Construction and Building Materials 135 (2017) 394–404

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Electrical and mechanical properties of asphaltic composites containing carbon based fillers

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HIGHLIGHTS

- The effects of carbon based fillers in conductive asphalt mixtures are investigated.
- The electrical conductivity of asphalt concrete highly depends on graphite type.
- Sufficiently high conductivity can be achieved only by adding flake type graphite.
- Adding graphite improves the indirect tensile strength of asphalt concrete.

ARTICLE INFO

Article history:
Received 9 June 2016
Received in revised form 8 December 2016
Accepted 30 December 2016

Keywords:
Electrical conductivity
Multifunctional material
Graphite
Percolation threshold
Asphalt concrete

ABSTRACT

Electrically conductive asphalt concrete has strong potential for diverse multifunctional applications including heated pavements to remove snow and ice, self-sensing, self-healing, and energy harvesting. In this study, the effects of powder type carbon based additives including eight graphite and carbon black on asphaltic composites are investigated. The physical, electrical, and mechanical properties of the raw materials, asphalt mastic, and asphalt concrete are experimentally evaluated focusing on electrical conductivity. The mastic test results indicate that electrical conductivity of the asphalt mastics substantially influenced by the particle shape, and flake type graphite is efficient in imparting conductivity. Based on the mastic test results, two flake type graphite were selected, and added into asphalt concrete specimens. The results showed that a sufficiently high electrical conductivity can be achieved by adding 2–3% of filler size flake graphite by volume of asphalt concrete. In addition, adding the flake graphite improves the indirect tensile strength of asphalt concrete up to 40%. The findings of the study will provide fundamental backgrounds in using carbon based powder type conductive additives for multifunctional applications of asphaltic composites.

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1. Introduction

Graphite is one of the most common allotropes of carbon having most stable crystal structure. Because of the good conduction property and low cost, graphite is used as a popular additive to produce multifunctional composites for various engineering applications. Multifunctional materials are structural materials that have non-structural functions (e.g., smart sensing, temperature control, electromagnetic shielding, etc.) in addition to the traditional structural functions (resistance to mechanical forces). While good mechanical properties such as strength and stiffness are the primary functions, the structural materials can have various smart functions by manipulating electrical, magnetic, optical, and other non-structural properties. Among those various non-structural properties, imparting and utilizing electrical conductivity has been actively studied because of its various potential applications such as self-sensing, self-healing, electromagnetic shielding, and energy harvesting [1,2]. According to Gibson [2], technical papers on multifunctional materials have been published since 2000, and have steadily increased till now.

Asphalt concrete – the mixture of various size aggregates and asphalt binder – is one of the most widely used infrastructure materials along with cement concrete. Asphalt concrete is a non-conductive composite by nature, but its electrical conductivity can be improved by using various conductive additives [3]. The conductive asphalt concrete has strong potential for diverse multifunctional applications including heated pavements to remove

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http://dx.doi.org/10.1016/j.conbuildmat.2016.12.221
0950-0618/Published by Elsevier Ltd.

snow and ice [4,5], self-sensing [6,7], self-healing [8,9], and energy harvesting [10–12]. For example, the self-healing and deicing of asphalt pavement are applications that stem from electrical heating [4,5,8,9]. Internal damages and strain of asphalt concrete can be evaluated without sensors by utilizing potential-drop method and piezo-resistivity [6], respectively.

In order to impart electrical conductivity into asphalt concrete, previous investigators have tested various conductive fibers and fillers including steel fibers [5,7,13], carbon fibers [5,14], steel wool [8,15], carbon black [16], and graphite powder [5,14,15,17]. Table 1 lists some selected previous studies on the conductive asphalt concrete and their applications. The conduction mechanism of composites containing conductive fibers and fillers are explained by percolation theory. The percolation in conductive composites refers that the conductive particles or fibers dispersed in non-conductive matrix are connected to each other and form conductive paths. A percolation threshold is the volume fraction of the conductive additives that the conductive paths form [23,24], and above the percolation threshold, the conductivity of the composites is governed by the contact resistance of conductive additives [1]. Fig. 1a and b show the conduction mechanism of non-conductive matrix containing conductive additive (reproduced based on Huang et al. [7]). Huang et al. [14] investigated the percolation thresholds of three additives – micro-steel fiber, carbon fiber, and graphite powder – and showed that the fiber type additives have relatively low percolation thresholds than graphite powder as shown in Fig. 1c. Garcia et al. [15] obtained similar results using steel wool (fiber type) and graphite. Most of the previous investigators selected fiber-type additives as their primary conductive additives rather than powder-type additives because relatively smaller amounts of fibers is needed to form the conductive paths than the powders.

On the other hand, the particle type conductive additives have some potential advantages over the conductive fibers. Clumping and balling of fibers during the mixing is one of the problems of fiber type additives that may degrade mechanical performance of asphalt concrete [25], but the powder type additives do not have such problem. By replacing some amount of traditional fillers (particles smaller than 75 μm), the powder type additives can impart conductivity without affecting the skeletal structure of asphalt concrete. Another potential benefit of powder type additives is a gradual transition from the conductive phase to non-conductive phase. As shown in Fig. 1c and a sudden drop of electrical resistivity occurs when the conductive fibers were used, while the graphite powder provides relatively gradual drop in resistivity. By narrowing the adjustable volume resistivity range of conductive asphalt, the sudden phase change introduces limitations for developing various multifunctional applications. For example, the piezoresistivity is the property of conductive composites that enables the self-sensing of strain. In piezo-resistive materials, deformation causes changes in conductive filler concentration and conduction network [26], and leads to changes in electrical resistivity. For a wide sensing range and consistent sensing and precise control of the composite conductivity, a gradual resistance change with the increase of conductive additive is favorable. In addition, graphite and carbon black are cheaper than carbon fibers, abundant materials, and chemically compatible [27] with asphalt binder.

As shown in Table 1, the powder type conductive additives – graphite and carbon black – have been used as primary or supplementary conductive additives in asphalt concrete by some researchers [4,5,7,15–17,21], but the efficiency of graphite in imparting conductivity is not consistent. According to the shape, size, origin and manufacturing process, there exists many different types of graphite. Park et al. [28] pointed out that the size and shape of graphite are important factors on imparting conductivity into asphalt, but no other investigators have focused on the effect of graphite type.

The objective of the study is to investigate the effects of various powder type conductive additives on the conductive phase transition and mechanical properties of asphalt concrete. Particularly, the study focuses on the different microstructures of graphite. As a first part of the study, the conductivity of asphalt mastics (mixture of asphalt binder and filler) containing nine different carbon based conductive fillers are investigated, and the physical properties of the conductive powders are compared. Based on the results, the most efficient conductive filler is selected and viscoelastic properties of a mastic containing the selected are evaluated. In the second part of the paper, a set of experiments for asphalt concrete (mixture of asphalt binder, filler, and coarse/fine aggregates) are conducted with selected graphite types. The conductive phase transition in asphalt concrete and the strength of the conductive asphalt concrete are examined.

2. Experimental methods

2.1. Specimen preparations

2.1.1. Raw materials

To minimize the effect on skeletal structure of asphalt concrete, the conductive additives were selected within the filler size

Table 1
Summary of previous research on conductive asphalt composites.

Author	Conductive filler used	Percentage of additive to attain resistivity of 10^3 Ω cm (Percent Vol. by Binder)	Purpose
Minsk [4]	Graphite (G)	G—17% and 21%	Snow and ice removal
Stratfull [18]	Coke breeze	–	Cathodic protection of steel rebars in concrete bridges
Fromm [19]	Coke breeze	–	Cathodic protection of concrete bridge decks
Zaleski et al. [20]	Graphite and coke	–	Deicing
Wu et al. [21]	Graphite	G—26%	Self-sensing applications
Wu et al. [16]	Carbon black (CB), graphite, and carbon fibers (CF)	CB—13%, CF—6%, or G—30%	Imparting conductivity CF > G > CB
Huang et al. [7]	Microscale steel fibers (SF), aluminum chips, and graphite	SF—0.75% or G—11%	Study conductivity, IDT, and beam fatigue test
Huang et al. [14]	Microscale steel fiber, carbon fiber, and graphite	SF—0.99%, CF—5%, or G—18%	IDT strength, IDT fracture energy, dynamic modulus, flow number, and asphalt pavement analyzer (APA) rut depth
Garcia et al. [15]	Graphite and steel wool (SW)	SW—6% or G—beyond 30%	Sand-bitumen ratio and effect of fiber content
Liu and Wu [6]	Graphite and carbon fiber	G—12%	Piezoresistivity
Liu and Wu [22]	Graphite and carbon fiber	G—15%	Marshall stability, resilient modulus, and dynamic stability
Park [17]	Graphite	G—21%	Electrical conductivity of different types of graphite
Wu et al. [5]	Graphite, steel fiber, steel slag, carbon fiber	Composite 3–28%	Deicing
Menozzi et al. [9]	Cast steel particles	33% (approximated)	Self-healing