Carbon Fiber-Reinforced Asphalt Concrete: An Investigation of Some Electrical and Mechanical Properties

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Abstract. Asphalt concrete is a composite material that is extensively used in the construction of highways, airport runways and parking lots. Riding comfort, durability and water resistance are some of the driving mechanical characteristics making it the most preferred choice in the pavement industry. Multifunctional materials have the simultaneous ability to exhibit non-structural functions apart from their regular structural functions. Structural materials can be designed multifunctional by integrating electrical, magnetic, optical, and possibly other functionalities that exhibit advantages beyond the sum of the individual capabilities. Asphalt concrete has the potential of being used as a multifunctional material by controlling its electrical conductivity. Asphalt concrete, by nature, is a non-conductive composite material, but its conductivity can be improved by using conductive materials. The method of inclusion of a conductive filler within the asphalt concrete matrix and its percolation threshold are the factors of interest within this work. The study of the effect of inclusion of the conductive material on the mechanical properties of the hot-asphalt concrete mixtures is another goal of the present work. The results showed that the incorporation of carbon fibers (CFs) within the dense graded asphalt concrete mixtures can enhance their mechanical and electrical properties. The embedding of only 1.5% CFs by volume of mixture improved the stability, IDT and electrical resistivity by 72%, 20% and more than nine orders, respectively. Accordingly, 1.5% CFs represent the percolation threshold of all of the studied properties.

1. Introduction

Asphalt concrete is one of the most commonly used materials as a binder or wearing course within the flexible pavement in the world. It can be seen in residential, industrial, commercial and agricultural facilities. It can be regarded that the damage resulting from the production of asphalt as a construction material, which is the main binding material in asphalt concrete, is less compared to other construction materials such as cement and reinforcing steel.

After the construction of flexible pavement, it is rare that maintenance is performed on it. When the maintenance operations begin late, at low levels of serviceability index, this means that a huge amount of money is required to be spent in order to raise the serviceability index by a few if it is possible. Sensing the need of maintenance early increases safety and service life, which reduces spending a high proportion of the funds compared to the previous case. This also provides multi alternate techniques to carry out the maintenance. To achieve the above objective, the development of a new property in asphalt
concrete, which enables early time monitoring of different distresses, has begun in concrete researches in recent years. This is the self-sensing ability.

The self-sensing composites can be produced by the addition of some materials that possess the properties of electrical conductivity so that they form with dielectric materials multifunctional semihomogeneous composites. Some examples of these materials are: carbon fiber, carbon nanotube, graphene nano platelets and carbon black. In order to get multifunctional semi-homogeneous composites, the conductive materials need to be well distributed within normal asphalt concrete through the use of effective techniques to help creation of a network of electrical conductors that make the resulting asphalt concrete composites with high electrical conductivity [1].

The method of inclusion of a conductive filler (micro-scale carbon fibers in the present study) within the conventional asphalt concrete matrix and its percolation threshold are the factors of interest within this work. The effect of inclusion of the conductive materials on some of the electrical and mechanical properties of the hot-asphalt concrete mixtures is the main goal of the present work.

Therefore, several previous studies were conducted to improve the mechanical properties of asphalt concrete by reinforcing it with fibers. Abtahi et al. [2] investigated the advantages of incorporating fibers within the asphalt concrete. They reviewed within their study the mechanical improvement, preparation of electrically conductive mixtures and creating a new market to manage the waste textile fibers. The study pointed out that the addition of fibers effectively within the asphalt concrete matrices can improve the creep compliance, moisture susceptibility and dynamic modulus, rutting and freeze-thaw resistances; and reduce the reflective cracking of flexible pavements. Two types of carbon fibers were utilized by Wang et al. [3] to improve the self-healing capability of asphalt mixture. One type of carbon fiber (CF) was first mixed with aggregates and then the binder was added to fabricate the mixture. On the other hand, the second type of CF was introduced to binder first and then mixed with aggregates. The results indicated that both types of CF achieved effective healing performances. Zhang et al. [4] dispersed a waster polyethylene and carbon fibers with the asphalt cement to modify its properties to meet the requirements of asphalt concrete pavements. They melted the asphalt at 170 °C and added the above two modifiers and mixed with asphalt with the aid of a shear mixer with 3800 rpm for 60 minutes to get a modified binder with improved physical properties like grade, softening point and ductility.

Recently, four types of fibers were incorporated with the asphalt concrete mixtures to investigate the optimal type and concentration of a fiber that has the ability to enhance its mechanical properties [5]. The fibers were polypropylene and polyester fibers with a length of 6 mm, nylon and carbon fibers all with a length of 12 mm. Their work showed that carbon fibers improved flexural strength, strain capacity and toughness of the manufactured asphalt concrete mixtures. These conclusions were inline with the findings of the works carried out by Yoo et al. [6] and Slebi-Acevedo et al. [7].

Although some studies have been conducted to determine the effects of the use of carbon fiber in asphalt concrete, it did not highlight on its electrical resistivity. Asphalt concrete has possibilities of being used as a multifunctional material by controlling its electrical conductivity. It, by nature, is a non-conductive composite material, but its conductivity can be improved by using conductive materials. The method of inclusion of a conductive filler within the asphalt concrete matrix and its percolation threshold are the factors of interest within this work. The effect of inclusion of the conductive materials on the electrical and mechanical properties of the hot-asphalt concrete mixtures is the main goal of the present work in order to enrich the studies within this area.

2. Materials and mixture proportions
2.1. Materials
The materials used in the present work are locally available (except the conductive filler), which include asphalt cement, aggregates (coarse and fine), cement (as a filler) and chopped carbon fibers, which were used as the conductive material. The grade of the asphalt cement is 40/50 with a specific gravity of 1.01. It is produced from Dhi Qar refinery. Physical properties of asphalt as determined in the present study are shown in Table 1.

Table 1. Physical properties of asphalt cement.

| Property                        | ASTM designation | Test results | SCRBR (Iraqi Specifications) |
|---------------------------------|------------------|--------------|------------------------------|
| 1- Penetration, 25°C, 100 gm, 5 sec, 0.1mm | D-5              | 43           | 40-50                        |
| 2-Ductility at 25 C, 5cm/min, (cm) | D-113            | 115          | >100                         |
| 3- Softening Point. (°C)        | D-36             | 50           | -                            |
| 4-Flash Point, (°C) (min.)      | D-92             | 268          | 232                          |
| 5-Loss on heating               | D-70             | 0.17%        | -                            |
| D-1754                          |                  |              |                              |
| D-5                             | 81               | >55          |                              |
| D-113                           | 90               | >25          |                              |

Fine aggregates used was natural sand passed from sieve No.4 (4.75 mm) and retained on sieve No.200 (0.075mm). The coarse aggregates are crushed gravels passed from sieve ¾ (19mm) and retrained on sieve No.4 (4.75 mm). The coarse and fine aggregates were cleaned by potable water.

Table 2 shows the dense gradations of coarse and fine aggregates required by the Iraqi specifications for wearing course type IIIA and the selected gradation to manufacture the laboratory specimens with a nominal maximum aggregate size of 12.5mm. The specific gravity of coarse and fine aggregates are 2.63 and 2.66 respectively.

Table 2. Aggregate gradations of wearing course type IIIA.

| Sieve Size | IQ Specifications % Passing | Selected gradations % Passing | % Retained |
|------------|-----------------------------|------------------------------|------------|
| 3/4        | 19                          | 100                          | 100        | 0          |
| 1/2        | 12.5                        | 90-100                       | 95         | 5          |
| 3/8        | 9.5                         | 76-90                        | 83         | 12         |
| No.4       | 4.75                        | 44-74                        | 59         | 24         |
| No.8       | 2.36                        | 28-58                        | 43         | 16         |
| No.50      | 0.3                         | 5-21                         | 13         | 30         |
| No.200     | 0.075                       | 4-10                         | 7          | 6          |
| Pan (filler) |                    |                               | 7          |            |

Ordinary Portland cement Type II was used as the mineral filler. It conforms the Iraqi specifications (IQ.S No. 5/1984). Its specific gravity is 3.01.

Chopped pan-based electrically conductive carbon fibers with 12 mm length and aspect ratio of 1600 was employed in this study during the fabrication of CF-reinforced asphalt concrete. The properties of the fibers can be seen in Table 3, as it was received from the supplier, while a digital camera, digital microscope and SEM images are provided in Figure 1.
Table 3. Typical properties of chopped carbon fibers.

| Typical Properties | Unit | Value |
|--------------------|------|-------|
| Carbon fiber content | %    | >98   |
| Fiber diameter      | µm   | 7     |
| Fiber unit weight   | kg/m³| 1700  |
| Fiber length        | mm   | 12    |
| Metal contamination | -    | <0.1g/1000g |
| Tensile strength    | MPa  | 4150  |
| Tensile modulus     | GPa  | 230   |

Figure 1. Carbon fiber used in the present study: (a) Digital camera image, (b) Digital microscopic image and (c) SEM image.

2.2. Mixture proportions
To determine the optimum binder content, five percentages of asphalt were specified by weight of mixtures according to the requirements of Iraqi Standards (4, 4.5, 5, 5.5 and 6%). Aggregate fractions, accordingly, were as shown in Table 2 by weight of Marshall specimen after subtracting the weight of binder. Therefore, a total of fifteen specimens were prepared to determine the optimum binder content (three specimens for each binder content). Table 4 abstracts the mix design of the plain asphalt concrete mixtures to determine the optimum binder content using the Marshall method with 75 blows at each face of the specimens.

Table 4. Results of Marshall mix design.

| Property                                          | Value  |
|---------------------------------------------------|--------|
| Optimum asphalt content (%)                        | 4.7    |
| Marshall Stability (kN)                            | 10     |
| Marshall flow (mm)                                 | 3.6    |
| Theoretical maximum specific gravity of mixture   | 2.504  |
| Bulk specific gravity of aggregates                | 2.663  |
| Voids in total mix (VTM) (%)                       | 4.5    |
| Voids filled with binder (%)                       | 69.6   |
| Voids in mineral aggregate (VMA) (%)              | 16.1   |
At the optimum asphalt content, CFs were added to the plain mixtures. The utilization percentages are 0, 0.5, 1.0, 1.5, 2.0 and 2.5% by volume of mixtures. These percentages are within the ranges of those that have been used by some of the previous studies [3, 5]. A total of 54 specimens were, then, prepared to measure the Marshall stability, indirect tensile strength and electrical resistivity of asphalt concrete at different percentages of CF. Figure 2 demonstrates the addition of CFs to the hot aggregates before the addition of binder.

3. Lab tests, results and discussions
3.1. Marshall stability and flow
To diagnose the effects of incorporation of CFs within the asphalt concrete matrix, three specimens were prepared with each percentage of CF (0.5 to 2.5%) in addition to three plain specimens without CF. Therefore, 18 specimens were manufactured to carry out this test as shown in Figure 3. The results of stability and flow were, then, averaged for each CF content. Figure 4 presents the results obtained from this test. It can be seen clearly that the incorporation of CF within the asphalt concrete mixtures enhanced their stability and flow. This is due the fact that the high aspect ratio of CF can improve the bonding between the aggregates and binder, which can be reflected into high stability values. The values of stability are increased by 23%, 49%, 72%, 80%, and 86% after the addition of 0.5, 1.0, 1.5, 2.0 and 2.5% carbon fibers by volume, respectively. The rate of increase of stability after 1.5% CF is relatively low, which may lead to a conclusion that this percentage (i.e. 1.5% by vol.) is the percolation threshold of CF in terms of stability.

Figure 2. Mixing of CFs with hot aggregates.
Flow values are, also, enhanced after the addition of CF, which means high resistance against permanent deformations of carbon fiber reinforced asphalt concrete pavements. No significant decrease in flow values can be seen in Figure 4 after 1.5% CF. This indicates that this percentage is, also, the optimum in terms of Marshall flow. It is worth mentioning that the flow value at 0.5% CF, which is more than those at other percentages, can be regarded as abnormal. This can be resulted commonly within the experimental works.

Figure 3. Marshall test setup with Marshall specimens incorporating different percentages of CF.

Figure 4. Marshall stability and flow results.

3.2. Indirect tensile strength
The indirect tensile strength test was carried out at room temperature on eighteen cylindrical dense graded hot-mix asphalt specimens with different percentages of CFs as previously mentioned. The test was performed in accordance with the procedures shown in ASTM-D6931 [8]. Figure 5 exhibits the test setup and one of the fractured specimens. The face of the specimens was painted by a white color to diagnose the cracks easily.
Figure 5. Indirect tensile strength setup.

Figure 6 demonstrates the results obtained from this test. It can be noticed that the addition of CFs to the asphalt concrete mixtures slightly enhances the indirect tensile strength at low percentages specifically up to 1.5% by volume of mixtures. However, an improvement of 20% was achieved. After that, the strength starts to decrease reaching to values less than the strength of 0% CF. It seems that the high percentages of inclusion of CFs within the asphalt concrete mixtures reduces the asphalt film thickness around the aggregates, which lead to a negative impact on the indirect tensile strength.

Figure 6. Results of the indirect tensile strength test of different contents of CFs.

3.3. Electrical resistivity
The geometrical properties of the material have effects on its electrical resistance values. Thus, a term, which is called “electrical resistivity, $\rho$”, can be used to represent the material resistance to the electrical conductivity taking into account the effects of geometrical dimensions of the material. This principle can be expressed through the following general equation:

$$\rho = R \times \frac{A}{L}$$

(1)
where, $\rho$, $R$, $A$ and $L$ stand for resistivity ($\Omega \cdot m$), electrical resistance ($\Omega$), cross-sectional area ($m^2$) of the specimen or the contact area of the electrodes inside it and length ($m$) of the specimen or the distance between the electrodes, respectively.

In the present work, an Avometer was used to measure the electrical resistance of the CF-reinforced specimens between two circular aluminum sheets having diameter of 101.6 mm, which were used as electrodes (Figure 7a). This device has the ability to measure up to 200 mega ohms. For higher values, an insulation tester was utilized to read the electrical resistance of die electrical asphalt concrete mixtures that have no CFs (Figure 7b). This device is capable to read up to 30 tera ohms.

![Avometer and Insulation tester](image)

**Figure 7.** The electrical devices used to measure the electrical resistance.

The specimens were put in a steel holder (Figure 8), which was manufactured within the experimental stages of this research, and the electrical resistance values of different specimens were recorded. Before reading of the electrical resistance, the two plates under and above the specimen should be pressed firmly on the specimen with the aid of the screws fixed on the four edges of the holder.

![Electrical resistance measuring setup](image)

**Figure 8.** Electrical resistance measuring setup.

The changes in electrical resistivity after the addition of CFs to the asphalt concrete mixtures can be diagnosed in Figure 9. As can be seen clearly, the electrical resistivity was decreased more than nine orders when the percentage of CFs reached to 2.5%. This is due to the fact that the conventional asphalt concrete is a dielectric material and there is no electrical current can be passed through its
matrix. CFs are responsible for creating an electrical network, which has the ability of paving the road for passing of the electrical current through the asphalt concrete matrix. Accordingly, the asphalt concrete becomes an electrical conductor, which can be, then, utilized as a self-sensor of the applied stresses and the resulting strains within the asphalt concrete pavement system [9-11]. It can be seen in Figure 9 that the decrease in electrical resistivity after 1.5% CF is small, which means that a continuous path of electricity can be created at this percentage of CF [12]. Therefore, this dosage (i.e. 1.5% by volume of mixture) can be regarded as the percolation threshold of the electrical resistivity of the fabricated mixtures within the present work.

![Figure 9. Electrical resistivity of various contents of CFs.](image)

4. Conclusions
In the present work, cylindrical specimens of asphalt concrete incorporated CFs were manufactured and evaluated in terms of Marshall stability, Marshall flow, indirect tensile strength and electrical resistivity. In accordance with the completed experimental studies, it was concluded that the incorporation of CFs within the dense graded asphalt concrete mixtures can enhance their mechanical and electrical properties. The embedding of only 1.5% CFs by volume of mixture improved the stability, IDT and electrical resistivity by 72%, 20% and more than nine orders, respectively. Accordingly, it can be concluded that 1.5% CFs represents the percolation threshold of all the studied properties.

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