# Electrical and mechanical properties of asphalt concrete containing conductive fibers and fillers

Wang, Haopeng; Yang, Jun; Liao, Hui; Chen, Xianhua

**DOI**
10.1016/j.conbuildmat.2016.06.063

**Publication date**
2016

**Document Version**
Accepted author manuscript

**Published in**
Construction and Building Materials

# Electrical and Mechanical Properties of Asphalt Concrete containing Conductive Fibers and Fillers

**Haopeng Wang*, Jun Yang, Hui Liao, and Xianhua Chen**

Section of Pavement Engineering, Faculty of Civil Engineering & Geosciences

Delft University of Technology, Stevinweg 1, 2628 CN Delft, The Netherlands

***Corresponding author:**

Email: H.Wang-10@tudelft.nl

**ABSTRACT**

Electrically conductive asphalt concrete has the potential to satisfy multifunctional applications. Designing such asphalt concrete needs to balance the electrical and mechanical performance of asphalt concrete. The objective of this study is to design electrically conductive asphalt concrete without compromising on the mechanical properties of asphalt concrete. In order to achieve this goal, various tests have been conducted to investigate the effects of electrically conductive additives (steel fiber and graphite) on the laboratory-measured electrical and mechanical properties of asphalt concrete. The results from this study indicate that the critical embedded steel fiber length is 9.6 mm to maximize the fiber's potential to bridge across the crack from single fiber tensile test. Both steel fiber and graphite can produce conductive asphalt concrete with sufficiently low resistivity, but steel fiber is much more effective than graphite to improve the conductivity of asphalt concrete. A combination of steel fiber and graphite can precisely control the resistivity of asphalt concrete over a wider range. Besides, asphalt concrete containing an optimized amount of steel fibers has a significant improvement in Marshall Stability, rutting resistance, indirect tensile strength, and low temperature cracking resistance compared to the plain concrete. The addition of graphite could increase the permanent deformation resistance with compromised stability and low temperature performance. Asphalt concrete containing steel fibers and graphite weakens the steel fiber reinforcing and toughening effect, but still has a significant improvement in mechanical performance compared to the plain concrete.

***Keywords:*** Asphalt concrete, Electrical conductivity, Mechanical properties, Fiber, Graphite

## 1. Introduction

Asphalt concrete (AC), contains two components, bitumen and aggregates. Bitumen is very sensitive to temperature and behaves brittle at low temperature and viscous at relative high temperature. Most of the deteriorations in asphalt concrete stem from the poor properties, also including thermal sensitivity, of asphalt binder [1]. From a historical viewpoint of asphalt mixture design technology, Roberts et al. [2] summarized that rather than mixture design, improvement of binder properties using modifiers or additives will lead to a true revolution in paving technology. According to Nichollos [3], the modifiers and additives are classified into four categories: (1) polymer modifiers, including plastomers and elastomers, (2) chemical modifiers, such as sulphur, copper sulphate, and other metallic compounds, (3) adhesion (anti-stripping) agents, like fatty amidoamine, acids, amine blends and lime, (4) fiber additives. Due to the successful applications of fiber reinforced concrete (FRC) in cement concrete [4], fibers have got much attention in asphaltic materials recently. Researches show that fiber-reinforced asphaltic materials develop good resistance to fatigue cracking, moisture damage, bending and reflection cracking [5, 6].

More recently, other promising applications of fibers in asphalt concrete have been claimed by various researchers [7-13], such as the electrothermal applications of asphalt concrete using conductive fibers (such as carbon fibers and steel fibers) and fillers. Electro-thermal conductivity makes the multifunctional applications of asphalt concrete become a reality, such as snow and ice removal, deicing [7], self-sensing of pavement integrity [8, 9], self-healing (induction heating) [10, 11], and energy harvesting [12,13].

A prerequisite for enabling multifunctional applications is the ability to precisely control the electrical conductivity of asphalt concrete. In many previous studies about electrically conductive cement and asphalt systems [14-16], it has been demonstrated how the conductivity is proportional to the volume content of conductive filler or fibers added. Figure 1 illustrates a typical pattern of electrical resistivity variation with the addition of conductive fillers and/or fibers content presented with solid line [16]. It can be seen from Figure 1 that the transition between insulated phase and conductive phase is abrupt. Such a sudden decrease in electric resistivity is called the percolation threshold [14], which is commonly observed in other studies on conductive asphalt concrete [15, 16]. Also, the adjustable volume resistivity range of conductive asphalt near the percolation threshold is quite narrow, which introduces limitations for developing various multifunctional applications. For example, assuming the situation of heating asphalt pavement for self-healing or deicing, the resistivity of asphalt pavement should be controlled properly to ensure the safety as well as the good energy efficiency. Therefore, as illustrated in Figure 1, the rapid drop of volume resistivity versus conductive additive content needs to be transformed into a curve (dashed line) with gradual slope to enable precise manipulation of electrical resistivity over a wide range [17].

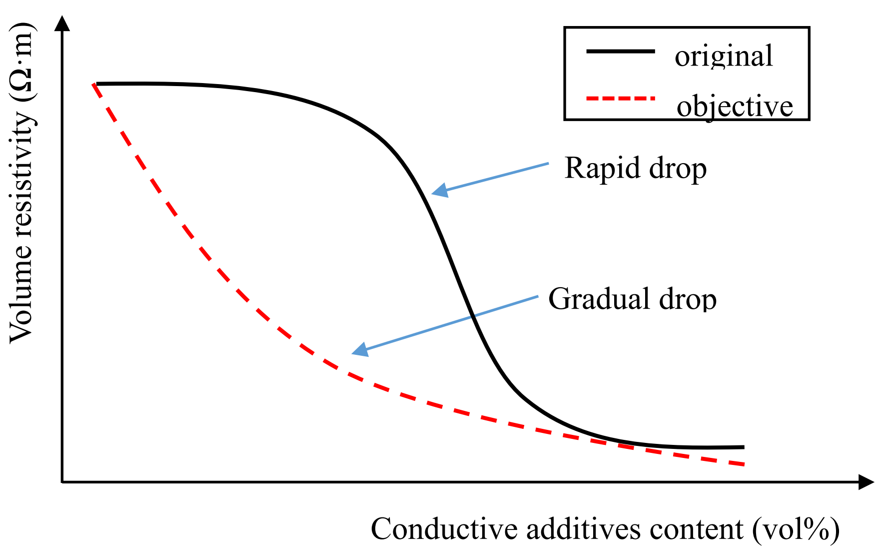



**Figure 1** Objective of imparting conductivity (compared to the result of Gracia et al. [16])

As mentioned before, the principal function of conductive fibers and fillers is to make asphalt concrete electrically conductive and suitable for its multifunctional applications. The addition of conductive fibers and fillers will definitely influence the mechanical properties and durablity of asphalt mixture. Liu et al. [9] indicated how an excess of conductive particles can cause the degradation of the pavement properties such as the strength or the workability of neat materials. Also, some researches [7, 8, 14, 15] have demonstrated that different types and contents of conductive fiber or filler have different effects on both electrical and engineering properties. In most instances, the road performance of conductive asphalt concrete dominates the selection of conductive additives. Therefore, the conductive additives are not supposed to influence the engineering properties of asphalt concrete negatively, but to ensure that the mixture satisfies the durability requirements.

To sum up, the key point of designing electrically conductive asphalt concrete is to optimize the balance between mechanical properties and electrical performance. While economic efficiency is certainly very important but not included in this study. On the basis of the above two considerations, the objectives of this study are to (1) design electrically conductive asphalt concrete with a gradual decease of resistivity over a wide range, and (2) investigate the effect of conductive additives on the properties of asphalt mixtures.

The effectiveness of additives was investigated through the electrical conductivity measurement on mixtures at different additive contents. The effect of the additives on asphalt mixture performance was evaluated through fiber-asphalt pull-out, Marshall test, wheel tracking, and indirect tensile strength tests.

## 2. Experimental investigation

### *2.1 Materials*

In this study, basalt aggregates and limestone fillers were used to product asphalt mixtures. The conventional asphalt binder used in this study was SHELL-70, which is equivalent to PG 64-22. The properties of asphalt binder are listed in Table 1.

**Table 1** Basic properties of asphalt binder

| Properties | Value |
|---|---|
| Penetration (25°C, 100 g, 5s, 0.1 mm) | 71 |
| Ductility (5 cm/min, 5°C, cm) | 32.2 |
| Softening point (R&B, °C) | 47.5 |
| Flash point (°C) | 272 |
| Rotational viscosity (60°C, Pa.s) | 203 |
| Wax content (%) | 1.6 |
| Density (15°C, g/cm$^3$) | 1.032 |

With regard to the electrically conductive particles, conductive steel fibers and graphite were added to the mixture. The steel fibers of type 4 are graded as "Extra Coarse" with a diameter of 0.10 ± 0.02 mm. They are low-carbon steel, with smooth face, resistivity of $7\times10^{-7}$ Ω·m, and density of about 7.5 g/cm$^3$. Graphite powder passing the No.200 sieve (0.075 mm) has a carbon content of 96.1%, an electrical resistivity of $10^{-4}$ Ω·m and a density of about 2.2 g/cm$^3$. Graphite powder, together with the limestone, work as fillers in the mixture.

The reason for selecting steel fibers and graphite as conductive additives is explained as follows. One of the objective in this study was to design electrically conductive asphalt concrete with a gradual slope of resistivity versus additive content curve. Figure 2 illustrates the strategy employed for controlling the electrical resistivity of asphalt concrete, which was also recommended by Park. As illustrated in the bottom right part of Figure 2, the resistivity of the asphalt mixture can be precisely controlled by filling the gap between aggregates and conductive fibers with conductive mastic.

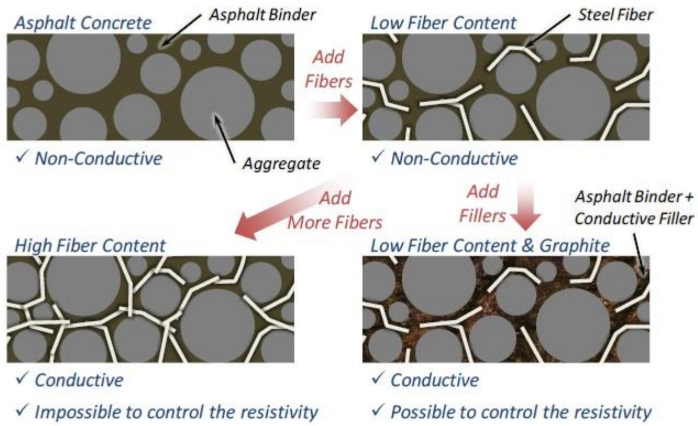



**Figure 2** Strategy for manipulating electrical resistivity of asphalt concrete [17]

*2.2 Mixture Design*

Dense asphalt concrete (AC-13) with 13.2-mm nominal maximum aggregate size was used in this research. Gradation is shown in Table 2 and was designed in accordance with standard Marshall Design method (ASTM D6926-04). The optimal asphalt content for the control mixture was 4.8%. No separate mix designs were performed for the mixtures containing conductive fillers/fibers. In order to compare the effects of conductive materials on electrical and mechanical performance of asphalt mixture, all the mixture samples were prepared with the same gradation and same asphalt content.

**Table 2** Gradation of AC-13

| Gradation | Sieve size, mm (% passing) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 16.0 | 13.2 | 9.5 | 4.75 | 2.36 | 1.18 | 0.6 | 0.3 | 0.15 | 0.075 |
| AC-13 | 100 | 96.6 | 81.1 | 48.0 | 31.2 | 18.9 | 11.7 | 7.7 | 6.7 | 5.7 |

*2.3 Test Sample Preparation*

Clumping or balling of fibers during mixing process is one of the important factors affecting the properties of fiber reinforced concrete [18]. The mixing procedure and dimension and amount of fiber have critical influence on the mixing quality of fiber reinforced asphalt concrete. According to the defined fiber distribution coefficient in previous study, the dry process and total mixing time of 270 s were used as the optimal mixing procedure to obtain well-distributed fibers in asphalt mixture [19]. Specifically, aggregates were first mixed with steel fibers for 90 s. Then, the liquid asphalt was poured into the bowl with another 90 s' stir. Finally, fillers and graphite (if had) were blended into the above mixture for 90 s' mixing.

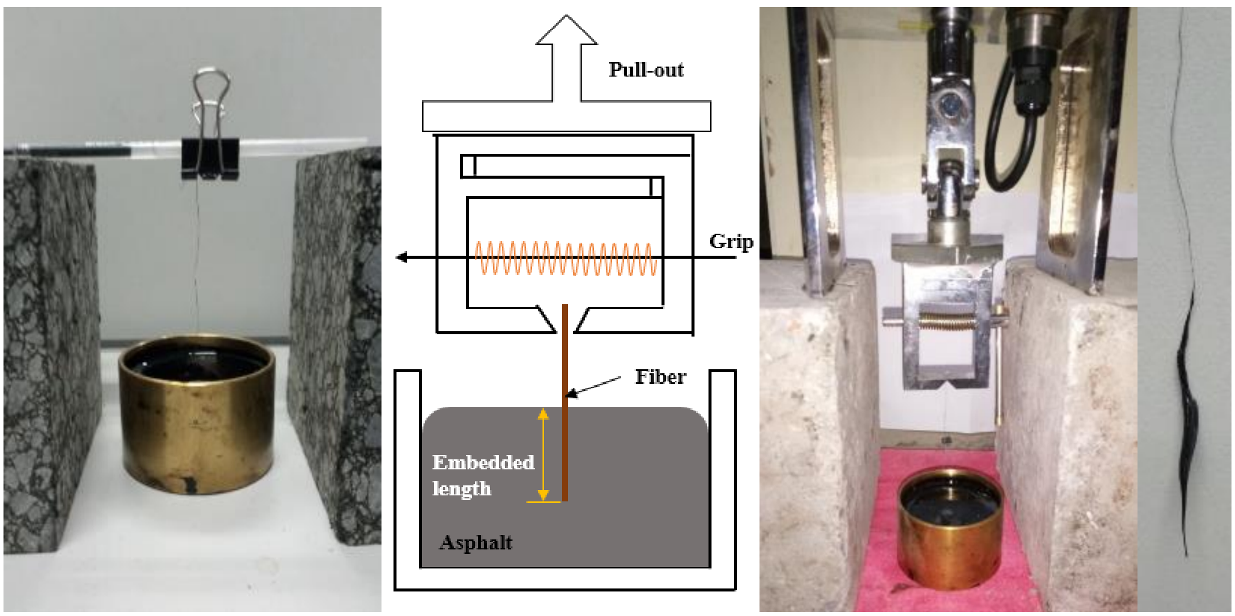
It is known that the significant effect of fibers on fiber reinforced composites occurs in the post-cracking phase, where fibers bridge crack and delay the failure process [20]. The joint of fibers across a crack to transfer the load can be simulated by pull-out tests [21], in which a single fiber is pulled out of asphalt binder rather than mixture for simulation convenience. Before the mixture specimen preparation, fiber-asphalt pull-out test was conducted to determine the critical embedded length of steel fiber. The detailed test description is presented in the following section.

After proper fiber length was determined, different percentages of conductive additives were added to the mixture. Cylindrical shape specimens with 100 mm diameter and 65 mm height were fabricated for Marshall Stability, indirect tensile strength tests as well as electrical resistivity measurement. The size of slab specimen for wheel tracking test is 300×300×50 mm (length × width × height). Specimens without fibers were also prepared in the same way to serve as control specimens. Each type of specimen has two replicates.

### *2.4 Test Methods*

➢ Single Fiber Pull-out Test

To prepare a pull-out specimen, the conventional asphalt binder without additive was firstly heated to 150±5 °C in an oil-bath heating container. It was then poured into a tin can with a diameter of 55 mm and a height of 35 mm used for penetration tests. The cleaned fibers were embedded at different lengths into the hot asphalt at the center of the tin can as shown in Figure 3a. A clip was held in place to prevent the fiber from sinking into the hot asphalt. After several hours cooling at room temperature, a simple tensile testing system with a maximum force capacity of 100 N was used to apply a constant displacement rate at 30 mm/min [17] to the test samples. Figure 3b and 3c show the sketch and real setup of pull-out test respectively. A typical pulled-out steel fiber is shown in Figure 3d. At relatively slow loading rate, the fiber's pull-out behavior depends mainly on the viscoelastic properties of the matrix (binder). Each test was repeated at least three times for each test condition.




(a)Fibers embedment (b)Schematic drawing of test setup (c) Photo in kind (d) Pulled-out steel fiber

**Figure 3** Pull-out test process

## ➢ Electrical Resistivity Measurement

The two-probe method was used for electrical conductivity measurement. The electrical resistivity measurements were done at room temperature of 15 °C. The electrical contact areas on the specimens were first painted with highly conductive silver paint. Two copper plate electrodes connected with the multimeter were placed at both ends of the cylindrical asphalt concrete samples. An UNI-T modern digital multimeter was used to measure the resistivity below $40\times10^6$ Ω. A resistance tester was used to measure the resistance higher than this value. The contact resistance between the two electrodes when directly connected is lower than 1 Ω, which is negligible with respect to the great resistances studied (higher than $0.1\times10^6$ Ω). The electric field of the resistance tester is assumed constant and the end-effects are considered negligible.

After measuring the resistance, the electrical resistivity of sample was obtained from the second Ohm-law in Equation 1:

$$\rho = \frac{RS}{L} \tag{1}$$

Where $\rho$ is the electrical resistance (Ω·m); $L$ is the internal electrode distance (m); $S$ is the electrode conductive area ($m^2$) and $R$ is the measured resistance (Ω).

- **Marshall Test**

Marshall Stability (MS) is one of the most important properties of asphalt mixtures because of the dynamic loads from vehicles, long-term static loads, stress caused by vehicle speeding and stopping, and shear effects or aggregate loss [22]. Different Marshall Stability tests were conducted at 60 °C to determine the optimum fiber content and compare the performance of asphalt mixtures with different conductive additives from a mechanical point of view (ASTM D 6927-06).

- **Wheel Tracking Test**

The wheel tracking test is applied to evaluate the permanent deformation characteristics of asphalt mixtures. A contact pressure of 0.7 MPa and total wheel load of 0.78 kN was applied to the slab specimens at 60 °C according to Chinese specification (JTG E20-2011). The test stops when either test time reaches to 1 hour or the maximum deformation exceeds 25 mm. Dynamic stability (DS) was calculated according to the plot of cumulative rut depths with number of loading applications for the mix as Equation 2.

$$DS = \frac{(t_1 - t_2) \times N}{d_1 - d_2} \quad (2)$$

Where, $t_1$ and $t_2$ are the time at 45 min and 60 min, respectively; $d_1$ and $d_2$ are deformation or rut depth at $t_1$ and $t_2$; $N$ is the number of cycles of wheel passing over the sample per minute.

➢ **Indirect Tensile Strength Test**

Indirect tensile strength (ITS) is a parameter that indicates the bond of the binder with aggregates and the cohesion in the mastics. Indirect tensile strength test was conducted on Marshall samples at -10 °C (ASTM D6391-2007) to examine cracking resistance at low temperature. The same servo-hydraulic mechanical testing system (UTM-25, IPC) was used to apply a constant displacement rate (50 mm/min) until the peak load was reached. The reaction force and vertical displacement were recorded by a data acquisition system. From the measured data, the indirect tensile strength could be calculated using Equation 3:

$$ITS = \frac{2F}{\pi DH} \quad (3)$$

Where $ITS$ is the indirect tensile strength (MPa); $F$ is the total applied vertical load at failure (N); $D$ is the diameter of specimen (m); $H$ is the height of specimen (m).

The fracture energy (FE) and post-cracking energy (FE) were also calculated from the test results. As suggested by Roque et al. [23, 24], FE is defined as the area under the stress-strain curve up to the failure strain ($\varepsilon_f$), and is a good indicator of the cracking potential for asphalt pavement. The area under the curve from $\varepsilon_f$ to $2\varepsilon_f$ is called PE, which is representative of ductility, especially useful to evaluate FRAC with post-cracking behavior. Toughness of the mixture is defined as the sum of FE and PE.

## 3. Results and discussions

*3.1 Single Fiber Pull-out Test*

The planned lengths of embedded fiber were 4, 6, 8, 10, 14, 18, and 22 mm respectively. However, precise control of the embedded depth during the specimen preparation is difficult because of thermal shrinkage of asphalt during cooling. Therefore, the location of the matrix surface was marked by painting the exposed part of the fiber just before the test, and the actual embedded length could thus be identified and measured after the test.

From Figure 4, it can be found that the average maximum load at failure in fiber pull-out test was 3.94 N. From the regression analysis between embedded fiber length and peak fiber pull out load, the critical embedded length of fiber was calculated as 9.6 mm. That means when embedded fiber length reaches approximate 9.6 mm or longer, fiber would rupture during the pull-out test. In order to maximize the steel fiber's potential to bridge across the crack and delay the crack propagation, the fiber length should not be shorter than 9.6 mm. Nevertheless, according to other researchers' and previous studies [19, 25], asphalt mixture reinforced with long steel fibers may influence the mixing quality and generate clumping or balling problems, which will definitely affect the mechanical properties of the mixture. Considering these, the final steel fiber length was chosen as 10 mm.

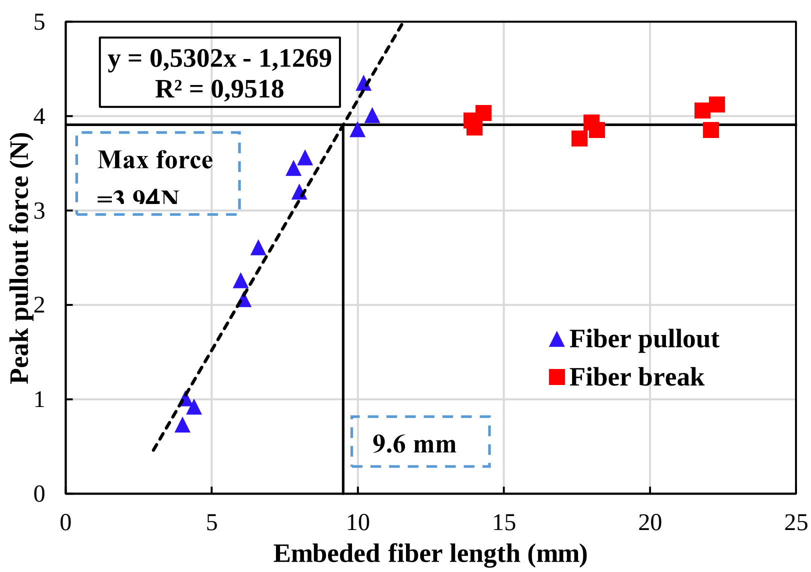


**Figure 4** Embedded fiber length determination in pull-out test

*3.2 Electrical Resistivity of Asphalt Mixture*

As mentioned before, conductive additives can transform insulated asphalt binder into electric conductive material. Seven graphite contents (2%, 6%, 10%, 14%, 18%, 22%, and 26% by volume of asphalt binders) and seven steel fiber content (0.1%, 0.2%, 0.4%, 0.6%, 0.8 %, 1.0% and 1.2% by weight of asphalt mixture) were involved in this study.

The electrical resistivity of asphalt mixture with different contents of steel fiber and/or graphite is displayed in Figure 5. It presents a typical pattern of electrical resistivity variation with the addition of conductive fillers content, which can be divided into four phases: insulated phase, transition phase, conductive phase, and excess of additives phase. When the graphite content reached to 6 vol%, adding more graphite led to a rapid decrease in resistivity. Such a sudden decline in resistivity is called the percolation threshold, as mentioned before. When the graphite content rose to 18 vol%, the resistivity of asphalt concrete had already reached a relatively low level, 1600 Ω·m. It can also be found that the variation in the resistivity of mixtures containing steel fiber followed a similar pattern as the ones containing graphite. It seems that steel fiber has greater effectiveness than graphite to improve the conductivity of asphalt mixture. When added a small amount of steel fibers, like 0.6 wt% (1.72 % by volume of asphalt binder), the resistivity of asphalt concrete reduced to 7600 Ω·m.

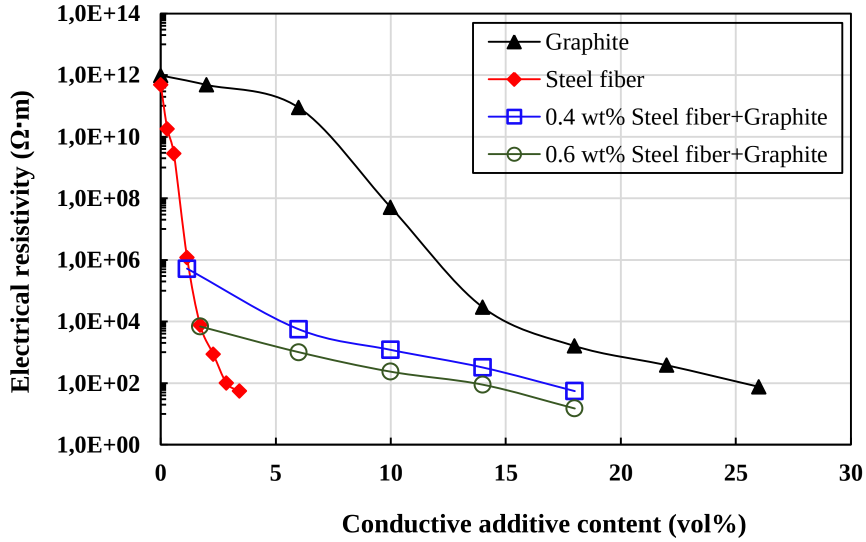



**Figure 5** Electrical resistivity of asphalt mixture with different contents of condutive additives

Sufficiently low electrical resistivity can be obtained by adding enough either graphite or steel fiber. However, the existence of the so-called threshold implies that it is difficult to manipulate its resistivity. In addition, these results support the hypothesis in Figure 2 that high steel fiber content can make asphalt concrete conductive, but that conductivity cannot be solely manipulated by the use of fibers. To enable precise conductivity manipulation, electrical resistivity needs to decrease gradually with the increase of conductive additive content. Therefore, the combination of fibers and fillers was investigated. For that, two sets of experiment were prepared: steel fiber content was fixed at 0.4% and 0.6% by weight of the mixture, then different volumes of graphite powder were added. With 0.4 wt% or 0.6 wt% steel fiber, the resistivity of asphalt concrete has already reached a certain low value. It seems as if a certain amount of steel fibers "help" the mixture only containing graphite pass over the percolation threshold. It was found from Figure 5 that the resistivity of asphalt concrete containing steel continued reducing gradually with the increase of graphite content. The slope of the resistivity variation curve of asphalt concrete with both fibers and fillers is much smaller than the ones with single fibers or fillers. At this point, the first objective of this study is attained.

*3.3 Mechanical Properties of Conductive Asphalt Concrete*

- **Marshall Test**

Marshall test was conducted to have an approximate idea of the durability of conductive asphalt concrete. Steel fibers added in the mixture are supposed to improve the electrical conductivity, and more importantly, to strengthen the mechanical properties. Figure 6 illustrates the MS values of asphalt concrete with different contents of steel fiber. With the increase of fiber content, the MS values rose significantly, reaching the peak (11.1 kN) at the fiber content of 0.4 wt%. Adding excess steel fibers resulted in decreases of MS values.

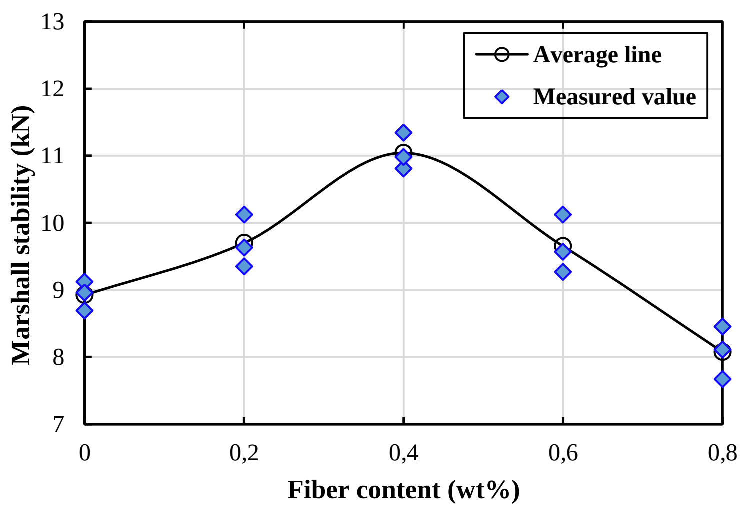



**Figure 6** Effect of fiber content on MS values

Combining with the electrical resistivity results, 0.4 wt% was selected as the optimal steel fiber content. In this study, 0.4 wt% steel fiber cooperates with 14 vol% graphite to obtain a low electrical resistivity of asphalt concrete (322 Ω·m), which could satisfy the requirements of conductive asphalt concrete.

In order to compare the effects of different combinations of conductive additives on the mechanical properties of asphalt concrete, four types of asphalt concrete specimens were prepared to investigate the laboratory performance. The four types of specimens are plain asphalt concrete as control one, steel fiber reinforced asphalt concrete (fiber content of 0.4 wt%), graphite modified asphalt concrete (graphite content of 14 vol%), and composite asphalt concrete with 0.4 wt% steel fiber and 14 vol% graphite, respectively.

Table 3 presents the Marshall experimental parameters of control mixture and conductive asphalt mixture with different additives. The mixtures containing graphite have the lowest MS values, which is possibly due to the oil-absorbing property of graphite with high surface area, lead to adhesion force drop. In contrast, steel fibers significantly increase the stability of asphalt concrete by 18.7 % as compared to the control one due to the reinforcing effect. As expected, the MS values of asphalt concrete containing steel fiber and graphite fell in between the above two ones. In terms of volumetric properties, the addition of steel fiber increases the bulk density of asphalt concrete due to its higher density. AV and VMA of steel fiber reinforced asphalt concretes are higher than that control ones. This is because steel fibers play interferential effect inside the aggregates due to its higher stiffness, which makes asphalt concrete samples difficult to be compacted. Graphite does not change the AV of asphalt concrete because graphite powders were added in the mixture by replacing certain amount of fillers using isovolumetric method.

**Table 3** Marshall experimental parameters of different asphalt concrete samples

| Parameters | Asphalt concrete with different conductive additives | | | |
|---|---|---|---|---|
| | Control | Graphite | Steel fiber | Graphite+Steel fiber |
| Bulk density(g/cm$^3$) | 2.536 | 2.535 | 2.538 | 2.539 |
| AV (%) | 5.0 | 5.0 | 5.8 | 5.5 |
| VMA (%) | 16.9 | 16.8 | 18.2 | 17.5 |
| VFA (%) | 70.4 | 70.2 | 68.1 | 68.6 |
| MS (kN) | 8.95 | 7.65 | 10.62 | 9.35 |
| FL (0.1mm) | 32.3 | 34.9 | 33.2 | 35.7 |

Note: AV=air voids; VMA= voids in mineral aggregate; VFA= voids filled with asphalt; MS= Marshall stability; FL=flow value.

- **Wheel Tracking Test**

The wheel tracking test is applied to evaluate the permanent deformation characteristics of asphalt mixtures. The permanent deformation resistance is an important factor in asphalt pavement design, especially highlighted with the increase of heavy traffic nowadays. In Figure 7, it can be found that both steel fiber and graphite can significantly increase the DS values of asphalt concrete compared to the control ones. In terms of asphalt mixtures containing graphite, it can be explained by the stiffening effect of graphite powders, which can absorb most lightweight fraction of asphalt and make asphalt stiffer. As for steel fiber reinforced asphalt concrete, steel fibers can transform more free asphalt to structure asphalt due the extra interface bonding, Besides, well distributed steel fibers can form 3-dimensional reticular structure, which can transfer more stress. So the rutting resistance of asphalt mixture containing steel fibers will increase.

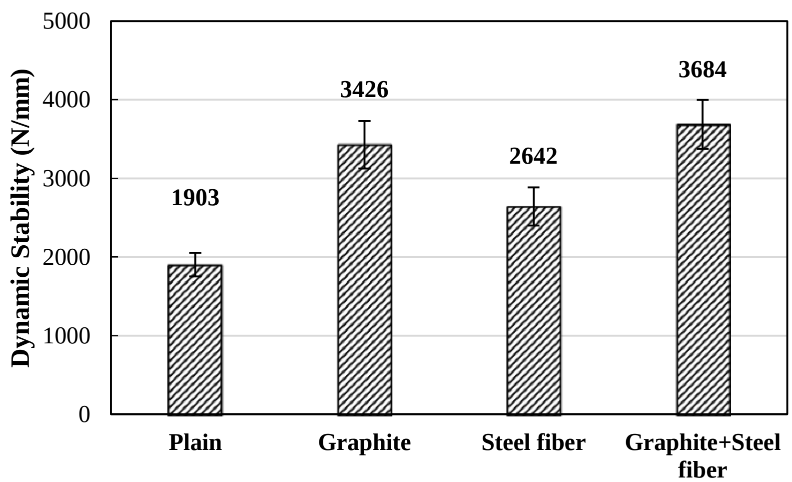


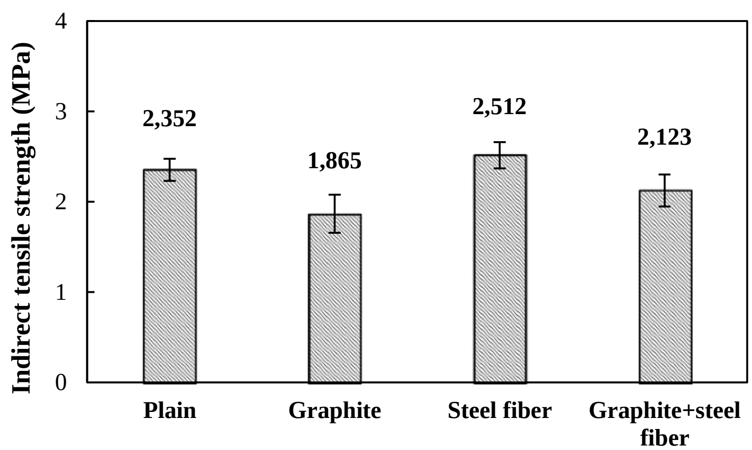

**Figure 7** Dynamic stablity of different asphalt concrete

- **Indirect Tensile Strength Test**

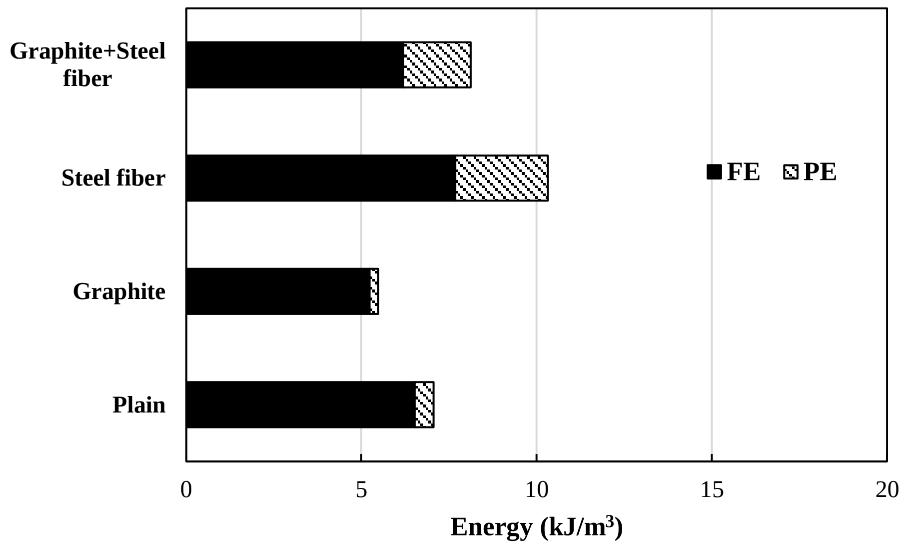
Focusing on low temperature cracking resistance, indirect tensile strength, fracture energy, and post-cracking energy were obtained from indirect tensile strength tests at -10 °C.

Figure 8 compared the indirect tensile strength test results of conductive asphalt concrete containing different additives to the control ones. As shown in Figure 8*a*, steel fiber reinforced asphalt concrete has the highest ITS, while asphalt concrete containing graphite has the lowest ITS.

In Figure 8*b*, it can be seen that FE, PE, and toughness have good correlations with ITS for these four asphalt concrete samples in this study. Due to the special layered structure of graphite powder, there is molecular interactions between layered structures of graphite, which belongs to weak Van der Waals force. So asphalt mastic containing graphite in the mixture is prone to produce interlayer slide when asphalt concrete samples are under tensile forces. The graphite has a lubricating effect to decrease the adhesion force between asphalt binder and aggregates. Therefore, the asphalt concrete containing graphite has the lowest resistance to cracking.




(a) ITS




(b) FE, PE, and toughness

**Figure 8** ITS and toughness of different asphalt concrete

In contrast, steel fibers significantly improve the cracking resistance of asphalt concrete. It is known that steel fiber has a high tensile strength. The single steel fiber tensile strength can be calculated from Figure 4, about 502 MPa, which is much higher than that of asphalt concrete. Hence, well distributed steel fibers in asphalt concrete can form a 3-dimensional reticular structure. The meshed structure has both reinforcing and toughening effect in the mixture, which can increase the tensile strength and deformation resistance of asphalt concrete. Furthermore, a shift in fracture mode was observed in fiber reinforced specimens during the test. Unlike the control and graphite modified mixture specimens, which split into two parts along a diametrical line in a brittle manner, the fracture mode of fiber reinforced specimens is close to a localized punching failure around the loading strip, and is accompanied by significant amounts of crushing of asphalt concrete around the fracture surface. These observations support aforementioned analysis and imply that fracture of steel fiber reinforced asphalt concrete is a combination of fiber pull-out accompanied by localized crushing of asphalt concrete.

## 4. Conclusions and recommendations

Asphalt concrete generally behaves as an insulated material. The addition of electrically conductive additives can endow the plain asphalt concrete with conductivity. This study intends to provide a design methodology of asphalt concrete that concludes both good electrical and mechanical properties. In order to achieve this goal, various tests have been conducted to investigate both electrical and mechanical performance of asphalt concrete containing steel fiber and/or graphite. Based on the testing results in this study, it is concluded:

(1) From the single fiber pull-out test results, the critical embedded steel fiber length is 9.6 mm, which can maximize the steel fiber's potential to bridge across the crack and delay the crack propagation.

(2) Electrical conductivity of asphalt concrete could be improved with the addition of either steel fiber or graphite. However, it is much more effective to reach the desired conductivity with steel fibers rather than graphite powders. A combination of steel fiber and graphite enables the gradual decrease of the resistivity of asphalt concrete. The improvement mechanism can be considered in view of the two following effects: conductive graphite powders exhibit the short-range contacts in the form of clusters, whereas fibers exhibit the long-range bridging effect and short-range contacting effect because of the high aspect ratio.

(3) An optimized amount of well-distributed steel fiber generally improves the mechanical properties (such as stability, rutting resistance, and low temperature cracking resistance) of asphalt concrete compared to the plain concrete due to the reinforcing effect. The addition of graphite could increase the permanent deformation resistance with compromised stability and low temperature performance. Asphalt concrete containing steel fibers and graphite weakens the steel fiber reinforcing and toughening effect, but still has a significant improvement in mechanical performance.

For future work, the authors intend to find a better conductive filler that can enhance both electrical and mechanical performance of asphalt concrete. Also, due to the difficulty of sample preparation and obtaining effective results of fiber pull-out test, a new multi-fiber pull-out test needs to be put forward to investigate the interfacial action between fibers and asphalt matrix.

**Acknowledgements**

The authors are very thankful to the financial support of the Specialized Research Fund for the Doctoral Program of Higher Education of China (Grant No. 20120092110053). The corresponding author would like to acknowledge the scholarship from China Scholarship Council. Special thanks are given to Dr. Weiguang Zhang at Pennsylvania State University for his insightful comments on this paper.

**References**

[1] Wang, H., J. Yang, M. Gong, and X. Shi. Laboratory Performance Evaluation of High-Modulus Asphalt Mixtures for Perpetual Asphalt Pavements. Presented at 94th Annual Meeting of the Transportation Research Board, Washington, D.C., 2015.

[2] Roberts, F.L., L.N. Mohammad, and L.B. Wang. History of hot mix asphalt mixture design in the United States. *Journal of Materials in Civil Engineering*, Vol. 14, No. 4, 2002, pp. 279-293.

[3] Nicholls, C. *Asphalt Surfacings*, E & FN Spon, New York, 1998.

[4] Akcay, B., and M.A. Tasdemir. Mechanical behaviour and fibre dispersion of hybrid steel fibre reinforced self-compacting concrete. *Construction and Building Materials*, Vol. 28, No. 1, 2012, pp. 287-293.

[5] Abtahi, S.M., M. Sheikhzadeh, and S.M. Hejazi. Fiber-reinforced asphalt-concrete - A review. *Construction and Building Materials*, Vol. 24, No. 6, 2010, pp. 871-877.

[6] Garcia, A., J. Norambuena-Contreras, and M.N. Partl. A parametric study on the influence of steel

wool fibers in dense asphalt concrete. *Materials and Structures*, Vol. 47, No. 9, 2014, pp. 1559-1571.

[7] Wu, S.P., P. Pan, M.Y. Chen, and Y. Zhang. Analysis of Characteristics of Electrically Conductive Asphalt Concrete Prepared by Multiplex Conductive Materials. *Journal of Materials in Civil Engineering*, Vol. 25, No. 7, 2013, pp. 871-879.

[8] Liu, X.M., S.P. Wu, Q.S. Ye, H. Qiu, and B. Li. Properties evaluation of asphalt-based composites with graphite and mine powders. *Construction and Building Materials*, Vol. 22, No. 3, 2008, pp. 121-126.

[9] Liu, X.M., and S.P. Wu. Study on the graphite and carbon fiber modified asphalt concrete. *Construction and Building Materials*, Vol. 25, No. 4, 2011, pp. 1807-1811.

[10] Liu, Q., E. Schlangen, and M. van de Ven. Induction Healing of Porous Asphalt. In *Transportation Research Record: Journal of the Transportation Research Board, No. 2305*, Transportation Research Board of the National Academies, Washington, D.C., 2012, pp. 95-101.

[11] Garcia, A., M. Bueno, J. Norambuena-Contreras, and M.N. Partl. Induction healing of dense asphalt concrete. *Construction and Building Materials*, Vol. 49, No., 2013, pp. 1-7.

[12] Menozzi, A., A. Garcia, M.N. Partl, G. Tebaldi, and P. Schuetz. Induction healing of fatigue damage in asphalt test samples. *Construction and Building Materials*, Vol. 74, No., 2015, pp. 162-168.

[13] Mallick, R.B., B.L. Chen, S., Bhowmick, and M. Hulen. Capturing Solar Energy from Asphalt Pavements. *Proc., International ISAP Symposium on Asphalt pavements and Environment*, International Society for Asphalt Pavements (ISAP), Zurich, Switzerland, 2008.

[14] Wu, S., L. Mo, Z. Shui, and Z. Chen. Investigation of the conductivity of asphalt concrete containing conductive fillers. *Carbon*, Vol. 43, No. 7, 2005, pp. 1358-1363.

[15] Huang, B.S., X.W. Chen, and X. Shu. Effects of Electrically Conductive Additives on Laboratory-Measured Properties of Asphalt Mixtures. *Journal of Materials in Civil Engineering*, Vol. 21, No. 10, 2009, pp. 612-617.

[16] García, Á., E. Schlangen, M. van de Ven, and Q. Liu. Electrical conductivity of asphalt mortar containing conductive fibers and fillers. *Construction and Building Materials*, Vol. 23, No. 10, 2009, pp. 3175-3181.

[17] Park P. Characteristics and applications of high-performance fiber reinforced asphalt concrete. PhD thesis, University of Michigan, Michigan, 2012.

[18] García, A., J. Norambuena-Contreras, M.N. Partl, and P. Schuetz. Uniformity and mechanical properties of dense asphalt concrete with steel wool fibers. *Construction and Building Materials*, Vol. 43, No., 2013, pp. 107-117.

[19] Wang, H. Design and Evaluation of Conductive Asphalt Concrete for Self-Healing. Matser thesis, Southeast University, Nanjing, 2016.

[20] Yoo, P.J., and I.L. Al-Qadi. Pre- and post-peak toughening behaviours of fibre-reinforced hot-mix asphalt mixtures. *International Journal of Pavement Engineering*, Vol. 15, No. 2, 2014, pp. 122-132.

[21] Lee, S.J., J.P. Rust, H. Hamouda, Y.R. Kim, and R.H. Borden. Fatigue cracking resistance of fiber-reinforced asphalt concrete. *Textile Research Journal*, Vol. 75, No. 2, 2005, pp. 123-128.

[22] Ahmedzade, P., and B. Sengoz. Evaluation of steel slag coarse aggregate in hot mix asphalt concrete. *Journal of hazardous materials*, Vol. 165, No. 1-3, 2009, pp. 300-305.

[23] Roque, R., and L. George. Development and Evaluation of a Simplified Superpave IDT Testing System for Implementation in Mix Design and Control. Final Report: FDOT-BD545-38, Florida Department of Transportation, 2008.

[24] Koh, C., and R. Roque. Characterization of the Tensile Properties of Open Graded Friction Course Mixtures Based on Direct and Indirect Tension Tests. *Journal of Testing and Evaluation*, Vol. 38, No. 4, 2010, pp. 412-423.

[25] García, Á., E. Schlangen, M.van de Ven, and G.van Bochove. Optimization of composition and mixing process of a self-healing porous asphalt. *Construction and Building Materials*, Vol. 30, No., 2012, pp. 59-65.