Hybrid Reinforcement of Asphalt-Concrete Mixtures Using Glass and Polypropylene Fibers

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ABSTRACT

There is a constant effort to improve the performance of asphalt-concrete (AC) mixtures. Among various modifiers for asphalt, fibers have received much attention for their improving effects. This paper introduces the novel concept of hybrid reinforcement of AC mixtures using polypropylene (PP) and glass fibers. Individually, glass fiber reinforced AC and PP fiber modified AC mixtures have exhibited superior performance compared to other fiber reinforced samples.

Therefore, in this work, these two types of fibers were used simultaneously to improve the performance of the AC mixtures. This type of hybrid AC composite can be engineered by taking advantage of the tacky property of PP fiber around its melting point and the high modulus of glass fiber. In this way, PP fibers with the length of 12 mm were blended with bitumen at different percentages. Glass fibers with the length of 12 mm were also added to aggregates. Marshall and Specific Gravity tests were performed on hybrid reinforced asphalt-concrete (HRAC) samples by taking advantage of a Superpave Gyratory Compactor. In the case of the bituminous specimens, penetration, softening point and ductility tests were carried out. The results revealed that PP fibers decrease penetration and ductility of modified bitumen, while the softening point value is increased compared to unmodified bitumen specimen. Marshall Test results illustrate that PP can statistically affect the properties and improve the consistency of the mixture. Using a combination of 0.1% of glass fiber plus 6% of PP presented the best hybrid reinforcement through increasing stability and decreasing flow. Therefore, it is concluded that this novel HRAC is suitable for use in hot regions due to growth in the void total mix (VTM) and stability.

Keywords: Polypropylene (PP) fiber, Glass fiber, Asphalt-Concrete, Marshall Stability, Hybrid Reinforcement.

INTRODUCTION

Asphalt concrete (AC), a mixture of bitumen and aggregates, is a sensitive material compared to other civil configurations [1,2]. Therefore, scientists and engineers are constantly trying to improve the performance of asphalt mixtures and pavements [3]. Modification of the asphalt binder is one approach taken to improve pavement performance [4]. Generally, fibers and polymers are two important materials used for this purpose, [5,6] but the most popular bitumen modification technique is polymer modification [7,8]. However, it has been claimed that among various modifiers for asphalt, fibers have received much attention for their improving effects [9].

In pavement engineering, fiber reinforcement is mainly like a coin with two sides. One side includes direct random inclusion of fibers into the asphalt concrete mixture and/or Portland cement concrete slabs. The outcome of this kind of reinforcement is known as fiber-reinforced asphalt-concrete (FRAC) mixture. The other side comprises oriented fibrous materials, such as the geo-synthetics family [10].

A comprehensive literature review shows that polypropylene [11,13], polyester [14,15] and cellulous [16,18] are the most prevalent fibers used in

FRAC mixtures. Polypropylene (PP) fibers, however, are preferred due to their low-cost and good consistency with asphalt pavement [19]. For instance, PP fibers reduce crack intensities and reflective cracking on the fiber modified overlay sections [20]. PP fiber modified mixtures are also slightly stiffer and show improved fatigue life [21]. Use of PP fibers in AC specimens increases the Marshall Stability values while flow values decrease significantly [22]. Moreover, a PP reinforced asphalt mixture exhibited good resistance to rutting [21]. Abtahi et al. [13] showed that the performance of PP fibers (12 mm long and 0.125% by the total weight of mixture) was more statistically desirable than styrene-butadiene-styrene (SBS) polymer in AC mixtures. The tests included Marshall Stability and Resilient Modulus [13].

There is little published information about glass fiber reinforced AC [23]. Due to their excellent mechanical properties, glass fibers offer an excellent potential for asphalt modification. Glass fibers have a high tensile modulus, i.e., about 60 GPa [24], an elongation of 3-4% [25], and elastic recovery of 100% [25]. These fibers will not burn, but become soft at 815°C and exhibit decreased stability at temperatures above 315°C [26]. In addition, glass fibers do not absorb water, but are brittle and sensitive to surface damage [22]. Adding glass fibers into asphalt mixtures enhances material strength and fatigue characteristics as well as improving ductility [27]. Glass fiber reinforced asphalt concrete can improve the stability and the deformability of the asphalt concrete without increasing the bitumen content of AC mixtures; this behavior will be useful in preventing rutting and bleeding at high temperatures during the hot season [28]. Moreover, with the new developments in production, glass fiber reinforced bituminous mixtures can be cost competitive as compared to modified binders [10].

Most studies focused on fiber-reinforced pavements have separately investigated the effect of one type of fiber on the performance of AC mixture. This paper introduces a novel idea of hybrid reinforcement of AC mixtures by using polypropylene and glass fibers. In a previous comparative study [29], different types of fibers including polypropylene, polyester, nylon and glass were used to reinforce asphalt concrete mixture. The results illustrated that glass fiber reinforced AC and PP fiber reinforced AC treatments had superior performance compared to other fiber reinforced samples. In this study, these two types of fibers were used simultaneously to improve the performance of the AC mixtures. Thus, this type of hybrid AC composite can be engineered by taking advantage of tacky property of polypropylene around its melting point and high modulus of glass fiber. Therefore, it is expected that PP fibers will reinforce AC due to their consistency with the mastic binder, while glass fibers modify AC due to their high modulus of elasticity.

MATERIALS AND METHODS

General Description

The bitumen used in this research was provided from the Highway Department of North Cyprus. The properties of the bitumen are shown in *Table I*. All the aggregate particles, coarse and fine; used in this research were crushed limestone aggregate obtained from the Cyprus Highway Department quarries in the Besparmak Mountains. The overall average values for specific gravity and water absorption of aggregates are given in *Table II*. The gradation was selected from Turkish Highway Standard of binder course which is seen in the *Table III*. Two types of fibers including polypropylene and glass were used in this study. *Tables IV and V* show some physical and mechanical properties of PP and glass fibers, respectively. All the experimental results in *Tables I to V* were derived by the authors.

TABLE I. Physical Properties of Asphalt Binder.

Property	Test Value	Standard
Penetration at 25 °C, 1/10 mm	83	ASTM D 36 – 06
Ductility at 25 °C (cm)	> 100	ASTM D 113 – 07
Softening Point	48.5	ASTM D 36 – 06
Flash point	278	ASTM D 92 – 05
Specific Gravity at 25 °C (gr/cm3)	1.003	ASTM D 70 – 09

TABLE II. Overall Average Values for Specific Gravity and Water Absorption of Aggregates.

Average bulk specific gravity (Dry)	2.758
Average bulk specific gravity (SSD)	2.794
Average Apparent specific gravity	2.853
Average Absorption, %	1.153

TABLE III. Gradation of the Aggregate.

	Range of Standard	Used
Sieve Size	Passing (%)	Passing (%)
25 mm (1 inch)	100	100
19 mm (3/4 inch)	82-100	91
12.5 mm (1/2 inch)	68-87	78
9.5 mm (3/8 inch)	60-79	70
4.75 mm (No.4)	46-65	56
2.36 mm (No.8)	34-51	43
0.425 mm (No.40)	17-29	23
0.180 mm (No.80)	9-18	14
0.075 mm (No.200)	2-7	5
Pan	0	0

TABLE IV. Physical Properties of PP Fibers Used in This Work.

Property	Standard	Value
Specific Gravity (gr/cm^3)	ASTM D-792	0.91
Diameter (µm)	-	22
Cross Section	-	Round
Length (mm)	-	12
Melting Point (^{0}C)	-	163
Tensile Strength	ASTM D-638	52.02
Failure Strain (%)	ASTM D-638	118.50
Tensile Modulus (MPa)	ASTM D-638	7.10

TABLE V. Physical Properties of the Glass Fiber Used in This Work.

Property	Standard	Value
Specific Gravity	ASTM D-792	2.59
Diameter (mm)	-	0.010
Cross Section	-	Almost Round
Length (mm)	-	12
Tensile Strength (CN/tex)	ASTM D-638	50.98
Failure Strain (%)	ASTM D-638	2.88
Tensile Modulus (N/tex)	ASTM D-638	21.2

Sample Preparation

In this study, PP and glass fibers, both with the length of 12 mm, were used to reinforce AC mixture. PP fibers were added to the mixture during a wet-mixing process while glass fibers were blended into the mixture during the dry-mixing method. In the dry process, the additive was mainly mixed with aggregates whereas in the wet method, the modifier was blended with the bitumen. Apart from the type of hot mix asphalt, the aggregates were preheated to 170 °C while, the blending temperature of bitumen and aggregates were generally set on 150 °C. At this temperature, PP fibers become tacky, and consequently, their consistency with bitumen satisfies the homogeneity of the composite mixture. That is why the wet procedure was selected for PP inclusion in the AC composite. On the other hand, the dry method is more applicable in the field as well as in the lab. Therefore, the dry procedure was chosen to modify AC samples by glass fibers.

Three different percentages of PP fiber-content (i.e. 2%, 4% and 6% by weight of the bitumen) were used in this study. These fiber contents were selected according to the previous laboratory experiments [30]. PP fibers were introduced to bitumen at the temperature of 151- 158 °C and mixed manually for 4-5 min (wet basis approach). Afterward, modified bitumen was added to the preheated aggregates which had been blended with glass fibers . Glass fibers were blended with the aggregates at a temperature of 170 °C for less than 1 min (dry base). The mixing temperature of glass-aggregate and PP modified bitumen was chosen at about 150 °C. The glass fiber content was selected as 0.05%, 0.1% and 0.2% by the weight of aggregates. *Figure 1* illustrates the schematic of the experimental design used in this study. The loose mixture, PP fiber modified bitumen, was blended with the glass fiber-aggregate by using an asphalt-concrete mixer (ELE 23-6191, Series 5, Capacity: 5 Lit.) with a beater rotational velocity of 285 rpm. Consequently, the composite AC mixture was left in an oven at compaction

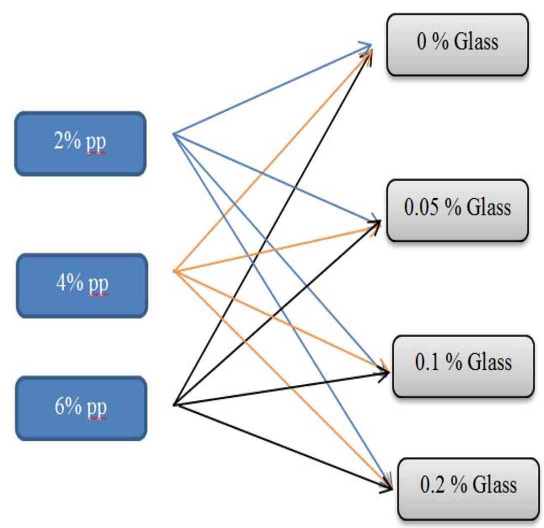

FIGURE 1. Schematic of the experimental design used in this study.

The loose mixture was then placed in a preheated mold (102 mm diameter with 64 mm height) quickly. Since the Marshall Stability test was applied for measuring the stability of the specimens, approximately 1200 grams of asphalt mixture were placed in the preheated mold. Following the preparation of the samples by the use of Gyratory Compactor method, the cool ready specimens were placed in a water bath at 60 ± 1 °C for 30 min before going for Marshall Stability testing. In addition, Air Void in Total Mix (VTM) and Unit Weight Tests were performed in accordance with ASTM D-1559.

RESULTS AND DISCUSSIONS

PP Modified Bitumen

All the modified and unmodified bitumen samples underwent different bitumen tests with the same conditions. To determine the effect of PP fibers on physical properties of the bitumen, penetration, softening, and ductility tests were carried out on both modified and unmodified bitumen in accordance with ASTM D 5, ASTM D 36 and ASTM D 113, respectively. Mainly, ductility is the property of bitumen that permits it to undergo great deformation or elongation. Ductility is defined as the distance in cm, to which a standard sample or briquette of the material will be elongated without breaking. Penetration testing measures the hardness or softness of bitumen by measuring the depth in tenths of a millimeter to which a standard loaded needle will penetrate vertically in 5 seconds. Softening point denotes the temperature at which the bitumen attains a particular degree of softening under specified condition. *Figures 2 and 3* illustrate the results of penetration and softening point tests while *Table IV* shows the ductility test results for modified and unmodified bitumen.

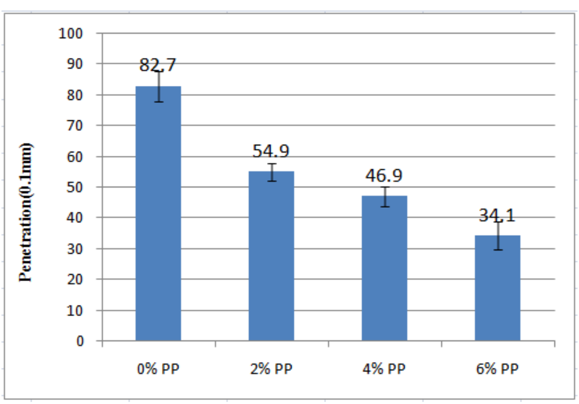

FIGURE 2. Penetration Test Result for Normal Bitumen and Polypropylene Modified Bitumen.

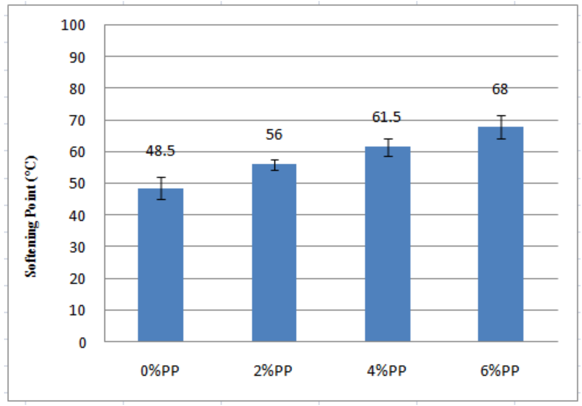

FIGURE 3. Softening Test Result for Normal Asphalt and Polypropylene Modified Bitumen

TABLE VI. Ductility Test Results for Neat and PP Modified Bitumen.

Treatment	0% PP	2% PP	4% PP	6% PP
Ductility	100 cm	46 cm	36 cm	33 cm
St. Dev.	3.70	3.44	3.58	4.10

As shown in *Figure 2*, penetration decreased as the percentage of PP fibers increased. The results indicate that PP modified bitumen samples are much stiffer than the neat bitumen and therefore the rutting resistance of the modified mixture is expected to be high. *Figure 3* illustrates that softening point increased with the addition of PP fibers. This means that PP modified bitumen is less susceptible to traffic-induced deformation at high temperature compared to unmodified bitumen. *Table VI* shows that ductility considerably decreased with an increase in the percentage of PP fibers in the mixture. Apparently, PP fibers are placed in the cross-section of bituminous specimen during the process of stretching. This phenomenon prevents bitumen from being stretched easily and causes the sample not to be able to show a good performance in ductility test.

It seems that the presence of PP fibers in the bitumen will result in an increase in the modulus of elasticity of bitumen. Consequently, this process changes the resistance of modified bitumen against any external load.

Hybrid-Reinforced Asphalt-Concrete Results

The Marshall Stability test was carried out on all the modified and unmodified samples. The results are shown in *Figures 4-9*.

As illustrated in *Figure 4*, increasing the percentage of PP fibers enhances the stability of HRAC samples in all glass fiber contents. This trend is reversed for flow (*Figure 5*). The presence of PP in the hybrid composite causes the glass-aggregate mixture to glue better to each other in the mix. Consequently, a more homogenous composite can be obtained. For this reason, by increasing PP fiber dosage, from 2% to 6%, at each glass fiber content level, the compressive strength of HRAC samples has been improved. Another outcome that is derived from *Figure 4* is that by increasing the glass fiber content up to 0.2%, the compressive strength of HRAC is improved at each PP fiber dosage level whereas in 0.2% glass fiber content, the Marshall Stability of HRAC samples is decreased compared to other glass fiber levels at each PP fiber content.

To explain the results, using fundamental equations of composite materials would be useful. According to the "law of mixtures," [33] the modulus of the hybrid reinforced material, E_c, can be expressed as:

$$E_c = E_{fp} \cdot v_{fp} + E_{fg} \cdot v_{fg} + E_m \cdot v_m \quad (1)$$

where E and v are the modulus of elasticity and volumetric fraction, respectively, and the indices of "f" and "m" represents the fiber and matrix, separately. In this study, two reinforcing elements, PP and glass fibers, were used to produce HRAC samples; therefore, indices "p" and "g" were applied for the two fibers in Eq. (1), respectively. Eq. (1) states that the modulus of elasticity of the hybrid composite increases as the content of both fibers increases. The outcome of this equation matches with the experimental results of up to 0.2% glass fiber. However, at the percentage of 0.2% glass fiber and more, the treatments do not obey the law of mixtures. Herein, it seems that the "shear lag theory" proposed by Cox explains the experimental results [31]. According to the short fiber composites theory generalized by Shao et al. for low twist yarns [32], it is assumed that a fiber is in a matrix under a compressive load P, as in Marshall Test. This load can make an interfacial shear stress τ, between fiber and matrix and consequently causes a tensile stress σ in the fiber. Now it is supposed that during extension, there is slippage near both ends of fiber and a central region along the fiber length gripped by the matrix which is called non slippage region. If λ is defined as the fiber slippage ratio, which is the ratio of fiber length of the slipping portion to the whole fiber length L_f, slippage will occur over a length from each end of the fiber [29,32]:

$$\lambda L_f / 2 \quad (2)$$

where λ is the value of fiber cooperation and assistance in the bearing of tensile stresses entered into the matrix. *Figure 10* shows the τ-x and σ-x diagrams related to the fiber considering slippage phenomena.

The fiber tensile stress σ_{1f} at the slippage region and σ_{2f} in non-slippage region at the central portion are determined by:

$$\sigma_{1f} = 4\tau x / d_f \quad (3)$$

$$\sigma_{2f} = E_f \times \varepsilon_f \quad (4)$$

where x is a position of point located on the fiber and d_f, E_f and ε_f are diameter, Young's Modulus and strain of the fiber, respectively. It is clear that at $x = \lambda L_f/2$, the tensile stresses σ_{1f} and σ_{2f} are equal, and so the combination of Eq. (1), (2) and (3) gives:

$$\lambda = (d_f \cdot E_f \cdot \varepsilon_f) / (2 \cdot \tau \cdot L_f) \quad (5)$$

Assuming that the shear stress τ is too great to produce fiber breakage during the application of load P, the fiber strain is equivalent to the strain at breakage point and the parameter λ can be obtained as the FRAC fails. It is clear that the interfacial shear stress τ derived between fiber and matrix is obtained through [32]:

$$\tau = \mu \times G \quad (6)$$

where μ is the coefficient of friction between fiber and matrix, and G is the normal pressure. Therefore, Eq. (5) becomes:

$$\lambda = (d_f \cdot E_f \cdot \varepsilon_f) / (2 \cdot \mu \cdot G \cdot L_f) \quad (7)$$

Eq. (7) states that as the coefficient of friction μ between fiber and matrix decreases, the fiber slippage ratio λ will increase, meaning that the fiber-matrix corporation will be reduced. By increasing the percentage of glass fiber over 0.2% in HRAC treatments, the slippage phenomenon may overcome the reinforcing performance due to the low coefficient of friction μ of glass fibers.

It is important to know that the increase in Marshall Stability is due to the fiber reinforcement effect. Marshall Stability, fundamentally, is the compressive strength of the AC sample. According to the composites law of mixtures, the ultimate strength of the composite, σ_c, can be determined using [33]:

$$\sigma_c = v_f \times \sigma_f + v_m \times \sigma_m \quad (8)$$

where σ is the ultimate strength, v is the volume fraction, and the indexes c, f, and m indicate the composite, fiber, and matrix, respectively. Eq. (8) implies that increasing the fiber volume fraction results in greater composite strength and greater Marshall Stability. A relationship similar to Eq. (8) is used for the elastic modulus of composites. Therefore, the ultimate strength and elastic modulus of HRAC are both increased by higher fiber volume fractions, and this leads to decreases in the failure strain. That is why flow, i.e., failure strain, decreases with an increase in fiber volume fraction (*Figure 5*).

Figure 9 presents the results of air void in total mix (VTM) for all treatments. VTM is the percentage of total air voids in the mixture. This index is one of the principals to obtain the optimum bitumen content in the AC mixtures. It is clear that fibers have increased the air voids through the mix in all specimens. This growth probably occurred due to the increase in surface area for the aggregate and fibers. Since glass fibers behave as filler materials which need to be wetted by the asphalt binder, lower asphalt (effective asphalt) cannot fill the space between the mineral aggregate and produces the increase in VTM. This finding is also supported by the results of Muniandy and Huat [34]. They have shown that the viscosity of fiber-reinforced asphalt-concrete may be increased by the attendance of fibers. The increase in viscosity can reduce bitumen penetration in the mixture. As VTM value increased, the unit weight values in all reinforced treatments have been decreased (*Figures 7 and 9*). Void filled with asphalt cement has an inverse relationship with air voids in mixture (VTM). When the amount of air voids in mixture is increased, a lower space is filled by asphalt cement (*Figure 6*). Void in mineral aggregate (VMA) is another important parameter of the Marshall Test. VMA generally depends on aggregate shape and gradation. *Figure 8* reveals that for all specimens, as the amount of PP fibers increases the VMA will also be increased. In addition, it is believed that when the percentage of glass fibers in a HRAC sample increases, a low amount of PP fiber (e.g., 2% PP) is not sufficient to glue all the glass fibers, and this lack decreases the probability of all fibers contributing to the performance of the HRAC composite. These non-participating fibers may adversely affect in the matrix. Since a glass fiber has a smooth surface with low interfacial skin friction, it may reduce the contact point of the aggregate and cause the asphaltic matrix to become heterogeneous which can decrease the stability value.

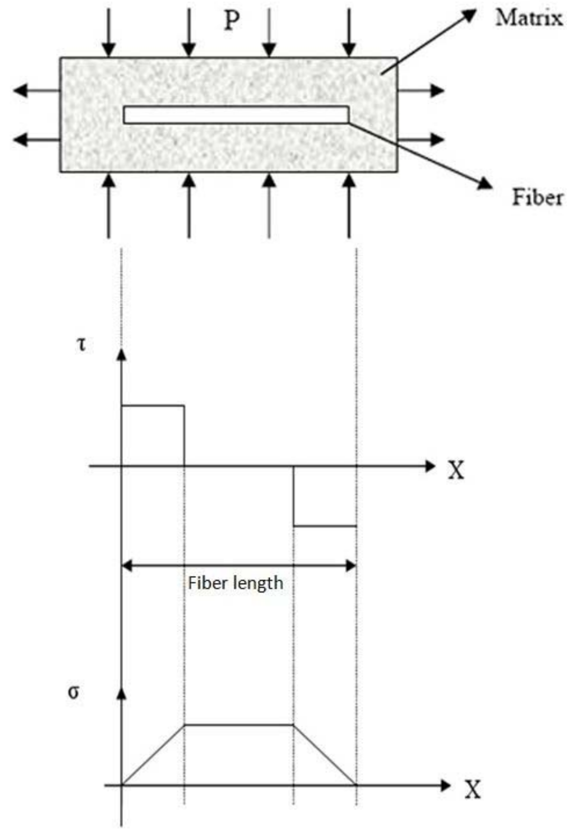

FIGURE 10. τ-x and σ-x diagrams related to the fibers regarding to slippage phenomenon [29].

Finally, it can be concluded that the HRAC treatment reinforced with "6% PP fiber of 12 mm in combination with 0.1% glass fiber of 12 mm" presents the most suitable mechanical properties. This combination improved the stability value by 25% compared to unmodified sample. In accordance with increasing VTM and also increasing the resistance of rutting and traffic-induced deformation at high temperature, it can be summarized that this hybrid asphalt-concrete is suitable for using in hot regions where flushing and bleeding mostly occur.

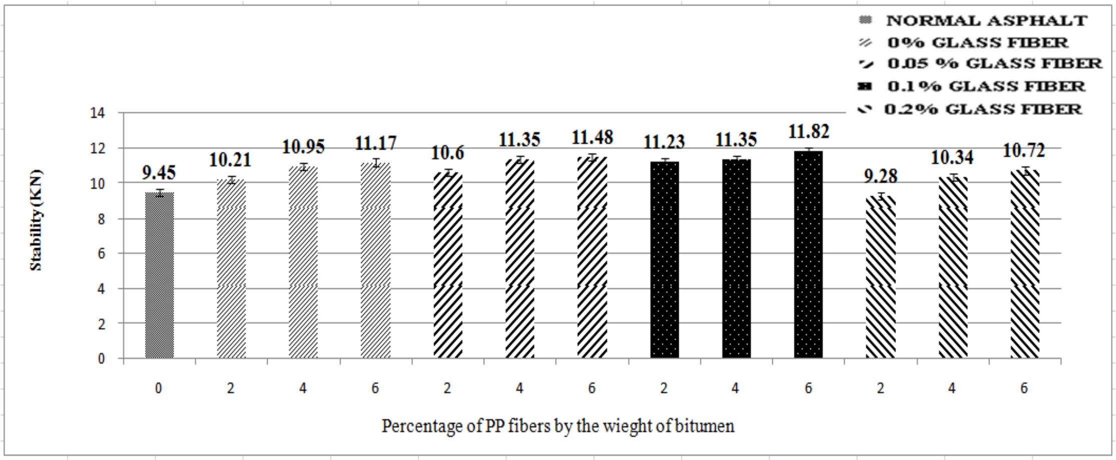

FIGURE 4. Stability for Different Percentages of Glass Fiber(0.05,0.1 And 0.2%) and Polypropylene (2,4 and 6%)

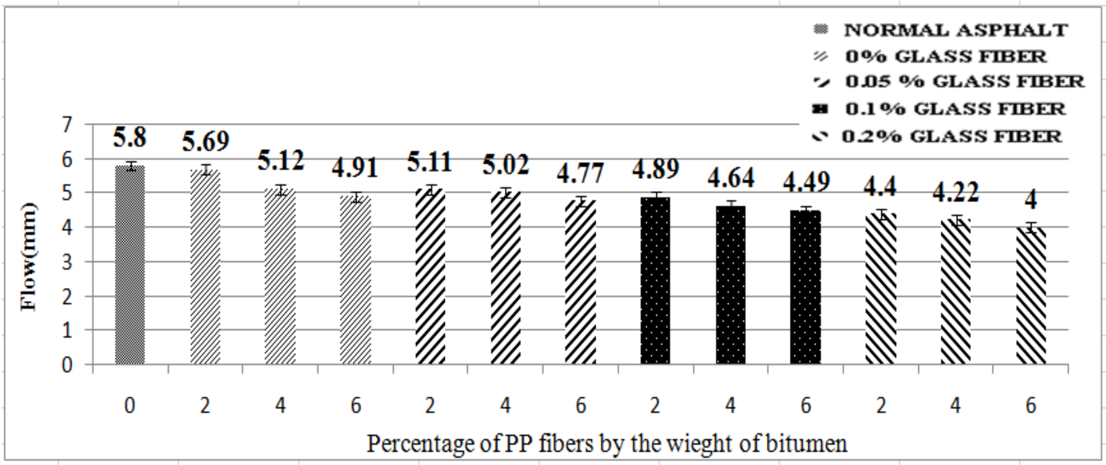

FIGURE 5. Flow for Different Percentages of Glass Fiber(0.05,0.1 And 0.2%) and Polypropylene (2,4 and 6%).

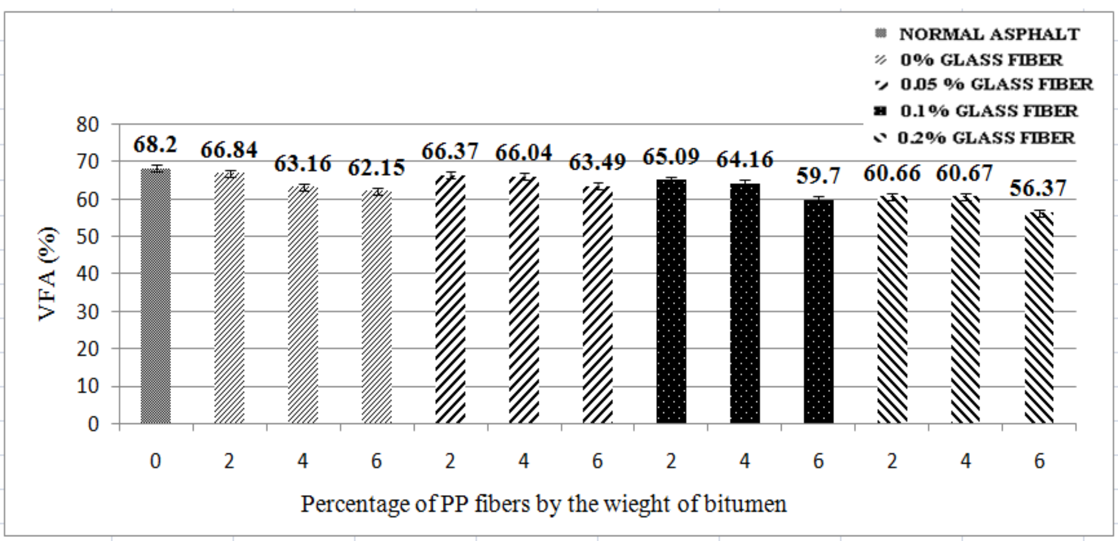

FIGURE 6. Void Filled Asphalt (VFA) for Different Percentages of Glass Fiber(0.05,0.1 And 0.2%) and Polypropylene (2,4 and 6%).

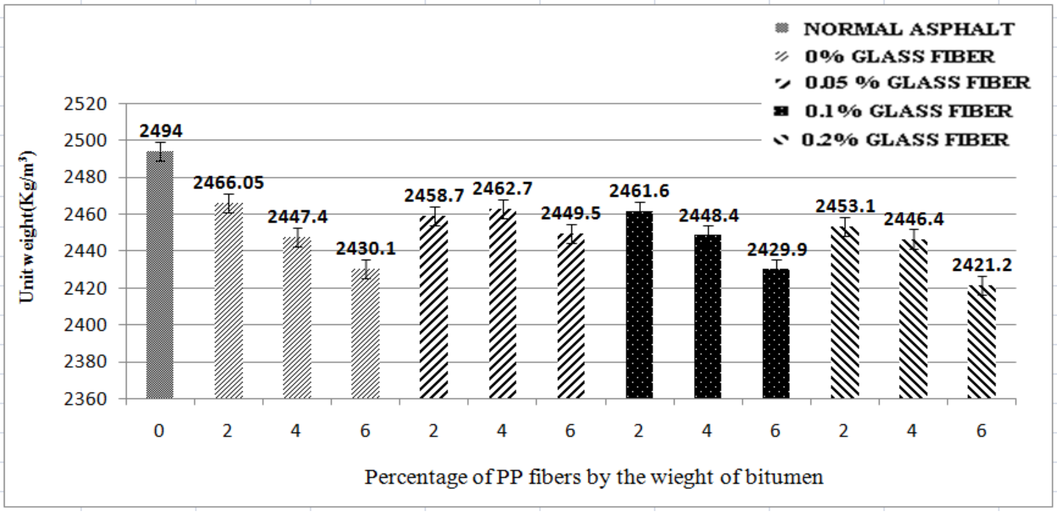

FIGURE 7. Unit weight for Different Percentages of Glass Fiber(0.05,0.1 And 0.2%) and Polypropylene (2,4 and 6%).

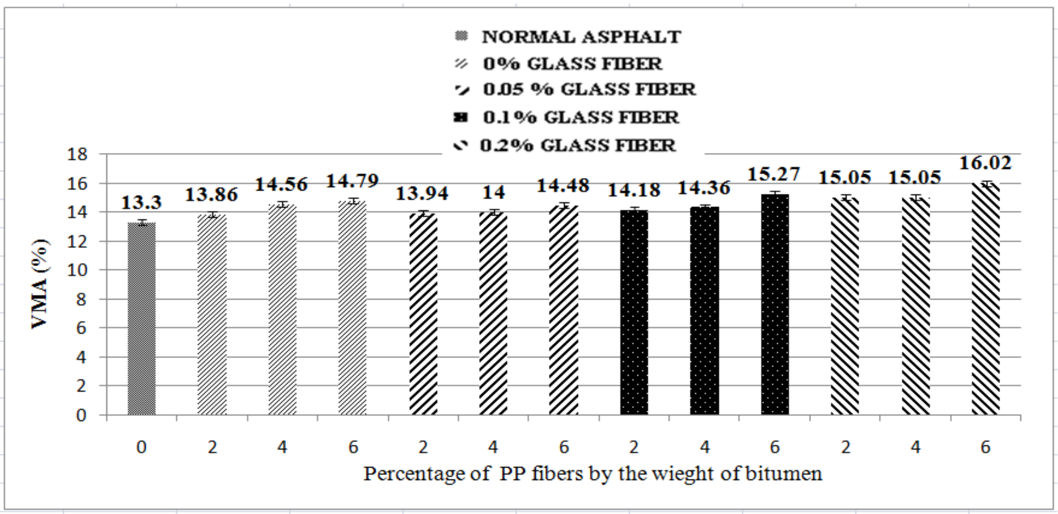

FIGURE 8. Void Mixture Asphlat (VMA) for Different Percentages of Glass Fiber(0.05,0.1 And 0.2%) and Polypropylene (2,4 and 6%).

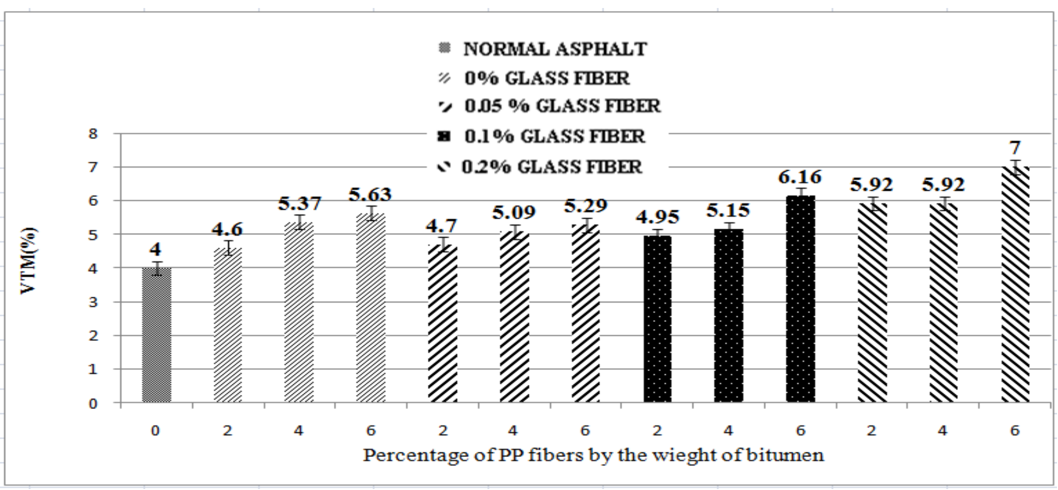

FIGURE 9. Void in Total Mixture (VTM) for Different Percentages of Glass Fiber(0.05,0.1 And 0.2%) and Polypropylene (2,4 and 6%).

CONCLUSION

This paper introduces a novel hybrid reinforcement asphalt concrete mixtures using polypropylene and glass fibers. The PP fibers were blended with bitumen through the wet method, whereas the glass fibers were added to the aggregates. Bitumen Test results indicate that the PP modified bitumen can improve the consistency and properties of asphalt concrete. PP modified asphalt samples exhibited decreased penetration, higher softening points compared to the unmodified asphalt, and reduced ductility. Increasing the amount of fiber in the modified AC samples led to increases in Marshall Stability and air void in total mix (VTM), while flow and unit weight tended to decrease. The PP fibers increase the stability up to 18% when compared to the unmodified asphalt concrete mixture. Furthermore, the use of 6% PP fibers combined with 0.1% glass fibers show the highest stability value and a more than 25% improvement compared to the unmodified mixture. It is believed that the addition of PP fibers in the glass reinforced AC matrix can not only improve the basic properties of asphalt concrete, but can act as glue to stick glass fibers to other particles of the AC mixture. These procedures would result in enhancing the stability.

Following the increase of VTM and raising the resistance of rutting and traffic-induced deformation, it can be concluded that this type of hybrid reinforced AC is suitable for use in hot regions.

Finally, the authors suggest chemical investigation of PP-modified bitumen via. FTIR tests. Subsequent research can be focused on developing equations to estimate and predict the exact participated percentage of fibers in the matrix. Meanwhile, other pavement specifications including resilient modulus, fatigue and creep are suggested for further studies about this type of hybrid reinforced AC mixture. Applying scanning electron microscopy (SEM) technique will be useful to investigate fracture of glass fibers during mixing.

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