

Economical and Technical Study on the Effect of Carbon Fiber with High Strength on Hot Mix Asphalt (HMA)

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ABSTRACT: In this article by adding different percentages of carbon fiber with high strength and doing the necessary Marshall tests, it was observed that the Marshall Resistance and its Flow increased. Due to their armed properties, the carbon fibers have a positive effect on Marshall Resistance. According to the results, increasing the percentage of fibers, reduces the resistance, so that the resistance of the sample containing 1.5% of carbon fiber is almost 32% more than the resistance of the sample without fiber. According to the results, the increased resistance compared to the previous researches and other fibers stems from the kind of fiber used in it and its high resistance. After increasing the fiber percentage to 3, a 12% decrease in the resistance was seen. On the other hand, by changing the percentage of the fibers added to the aggregates, the Flow will change, so that the sample containing 3% of fiber is almost 189% more Flow than the base sample. The economic analysis was used for a three-lane road. The results showed that economically speaking, due to their high price, these types of fibers are recommended to be used in restricted and optimal areas.

Keywords: Carbon Fiber, Asphalt, Marshall, Economic Analysis.

1 INTRODUCTION

Improvement of the properties of asphalt mixture and soil has been evaluated by engineers [1]. Due to the weaknesses seen in the asphalt mixture properties, removing these weaknesses can surely be beneficial. Certainly, doing the tests and using appropriate materials as additives to the asphalt can be a good idea to improve its mechanical properties [2-16]. One of the main objectives of the Marshall test is to improve Marshall Resistance and to put the amount of Flow and other related parameters in a desired range. Various additives have been added to the bitumen and asphalt mixtures to improve the pavements. The classification of the additives is as follows:

1. Fine fillers (lime, Portland cement, sulfur, carbon soot)
2. The material with high porosity and surface area (sulfur, charcoal)
3. Rubbers: (natural rubber, synthetic rubber, polymer, modified rubber)
4. Plastic: polyethylene, polypropylene, EVA, PVC
5. Polymeric mixtures of porous materials, rubbers, plastics

6. Fiber: asbestos, polypropylene, polyester
7. Oxides, carbon, calcium salt
8. Hydrocarbons: oil

Compared with other fibers, carbon fiber is more suitable for equipping and reforming the bitumen in asphalt mixtures. Due to the fact that it is made of carbon fibers and the bitumen is a hydrocarbon, the two materials are inherently compatible with each other.

Since carbon fibers are produced at very high temperatures (1000 °C), melting of the fibers seems to be almost impossible due to the high mixing temperature required to produce the asphalt mixture. Because of the high tensile strength, the fibers can play an important role in increasing the tensile strength of the asphalt mixtures. As reported in other studies, the increase in the stiffness which stems from adding other fibers to the asphalt mix, may also improve the life of the asphalt by adding carbon fiber [17].

In their study, Abtahi et al (2010) stated that adding the fibers increases Marshall Stability, reduces the Flow, and increases the amount of voids in the mixture. The results show that the carbon fibers increase the potential resistance to structural damages of the pavement caused by the heavy traffic, and thus improve the fatigue. It also increases the re-

sistance to cracking and permanent deformation. Interestingly, the carbon fibers in the asphalt mixture improve the conductivity of electrical current. The carbon performance is better than the graphite. So electric heating method is a possible way for melting snow and ice on the surface of pavement during the winter [18].

Jahromi et al. (2008) used carbon fibers of 0.1, 0.2, 0.3, 0.4 and 0.5% by weight of the asphalt mix and did Marshall Test, resilient modulus, dynamic creep test, and indirect tensile fatigue test. Dynamic creep test was done by applying repeated sinusoidal shape with 0.2 seconds boot time. The rest time was 8.0 seconds at 40°C. After 6500 cycles of loading, the strain created in the sample was compared with the other ones [17].

Based on their study persistent strain decreases with increasing carbon fibers. But they concluded that an increase in the fiber in certain amounts can lead to permanent deformation recovery since it strongly keeps the aggregates in the adhesive mortar mix. However, in higher amounts of fibers, some amount of bitumen is used to cover the fibers. As a result, the surface of some aggregates and fibers are left uncoated. This can reduce the other asphalt properties such as resilient modulus [17].

As it can be seen, there are not many researches on the effects of carbon fiber on the technical properties of the asphalt. Lack of adequate information in this field can clearly be seen. Applying these kinds of fibers in the technical properties of the asphalt can make researchers more familiar with this type of material. Accordingly, in this study, we evaluate the fibers technical and economic effects on the mix by applying carbon fibers on the asphalt mix and analyzing it economically.

2. MATERIALS AND METHODS

2.1 Materials

Materials needed for this experiment are bitumen, stone, and carbon fiber respectively which will be discussed further.

2.1.1 Bitumen

In order to assess the effect of carbon fiber on the mechanical properties of the asphalt mix, asphalt samples were made of the standard 85-100 bitumen of Kermanshah refinery. Aggregates gradation, type and characteristics of the carbon fiber, and the method of making asphalt samples are shown in Table 1.

Table 1. The results of standard tests used in research on bitumen

Type of test	Standard	Results	The standard value
Specific gravity at 25°C	T228	1.012	-
The degree of influence in 25°C (100 g -5 seconds), based on the 0.1 mm	T49	98	85-100
Softening point (ring and ball), in °C	D36	45	45-528

2.1.2 Aggregates

Gradation curves from the mixing of the required weight percentages have been compared with the grain used in the preparation of the samples in Figure 1.

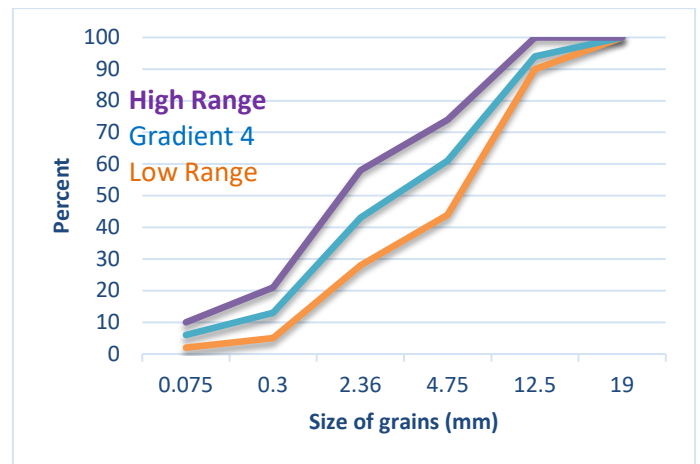


Figure 1. Aggregate gradation of asphalt mixture of Topeka layer 19-0 mm

By taking the maximum nominal size of the aggregates and according to the results of the grain aggregate sample, mixing ratios in Table 2 were determined for a layer of Topeka.

Table 2. Mixing ratios of asphalt mix aggregates

View aggregates	The percentage of the aggregate layer Topeka
Coarse gravel	0
Medium gravel	7
Fine gravel	29
Broken sand	62
Filler aggregates	2

Considering the ratios of the mix in Topeka layer in Table 1, weight percentages of the aggregates passed from the sieve are shown in Table 3.

Table 3. Gradation of aggregate blends

Screen size	Rejected wt.% from mixing with the above
¾ inch	100
½ inches	95
Number 4	62
Number 8	46
Number 50	11
Number 200	6

2.1.3 Applied Fiber

Carbon fibers used in this study were made in America in 10 mm length, Figure 2 and were cut by scissors. Table 4 shows the properties of carbon fibers used in the project.

Table 4. Properties of carbon fibers

Structure	Density)g/cm ³ (modulus of elasticity)N/mm ² (Tensile strength)N/mm ² (
Radioisotope	1.5-1.6	40000	900-1100



Figure 2 Carbon fiber with a length of 1 cm

3. PRODUCING THE SAMPLES

Construction of the asphalt mix was performed according to the standard procedure of ASTM-D 1559 [19]. Regarding the fact that the materials of the

mixture belonged to Sanandaj municipality in 2014, the optimum bitumen (5%) was available; therefore, for percentages of 0.5, 1, 1.5 and 3% of polyester fiber with high strength, asphalt samples were made in this study and Marshall Tests were performed on it. There are two main methods for mixing the fibers with a mixture of asphalt:

A) Dry method: In this method, the fiber is thoroughly mixed with aggregates pre-heated in Owen. Then bitumen is added.

B) Wet method: In this method, the fiber is mixed with bitumen and then it is added to the aggregate.

It should be noted that in order to avoid the necking phenomenon (fibers sticking together), the dry method was used in this study (Figure 3).



Figure 3. Mixture made by mixing the fibers with aggregate based on the dry method

4. MARSHALL TEST RESULTS

Construction method of the asphalt mixture was based on ASTM-D 1559 standard [19]. Regarding the fact that the materials of the mixture belonged to Sanandaj municipality project in 2014, optimum bitumen (5%) was available; therefore, the asphalt samples of the study were made for 0.5, 1, 1.5 and 3 percentages of carbon fiber with high strength, and Marshall Tests were performed on it.

4.1 Analysis of Marshall Resistance Results

Having equipped the asphalt mix with fibers and using it in the bitumen and aggregates, it is absorbed homogenously in the mix; Carbon fibers increase the resistance of the mix. The results show that by increasing the percentages of fibers, the resistance increases. The sample including 1.5% of carbon fibers is almost 32% more resistant than the fiber-free sample (Fig. 4). It's worth mentioning that by increasing the fiber percentage, first, an increase and then a decrease is seen in the Marshall Resistance. This is the best possible mixture. The highest

amount of Marshall Resistance is seen in the peak. A sharp drop in the resistance was seen in higher percentages due to a massive increase in the fibers and a decrease in the connectivity.

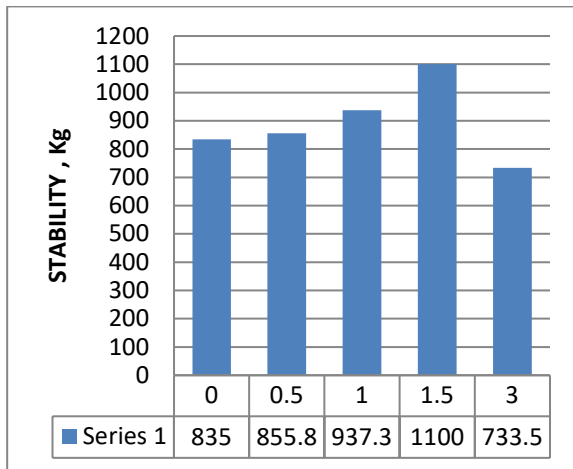


Figure 4. Effect of different percentages of carbon fiber on Marshall Resistance

4.2 Results of the Specific Weight of the Samples Equipped with Fibers

By increasing the fiber percentage in the mixture, the specific weight reduces. This can be due to the increase in the amount of the aggregates. According to the graph, the specific weight of the sample containing 3% of fiber is about 8.5% lower than the sample without fibers (Fig. 5).

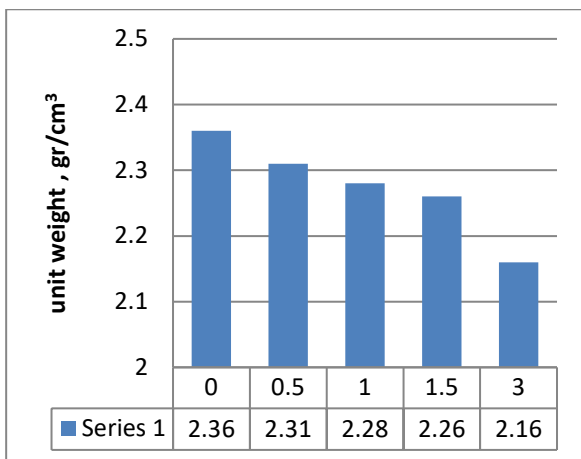


Figure 5. Effect of different percentages of carbon fiber on the specific weight

4.3 VTM Result of the Samples Equipped with Fiber

By increasing fiber percentage in the mix, the voids in the whole mix increases. This increase is the highest in 3% of fibers, so that at this percentage

(3%), a 177% increase can be seen in the total amount of the mixture (Figure 6).

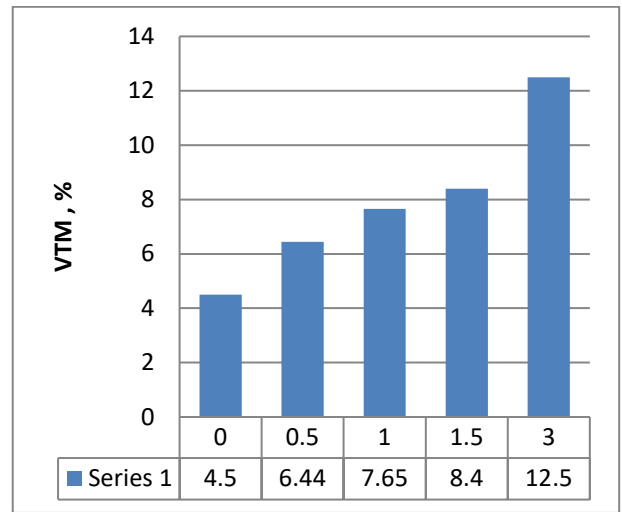


Figure 6. Effect of different percentages of carbon fiber on VTM

4.4 VMA Results of the Samples Equipped with Fibers

According to the graph and based on the results, the voids in the aggregates increase in the presence of the fibers, so that, having 3% of fibers, a 44% increase is seen in the voids of the aggregates. This is probably because of the absorption of the bitumen into the fibers (Figure 7).

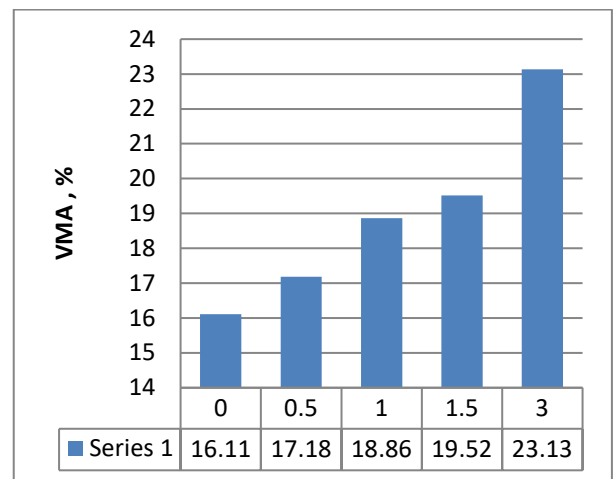


Figure 7. Effect of different percentages of carbon fiber on VMA Resistance

4.5 VFA Results of the Samples Equipped with Fibers

According to the results, the addition of carbon fiber, the percentage of the voids filled with bitumen decreases. Having 3% of fiber, a 36% decrease can be seen compared to the base sample (Figure 8).

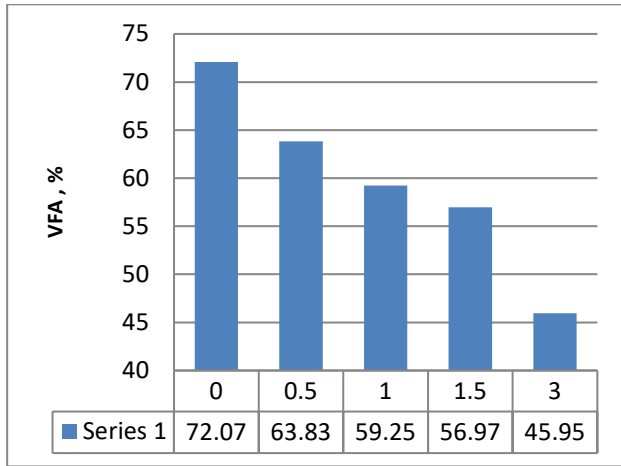


Figure8. Effect of different percentages of carbon fiber on VFA

4.6 Analysis of the Results of Marshall Flow

By changing the percentages of fibers added to the aggregates, Flow changes, too. As it was expected, the results of Marshall show that by increasing the percentages of fibers, Flow increases so that, as shown in Figure 9, the samples containing 3% of fiber are approximately 189% more fluent than the base sample.

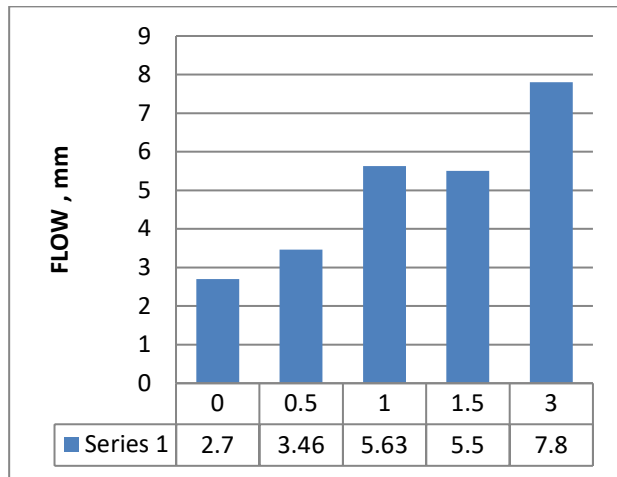


Figure 9. Effects of different percentages of carbon fiber on Flow

5. ECONOMIC ANALYSIS of APPLYING CARBON FIBERS

Due to the high cost of using carbon nanotubes in asphalt mixtures, applying it in the bitumen must be economically justifiable. One kilogram of carbon fibers used in this study costs 100 USD. Asphalt samples (1200 grams) with different percentages are shown in Figure 10. For 1200gr Marshall Sample this amount is required which is not affordable in big

projects. This type of fiber cannot be used in ordinary works. However, due to very high resistance caused by using different percentages of this material in the asphalt, this type of fiber can be used in special places such as turns or areas like the speed bump where asphalt is more susceptible to destruction. However, due to the increased strength of the asphalt with fibers, pavement layers can be thicker than the control sample and thus some amount of carbon-related costs can be saved. Based on Marshall Parameters, the samples, especially the Marshall resistance, and the costs shown in Figure 9, using samples 1 with 1.50 percent of nanotube, can be a good way to improve the mechanical properties of the asphalt mix.

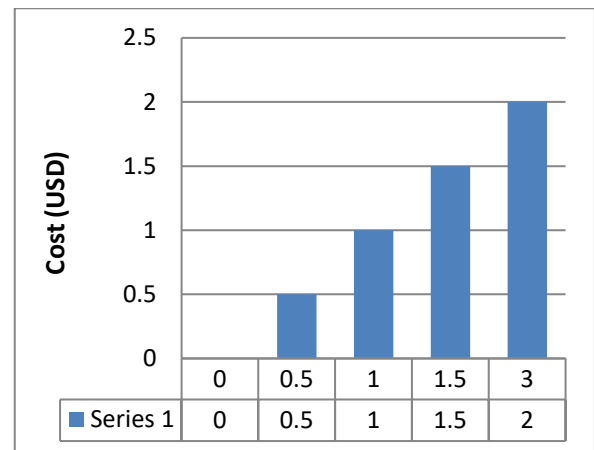


Figure 10. Comparison of the additional costs imposed to the 1200gr sample in different percentages of carbon fiber

6. ECONOMIC ANALYSIS

The economic analysis of adding carbon fiber to asphalt mixtures was investigated [20-23]. In this section, the costs and benefits of adding Additives was investigated. For this purpose, construction of a 6-line path (each direction 3 lines) for 1 km was evaluated. The special weight of asphalt was considered (unlike the previous research, the test results of section 4.2 were used): $\gamma = 2.36, 2.31, 2.28$ and 2.16 ton/m^3 and the price of each ton of asphalt and glass fiber (per kg) were considered about 51\$, 100\$, respectively. The price of lignin was considered zero. The cost of adding carbon fiber is calculated:

$$\text{Benefit} = 1000 * 6 * 3.65 * \frac{D_i * 2.54}{100} * \gamma * \text{asphalt price} - 1000 * 6 * 3.65 * \frac{D_0 * 2.54}{100} * \gamma * \text{asphalt price} \quad (1)$$

$$\text{Cost} = 1000 * 6 * 3.65 * \frac{D_i * 2.54}{100} * \gamma * 1000 * \text{additive percent} * \text{carbon fiber} \quad (2)$$

Table 5 and 6 show the results of design and economic analysis respectively:

Table 5. Design Result

Additive %	Marshall stability (Pound)	a_1	D_i
0	0	0	0
0.5	1887	0.415	4.75
1	2068	0.45	4.37
1.5	2425	0.472	4.17
3	1618	0.32	6.16

Table 6. Economical Result

Additive %	Benefit	Cost	Benefit-Cost
0	0	0	0
0.5	3794	3049846.243	-3046052.24
1	27626	5552216.48	-5524590.48
1.5	40466	7870489.742	-7830023.74
3	-82808	22190602.05	-22273410.0

According to table 6, adding carbon fiber to asphalt mixtures will make the project uneconomic. This result ensures the use of additives on a small scale.

7. CONCLUSION

In this study, high-strength carbon fibers were used. We concluded that the effect of carbon fibers in lower percentages increased Marshall Resistance. Certainly, this additive has got a positive effect on the Marshall Test and Flow, so that:

This study aimed at evaluating the optimum percentage of carbon fiber on Marshall Resistance.

The carbon fiber arms the asphalt mixture and increases its resistance. Adding 1.5 % of it, causes a 32% increases (i.e. 1,100 kg) in Marshall Resistance compared to the normal sample. The reason for this significant increase can be related to the compatibility of the asphalt mixture with carbon fibers and the high resistance of these fibers. In higher percentages, an increase in resistance is seen due to the participation of fibers in transportation and the reduction of connectivity between the grains.

Specific weight of the asphalt mixture decreased due to the low Specific weight of the fibers.

Due to the high specific surface of the fibers, VMA and VTM decreased.

By increasing the percentage of fibers, Flow rises so that the sample containing 3% of fibers is about 189% more fluent than the base fiber.

In terms of economy, this activity is not economic but due to the modification of the technical properties of the asphalt, it can be used in restricted areas (Specific and sensitive locations).

Finally, according to the results, the use of the additive is recommended in temperate zones and heavy traffic in specific and small areas.

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