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Experimental study of the mechanical behavior of clay–aggregate mixtures

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ABSTRACT

Clay–aggregate mixtures are widely distributed in nature and are often used in engineering applications. To improve the understanding of the effects of coarse particles on the mechanical behavior of clay–aggregate mixtures, a series of oedometer and triaxial tests were conducted on clay–steel bead and clay–fine gravel mixtures. Based on computed tomography scans, both the number and total volume of the inter-particle voids were observed to increase with the coarse aggregate content. Because of the combined effects of the inter-particle voids and clay–aggregate skeleton, the compression index of the mixture first increased and then decreased with the coarse aggregate content. During the undrained loading, the specimen with higher compressibility tended to generate a larger pore-water pressure and exhibit a smaller shear strength. The effective friction angle was observed to increase with the coarse aggregate content. For the clay specimens mixed with 33.3% 1-mm beads, 2-mm beads, and fine gravels, the increases in the effective friction angles were 4.4°, 3.4°, and 6.2°, respectively.

1. Introduction

Clay–aggregate mixtures are a composite of clay and coarse aggregates such as sand, gravel, or cobble particles. Clay–aggregate mixtures are very common in engineering practices. For example, to reduce the post-construction settlement and arching effect of earth-rockfill dams, coarse particles are usually added to the clay core. A complete understanding of the compression and shear behavior of such composite materials is critical for geotechnical engineers.

In the past decades, the mechanical behavior of clay–aggregate mixtures has attracted the attention of researchers. Miller and Sowers (1958) investigated the shear strength of clay–sand mixtures using consolidated-undrained triaxial tests. It was demonstrated that the shear strength decreased slightly with the sand content up to approximately 67% (by weight). Between 67% and 74% sand content, there was a significant increase in the shear strength. Beyond 74%, the increasing rate of the shear strength gradually decreased. Rico and Orozco (1975) observed that the undrained strength increased with increases in the fines up to approximately 5 to 10%(by weight) but then decreased sharply to a value less than that of the original sandy gravel. Shafiee et al. (2008) reported that the undrained shear strength in compression increased with the sand content, especially when the sand mass content exceeded approximately 60%. Cabalar and Mustafa (2015) pointed out that the undrained shear strength decreases with an increase in the amount of sand.

The conflicting pattern observed in the shear strength with the coarse aggregate content is a reflection of the roles of clay and coarse aggregates in the load transfer (Vallejo, 2001; Thevanayagam et al., 2002; Peters and Berney, 2009). When the coarse aggregate content is low, there is little contact between coarse particles, and the shear strength is controlled by the clay fraction. When the coarse aggregate content is large, the coarse particles are in contact with one another, and the formed coarse particle structure dominates the shear strength, whereas the clay fraction acts only to fill the voids between coarse particles. For this case, the inter-granular void ratio was suggested to use to describe the behavior of the soil (Salgado et al., 2000; Thevanayagam and Mohan, 2000; Chu and Leong, 2002; Cabalar, 2011).

The coarse aggregate content also has a significant influence on the compression behavior. Monkul and Ozden (2007) and Cabalar (2010) reported that the compression behavior of the soil mixture was mainly governed by the coarse aggregate content up to a transition fines content. As the fine concentration exceeded the transition fines content, the compression behavior was governed by the fine fraction. Cabalar and Hasan (2013) studied the compressional behavior of various size/shape sand–clay mixtures. In the study, the roundness and the sphericity of a sand particle were evaluated by visual methods (Cabalar et al., 2013). They observed that the void ratio of the soil mixture was increased significantly with the addition of the fine platy particles, accompanied with an increased compressibility. Rahman and Lo (2014) concluded that the addition of fines led to increasing of the compressibility for a fines content in the range of 5–30%. However, Zhao et al. (2013) observed a different trend. These researchers reported that the soil compression initially increased with the coarse aggregate content

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and reached a maximum value at a coarse aggregate content of 68% (by weight). Beyond this point, the soil compression decreased with further increases of the coarse aggregate content.

As reviewed, for an extremely low or high coarse aggregate content, the mechanical behavior of clay–aggregate mixtures is governed by the clay or coarse fraction, respectively. However, for the soil mixtures with moderate coarse aggregate contents, the composite clay core of a dam for example, the published experimental data are very limited, and some findings are conflicting. To obtain a full understanding of the effects of the coarse particles on the mechanical behavior of clay–aggregate mixtures, a series of oedometer and triaxial tests were performed in this study. Computed tomography (CT) scan tests were also performed to identify the microstructure of the soil mixtures. Based on the test results, the effects of the coarse aggregate content on the soil compressibility, undrained shear strength, excess pore water pressure, and effective angle of shearing resistance were analyzed. In addition, the effects of the coarse particle shape and size were also examined.

2. Experimental program

2.1. Test materials

In this study, two types of experiments were conducted. A series of oedometer tests were conducted on different types of clay–aggregate mixtures to investigate the effects of the coarse particles on the soil compressibility. In addition, triaxial tests were performed to characterize the shear behavior of these soils.

The clay used in the research was quarried from Baoyin, Jiangsu Province, China. Its liquid limit and plastic limit were 54 and 29, respectively. The specific gravity of the clay was 2.72. For all the specimens, the dry density of the clay was kept constant at 1.50 g/cm^3, approximately 90% of the maximum dry density determined by a standard compaction test. The water content of the clay used to prepare the specimens was 18%.

Three types of materials were used as the coarse fraction added into the clay: (i) 1-mm-diameter steel beads, (ii) 2-mm-diameter steel beads, and (iii) fine gravel. The mean size of the fine gravel was 2.6 mm with a coefficient of uniformity of 1.5. The specific gravity of the steel beads was 7.78, and that of the fine gravel was 2.70. The particle size distributions of the clay and gravel used in this study are shown in Fig. 1. The main purpose of using the uniform-sized beads was to highlight the effects of the coarse aggregate content, and the differences between the test results of the clay–bead mixture and the clay–gravel mixture were used to analyze the effect of the particle shape.

The volume of the coarse particles relative to the total volume of the mixture was selected as 0, 1:7, 1:5, and 1:3, which indicates that the concentrations by volume were 0%, 14.3%, 20.0%, and 33.3%, respectively. These coarse aggregate contents cover the normal range used in the composite clay core of dams.

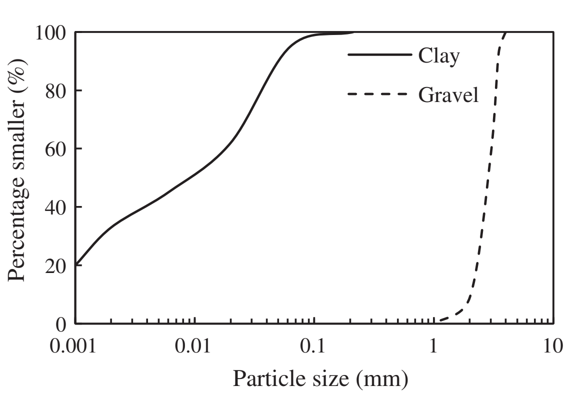

Fig. 1. Particle size distributions of the clay and gravel.

2.2. Specimen preparation and test procedure

2.2.1. Oedometer test

The oedometer specimens were 6.18 cm in diameter and 2 cm in height. All the test specimens were prepared using a moist tamping technique. First, the coarse material was mixed with the dry clay according to the designated coarse aggregate content. Then, based on the target water content of the clay, the required amount of water was added to the soil mixture. For moisture homogenization, the well-mixed wet soil was kept inside a plastic bag for 7 days. Afterward, the soil was compacted using a 2.5-kg rammer to the desired dry density of the clay. The number of rammer blows for each coarse aggregate content was determined by trial and error.

All the specimens were vacuumed for 24 h for saturation and then loaded incrementally in submerged containers with draining permitted at the bottom and top of the specimens. The initial vertical pressure was 50 kPa, and then, a sequence of pressures was applied to the specimen, each being double the previous value. The maximum vertical effective stress was 400 kPa. Each pressure was maintained for 24 h, and the thickness of specimen was measured at suitable intervals during this period.

2.2.2. Triaxial tests

Consolidated-undrained triaxial tests were performed on cylindrical specimens (3.91 cm in diameter and 8.0 cm in height). The specimens were saturated by vacuum-pumping and exhibited Skempton B values greater than 0.95. The specimens were first isotropically consolidated at four different confining pressures of 100, 200, 300, and 400 kPa and then compressed to failure at a strain rate of 0.6%/min in the undrained condition. The axial load, axial deformation, and pore pressure were recorded during the test process.

3. Oedometer results

3.1. Effect of coarse aggregate content on compressibility

Fig. 2 presents the compression curves of different specimens in the $e \sim \log \sigma'_v$ diagram, where σ'_v is the vertical effective stress and e is the global void ratio of the mixture. The initial global void ratio e_0 was calculated using the following equation:

$$e_0 = \frac{1}{m_{sc}/(V\rho_w G_{sc}) + P} - 1, \tag{1}$$

where m_{sc} is the dry mass of the clay matrix, V is the total volume of the specimen (60 cm^3), ρ_w is the density of the water, and G_{sc} is the specific gravity of the clay. P is the coarse aggregate content by volume.

As observed in Fig. 2, all the compression curves are almost straight under relatively large vertical effective stresses. The slope of the straight line is known as the compression index C_c ($C_c = \Delta e/\Delta \log \sigma'_v$, where Δe is the change of the global void ratio). It is interesting that the values of the initial void ratios are scattered in a relatively wider band and decrease with the coarse aggregate content even though the dry densities of the clays were the same. According to traditional soil mechanics, a smaller global void ratio usually implies a denser state and a smaller compressibility. However, the observed relationship between the compression index and coarse aggregate content indicates a different trend. To better compare the compressibility of specimens with different coarse aggregate contents, the change in compression index with the coarse aggregate content is plotted in Fig. 3.

Some researchers have noted that the compression behavior of clay–aggregate mixtures is mainly governed by the clay matrix up to a transition coarse aggregate content (Martins et al., 2001; Monkul and Ozden, 2007; Cabalar and Hasan, 2013). This transition content can be estimated by the maximum void ratio or porosity of the coarse particles alone. For one-size spheres packed in a simple cubic pattern, the value of