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

Haopeng Wang [a,*], Jun Yang [b], Hui Liao [b], Xianhua Chen [b]

[a] Section of Pavement Engineering, Faculty of Civil Engineering & Geosciences, Delft University of Technology, Stevinweg 1, 2628 CN Delft, The Netherlands
[b] School of Transportation, Southeast University, No. 2 Sipailou, Nanjing 210096, PR China

HIGHLIGHTS

- We use the combination of steel fiber and graphite as the conductive additives.
- Single fiber pull-out test was conducted to obtain critical steel fiber length.
- We proposed a design methodology of asphalt concrete that concludes both good electrical and mechanical properties.
- A combination of steel fiber and graphite enables to manipulate and precisely control the resistivity of asphalt concrete.

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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.

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

* Corresponding author.
E-mail address: crazywhp@seu.edu.cn (H. Wang).

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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. Fig. 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 Fig. 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 Fig. 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].

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 durability 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.

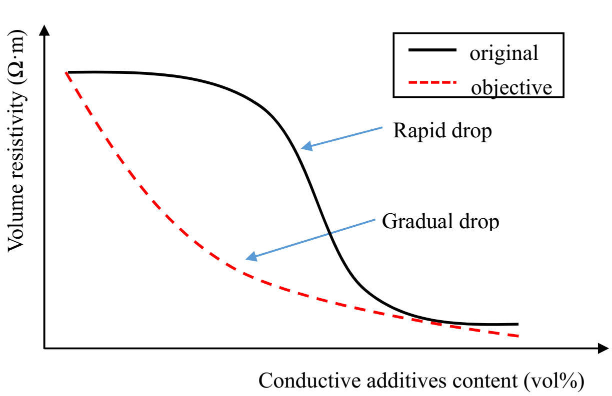

Fig. 1. Objective of imparting conductivity (compared to the result of Gracia et al. [16]).

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.

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 7×10^{-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. Fig. 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 Fig. 2, the resistivity of the asphalt mixture can be precisely controlled by filling the gap between aggregates and conductive fibers with conductive mastic.

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.

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

Table 1
Basic properties of asphalt binder.

Properties	Value
Penetration (25 °C, 100 g, 5 s, 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