Geotextiles and Geomembranes 46 (2018) 414–425

Contents lists available at ScienceDirect

Geotextiles and Geomembranes

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

Comparative flexural performance of compacted cement-fiber-sand

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ARTICLE INFO

Keywords:
Fiber-reinforced soil
Flexural performance
Geosynthetics
Pavement materials
Soil stabilization
Toughness

ABSTRACT

This research investigates the influence of seven different fiber types on the flexural performance of compacted cement-fiber-sand (CCFS) with four fiber fractions (0.5, 1, 1.5 and 2% by volume). The seven types of fibers are 12 mm polypropylene, 19 mm polypropylene, 40 mm polypropylene, 55 mm polypropylene, 33 mm steel, 50 mm steel and 58 mm polyolefin fibers. The overall CCFS performance was divided into seven sub design performance indicators: (1) peak strength; (2) peak strength ratio; (3) residual strength ratio; (4) ductility index; (5) toughness; (6) equivalent flexural strength ratio; and (7) maximum crack width. The interaction mechanism of the fiber/cement-sand interface was investigated by scanning electron microscopy. Finally, the effectiveness of each fiber type was compared and rated in terms of the overall performance. The results show that the 50 mm steel fiber provided the best overall sub performance, resulting in an excellent overall flexural performance; in comparison, the 12 mm polypropylene fiber exhibited very poor performance. However, the 19 mm polypropylene and 33 mm steel fiber specimens provided very good and good overall performances, respectively. The nature of the fiber surface and the fiber length affects the overall performance of CCFS. The surface of the steel fibers, compared to the other synthetic fiber types, is more hydrophilic and is more compacted in a cemented-sand matrix without separation of the interfacial zone, providing the best overall flexural performance.

1. Introduction

Cement-treated soils are extensively utilized worldwide as a pavement base and in subbase applications (Consoli et al., 2011a; Horpibulsuk et al., 2013; Ma et al., 2014; Mohammadinia et al., 2015; Yi et al., 2015; Güllü and Fedakar, 2016; Jiang et al., 2016; Phummiphan et al., 2016) due to their high compressive strength and stiffness. In reality, the structural layers in pavement are subjected to tensile and flexural stresses rather than compressive stresses, whereas cement-treated soils have very low tensile and flexural strengths compared to their compressive strengths. Moreover, cement-treated soils exhibit brittle behavior under flexural loading (Plé et al., 2012; Sukontasukkul and Jamsawang, 2012; Onyejekwe and Ghataora, 2014; Jamsawang et al., 2015a; Disfani et al., 2014), while ductile behavior is required for pavement materials to prevent immediate failure due to excessive traffic loads and to save cost in terms of increasing the performance life of the pavement and reducing the frequency of maintenance operations (Disfani et al., 2014). The inclusion of randomly oriented discrete synthetic fibers in cement-treated soils led to substantive improvements in their tensile and flexural performances (Estabragh et al., 2012; Hejazi et al., 2012; Olgun, 2013; Chen et al., 2015; Correia et al., 2015; Jamsawang et al., 2015a; Ates, 2016; Kumar and Gupta, 2016; Anggraini et al., 2016, 2017; Oliveira et al., 2016; Ayeldeen and Kitazume, 2017; Festugato et al., 2017; Kim and Kim, 2017) because fibers capture and redistribute loads through their tensile strength, mobilizing a wider mass of cement-treated soil (Festugato et al., 2017).

Compacted cement-sand (CCS) is mostly used as a base or subbase of pavement structures (Al-Aghbari et al., 2009; Consoli et al., 2011a; Jamsawang et al., 2015a; Ates, 2016). Most previous researchers concentrated on the effect of fiber inclusions on the splitting tensile strength of compacted cement-fiber-sand (CCFS) due to the availability of test apparatuses, the convenience of specimen preparation and their familiarity with the splitting test rather than the flexural test, even though flexural strength tests have the potential of more accurately simulating field conditions than those in splitting tensile strength tests,

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https://doi.org/10.1016/j.geotexmem.2018.03.008
Received 25 November 2017; Received in revised form 13 March 2018; Accepted 16 March 2018

for a better prediction of the actual performance of pavement structures (Viswanadham et al., 2010; Onyejekwe and Ghataora, 2014), and often concluded that the splitting tensile strength of CCFS increases with the volume fraction, aspect ratio (length/diameter) and orientation of the fibers, cement content, and soil type and properties (Consoli et al., 2011b; Consoli et al., 2012, 2013; Festugato et al., 2017, 2018). Moreover, flexural strength is significant in pavement design and is used to determine slab thickness (ASTM D1635-00, 2000).

However, limited research on flexural strength performance of CCFSs was reported until Onyejekwe and Ghataora (2014) studied the influence of fiber inclusions on the flexural performances of CCS according to ASTM D1635-00 (2000) and found that the inclusion of the fibers led to significant improvements in the flexural load-carrying capacity of the CCSs, increasing the toughness of the specimens and degree of residual load after the first crack over those of unreinforced specimens and their brittle, catastrophic failure. The residual load of the CCFSs was as much as 75% of the maximum load at 10 times the deflections of the CCSs at first crack.

In fact, standard ASTM D1635-00 (2000) can only determine the flexural strength of CCS without fiber inclusion, which is unusual for CCFS, whereas standard ASTM C1609/C1609M-10 (2010) is commonly used to investigate the flexural performances of concrete and concrete-type materials, or so-called fiber-reinforced cementitious composite (FRCC) (Sukontasukkul and Pomchiengpin, 2010; Kim et al., 2011; Nematollahi et al., 2014). The flexural performance of CCFS can be considered similar to that of FRCC; therefore, Jamsawang et al. (2015a) presented the effect of fiber and cement contents on the flexural response of CCFS according to ASTM C1609/C1609M-10 (2010) using one type of polypropylene fiber. The fiber contents of 0.5–2% and cement contents of 3–7% were employed in the study. CCFSs can exhibit a higher strength, residual strength, ductility and toughness and a smaller crack width than CCSs, which fail in tension immediately after the formation of a single crack. The performance of a CCFS can be improved to exhibit a deflection-hardening response in bending accompanied by multiple cracks after initial cracking, depending on the fiber content. In such a case, the CCFS is known as a deflection-hardening CCFS; thus, a much smaller amount of fiber is required to obtain a deflection-hardening response than to induce deflection-softening behavior. The minimum polypropylene fiber content of 1% was required to obtain a deflection-hardening response for the CCFS, and a higher cement content provided better flexural performance due to the increase in interfacial bond between the polypropylene fiber and cement-sand matrix.

The flexural performances of FRCC depends on various factors, such as the fiber material properties (strength and stiffness), fiber geometry (smooth, hooked end, crimped, or twisted), fiber volume content, strength of the matrix properties, and interface properties (adhesion, friction, and mechanical bond) (Cho et al., 2006; Tang et al., 2010; Kim et al., 2011; Nematollahi et al., 2014; Hannawi et al., 2016; Sarir et al., 2016; Simoes et al., 2017). Clearly, for a given matrix, the type and quantity of fiber are key parameters that influence the performance of FRCC, as well as the material cost. All else being equal, matrixes in which a low fiber-volume fraction can be used while still attaining a strain-hardening or deflection-hardening response are attractive in terms of cost (Kim et al., 2011; Nematollahi et al., 2014). The summary of suitable fiber types was often present in term of individual sub performance, whereas the overall performance is required to specify the best fiber type for FRCC.

The influence of fiber types on the flexural performance of cement-admixed soft clay was investigated by Sukontasukkul and Jamsawang (2012) sing short steel, long steel and polypropylene fibers at three different volume fractions of 0.5, 0.75 and 1.0% under test standard ASTM C1609/C1609M-10 (2010). The high cement content of 20% was used to attain the required compressive strength of 700 kPa. With fiber inclusions, the flexural performance of the cement-admixed soft clay was improved in terms of its toughness, equivalent flexural strength ratio and residual strength but not its peak flexural strength. The degree of improvement increased with the fiber volume fraction. The polypropylene fiber is found to perform better than the steel fibers without using a comparative evaluation method to determine the ability of each fiber type and without microstructural analysis on the nature of the interfacial bonds between the fiber surface and surrounding cement-admixed clay matrix, which is significant for investigating the influence of fiber types (Tang et al., 2010; Hejazi et al., 2012; Hannawi et al., 2016; Simoes et al., 2017) on the flexural performances.

Previous studies of the flexural response of CCFS used unusual test standards and addressed different matrix composition and fiber volume fractions with only one fiber type in each experiment. In addition, the comparative flexural performance of CCFS with various fiber types has not yet been comprehensively studied at the macro-scale and micro-scale. Moreover, no reasonable comparative guideline has been proposed to determine how to select the most suitable fiber type for a pavement structure. Therefore, the current status of CCFS research in the literature and the need to isolate the effects of fiber type on the flexural performance of CCFS, including the hardening or softening responses, have motivated the experimental study reported in this paper. Specifically, this study focuses on the sub flexural performance indicators of peak strength, peak strength ratio, residual strength ratio, ductility index, toughness, equivalent flexural strength ratio and maximum crack width. The interactions between the fiber surface and the stabilized soil were analyzed by means of scanning electron microscopy (SEM). Finally, the effect of the fiber type on the overall performance of CCFS was evaluated and rated in this study to determine a suitable fiber type for use in pavement materials.

2. Experimental program

The experimental program was carried out in three parts. First, the geotechnical properties of the studied sand and physical and engineering properties of all fiber types were characterized. Second, a series of flexural strength tests were carried out for both the CCS and CCFS specimens. Finally, a series of SEM analyses was conducted on the CCFS samples to observe the interaction mechanism of a fiber/cement-sand interface and to describe the effect of fiber type on the flexural performances of the CCFS test beam.

2.1. Materials

The sand used in the present experimental tests was obtained from Ayutthaya province, Thailand, and is commonly used as a construction material for embankment, fill and pavement applications. The grain size distribution curve and physical properties of Ayutthaya sand are shown in Fig. 1 and Table 1, respectively. This sand is classified as poorly graded sand (SP) according to the Unified Soil Classification System (USCS). Fig. 1 also shows an enlargement of the sand particles obtained from the SEM analysis, which illustrates angular and sub-angular shapes with a rough surface. The results of X-ray diffraction (XRD) analysis show that the mineral composition of the sand used was 60% feldspar and 40% quartz. The cement used in the test was ordinary Portland cement type I with a specific gravity of 3.15. Table 2 is a summary of the chemical composition of the cement used. Fibers used in this study were divided into two major types, depending on the size of the fibers: micro-fibers and macro-fibers. The size of the macro-fiber can be simply specified by ordinary mechanical measuring instruments, whereas the microscopic size of the micro-fiber is unspecified. A total of seven fiber types were used in the current study, which consisted of two macro-fiber and five micro-fiber types, respectively. Fig. 2a–g shows the shape and feather of the seven fiber types, namely, the micro 12 mm polypropylene, micro 19 mm polypropylene, macro 40 mm polypropylene, macro 55 mm polypropylene, 33 mm steel fiber, 50 mm steel and macro 58 mm polyolefin fibers. These fibers were distinguished mainly by their materials (steel or synthetic), dimensions (macroscopic