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Effect of carbon fiber and nanosilica on shear properties of silty soil and the mechanisms

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HIGHLIGHTS

- Carbon fiber and nanosilica have been utilized to improve the properties of silty soil.
- The carbon fiber could improve internal friction angle of silty soil up to 12%.
- The nanosilica can increase 117% cohesion of silty soil.
- The residual shear strength was increased by 128.27% compared with the control specimens at a normal stress of 100 kPa.

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ABSTRACT

In this study, the effects of carbon fiber and nanosilica on properties of silty soil including physical, microstructural characteristics and shear resistance were investigated. Soil samples treated with different contents of carbon fiber and nanosilica were prepared and studied. The samples were tested by direct shear method under different normal pressure levels. Besides, SEM (scanning electron microscopy) tests were performed to examine the microstructural changes. The test results indicated that the shear strength of treated soil samples was significantly improved compared with the untreated soil samples. Carbon fiber was found effective in improving internal friction angle and cohesion thanked to the interface friction between fiber and soil. On the other hand, nanosilica could improve cohesion effectively due to full filling of the pores between soil particles. The results also showed that the combination of 2 wt% carbon fiber and 3 wt% nanosilica could improve the shear stiffness and particularly the residual shear strength, which was increased significantly by 128.3% compared with the untreated soil sample at a normal stress of 100 kPa. The results demonstrated that the use of carbon fibers and nanosilica can be an effective method to improve silty soil in lieu of traditional cement grouting in mitigating geotechnical engineering disasters.

1. Introduction

Soil reinforcement is an effective and reliable technique which is widely used in geotechnical engineering practice for slope stability and strengthening, bearing capacity of road pavement, embankment, earthquake liquefaction and solving foundation capacities problems. There are many ways to reinforce soil in geotechnical engineering. One of them is using additives such as cement. Cement has been extensively used in soil stabilization and is usually used as a major addition material to improve the mechanical properties (strength and stiffness) of soil in the past decade. However, there are some issues associated with the use of cement. For example, curing time is inevitably required for cement treated soil and the use of cement will have a great impact on the ecology and surrounding environment. Moreover, the cement grouting often requires high pressure to inject cement slurry into the target soil. Therefore, the adjacent buildings may have higher risk of damage [1].

The method of using fibers to reinforce silty soil has attracted much attention from researchers in many applications due to the desirable properties and advantages of fibers, such as reliable strength, slow biodegradation rate, and low cost [2]. In particular, the short synthetic fibers have attracted increasing attention in the study of soil modification over the past years owing to their high tensile resistance that could impart greater strength to the soil compared with natural fibers. However, reinforcing soil with synthetic fiber is still a relatively new technique and the mechanism

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of soil-fiber performance needs to be fully examined in each geotechnical project. Zhu et al. [3] studied the pullout behavior of soil reinforced with 5 mm short polypropylene fibers and showed that the interfacial peak/residual shear strength and shear stiffness of fiber-modified soil were mainly determined by the compaction conditions. Ates [4] added glass fiber and cement to improve the structure and mechanical properties of silty soils. Choo et al. [5] reinforced soil with randomly distributed synthetic fibers and evaluated the compressibility and small strain stiffness characteristics of fiber-reinforced soils. Other experimental and modelling studies [6,7] can also be found in the literatures. Sharma and Kumar [8] reported that the strength and bearing capacity of the fiber-reinforced soil increased remarkably with increasing the relative density of the soil. Besides, it has been suggested that fibers can improve the ductility and liquefaction resistance of soil [9,10]. These existing studies confirmed the effectiveness of fibers in improving the mechanical behavior of silty soil. However, there are still some problems with fiber treated silty soil to be solved including their uniform distribution and orientation in soil, fiber-soil interface bonding, uncompressed property of fiber, brittleness of fiber-soil mixture etc.

Nowadays, with the emergence of nanotechnology, the use of nanomaterials in soil improvement has received a lot of research interest, especially for cohesion-less soil such as silty soil. It is believed that the use of nanomaterials can enhance the mechanical properties of soil through different mechanisms [11]. For instance, Iranpour and Haddad [12] found that nanosilica can contribute to a compact microstructure of soil structure by filling the pores. Changizi et al. [13] showed that the use of nano particles in soil which treated with recycled polyester fiber could obtain effective results. Choobbasti et al. [14] carried out a series of tests on unconfined compression for investigating the mechanical properties of silty soils stabilized with Portland cement and nanoparticles. They found that the unconfined compressive strength increased with increasing nanosilica content. Kutanaei and Choobbasti [15] examined the synergic effects of randomly distributed fibers and nanosilica on durability and mechanical characteristics of cement-treated silty soils. They reported that the behavior of cement-treated silty soils improved significantly when randomly distributed fibers were used in conjunction with an optimum percentage of nanoparticles. In addition, the studies of Bahmani et al. [16,17] also confirmed the positive impact of nanosilica on cement modified residual soil at different curing times. Despite the mixing preponderance of nanomaterials with other materials has been well understood in the study of soil stability, there has been very few studies focused on the combination use of nanomaterials and short synthetic fibers, such as carbon fiber, in soil reinforcement.

From the above literature review, it can be known that most of the previous studies are related to the mixture of cemented silty soil with either nanosilica or fiber. Due to the difficulty to treat silty soil without cement, so only few attentions have been paid to the combination use of nanosilica and fiber without using traditional cement. To treat silty soil without cement is a new challenge and the influences of different contents of nanosilica and fiber on improvement of silty soil matrix need to be investigated as well.

The purpose of this study was to investigate the influences of different carbon fiber and nanosilica dosages on mechanical properties of silty soil. In order to accomplish this aim, a series of laboratory tests on silty soil samples treated by randomly distributed carbon fiber and nanosilica particles was carried out. First, the effects of different carbon fiber and nanosilica contents (1 wt%, 2 wt%, 3 wt%) on performance of soil samples were examined and discussed separately. Then, the soil samples containing 2 wt% carbon fiber combined with different nanosilica contents (1 wt%, 2 wt%, 3 wt%) were examined and the synergic effects of carbon fiber and nanoscilica on mechanical properties of soil samples were revealed. The microstructural properties of treated and untreated silty soil were inspected using X-ray diffraction (XRD), scanning electron microscopy (SEM) and direct shear tests. This study can fill the relevant knowledge gap and reveal the synergic effects of carbon fiber and nanosilica on mechanical properties, shear strength development, and microstructure of the silty soil.

2. Materials and experimental procedure

2.1. Soil properties

The soil employed in this study was obtained from an excavation operation at a depth of 6 m in Longgang District, Shenzhen, China. The geotechnical properties of soil were tested according to the procedures of China national standard of GB/T 50123-1999 (Standard for soil test method) [18]. Table 1 presents the test results.

The particle size distribution of the soil is displayed in Fig. 1. In line with the distribution of the particle size of the soil, the soil can be defined as silty soil. It is worth noting that silty soil is widely distributed throughout the coastal regions and mountainous areas in China. So the issues of slope instability and liquefaction associated with silty soil need to be addressed efficiently and environmentally. Fig. 2 shows the results of X-ray diffraction analysis. From this figure, it can be illustrated that the soil has high silica content with some kaolin.

2.2. Carbon fiber and nanosilica

A synthetic carbon fiber (see Fig. 3a), made by Toray Group in China, was utilized as the reinforcement material in this research. The fiber has a length of 3 mm with a diameter of 7 μm. The tensile strength of fiber is 4.9 GPa, whereas its elastic modulus, elongation and density are 230 GPa, 2.1%, and 1.8 g/cm^3, respectively. Based on these excellent properties, a small amount of carbon fiber was expected to enhance the properties of soil efficiently.

It is worth noting herein that the long fibers are easily to aggregate and rolled in the soil. So a randomly distributed fiber-soil mixture is difficult to obtain when long fibers are used and the reinforcement effect would be heavily affected. The purpose of using 3 mm short fibers in this study was to fill pores in soil and provide some interfacial friction between fiber-soil particles. In addition, the 3 mm carbon fibers are more easily to distribute uniformly in soil and can be simply added and mixed randomly with soil, much like cement, lime, or other additives, to provide isotropic increase in strength of the soil composite. This is different from the function of long fibers which can form interlocking network and restrain soil particle movement that has been confirmed by pull out tests.

Table 1
Geotechnical properties of silty soils.

Items of the properties	Test result
Natural density (g/cm^3)	2.13
Natural moisture content (%)	16.1
Specific gravity	2.711
Liquid limit (%)	21.95
Plastic limit (%)	15.02
Plasticity index (%)	6.93

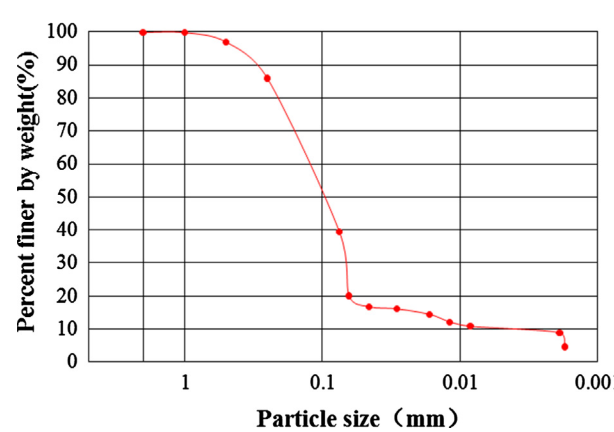

Fig. 1. Particle size distribution of the soil.