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Evaluation of compressibility and small strain stiffness characteristics of sand reinforced with discrete synthetic fibers

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ABSTRACT

This experimental investigation evaluates the compressibility and small strain stiffness of sand reinforced with discrete synthetic fibers. Varying fiber contents (FC), fiber aspect ratios (AR), and void ratios were selected as testing variables in this study, and the modified oedometer tests were conducted to measure the compression index (C_c) and maximum shear modulus (G_{max}) of fiber-reinforced sand. The results of this study demonstrate that the C_c of the tested fiber-reinforced sand increases with an increase in FC because the packing of sand grains in the fiber-reinforced sand is very loose due to a disruption of direct contact between the sand grains due to the presence of long discrete fibers. Additionally, this disruption of direct contact between sand grains due to the fibers results in a reduction of interparticle contact and coordination number between sand grains. Therefore, the G_{max} of tested fiber-reinforced sand decreases with an increase in FC. Most notably, the G_{max} of the tested fiber-reinforced sand with varying FC and AR can be expressed as a single function of the void ratio at a given applied stress, which implies that the inclusion of fibers just alters the packing state of sand grains, and the interparticle contact stiffness is mainly determined by the contacts between sand grains.

1. Introduction

The inclusion of discrete fibers in the matrix of sand grains can significantly enhance the engineering properties of unreinforced sand grains (Gray and Alrefeai, 1986; Heineck et al., 2005; Maher and Woods, 1990). Additionally, the discrete fiber reinforcement technique has several advantages over conventional reinforcement materials: 1) Conventional construction equipment can be used; 2) Reinforcement can be performed regardless of weather conditions; and 3) Potential planes of weakness do not develop (Li, 2005; Tang et al., 2010). Therefore, a number of studies have been performed to evaluate the engineering properties of fiber-reinforced sand. The engineering properties that have been most widely studied include the large strain shear strength of sand with fibers (Hejazi et al., 2012). Because the mobilized fiber-induced tensile strength at large strain can contribute to the shear resistance of sand (Alrefeai, 1991; Consoli et al., 2007; Diambra et al., 2010; Eldesouky et al., 2016; Gray and Alrefeai, 1986; Ibraim and Fourmont, 2007; Michalowski and Cermak, 2003), these previous studies showed an increase in shear strength of sand with an increase in fiber content.

The small strain stiffness or maximum shear modulus (G_{max}) is a fundamental property of soils for the design and analysis of soils and soil-structure interactions (Skels and Bondars, 2017; Tatsuoka and Shibuya, 1991). Additionally, G_{max} is an very important parameter to predict the deformation characteristics of soils (Choo et al., 2016a; Enomoto et al., 2013); therefore, the G_{max} of various natural geomaterials has been studied by numerous researchers (Mitchell and Soga, 2005). However, studies investigating the G_{max} of fiber-reinforced sand have been limited. Previous studies reporting the maximum shear modulus (G_{max}) of fiber-reinforced sand showed debatable results, with some investigations (first group) reporting that G_{max} increases with an inclusion of discrete fibers in the matrix of sand grains (Maher and Gray, 1990; Maher and Woods, 1990; Noorzad and Amini, 2014). Others (second group) demonstrated that the G_{max} of fiber-reinforced sand is essentially the same as that of unreinforced sand, reflecting a negligible effect of fibers on the G_{max} of sand (Heineck et al., 2005;

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Yetimoglu and Salbas, 2003). Other investigations (last group) showed that the G_{max} of fiber-reinforced sand is smaller than that of unreinforced pure sand (Clariá and Vettorelo, 2015; Michalowski and Cermak, 2003). These contradictory results, which reflect the lack of systematic analysis of the G_{max} of fiber-reinforced sand, may be attributed to the difference in testing conditions such as packing density and sand and/or fiber types.

The compression index (C_c) is a fundamental property of soils that characterizes the relationship between the applied stress and volume change of soils (Gregory et al., 2006); thus, it is a required parameter in the design of many geostructures (Holtz et al., 2010). Because the volume change (or settlement) of soils can be directly calculated using C_c, many researchers investigated the variations of C_c of various geomaterials (Das, 2008; Mitchell and Soga, 2005). However, limited studies have been performed to elucidate the compressibility/deformability of fiber-reinforced sand (Consoli et al., 2005; Dos Santos et al., 2010; Pino and Baudet, 2015). It should be noted that these previous studies measured the compression index (C_c) of fiber-reinforced sand at a very high applied stress (>3 MPa), and demonstrated that the C_c of sand is not affected by the addition of fibers. However, studies reporting the compressibility of fiber-reinforced sand at a low confining stress (<1 MPa) have been very limited up to now.

Consequently, the aim of the present investigation is to investigate the compressibility and small strain stiffness of discrete synthetic fiber-reinforced sand. Various fiber contents, fiber aspect ratios, and void ratios were selected as the testing variables in this study, and modified oedometer tests were conducted to measure both the shear wave velocity and the compressibility of fiber-reinforced sand under vertical stresses ranging from 7.0 kPa to 447.48 kPa.

2. Experimental program

2.1. Materials

Crushed K-6 sand, which was used as received from the Kyung In material company, South Korea, was selected for use as the host sand grains in this study. The tested K-6 sand is mainly composed of SiO_2 (>98%) and can be classified as poorly graded sand (SP) according to the Unified Soil Classification System (USCS). The basic index properties of the tested sand were determined as follows: 1) Median grain size was 0.467 mm according to ASTM D422; 2) Uniformity coefficient was 1.52 according to ASTM D422; 3) Specific gravity was 2.65 according to ASTM D854; 4) Maximum void ratio was 1.035 according to ASTM D4254; 5) Minimum void ratio was 0.656 according to ASTM D4253.

Two types of polypropylene fibers (Nycon Materials Company, South Korea) with different lengths, 6 mm and 12 mm, respectively, were used to prepare fiber-reinforced sand. Except for the length, the two fibers used in this study have the same diameter (0.04 mm), specific gravity (0.91), tensile strength (360 MPa), and elastic modulus (3.9 GPa).

No standardized method is available for the determination of extreme void ratios of fiber-reinforced sand (Dos Santos et al., 2010). Because the vibratory table method might not yield segregation between sand grains and fibers, the minimum void ratios (e_{min}) of the tested fiber-reinforced sand were determined according to ASTM D4235, and are reported in Fig. 1 and Table 1. In contrast, the methods for the determination of maximum void ratio (e_{max}) (e.g. funnel pouring in ASTM D4254), can yield significant segregation between sand grains and fibers. Therefore, e_{max} of fiber-reinforced sand was calculated from the difference between e_{min} of fiber-reinforced sand and e_{min} of unreinforced pure sand, based on the assumption that the difference in e_{max} between fiber-reinforced sand and unreinforced sand is equal to that of e_{min} (Dos Santos et al., 2010).

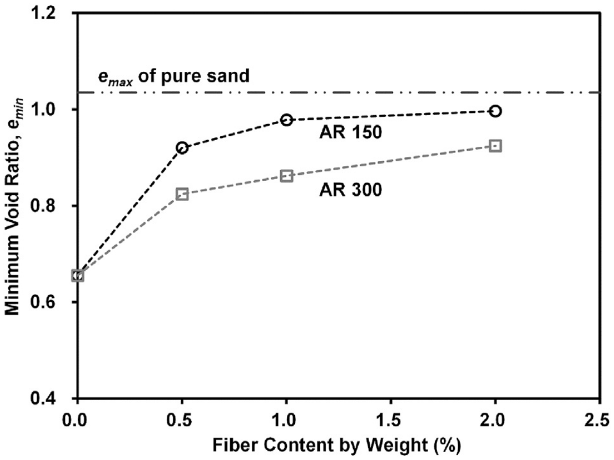

Fig. 1. Variation of minimum void ratios of the tested fiber-reinforced sand as a function of fiber content by weight. Note: AR 150 = fiber-reinforced sand with aspect ratio of 150; AR 300 = fiber-reinforced sand with aspect ratio of 300; e_{min} = minimum void ratio; e_{max} = maximum void ratio.

2.2. Sample preparation and testing program

Table 2 shows the test matrix of this study. In order to prepare the mixtures of sand and discrete synthetic fibers with varying aspect ratios and fiber contents, two types of polypropylene fibers with different lengths were added to the sand at a fiber content by weight (FC = weight of fibers/total weight) = 0, 0.5, 1.0, and 2.0%. Note that the fiber content of previous studies on fiber-reinforced soils was generally smaller than 1.5% (Deb and Narnaware, 2015; Estabragh et al., 2014). However, the tested maximum fiber content of this study was set to be 2% because one of the aims of this study is to evaluate the effect of varying fiber contents on the variation of compressibility and maximum shear modulus of fiber-reinforced sand. The acronyms “AR 150” and “AR 300” in Table 2 indicate fiber-reinforced sands with aspect ratios of 150 (use of fibers of 6 mm length) and 300 (use of fibers of 12 mm length), respectively. To prevent segregation between sand grains and discrete fibers during mixing, water with 10% of water content (weight of water/weight of solid) was added in the manual mixing of sand and fibers according to the suggestions in previous studies (Heineck et al., 2005; Ibraim and Fourmont, 2007). To prepare the specimens for testing with initial relative densities of around 30%, 50%, and 70% (Table 2), each wet mixture of sand and fibers was carefully scooped into an oedometer cell. Then, the oedometer cell was placed on the shaking table to achieve the desired relative density through control of the frequency and duration of vibration. Tests were conducted after the oedometer cell had been submerged in a water bath for one day.

2.3. 1-D compression tests with shear wave velocity measurements

The shear wave velocity (V_s = vertically propagating and horizontally polarized shear wave velocity) and the compressibility of fiber-reinforced sand with varying aspect ratios and fiber contents were measured as a function of increasing confining stress by using a modified oedometer cell, with bender elements fitted in the top cap and bottom plate of the cell. The prepared samples with 100 mm in diameter and 65 mm in height were tested in the K_0 (zero lateral strain) condition under vertical stresses ranging from

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