt Content (OAC).

3.2 Experimental Program

Modifier additives are usually added to mixture under wet or dry conditions. During the wet process, additive first mixed with bitumen with a proper mixer until achieving a homogenous blend. Then blended materials were added to aggregates. In the dry method, according to additive's type and nature this material is mixed with hot aggregates before adding bitumen or added after mixing the bitumen and aggregates as a part of solid materials. In this investigation, dry method was followed and fiber was added to the hot aggregate with quantity of 0.5% by the weight of aggregate.

3.2.1 Determination of Mixing and Compaction Temperature

Rotational Brookfield Viscometer was used for the viscosity tests were conducted on unaged unmodified bitumen 80/100 penetration grade in order to determine the mixing and compaction temperatures of hot mixture asphalts (HMAs) at 135°C and 165°C, respectively. The rotational viscosity was determined by measuring the torque required to maintain a constant rotational speed of 20 rpm of a cylindrical spindle (Z3DIN 25 mm) while submerged in bitumen maintained at a constant temperature.

The viscosity values were plotted on the derived temperature-viscosity graph and a regression line was drawn. It is desired that the bitumen binder exhibits viscosities of 170 ± 20 cP for mixing and 280 ± 30 cP for compaction. The temperatures for the corresponding viscosity values were then selected as the mixing and compaction temperatures. To maintain workability, the viscosity value at 135°C should not exceed 3 Pa.s (3000 cP). The results obtained from viscosity tests are given in Table 2 and depicted in Figure 4, showing that the binder fulfilled the workability requirement. On the basis of above criterion the compaction and mixing temperatures were kept constant between 140 –160° C respectively.

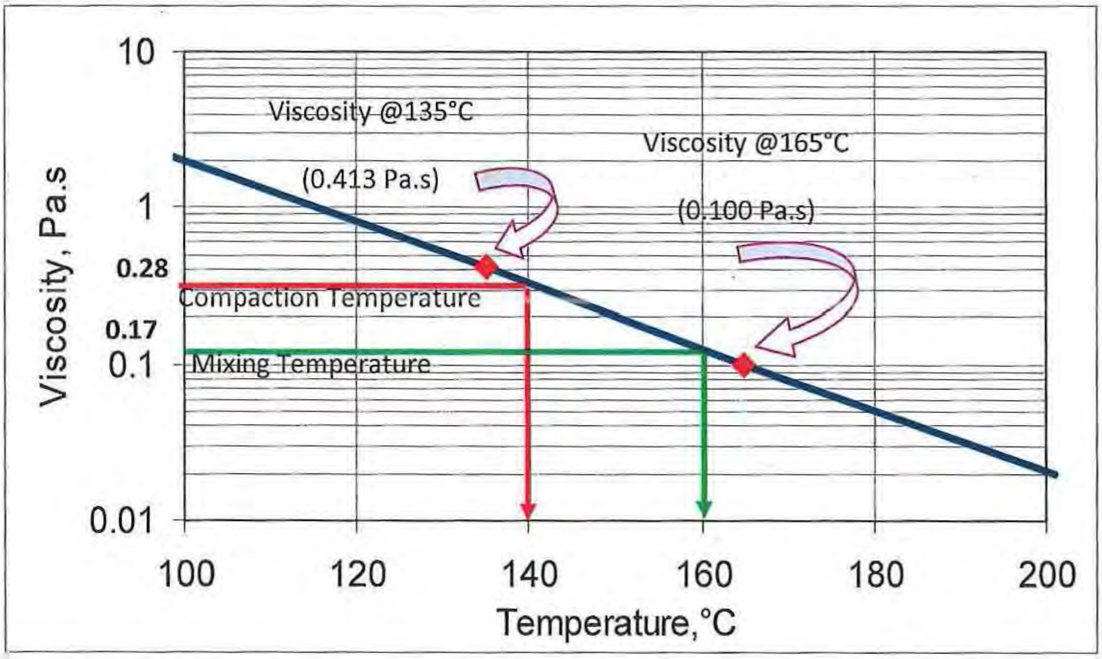

Figure 4: Viscosity–Temperature Relationships for 80/100 Asphalt Binder

3.2.2 Marshall Mix Design and Specimen preparation

Aggregates were heated in an oven at 180° C which is about 20°C higher than the mixing temperature (i.e.160° C) to facilitate mixing temperature which was obtained from viscosity-temperature graph then Fibers were mixed with aggregates thoroughly. Consequently, the melted asphalt binder at 160°C was added into fiber aggregate mixes and mixed thoroughly till resulting in a well coated and evenly distributed mixture. Subsequently, the hot mixtures were placed in a steel mold and compacted under 50 blows on each side at 145°C to attain a Marshall specimen measuring 101.6 mm (diameter) by 63.5 mm (height) according to the specification. A total of 128 Marshall Specimens were made (4 types of mixtures (2 control without fiber ACWC14, ACBC28 plus 2 with fiber ACWC14, ACBC28) by 15 specimens (3 specimens at 5 different asphalt contents) plus 5 loose specimens by 4 types of mix for determine Theoretical Maximum Density (TMD) using Rice method. These specimens were then used for the laboratory tests of volumetric properties and 12 specimens from 4 types of mix (3 specimens for rutting, 3 specimens for fatigue and 6 specimens for TSR analyasis. These specimens will be used for the advanced testing as discussed later. Each sample included approximately 1200 gram of aggregate, specific percent of asphalt by the weight of total mix and 0.5 percent of fiber by the weight of aggregate. Figure 5 (See Appendix) shows the process of making the Marshall samples. A mixture design was completed for the granite aggregate using 50 blows per specimen face of a flat-face, static base, mechanical Marshall Hammer to compact the specimens and, then the volumetric properties of mixture samples were determined and tested for Resilient Modulus, Marshall Stability, and Flow.

3.2.3 Volumetric Properties

The bulk specific gravity test was performed as soon as the freshly-compacted specimens have cooled down to room temperature. Since the lateral side of the specimens was not porous, ASTM D 2726 "Bulk Specific Gravity of Compacted Bituminous Mixtures Using Standard Surface-Dry Specimens" was selected for determination of bulk specific gravity. Bulk Specific Gravity of mix (G_{mb}) was calculated using the following equation:

$$G_{mb} = \frac{A}{C - B} \tag{1}$$

Where,

A: weight of specimen in air, g, B: weight of specimen submerged in water, g

C: saturated surface dry (SSD) weight of specimen, g

The maximum specific gravity (Gmm) or Rice Method was determined by AASHTO T209/ASTM D2041 (Theoretical Maximum Specific Gravity and Density of Bituminous Paving Mixtures) in which vacuuming was used to extract all the air from the mixtures. This represents 100% density (assumed to be no air voids) for a particular asphalt mixture. This value is used in conjunction with the bulk specific gravity to determine the density of the compacted specimens for that mixture. The maximum specific gravity (Gmm) was calculated using the following equation:

$$G_{mm} = \frac{(C - A)}{(C - A) - (D - B)} \tag{2}$$

Where;

A = Weight of Container in air, B = Weight of Container in water

C = Weight of Container and Sample in air, D = Weight of Container and Sample in water

TMD = Theoretical maximum density of the mix = G_{mm} x γ_w g/cm^3

γ_w = Specific gravity of water (1 g/cm^3)

For each set of Marshall Mix design specimens, one loose mixture (Figure 6 See Appendix) was prepared. The loose mixture was cooled in room temperature, then put in a wire basket, and then weighed in air and water (submerged) respectively. A vacuum with residual pressure of 30 mm Hg was applied for 25 minutes to remove the entrapped air. The wire basket and contents were agitated automatically by vigorous shaking during vacuuming. The weight of loose specimen submerged in water was determined.

The following equations were employed to determine the volumetric properties, voids in total mix, voids in mineral aggregate, and voids filled with asphalt (VTM, VMA, and VFA) respectively.

$$VTM = 100\left(1 - \frac{G_{mb}}{G_{mm}}\right) \tag{3}$$

$$VMA = 100\left(1 - \frac{G_{mb}(1 - P_b)}{G_{sb}}\right) \tag{4}$$

$$VFA = 100\left(\frac{VMA - VTM}{VMA}\right) \tag{5}$$

3.2.4 Resilient Modulus

Resilient Modulus is a relative measure of mixture stiffness and load distribution ability; higher resilient modulus values lead to stiffer mixtures with higher load distribution ability. The Resilient Modulus was determined from tests on cylindrical specimens for each mixture at designed asphalt contents in the indirect tension mode. The test was carried out using

The Material Testing Apparatus (MATTA) in accordance with ASTM D 4123 at temperature of 25 °C. The Resilient Modulus in Mega Pascal (MPa) is calculated by the following equation:

$$S_m = \frac{L(v + 0.27)}{D.t} \tag{6}$$

Where; L is the peak value of the applied vertical load (N), D is the mean amplitude of the horizontal deformation obtained from 5 applications of the load pulse (mm), t is the mean thickness of the test specimen (mm), and v is the Poisson's ratio (a value of 0.35 is normally used). The magnitude of the applied force conditioning pulses such that the specified target transient diametral deformation was achieved.

3.2.5 Stability and Flow Test

The Marshall stability was measured based on ASTM D1559. In the test a compressive loading was applied on the specimen at a rate of 50.8 mm/min till it was broken.

The maximum loading at material failure is called Marshall Stability, and the associated plastic flow (deformation) of specimen is called flow value. Marshall Stability and Flow tests were carried out on compacted specimens at various asphalt cement contents (4.5 – 6.5%) based on ASTM D1559. Triplicate specimens were tested for each asphalt contents and the average of the Marshall Stability and Flow values were assessed. Figures in Appendix shows water bath for Marshall samples Marshall Test Apparatus.

3.2.6 Determination of Optimum Asphalt Content

In this investigation, one binder (80/100 penetration grade) and two different gradations were used to produce four different mixtures (2 control without reinforced fiber ACWC14, ACBC28 and 2 with reinforced fiber ACWC14, ACBC28) respectively. The optimum bitumen contents of the mixtures were calculated in accordance with Marshall Method of mix design. The optimum bitumen content is the amount of bitumen at which the stability and bulk specific gravity reach the maximum level, the air void equals 4%. The stability, flow and the ratio of stability (kN) to flow (mm), which is defined as the Marshall Quotient (MQ) and is an indication of stiffness of the mixtures, were determined. It is known that, for a material, MQ is a measure of resistance to shear stress, permanent deformation and hence rutting. High MQ values indicate a mixture with high stiffness, high capability to distribute the applied load and high resistance to creep deformation. For each mixture, three specimens were prepared at 4.5%, 5.0%, 5.5%, 6.0%, and 6.5% asphalt contents to determine the optimum bitumen content and five loose specimens to were prepared to determine the TMD. The obtained values were compared with the criteria indicated in the JKR specification.

4. PERFORMANCE TESTING

4.1 Permanent Deformation Characteristics.

The static (confined/unconfined) creep test has been used to evaluate the deformation resistance (Rutting susceptibility) of asphalt mixture. The most popular static creep test is the unconfined static creep test (also known as the simple creep test or uniaxial creep test). A static creep test applies a load of fixed magnitude for a period of 1 hour to a cylindrical test specimen at a temperature of 40°C (104°F).

The cumulative permanent deformation as a function of time is recorded and was correlated to the rutting potential of asphalt mixtures. Tests can be run at different temperatures and varying loads. A static creep test (Figure 5) is conducted by applying a static load to an HMA specimen and then measuring the specimen's permanent deformation after unloading (Figure 6). The observed permanent deformation is then correlated with the rutting potential. A high value of permanent deformation may correlate to higher rutting potential.

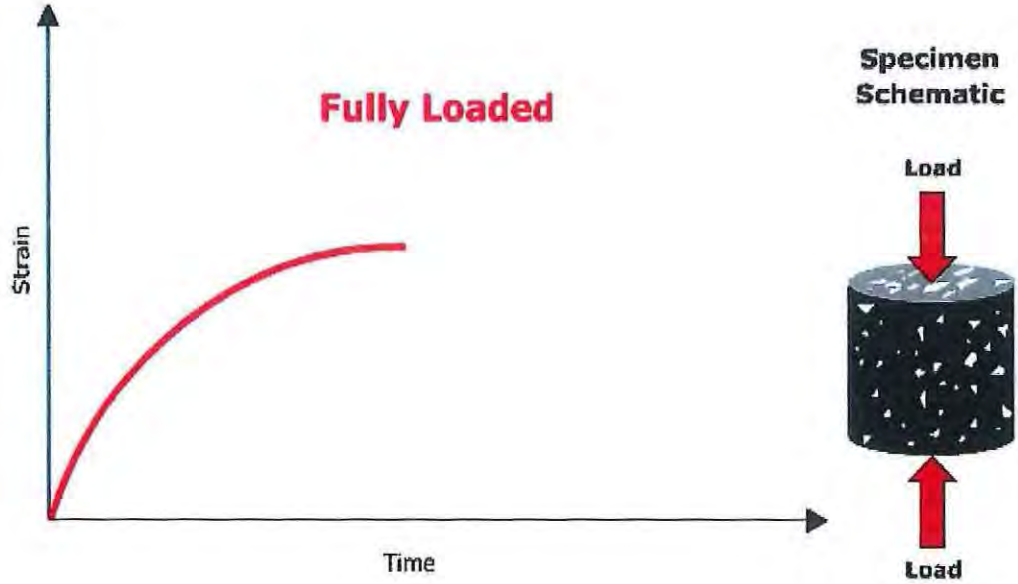

Figure 5: Static Creep Test Plot (Fully Loaded)

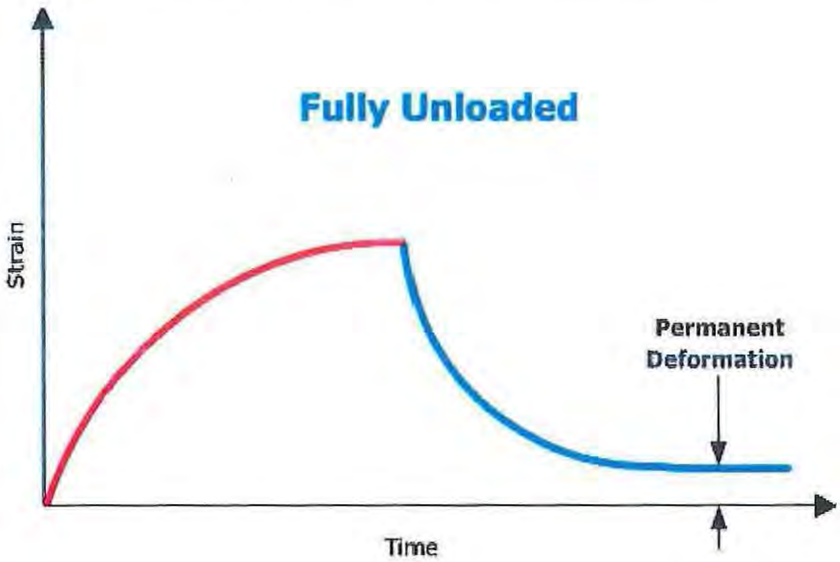

Figure 6: Static Creep Test Plot (Fully Unloaded)

Asphalt concrete wearing course (ACWC14), binder course (ACBC 28), and two control mixes were subjected to static axial compressive loading also known as static creep. Axial deviator stress of 300 kPa and contact stress of 10 kPa was applied. Prior to testing, the specimens were conditioned at 40°C in an environmental chamber for 3 hours. All specimens were tested under unconfined condition for 1 hour; the stress was applied using an upper platen 100 mm in diameter. The resulting permanent axial strains were measured as a function time. These loading conditions were selected so as to evaluate the relative performance of different asphalt concrete mixtures, following the specifications in BS EN 12697 – 25: 2005 for determining the resistance of bituminous mixtures to permanent deformation. For four Asphalt Concrete ACWC14 and ACBC28 (with and without fiber) specimens used in the static creep test had been polished smoothly on both sides and capped by aluminum foil applied at the top and bottom surface of the specimen after applying graphite powder (Figure 7); this would minimize the friction with loading plates and thus ensure a uniaxial stress condition. Three material properties were measured from the static creep test; permanent strain, Creep (stiffness) Modulus, and slope of the steady-state curve (Figure 8). Figures in Appendix shows Static unconfined creep test in progress.

Figure 7: 100 mm Diameter AC Specimen after Capping

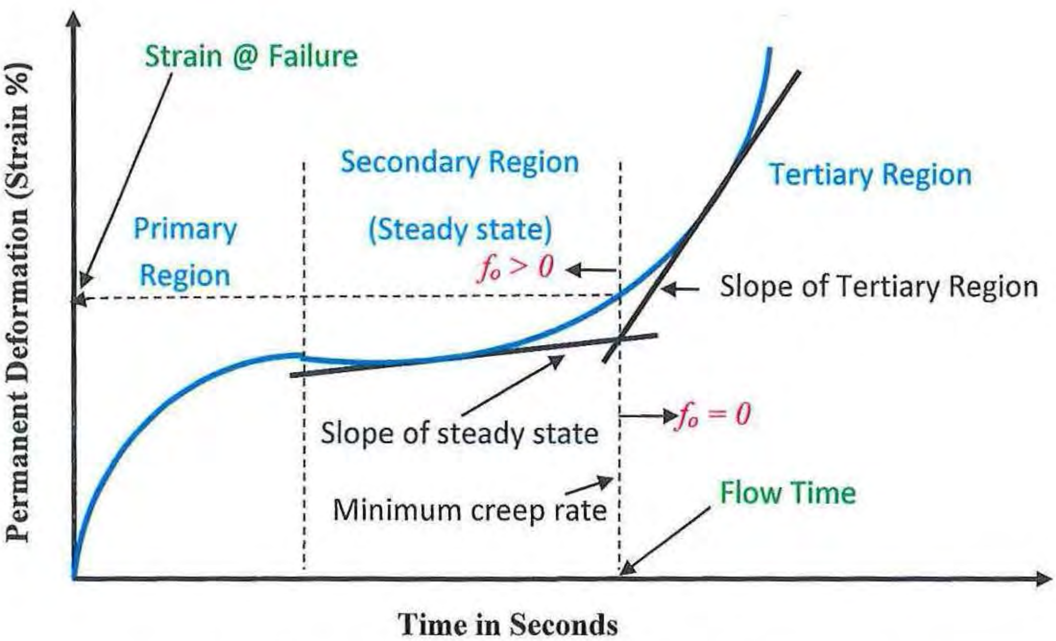

Figure 8: Typical Permanent Deformation Curve (f_o = Creep Rate)

4.2 Moisture Sensitivity (Tensile Strength Characteristics)

The indirect tensile test was used for the determination of the asphalt concrete mixture moisture susceptibility according to ASTM D 4123 (1995)/Modified Lottman test (AASHTO T283) specifications. Marshall core specimens were saturated 5 minutes @ 20" HG then placed in a water bath at 60°C for 24 h, and then were placed in an environmental chamber maintained at 25°C for 25 minute. These conditioned specimens were then tested for indirect tensile strength as depicted in Figure 9. The dry specimens were placed in a water bath maintained at 25°C for 25 minutes. The test was conducted at 25°C and the applied deformation rate was 50.8 mm/min. as shown in Figure in Appendix. The ratio of the tensile strength of the water-conditioned specimens to the dry specimens is reported as the Tensile Strength Ratio (TSR). The reported results are averages of three samples. Equation (7) was used to calculate the tensile strength of the mix,

$$TS = \frac{2P}{\pi DT} \tag{7}$$

Where, P is the peak value of the applied vertical load (kN); T is the mean thickness of the test specimen (m); and D is the specimen diameter (m). The maximum indirect tensile force was recorded and the corresponding Indirect Tensile (IDT) Strength of the asphalt mixture

was determined. The Tensile Strength Ratio (TSR), a ratio of the IDT strength of conditioned specimens to the IDT strength of unconditioned specimens, was calculated and used as a moisture susceptibility index of asphalt mixtures. Equation (8) was used to calculate the Tensile Strength Ratio (TSR),

$$TSR = \frac{TS_{cond.}}{TS_{uncond.}} \times (100) \tag{8}$$

Where:

TS_{cond} is the tensile strength of wet specimens and

TS_{uncond} is the tensile strength of dry specimens.

Figure 9: IDT Strength Test Set up and Failure Plane Using Indirect Tensile Jig

4.3 Indirect Tensile Fatigue Test (ITFT)

The test was performed according to BS DD213 ABF British Standard Draft for Development / ASTM D 4123. Marshall Specimens were used as specimens. The load was applied through a 12.5 mm wide stainless steel curved loading strip. The horizontal deformation of the specimen under load pulse and its subsequent recovery were measured by placing linear variable transducers (LVDT) at opposite horizontal ends.

A haversine loading pulse with a frequency of 10 Hz was used which is approximately equivalent to a vehicle speed of 50mph (80km/h). The loading period of the pulse, 0.1 second was followed by a rest period of 0.9 second. The Poisson's ratio was assumed to be 0.35 at 20°C. The tests were performed in an environmental chamber at 20°C. The specimens were preconditioned for about 3 hours at the test temperature. The applied stress level was fixed at 1500 N. The reported results are averages of three samples. The horizontal deformations (resilient) of the specimen were recorded after 3600 load repetitions used to compare the different mixes performance. The fatigue performance was taken as permanent horizontal deflection at the 3600 cycles. Figures in Appendix show Diametral Indirect Tensile Fatigue test in progress.

5. TEST RESULTS AND DISCUSSION

5.1 Volumetric Properties for the AC mixtures

The Optimum Asphalt Content (OAC), bulk specific gravity (Gmb), air void (VTM), Voids in Mineral Aggregate (VMA), Voids Filled with Asphalt (VFA), Marshall Stability, and Flow values belonging to the specimens prepared at their respective optimum asphalt contents are presented in Table 5.

Table 5: Summary of Properties Characterization for the four AC Mixtures at OAC

Property	Mix Type			
	Control (ACWC14)	**ACWC14**	**Control (ACBC28)**	**ACBC28**
OAC	5.55	5.65	5.46	5.63
Bulk Density	2.335	2.293	2.342	2.326
TMD	2.412	2.366	2.443	2.425
VTM	3.287	3.073	3.814	3.98
VMA	14.31	15.85	13.86	15.52
VFA	77.38	80.71	72.37	72.67
Stability, kN	10.87	16.01	12.08	14.31
Flow, mm	3.18	5.11	5.18	6.01
Resilient Moulus, MPa	1540	1686	1368	1666

As seen in Table 5, it was observed that the optimum asphalt contents for the four mixes ranged from a low of 5.46 percent to a high of 5.65 percent as depicted in Figure 10.

A general trend was observed that, the optimum asphalt content increases with decrease of aggregate particle size, the reason for this phenomenon is due to the fact that more asphalt binder is needed with fine size particle to form the same amount of mastic to lubricate the aggregate. The optimum asphalt content increases after the addition of the fiber, due to the absorption of asphalt by the fiber and due to the fact that smaller aggregate particles (ACWC14) have larger surface areas than larger particles (ACBC28) at the same volume concentration, which demands more asphalt. Also the slight difference in optimum asphalt content for the four mixtures is attributed to the differences in specific gravity for the coarse, medium, and fine particle size of aggregate. Since the fine particle size had a slightly higher specific gravity, it occupied a slightly lower volume in the compacted mix, leaving slightly more space for asphalt binder.

High stability values were obtained for mixtures with reinforced fiber, and the volumetric properties obtained within the specified limits (See Table 5 through 9 and Figure 11 through 15). Furthermore, AC mixtures with reinforced fiber showed higher VMA, VFA, Stability, and Resilient Modulus values compared to the control mixtures.

It was found that the stability improved by 47.3% after using reinforced fiber for ACWC14; whereas the increase in stability was 18.5% for ACBC28 compared to the control mixtures and the Resilient Modulus values of the ACWC14 and ACBC28 mixtures increased with the utilization of reinforced fiber by 9.5% and 21.8% respectively compared to the control mixtures. Thus, it can be inferred from these results that mixtures with reinforceed fibers are more effective compared to the mixture without reinforced fiber in terms of Stability and Resilient Modulus values.

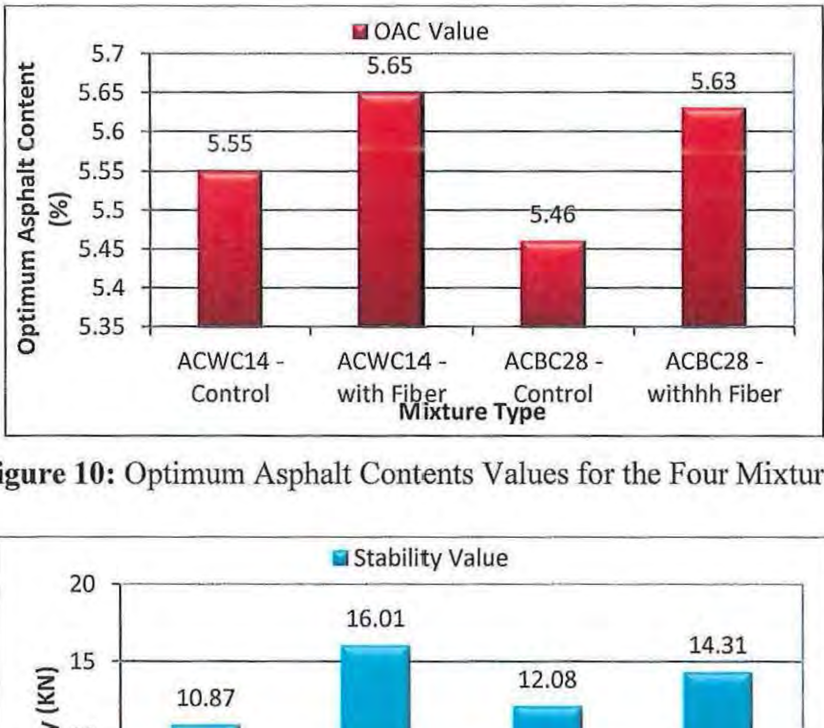

Figure 10: Optimum Asphalt Contents Values for the Four Mixtures

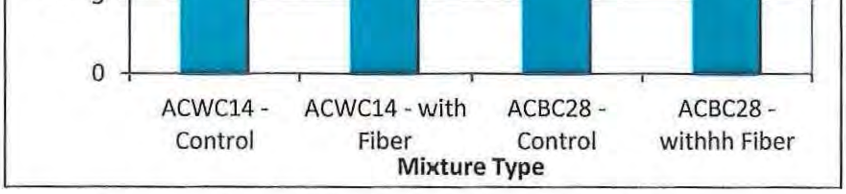

Figure 11: Stability Values for the Four Mixtures

Table 6: Data of Volumetric Properties of Asphalt Concrete Wearing Course (ACWC14) with Reinforced Fiber

Sample	Average		Weight (g)			Mix Volume (cc)	Specific Gravity		VOLUMES		Unit Weight (pcf)	VOIDS			STABILITY (KN)	FLOW (mm)	Resilient Modulus (Mpa)
	Height (mm)	Diameter (mm)	In Air	In Water	SSD		Bulk (G_{mb})	TMD (G_{max})	Aggregate Volume (%)	AC by Volume (%)		VTM (%)	VMA (%)	VFA (%)			
4.5 A	69.42	101.62	1264.3	709.2	1271.8	562.6	2.25	2.386	82.64	9.83	140.4	5.7	17.36	67.17	15.86	4.96	1635
4.5 B	68.73	101.36	1245.4	703.9	1253.7	549.8	2.27		83.38	9.92	141.65	4.86	16.62	70.76	15.13	4.14	1673
4.5 C	69.87	101.37	1263.3	711.2	1269.7	558.5	2.26		83.01	9.87	141.02	5.28	16.99	68.92	16.02	4.95	1669
Average							**2.26**				**141.02**	**5.28**	**16.99**	**68.95**	**15.67**	**4.68**	**1659**
5.0 A	69.12	101.33	1260.1	713.6	1263.7	550.1	2.29	2.373	83.67	11.12	142.9	3.5	15.89	77.97	16.95	6.1	1777
5.0 B	69.53	101.67	1262.4	711.2	1269.7	558.5	2.26		82.57	10.97	141.02	4.76	16.99	71.98	15.85	4.49	1813
5.0 C	70.37	101.41	1265.1	713.2	1272.4	559.2	2.26		82.57	10.97	141.02	4.76	16.99	71.98	14.01	4.17	1516
Average							**2.27**				**141.65**	**4.34**	**16.62**	**73.98**	**15.6**	**4.92**	**1702**
5.5 A	69.73	101.34	1264	716.2	1269.4	553.2	2.28	2.367	82.69	12.17	142.27	3.68	16.25	77.35	15.34	5.57	1703
5.5 B	69.78	101.27	1273.2	717.6	1275.8	558.2	2.28		82.87	12.17	142.27	3.68	16.25	77.35	16.65	5.63	1696
5.5 C	69.67	101.2	1270.5	722.1	1273.2	551.1	2.31		83.96	12.33	144.14	2.41	15.15	84.09	16.36	4.21	1605
Average							**2.29**				**142.89**	**3.26**	**15.88**	**79.6**	**16.12**	**5.14**	**1668**
6.0 A	69.62	101.13	1274.6	721.3	1276.2	554.9	2.30	2.358	83.15	13.39	143.52	2.46	15.52	84.15	16.67	6.5	1727
6.0 B	69.43	101.23	1269	717.5	1271.6	554.1	2.29		82.79	13.33	142.9	2.88	15.89	81.88	15.21	4.39	1711
6.0 C	69.07	101.4	1267.6	716.9	1268.8	551.9	2.30		83.15	13.39	143.52	2.46	15.52	84.15	16.33	4.33	1605
Average							**2.3**				**143.31**	**2.6**	**15.64**	**83.39**	**16.07**	**5.07**	**1681**
6.5 A	68.86	101.33	1262.7	715.3	1269	553.7	2.28	2.352	81.99	14.39	142.27	3.06	16.25	81.17	15.82	5.29	1696
6.5 B	69.43	101.33	1279.6	717.8	1285.8	568	2.25		80.91	14.20	140.4	4.34	17.36	75	15.14	5.23	1685
6.5 C	68.67	101.47	1278.5	714.8	1279.8	565	2.26		81.27	14.26	141.02	3.91	16.99	76.99	15.34	5.25	1590
Average							**2.26**				**141.23**	**3.77**	**16.87**	**77.72**	**15.43**	**5.26**	**1657**

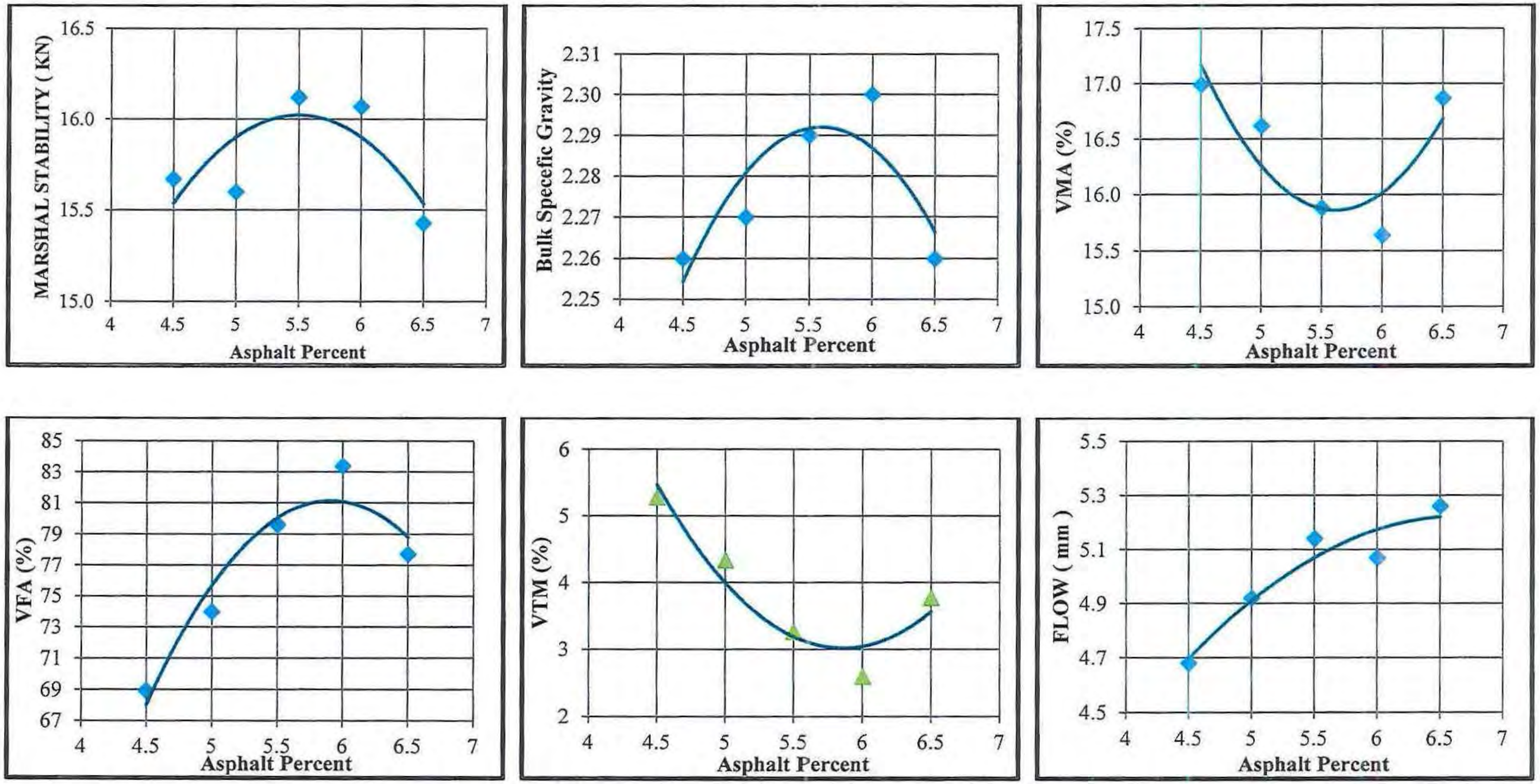

Figure 12: Volumetric Properties Graphs of ACWC14 with Reinforced Fiber

Table 7: Data of Volumetric Properties of Asphalt Concrete Wearing Course (ACWC 14) Control Samples (without Fiber)

Sample	Average		Weight (g)			Mix Volume (cc)	Specific Gravity		VOLUMES		Unit Weight (pcf)	VOIDS			STABILITY (KN)	FLOW (mm)	Resilient Modulus (Mpa)
	Height (mm)	Diameter (mm)	In Air	In Water	SSD		Bulk (Gmb)	TMD (Gmax)	Aggregate Volume (%)	AC by Volume (%)		VTM (%)	VMA (%)	VFA (%)			
4.5 A	67.83	105.07	1234.8	679.7	1239.3	559.6	2.21	**2.358**	81.18	9.66	137.9	6.28	18.83	66.65	4.87	5.87	1275.00
4.5 B	67.95	102.07	1244	704.1	1249.7	545.6	2.28		83.75	10.18	142.27	3.31	16.25	79.63	10.58	4.81	1559.00
4.5 C	67.64	101.55	1238.5	697	1243.6	546.6	2.27		83.38	9.92	141.65	3.73	16.62	77.56	10.45	3.25	1477.00
Average							**2.25**				**140.61**	**4.44**	**17.23**	**74.61**	**8.63**	**4.64**	**1437.00**
5.0 A	66.69	101.97	1247.6	712.1	1249.5	537.4	2.32	**2.392**	84.77	11.26	144.77	3.01	14.78	79.63	14.06	4.22	1548.00
5.0 B	66.71	101.79	1245.3	693.8	1249.2	555.4	2.24		81.85	10.87	139.78	6.35	17.72	64.16	7.58	1.19	1486.00
5.0 C	66.18	101.55	1255.2	718.5	1256.3	537.8	2.33		85.13	11.31	145.39	2.59	14.42	82.04	12.52	3.24	1475.00
Average							**2.30**				**143.31**	**3.98**	**15.64**	**75.28**	**11.39**	**2.88**	**1503.00**
5.5 A	66.53	101.47	1250.2	718.8	1251.3	532.5	2.35	**2.415**	85.41	12.55	146.64	2.69	13.68	80.34	12.27	4.14	1516.00
5.5 B	66.39	101.96	1224.6	700	1227.8	527.8	2.32		84.32	12.39	144.77	3.93	14.78	73.41	9.19	1.05	1413.00
5.5 C	68.35	101.49	1255	715.6	1257	541.4	2.32		84.32	12.39	144.77	3.93	14.78	73.41	7.94	3.43	1570.00
Average							**2.33**				**145.39**	**3.52**	**14.41**	**75.72**	**9.8**	**2.87**	**1500.00**
6.0 A	66.67	101.17	1212.5	696.5	1213	516.5	2.35	**2.411**	84.96	13.69	146.64	2.53	13.68	81.51	9.5	6.05	1614.00
6.0 B	66.97	101.49	1270.2	727.8	1271	543.2	2.34		84.60	13.63	146.02	2.94	14.05	79.07	10.31	3.74	1456.00
6.0 C	66.82	101.32	1257.1	724.4	1257.4	533	2.36		85.32	13.75	147.26	2.12	13.32	84.08	12.32	3.95	1589.00
Average							**2.35**				**146.64**	**2.53**	**13.68**	**81.55**	**10.71**	**4.58**	**1553.00**
6.5 A	67.23	101.42	1264.1	727.6	1264.6	537	2.35	**2.409**	84.51	14.83	146.64	2.45	13.68	82.09	10.04	3.7	1211.00
6.5 B	66.07	101.46	1160.9	664.2	1161	496.8	2.34		84.15	14.77	146.02	2.86	14.05	79.64	7.63	4.62	1441.00
6.5 C	66.64	104.33	1252	719.2	1252.4	533.2	2.35		84.51	14.83	146.64	2.45	13.68	82.09	7.27	5.42	1261.00
Average							**2.35**				**146.43**	**2.59**	**13.8**	**81.27**	**8.31**	**4.58**	**1304.00**

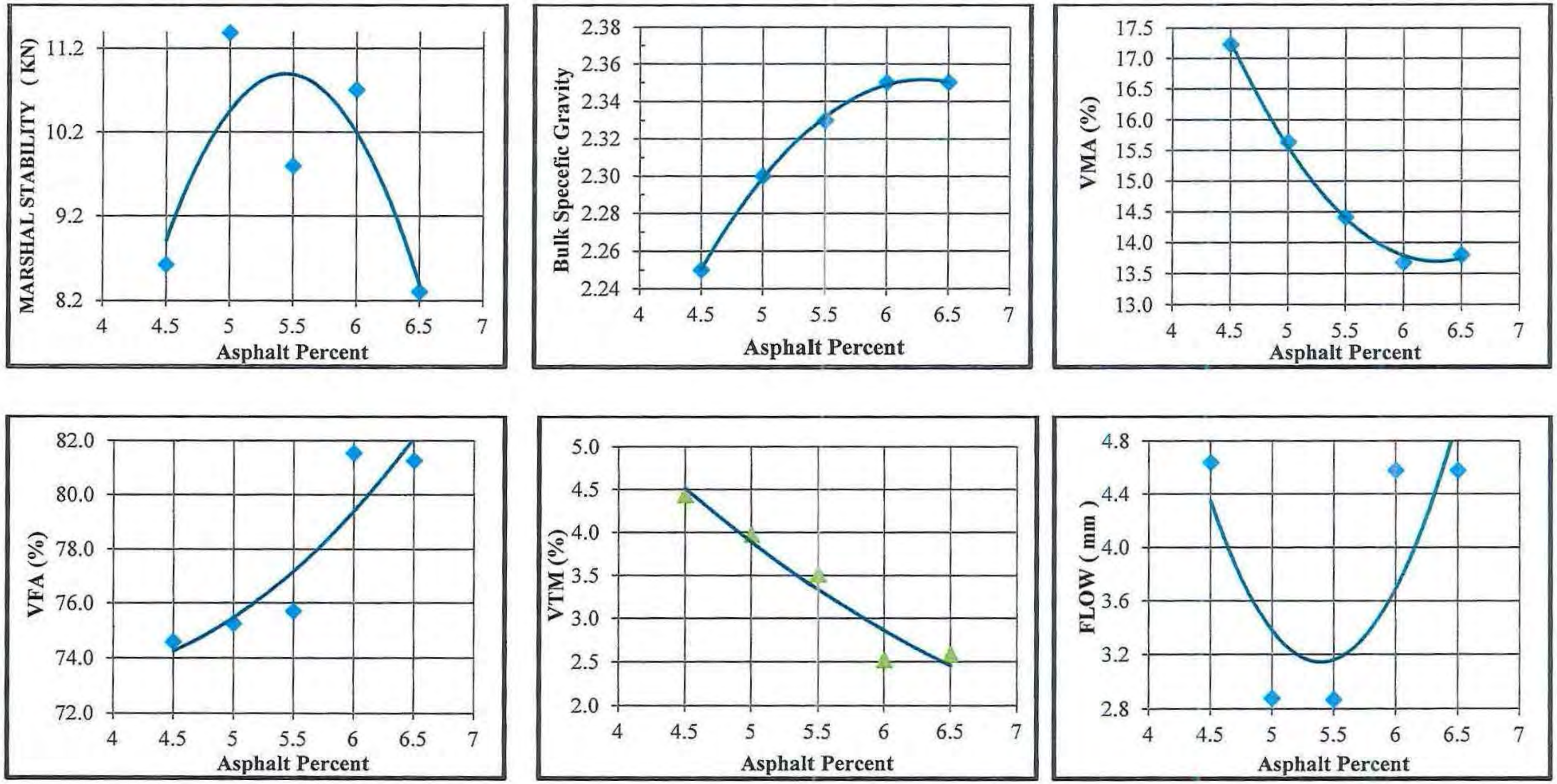

Figure 13: Volumetric Properties Graphs of ACWC14 without Fiber (control samples)

Table 8: Data of Volumetric Properties of Asphalt Concrete Binder Course (ACBC 28) with Reinforced Fiber

Sample	Average		Weight (g)			Mix Volume (cc)	Specific Gravity		VOLUMES		Unit Weight (pcf)	VOIDS			STABILITY (KN)	FLOW (mm)	Resilient Modulus (Mpa)
	Height (mm)	Diameter (mm)	In Air	In Water	SSD		Bulk (Gmb)	TMD (Gmax)	Aggregate Volume (%)	AC by Volume (%)		VTM (%)	VMA (%)	VFA (%)			
4.5 A	68.84	101.21	1280.4	721.9	1277.1	555.2	2.306	2.432	84.70	10.07	143.89	5.18	15.30	66.14	9.42	5.82	1717.00
4.5 B	68.65	101.47	1275.1	730.7	1279.8	549.1	2.322		85.29	10.14	144.89	4.52	14.71	69.27	9.26	5.14	1689.00
4.5 C	69.64	101.25	1278.2	716.2	1265.7	549.5	2.326		85.44	10.16	145.14	4.36	14.56	70.05	9.61	5.57	1583.00
Average							**2.318**				**144.46**	**4.69**	**14.86**	**68.44**	**9.43**	**5.51**	**1663.00**
5.0 A	68.42	101.77	1276.5	731.9	1282.4		2.319	2.433	84.73	11.26	144.71	4.69	15.27	69.29	12.28	5.96	1911.00
5.0 B	69.61	101.79	1284.4	735.9	1288.1		2.326		84.99	11.29	145.14	4.40	15.01	70.69	12.65	6.02	1868.00
5.0 C	68.18	101.75	1282.3	735.7	1286.8		2.327		85.03	11.30	145.20	4.36	14.98	70.89	12.84	5.69	1774.00
Average							**2.324**				**145.02**	**4.48**	**15.09**	**69.40**	**12.59**	**5.89**	**1851**
5.5 A	67.33	101.47	1299.6	742.5	1300.5		2.329	2.421	84.65	12.44	145.33	3.80	15.35	75.24	13.95	6.12	1737.00
5.5 B	66.38	101.68	1293.7	739.0	1295.2		2.326		84.54	12.42	145.14	3.92	15.46	74.64	14.86	6.26	1705.00
5.5 C	68.13	101.55	1298.9	738.8	1303.7		2.329		84.65	12.44	145.33	3.80	15.35	75.	14.84	6.28	1643.00
Average							**2.328**				**145.27**	**3.84**	**15.39**	**73.50**	**14.55**	**6.22**	**1695.00**
6.0 A	66.82	101.44	1285.2	735.9	1288.1		2.326	2.418	84.09	13.55	145.14	3.80	15.91		13.55	5.86	1722.00
6.0 B	66.77	101.66	1284.4	732.9	1283.5		2.324		84.02	13.54	145.02	3.89	15.98		13.92	5.65	1618.00
6.0 C	66.65	101.52	1300.1	738.3	1302.9		2.313		83.62	13.47	144.33	4.34	16.38		13.15	5.56	1577.00
Average							**2.321**				**144.83**	**4.01**	**16.09**	**72.81**	**13.54**	**5.69**	**1639.00**
6.5 A	67.23	101.52	1271.5	723.4	1272.6		2.315	2.415	83.25	14.61	144.46	4.14	16.75		9.66	6.22	1712.00
6.5 B	67.87	101.36	1269.9	724.1	1271.8		2.319		83.39	14.63	144.71	3.97	16.61		11.26	6.39	1605.00
6.5 C	67.66	101.38	1271.7	722.5	1272.8		2.311		83.11	14.58	144.21	4.31	16.89		11.99	6.59	1624.00
Average							**2.315**				**144.46**	**4.14**	**16.75**	**71.29**	**10.97**	**6.40**	**1647.00**

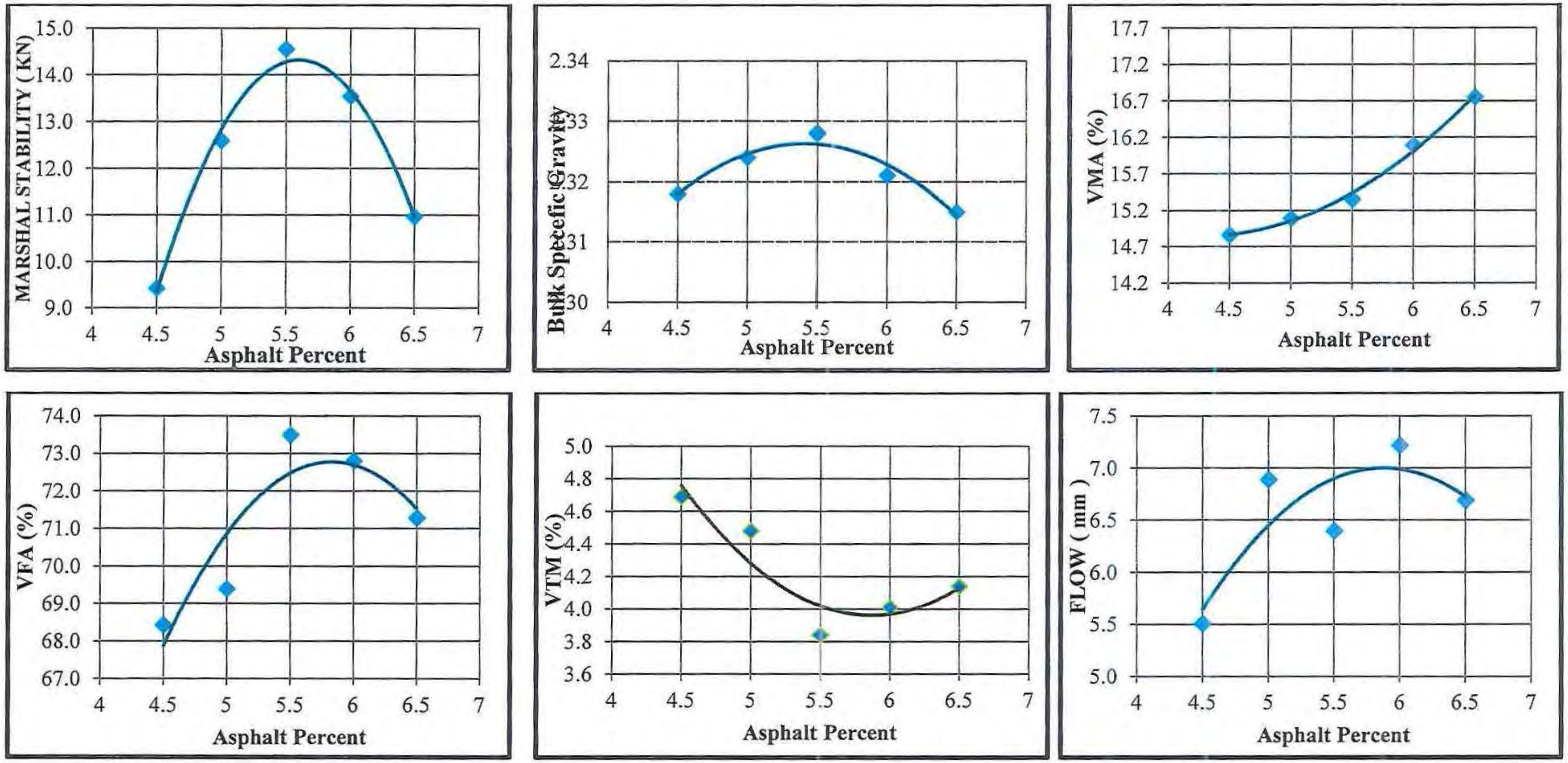

Figure 14: Volumetric Properties Graphs of ACBC28 with Reinforced Fiber

Table 9: Data of Volumetric Properties of Asphalt Concrete Wearing Course (ACBC 28) Control Samples (without Fiber)

Sample	Average		Weight (g)			Mix Volume (cc)	Specific Gravity		VOLUMES		Unit Weight (pcf)	VOIDS			STABILITY (KN)	FLOW (mm)	Resilient Modulus (Mpa)
	Height (mm)	Diameter (mm)	In Air	In Water	SSD		Bulk (Gmb)	TMD (Gmax)	Aggregate Volume (%)	AC by Volume (%)		VTM (%)	VMA (%)	VFA (%)			
4.5 A	69.57	101.13	1226.7	711.5	1235.1	523.6	2.34		85.95	10.22	146.02	4.53	14.05	67.76	10.92	5.67	1458.00
4.5 B	70.07	101.17	1250	723.7	1257.5	533.8	2.34	2.451	85.95	10.22	146.02	4.53	14.05	67.76	8.46	6.92	1330.00
4.5 C	70.37	101.1	1269.1	732.7	1275.3	542.6	2.34		85.95	10.22	146.02	4.53	14.05	67.76	8.39	5.12	1316.00
Average							**2.34**				**146.02**	**4.53**	**14.05**	**67.76**	**9.26**	**5.9**	**1368.00**
5.0 A	69.77	100.7	1235.5	713.4	1243.8	530.4	2.33		85.13	11.31	145.39	4.82	14.42	66.57	11.08	5.98	1423.00
5.0 B	69.64	100.93	1112.4	644.9	1115.3	470.4	2.36	2.448	86.23	11.46	147.26	3.59	13.32	73.05	10.67	5.6	1396.00
5.0 C	69.83	101.1	1254.5	724.3	1258.8	534.5	2.35		85.87	11.41	146.64	4	13.68	70.76	12.64	5.51	1279.00
Average							**2.35**				**146.43**	**4.14**	**13.81**	**70.13**	**11.46**	**5.7**	**1366.00**
5.5 A	69.87	100.67	1243.3	718.9	1246.8	527.9	2.36		85.78	12.60	147.26	2.52	13.32	81.08	9.68	3.1	1420.00
5.5 B	69.57	100.63	1255.6	719.9	1263.3	543.4	2.31	2.421	83.96	12.33	144.14	4.58	15.15	69.77	10.81	4.64	1382.00
5.5 C	69.73	100.97	1231.9	707.7	1237.1	529.4	2.33		84.69	12.44	145.39	3.76	14.42	73.93	16.56	7.54	1368.00
Average							**2.33**				**145.6**	**3.62**	**14.3**	**74.93**	**12.35**	**5.09**	**1390.00**
6.0 A	70.82	100.63	1323.6	763.5	1324.8	561.3	2.36		85.32	13.75	147.26	3.75	13.32	71.85	11.03	4.77	1282.00
6.0 B	69.63	101.43	1323.6	763.5	1324.8	561.3	2.36	2.452	85.32	13.75	147.26	3.75	13.32	71.85	10.47	5.55	1367.00
6.0 C	70.31	101.1	1261	725.7	1264.7	539.0	2.34		84.60	13.63	146.02	4.57	14.05	67.47			1272.00
Average							**2.35**				**146.85**	**4.02**	**13.56**	**70.39**	**10.75**	**5.16**	**1307.00**
6.5 A	71.53	100.27	1259.8	723.8	1263.9	540.1	2.33		83.79	14.70	145.39	3.64	14.42	74.76	10.88	7.22	1312.00
6.5 B	69.97	100.57	1254.3	718.6	1255.4	536.8	2.34	2.418	84.15	14.77	146.02	3.23	14.05	77.01	8.94	4.17	1249.00
6.5 C	71.73	100.47	1241.1	705.5	1245.9	540.4	2.30		82.71	14.51	143.52	4.88	15.52	68.56	6.16	6.66	1246.00
Average							**2.32**				**144.98**	**3.92**	**14.66**	**73.44**	**8.66**	**6.02**	**1269.00**

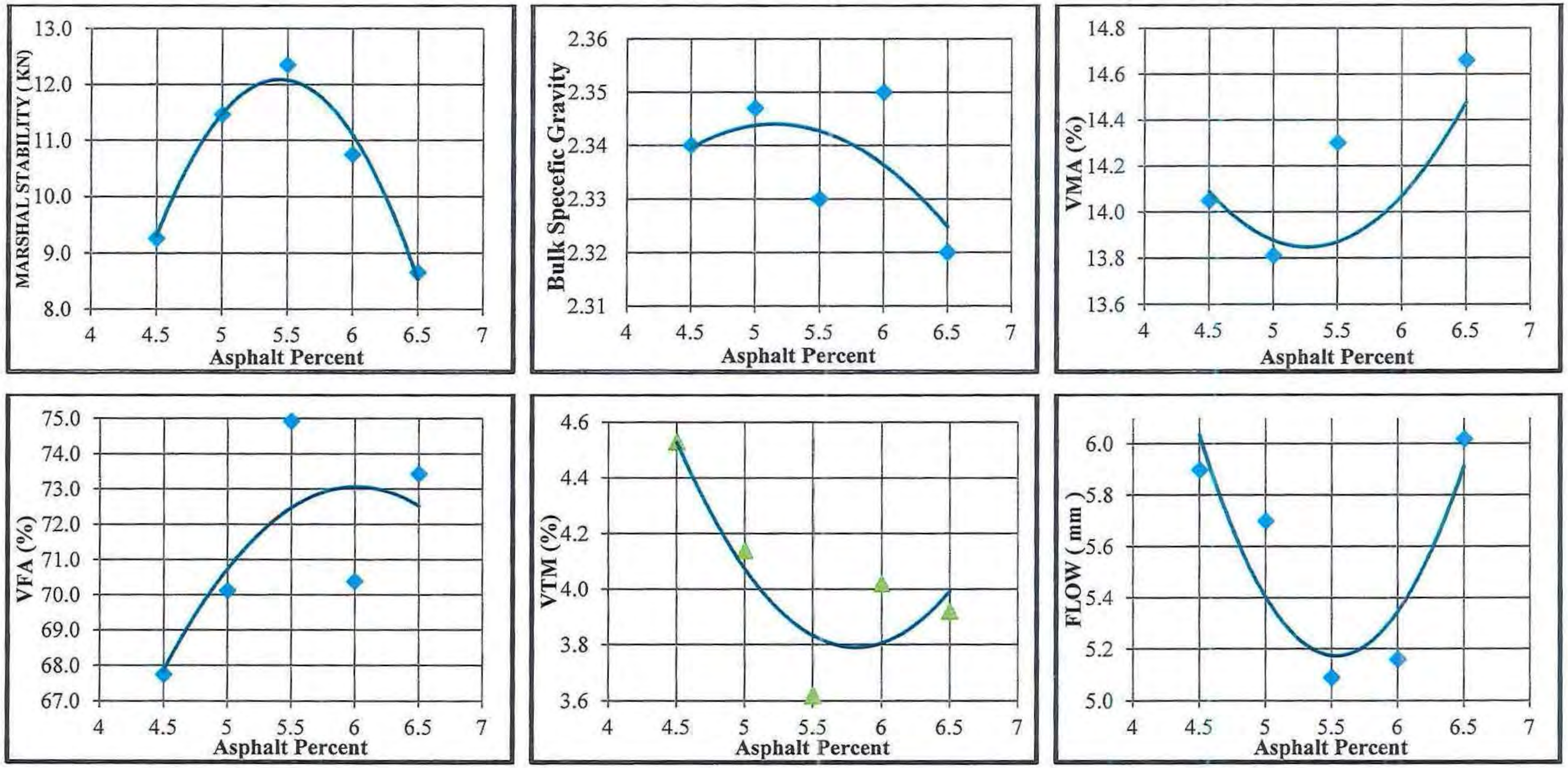

Figure 15: Volumetric Properties Graphs of ACBC28 without Fiber (control samples)

5.2 Permanent Deformation (Rutting)

This report presents the results of the experimental measurements are discussed in the previous paragraph. The results produced in this investigation are applicable to and based on the following setup parameters (JKR requirements) for the static unconfined creep using the Universal Testing System (UTS) in UPM laboratory:

- Test temperature: 40°C
- Loading condition: controlled-stress
- Loading Stress: 300 kPa
- Loading time: 3600 second (1 hour)
- Termination time count: 1 hour
- Preload static axial stress (10 kPa) for 60 seconds
- Confine stress: 0.00 kPa
- Total No of Samples = 3

In this report the permanent deformation performance of the ACWC14 and ACBC 28 with and without reinforced fiber mixtures was quantified by the percentage strain after 3600 seconds, time to failure, and by the minimum rate of strain over the linear phase of the deformation response calculated by linear regression through the 3600 loading time. The creep rates (f_o), were calculated for time period at 3600 and 2600 seconds while the creep modulus (E_n) was calculated after 3600 cycles of load applications, in Mega-Pascal (MPa). The static creep results for AC specimens are summarized and presented in Table 10 and graphically in Figure 16 through 19. The plots showed that, the accumulation of permanent strain for the ACWC14 and ACBC28 mixtures with reinforced fiber were low and clearly indicated a superior resistance to permanent deformation (lower percent strain is desirable).

Higher Creep Modulus and lower creep rate both are desirable. Higher creep modulus values (Figure 14) are desirable as they correspond to a strong and durable mixture. In contrast, the lower the creep (strain) rate value per cycle , the higher the amount of energy absorbed by the mixture under tensile strain which eventually decreases the chances of developing fatigue cracks. As depicted in Figure 16, 17, 18 and Table 10 ACWC14 and ACBC28 Shown lower strain percent, lower creep rate, and higher creep modulus compared to the control mixtures.

It was observed from Figure14 that, the Creep Modulus improved by 39.1% after using reinforced fiber for ACWC14; whereas the increase in Creep Modulus was 41.8% for ACBC28 compared to the control mixtures. The drop in strain value at the end of 3600 loading cycles was 28.3% after using reinforced fiber for ACWC14; whereas the drop in strain value was 29.1% for ACBC28 compared to the control mixtures.

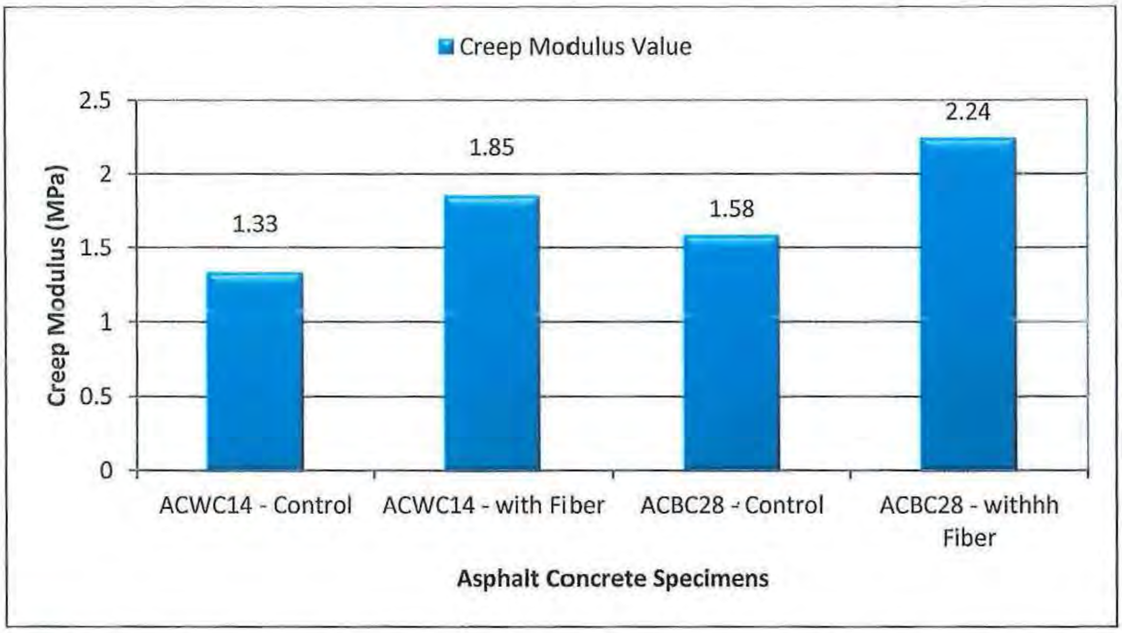

Figure 16: Comparison graph of Creep Modulus for ACWC14 and ACBC28 Mixtures with and without Reinforced Fiber

Table 10: Summary of RLAT Test Results of ACWC14 Mixtures

Mix Type	Strain % @ 3600 Cycle	Strain % @ 2600 Cycle	Creep (Stiffness) Modulus (MPa)	Strain Rate (με/second)
ACWC14 Control	0.226	0.220	1.33> 1MPa	6×10^{-6}
ACWC14 with Reinforced Fiber	0.162	0.161	1.85 > 1MPa	1×10^{-6}
ACBC28 Control	0.189	0.187	1.58 > 1MPa	2×10^{-6}
ACBC28 with Reinforced Fiber	0.134	0.133	2.24 > 1MPa	1×10^{-6}

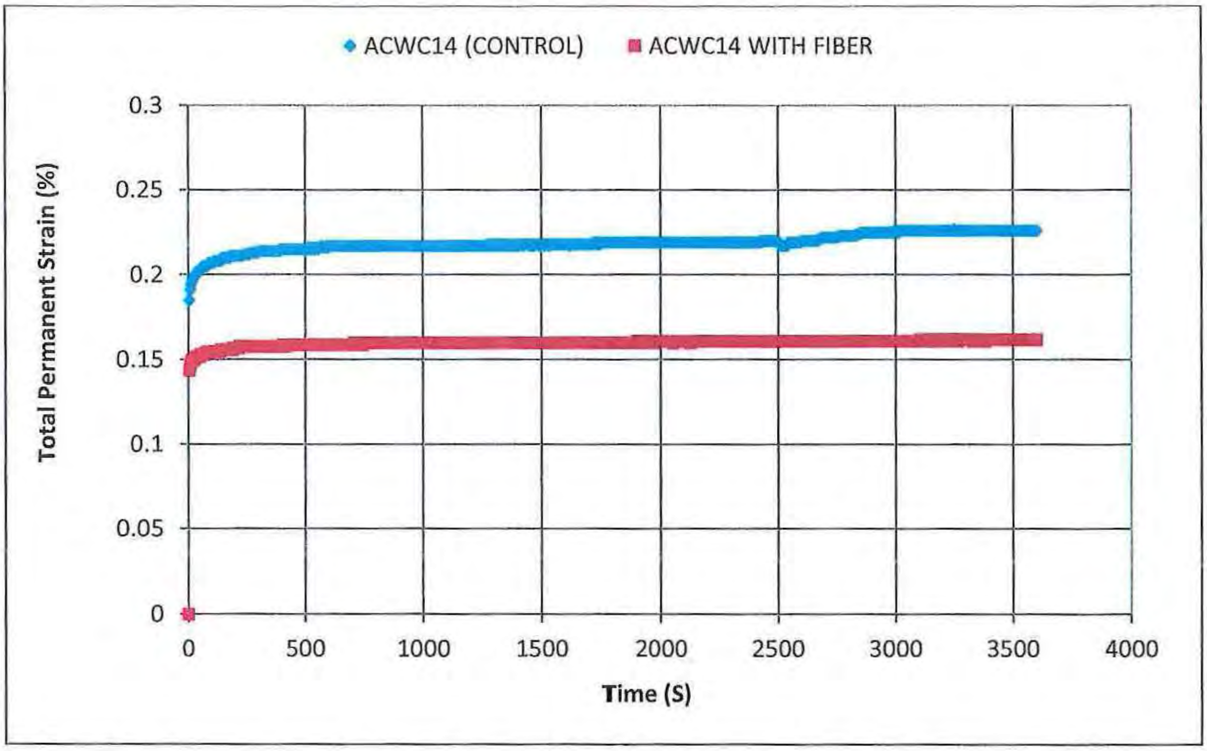

Figure 17: Comparison graphs of Strain percent Vs Time for Static Unconfined Creep Test for Specimens of ACWC14 Mixtures

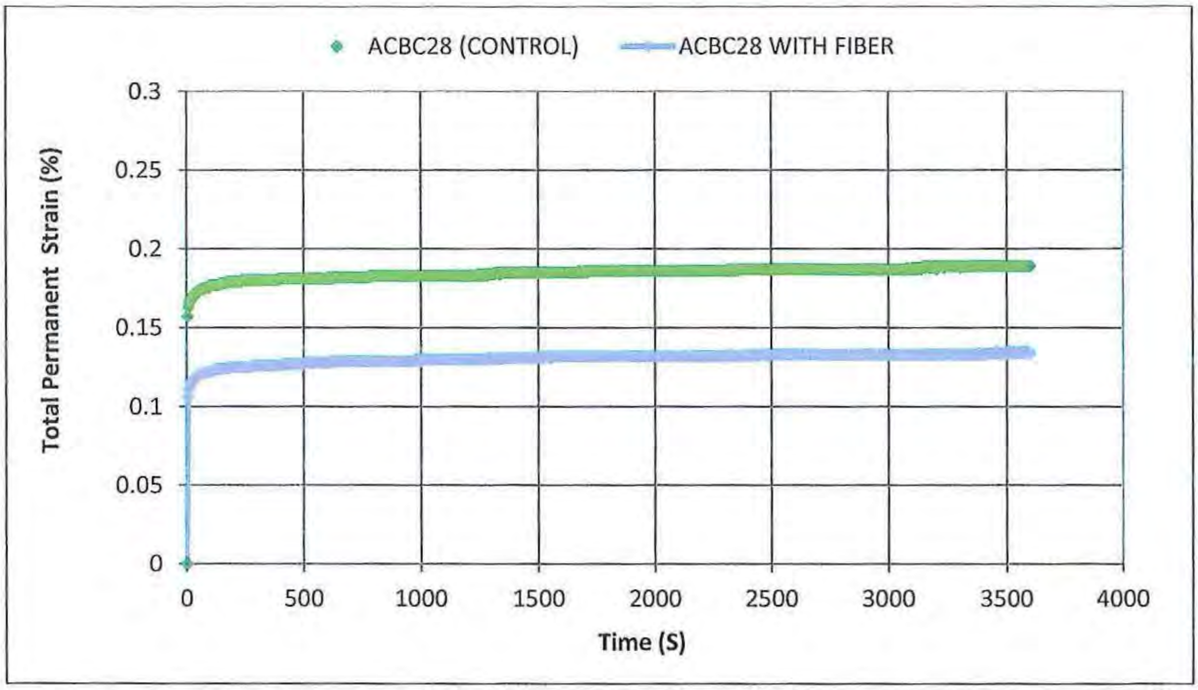

Figure 18: Comparison graphs of Strain percent Vs Time for Static Unconfined Creep Test for Specimens of ACBC28 Mixtures

The Slope of the steady- state region was calculated through regression analysis. The Log of cumulative strain is plotted against Log time, in seconds, for the average of the three specimens at designated asphalt content for the four mixture. From this plot, the slope of the steady-state curve was obtained and the results are presented in Table 11 and graphically in Figure 19. Slope of the linear portion of the permanent deformation Strain vs Cycles (Steady state region) Figure 19 shown that AC mixtures with reinforced fiber had lower slope compared to AC mixtures without reinforced fiber (The larger the slope, the greater the potential for rutting in the field and the faster the rutting accumulates). Once again AC mixtures shown lower slope and lower intercept values compared to the control mxtures.

Table 11: Coefficients of the Linear Relationship between Log-Cumulative Strain and Log-Time of Loading of Steady State Region for Four Mixtures

Sample No.	Regression Coefficients		
	Slope	Intercept	R^2 (%)
ACWC14 Control	4.00×10^{-6}	0.218	86.55
ACWC14 with Reinforced Fiber	2.00×10^{-6}	0.159	85.18
ACBC28 Control	3.00×10^{-6}	0.181	93.65
ACBC28 with Reinforced Fiber	1.00×10^{-6}	0.127	84.73

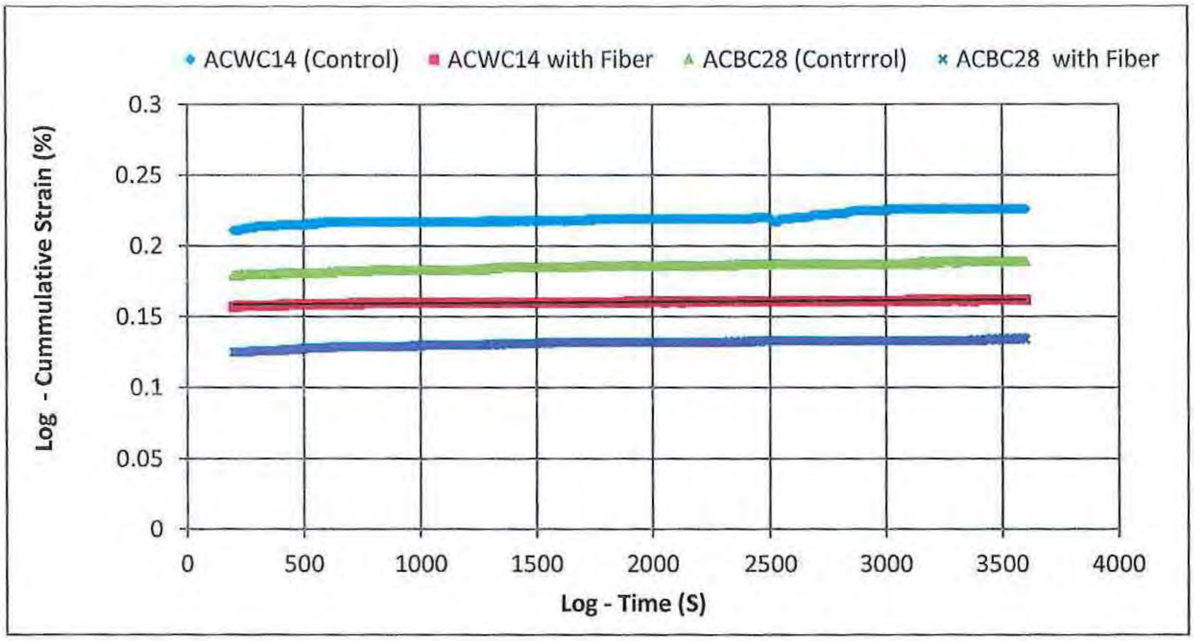

Figure 19: Comparison graphs of Strain vs Pulse Count for Specimens of ACWC14 and ACBC28 Mixtures with and without Reinforced Fiber

5.3 Moisture Sensitivity

The results of the Indirect Tensile Strength (ITS) tests for the mixtures before and after conditioning are presented in Table 12 through Table 14 for ACWC14 and summarized in Table 15 for the four mixtures. Each value represents the mean value obtained from testing of three specimens.

Table 12: Results of Moisture Induced Damage Test for Unconditioned Samples (Dry)

Compacted Sample		ACWC 14			Mean
Sample No.		1	2	3	
Diameter	D	101.27	101.17	101.20	101.21
Thickness	T	68.12	68.18	68.01	68.10
Dry mass in air	A	1272.30	1266.20	1275.50	1270.85
SSD mass	B	1274.50	1267.80	1276.20	1272.00
Mass in water	C	723.72	717.28	729.40	724.70
Volume	E	550.78	550.52	546.80	547.30
Bulk Sp. Gr.	F	2.31	2.30	2.29	2.32
TMD	G	2.366	2.366	2.366	2.366
% Air Void	H	2.37	2.79	1.52	1.95
Vol. of Air Voids	I	13.05	15.36	8.31	10.65
Load, N	P	16030.00	15590.00	16050.00	15890.00
Dry Strength, MPa	**S1**	1.48	1.44	1.49	**1.47 > 1**

Table 13: Results of Moisture Induced Damage Test for Conditioned Samples (Wet)

Compacted Sample		ACWC 14			Mean
Sample No.		4	5	6	
Diameter	D	101.20	101.23	101.43	101.29
Thickness	T	68.51	68.78	68.47	68.59
Dry mass in air	A	1269.40	1267.00	1267.90	1268.10
SSD mass	B	1278.80	1276.80	1269.30	1274.97
Mass in water	C	722.05	723.52	715.10	720.22
Volume	E	556.75	553.28	554.20	554.74
Bulk Sp. Gr.	F	2.28	2.29	2.27	2.28
TMD	G	2.366	2.366	2.366	2.366
% Air Void	H	3.63	3.21	3.34	3.39
Volume of Air Voids	I	20.21	17.76	18.50	18.82
Saturated 5 minutes @ 20" HG					
Thickness	T'	69.04	69.48	68.94	69.15
SSD mass	B'	1282.07	1279.69	1280.88	1280.88
Mass in water	C'	723.02	723.59	724.13	723.58
Volume	E'	559.05	556.10	556.75	557.30
Vol. Abs. Water	J'	12.67	12.69	12.98	12.77
% Saturation		62.67	71.45	70.16	**68.09**
% Swell		0.41	0.51	0.46	**0.46**

Table 14: Results of Moisture Induced Damage Test for Conditioned Samples (Wet)

Compacted Sample		ACWC14			Mean
Sample No.		4	5	6	
Diameter	D	101.20	101.23	101.43	101.29

Thickness	T	68.51	68.78	68.47	68.59
Dry mass in air	A	1269.40	1267.00	1267.90	1268.10
SSD mass	B	1278.80	1276.80	1269.30	1274.97
Mass in water	C	722.05	723.52	715.10	720.22
Volume	E	556.75	553.28	554.20	554.74
Bulk Specific Gravity	F	2.28	2.29	2.27	2.28
TMD	G	2.366	2.366	2.366	2.366
% Air Void	H	3.63	3.21	3.34	3.39
Volume of Air Voids	I	20.21	17.76	18.50	18.82
Soaked in water for 24 hours @ 60°C and then Soaked for 2 hours @ 25°C					
Thickness	T"	69.55	69.14	68.95	69.21
SSD mass	B"	1282.67	1280.29	1281.48	1281.48
Mass in water	C"	723.52	724.09	724.63	724.08
Volume	E"	559.15	556.20	556.85	557.40
Vol. Absorbed Water	J"	13.27	13.29	13.58	13.38
% Saturation		**65.66**	**74.83**	**73.41**	**71.30 > 55%**
% Swell		**0.43**	**0.53**	**0.48**	**0.48**
Load	P'	15068.00	13719.00	15087.00	14625.00
Wet Strength, **MPa**	S2	1.38	1.26	1.38	**1.34 > 1**
TSR = S2 / S1	*%*	0.93	0.88	0.92	**0.91 > 0.85**

Table 15: Summary of Moisture Induced Damage (Tensile Strength) Test Results of the four Mixtures

Property / **Mix Type**		**ACWC14 Control**	**ACWC14 with Fiber**	**ACBC28 Control**	**ACBC28 with Fiber**
Dry Load, N	P	13454.00	15890.00	14670.00	15975.00
Dry Strength, MPa > **1**	S1	1.25	1.47	1.29	1.45
Wet Load, N	P'	11589.00	14625.00	12417.00	14650.00
Wet Strength, MPa > **1**	S2	1.064	1.34	1.085	1.34
Tensile Strength Ratio *TSR = S2 / S1* **> 80%**	%	85.19	91.16	90.88	92.11
Percent Saturation> **55%**	%	72.28	71.30	69.84	68.92
*Percent Swell < **1%**	%	0.72	0.48	0.49	0.39

*If the swelling of the specimen is greater than 1% , this means the specimen is internally damaded

The TSR values of between 70 - 80 percent, percent saturation of greater than 55%, and percent swell of less than 1% of AC mixtures were set as the minimum requirement by AASHTO T 283/ ASTM D 4867 standard.

From Table 15 it was observed that, the ACWC14 and ACBC28 mixtures with and without reinforced fiber produced percent saturation values greater than 55. It appears that the mechanical bonding between reinforced fiber and asphalt binder plays an important role in increasing the tensile strength of HMA mixtures. As seen in Table 15 , using reinforced fiber for both ACWC14 and ACBC28 mixtures improved the indirect tensile strength values both prior to and after the conditioning. The average Strength for wet ACWC14 and ACBC28 asphalt mixtures were 1.34 MPa and it is within the specified limit (> 1 MPa). If strength values of the four mixtures before and after conditioning are compared, it can be seen that for ACWC14 (control) mixtures prepared without reinforced fiber had a tensile strength droped by 14.84% compared to 8.84% drop for ACWB14 mixtures prepared with reinforced fiber, while ACBC28 (control) mixtures prepared without reinforced fiber had a tensile strength droped by 15.81% compared to 7.58% drop for ACBC28 mixtures prepared with reinforced fiber. Furthemore, the study showed considerably high TSR values for the four mixtures tested which meant less moisture sensitivity as depicted in Figure 20. This indicates that ACWC14 and ACWBC28 with fiber reinforced do not cause a decrease in the strength of the HMA due to the intrusion of water into the mix and therefore complies with moisture susceptibility requirements. The increase in the tensile strength implies that there is good adhesion between asphalt binder and fiber. With this good adhesion, asphalt binder is able to hold fiber together during loading. As a result, the tensile strength of the system increases. In general, the addition of reinforced fiber had a greater influence on ITS values and improved the resistance against moisture-damage of hot mix asphalts.

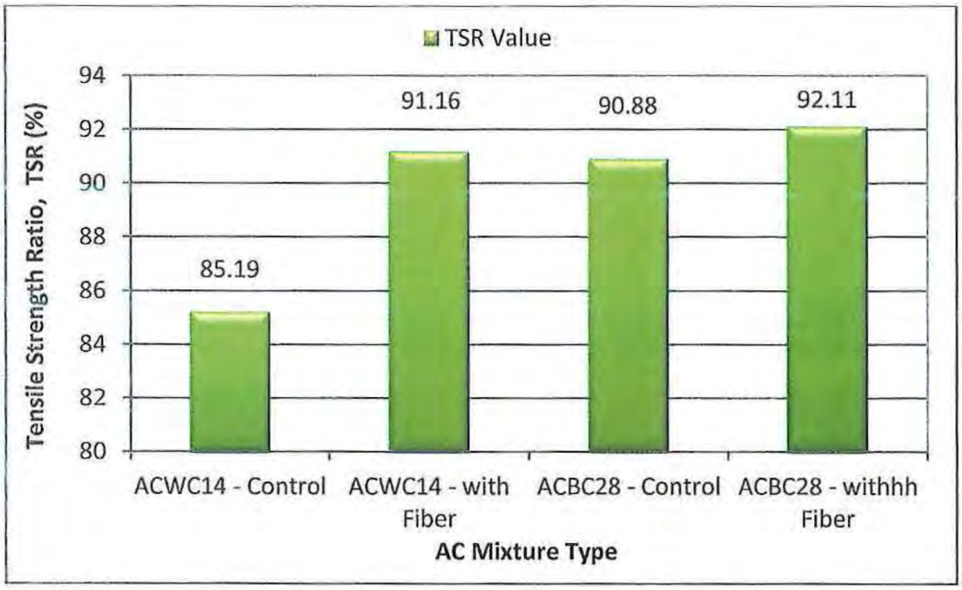

Figure 20: Comparison Graph of Tensile Strength Ratio of the Four AC Mixtures

5.4 Fatigue Cracking

In order to determine the strength of hot mix asphalts against fatigue cracks induced by repeated loads, three specimens were subjected to IDTF tests for each mixture. These tests were continued for 1 hour (3600 cycles). The recoverable horizontal and vertical deformation values at 3600 cycles in microstrain (μm) of the four AC mixtures are shown Figure 21 through Figure 25. As seen in these figures, the fiber extended fatigue life of the AC mixture.

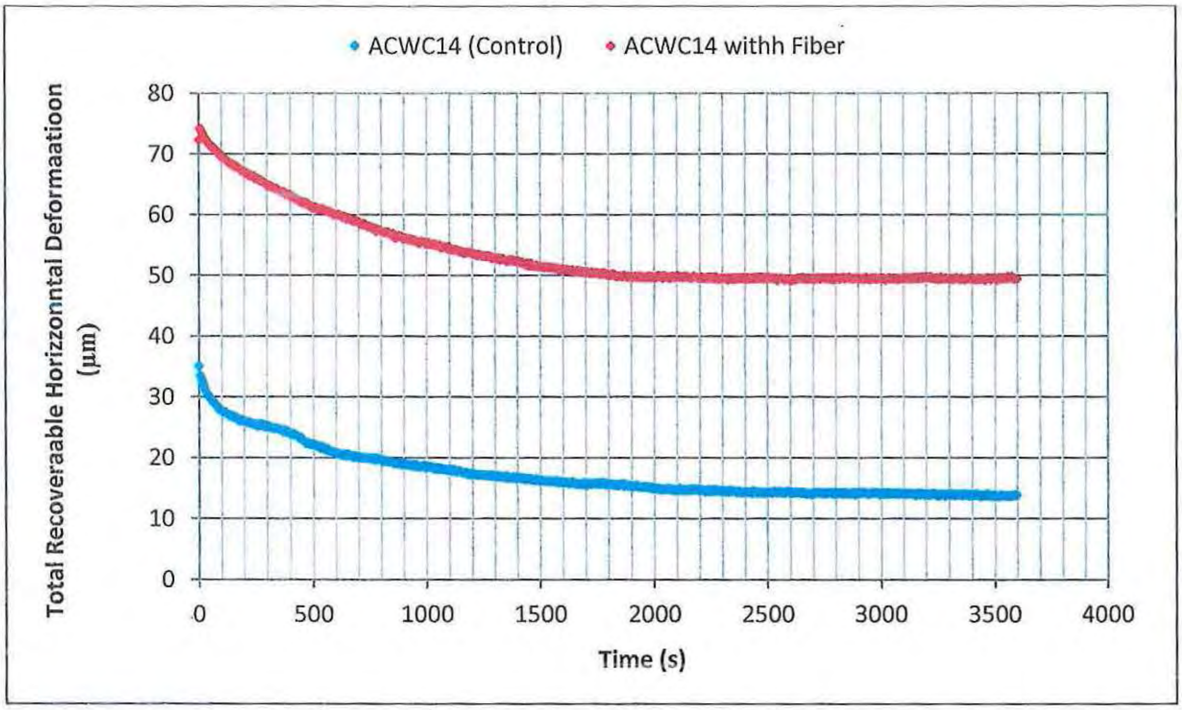

Figure 21: Total Recoverable Horizontal Deformation of ACWC14 from IDFT Test Data

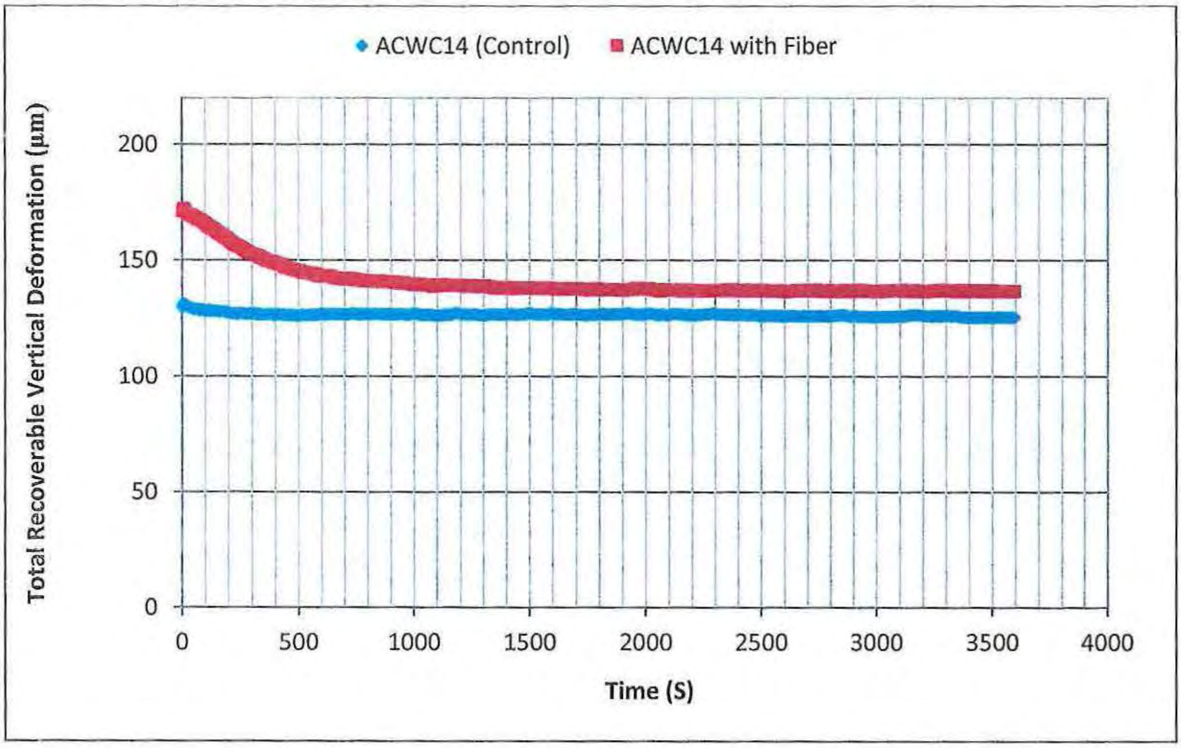

Figure 22: Total Recoverable Vertical Deformation of ACWC14 from IDFT Test Data

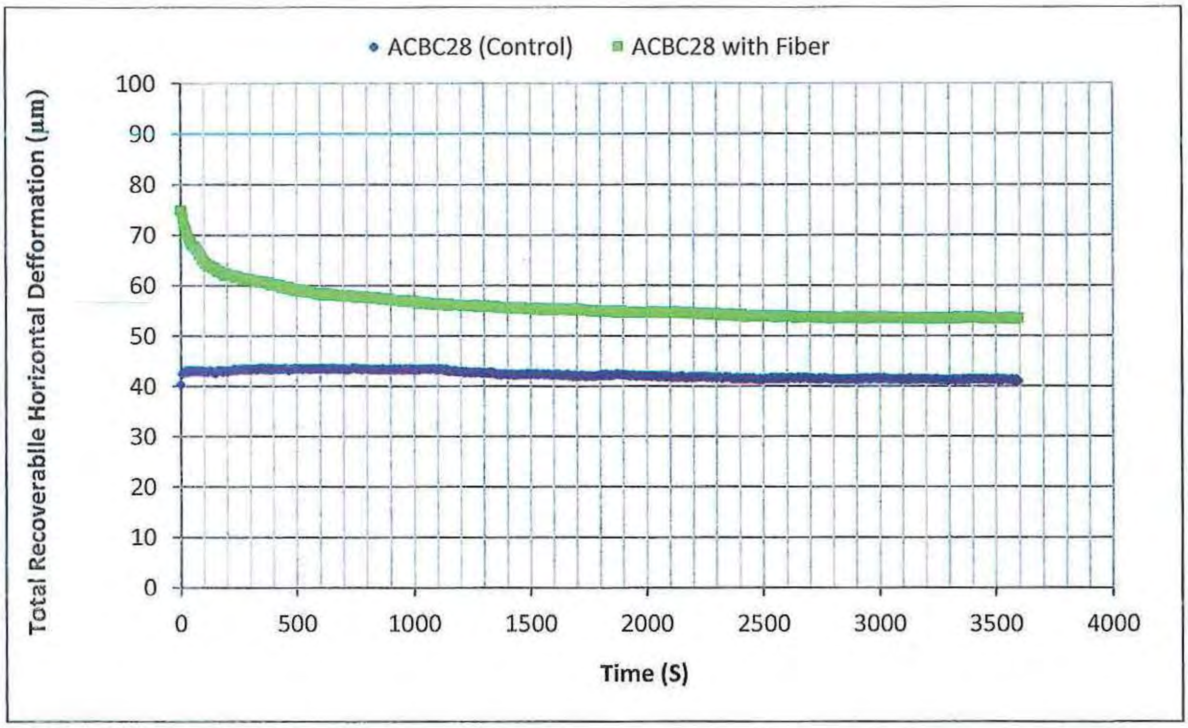

Figure 23: Total Recoverable Horizontal Deformation of ACWC28 from IDFT Test Data

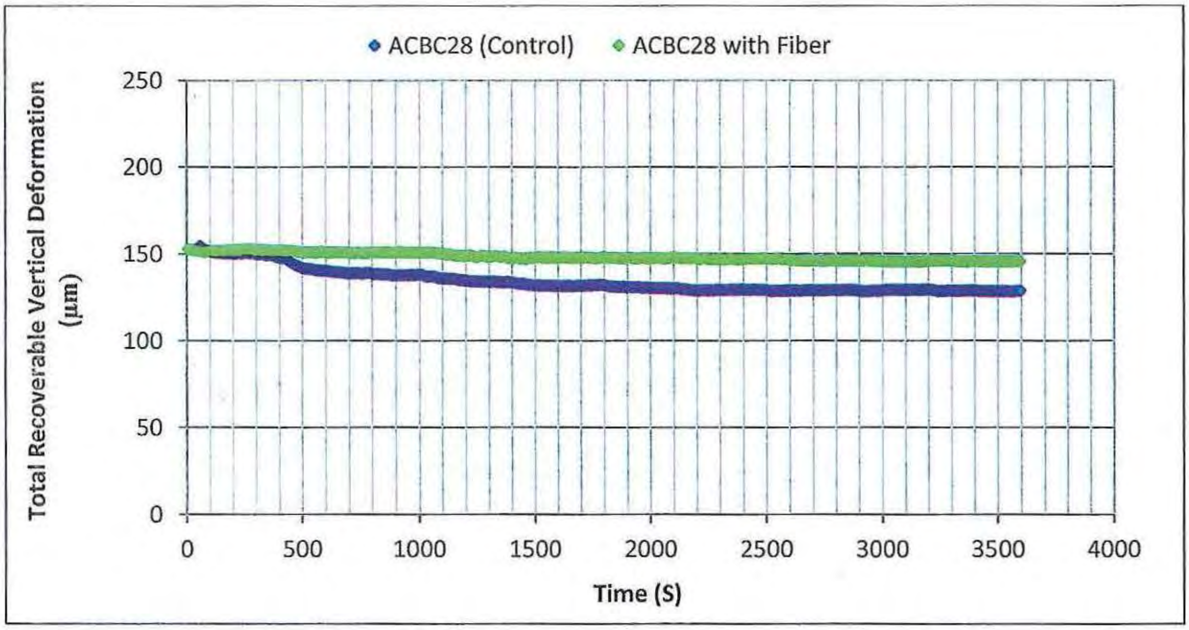

Figure 24: Total Recoverable Vertical Deformation of ACWC28 from IDFT Test Data

In order to evaluate the impact of fiber more clearly, the applied load throughout the 3600 cycles causing way less than 1 mm of horizontal and vertical deformation as shown in Figure 25 and 26 compared to the control mixture.

If permanent horizontal deformation values of the four mixtures are compared, it can be seen that for ACWC14 mixtures prepared with reinforced fiber had a total horizontal permanent deformation value droped by 55.36% compared to the control ACWB14 mixtures prepared without reinforced fiber, while ACBC28 mixtures prepared with reinforced fiber had a permanent deformation value droped by 65.76% compared to the control ACBC28 mixtures prepared without reinforced fiber as depicted in Figure 25.

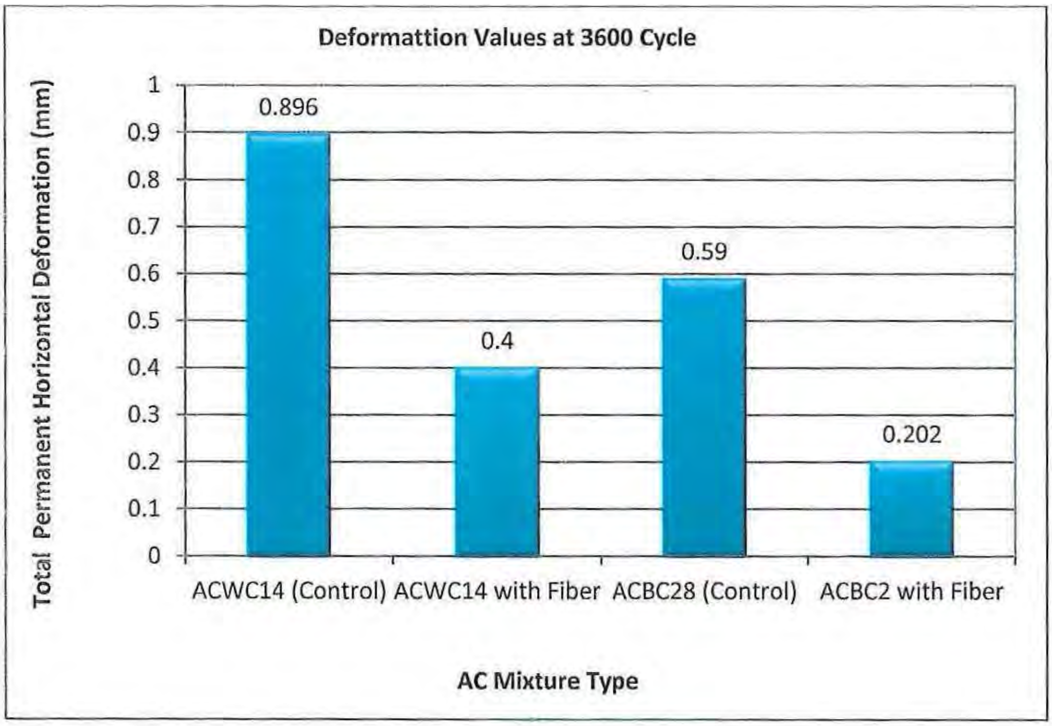

Figure 25: Total Permmanent Horizontal Deformation of AC Mixtures at 3600 Load Cycles

It can be seen in Figure 26 that, the ACWC14 mixtures prepared with reinforced fiber had a total vertical permanent deformation value droped by 41.96% compared to the control ACWB14 mixtures prepared without reinforced fiber, while ACBC28 mixtures prepared with reinforced fiber had a total vertical permanent deformation value droped by 47.93% compared to the control ACBC28 mixtures prepared without reinforced fiber.

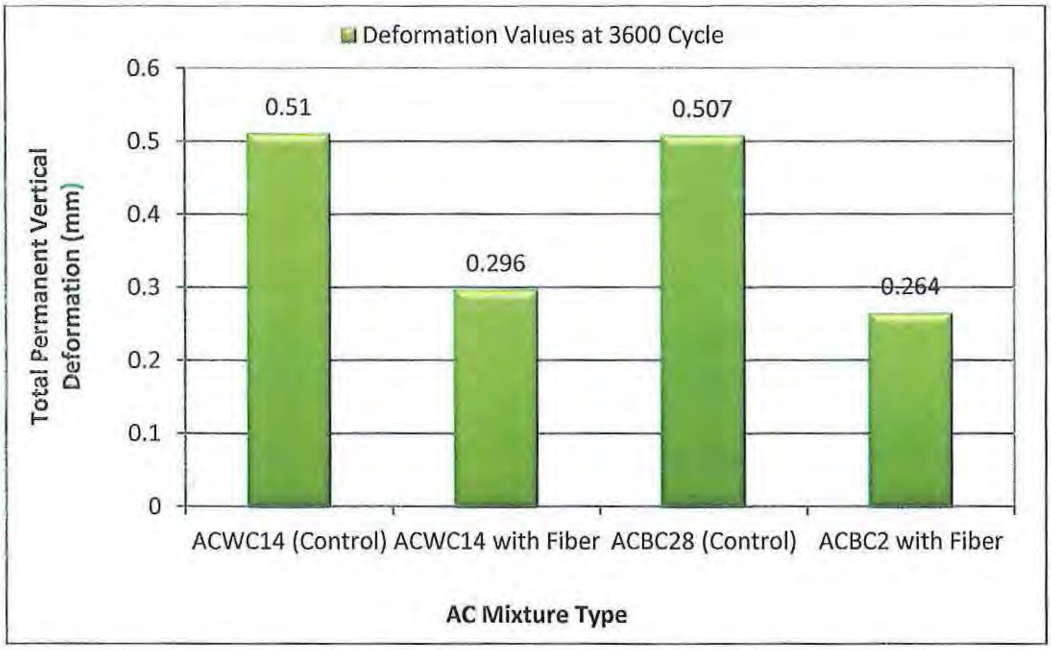

Figure 26: Total Vertical Permanent Deformation Values of Mixtures at 3600 Load Cycles

Furthemore, the study showed considerably high total recoverable horizontal and vertical deformation values at the end of 3600 loading cycles of ACWC14 and ACWBC28 with fiber reinforced which meant less potential for fatigue cracking compared to ACWC14 and ACWBC28 mixtures withoout fiber reinforced as presented in Table 14. In general, the addition of reinforced fiber had a greater influence on deformation values and improved the resistance against fatigue cracking of hot mix asphalts.Moreover, assessing these results as a whole, AC mixture with fiber was found to be more influential on the fatigue life compared to AC mixture without fiber.

Table 14: Summary Comparison of Fatigue Cracking Performance Properties for the Four AC Mixtures at OAC

Property	**Mix Type**			
	Control	**ACWC14**	**Control**	**ACWC28**
Total recoverable horiz. deform. value at 3600 cycles (μm)	13.80	49.4	41.00	53.54
Total recoverable vertical deform.value at 3600 cycles (μm)	125.3	136.6	128.9	145.5
Total permanent horiz. deform. value at 3600 cycles (mm)	0.896	0.40	0.59	0.202

Total permanent vertical deform. value at 3600 cycles (mm)	0.51	0.296	0.507	0.264

6. CONCLUSIONS AND RECOMMENDATIONS

This report is based on the design and evaluation of FORTA FI fiber-reinforced asphalt mixtures. Two mixtures (ACWC14 and ACWC28) of polypropylene and aramid fibers was used in a laboratory study to evaluate the performance characteristics of the modified asphalt mixtures. The laboratory experimental program on the mixes included: Volumetric properties, Stability, Stiffness Modulus, Tensile Strength, Permanent Deformation, Diametral Indirect Tensile Fatigue tests. The data was used to compare the performance of the fiber modified mixture to the control. The results showed that the fibers improved the mixture'sperformance in several unique ways as summerized below:

- The optimum asphalt content of the mixture increased for ACWC14 and ACBC28 mixtures after adding fibers due to absorption of asphalt by the fiber.
- Air Void (VTM) increased but still within the specification limits of 3 to 5%, Voids in Mineral Aggregate (VMA) increased, and the mixtures with fibers pose higher voids filled with asphalt (VFA) due to these fibers' higher effects of asphalt adhesion, while bulk specific gravity slightly decreased after adding fibers into asphalt mixture for both mixtures.
- The fiber mixture using the optimum asphalt content shows to have higher performances than the mixture using the optimum asphalt content of ordinary (control) mixture in terms of the volumetric properties.
- The mixtures with fibers pose higher Marshall Stability, higher stiffness modulus, higher TSR, higher Rutting resistance, and higher recoverable deformation due to these fibers' higher networking effect. Fibers can reinforce asphalt binder through their functions of spatial networking, absorption and adhesion of asphalt.

- Permanent deformation tests for the fiber-reinforced mixture showed lower permanent strain accumulation compared to the control mix. Two characteristics were observed for the fiber-reinforced mixture in these tests: an extended endurance period in the secondary stage of the permanent deformation curve, and the gradual (less) accumulation of permanent strain beyond tertiary flow. Both of these characteristics were attributed to the presence and mobilization of the fibers distributed in the mix.
- The measured Resilient (Stiffness) Modulus values were higher for the fiber-reinforced mix. The difference between the two mixtures (ACWC14 and ACWC28) was less, due to dominant effect of the binder and less contribution of the role of fibers.
- The fatigue cracking test was different in that, unlike the other tests, the stress level was held constant at 1500 N. The horizontal and vertical deformation values was lower for the ACWC14 and ACBC28 mixtures compared to control mixtures at the end of 3600 cycles.
- The dry tensile strength measured from the Indirect Tensile Strength test showed that at test temperature (25°C), the fiber-reinforced mix exhibited the highest values; an increase of 17.6% for ACWC14 and an increase of 12.41% for ACBC28 compared to the control mix for the tensile strength respectively, and the Tensile Strength Ratio (TSR) of ACWC14 was 7% higher compared with the ACWC14 control mixture, while the Tensile Strength Ratio (TSR) of ACBC28 was 1.5% higher compared with the ACBC28 control mixture . Generally, lower thermal cracking should be expected as the Tensile Strength and TSR are increased.

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