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Particle breakage of artificially crushable materials subject to drained cyclic triaxial loading

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ABSTRACT

Upon cyclic loading, particle breakage of constituent granular materials occurs when the resulting local stresses exceed their strength, which has a significant influence on the deformation of the embankment, foundation and pavement structures. In this study, the artificially crushable materials were tested to investigate the particle breakage properties of these structures when subjected to drained cyclic triaxial loading. Twelve sets of samples were tested at the confining pressures of 100, 125, 150 and 175 kPa and a frequency of 1.0 Hz using a GCTS triaxial system. The cyclic test results indicate that at the same confining pressure, the residual volumetric strain increases with decreasing maximal deviatoric stress q_{max} at a given ratio of the number of cycles (N) to the number of cycles of failure (N_f). The cumulative crushing ratio R_{cc} decreases with increasing q_{max}, leading to a reduction in N_f. The internal frictional angle decreases with increasing R_{cc}, and R_{cc} increases with increasing N_f. Furthermore, the confining pressure, maximal cyclic deviatoric stress and N have significant influences on the degree of particle breakage, which leads to volumetric contraction during the cyclic loading process. Finally, the resilient modulus at failure increases linearly with increasing R_{cc}.

1. Introduction

Earth structures, including embankments, foundations and pavement, are subjected to cyclic loading when an earthquake occurs and may undergo permanent or residual deformation and material degradation resulting from particle breakage of the constituent granular materials once the resulting local stresses exceed their strength. Particle crushing is influenced by many factors, including the particle size, grade, strength of the original materials, particle shape, degree of compaction, fabric, loading conditions, boundary conditions, loading duration and saturation of the materials, which results in granular materials having complex mechanical properties [1–6]. During the loading process, the particles of the constituent granular materials may slide, rotate and crush or break up, and these distinct particles interact with each other and associated voids to bear external actions [7,8].

A number of detailed studies, mainly including laboratory tests, theoretical studies and numerical simulations, have recently been performed to investigate the relationship between particle breakage and the soil response [9–13]. Many researchers have proposed indices to quantify the degree of breakage under particle crushing based on test results of sands, rockfills and other crushable materials. The breakage indices proposed by Marsal [14], Hardin [15], Lade et al. [16], Wood [9] and Einav [10] are widely employed in geotechnical communities. Some relationships between the breakage index and the hardening parameter, plasticity work and total energy have been obtained to formulate the constitutive model considering particle breakage [17–22]. When particle crushing of the constituent granular materials occurs, the particle becomes smaller, and more fine particles are produced; this results in fabric adjustment and sample rearrangement, potentially reducing the strength of the material. The dilatancy of the sample is inhibited to some degree with increasing particle breakage, which has been considered when establishing constitutive model of these materials. Samples of railway ballasts and carbonate sands have been tested under cyclic loading to investigate the influence of particle breakage on their dynamic mechanical properties [23–25]. Furthermore, the numerical simulation method has also been used to explore the deformation mechanism of granular materials by introducing the pattern and criterion of particle crushing [26,27]. A link between particle crushing and the soil response at the macroscopic scale and force

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chain evolution, contact force distribution and breakage process at the microscopic scale can be formulated through the discrete element method (DEM), which is useful in connecting the microparameters to the macroparameters to further explain the soil response to particle crushing [28,29].

The aforementioned studies mainly focused on the influence of particle crushing on the deformation mechanism and the mechanical properties of granular materials under static loading [30,31]. Upon cyclic loading, however, the particles of a soil element can be crushed or broken [23–25,32], which significantly affects the cyclic stress–strain and strength behavior of soil samples. Although several numerical methods have been employed to study the crush mechanism of granular materials upon cyclic loading, the simulation results must be verified experimentally. To formulate the constitutive model of granular materials subject to cyclic loading that can account for the influence of deformation mechanisms considering particle crushing, the tests on crushable granular materials are required and were carried out in this study.

The objective of this study is to consider artificially crushable materials that exhibit particle crushing and investigate the influence of particle breakage on the dynamic mechanical properties and degradation of these materials under drained cyclic triaxial loading conditions with a frequency of 1.0 Hz at confining pressures of 100, 125, 150 and 175 kPa. Furthermore, the qualifying index of particle breakage is analyzed, and its influences on the residual deformation, dynamic properties and resilient modulus at failure are also explored.

2. Test materials and methods

2.1. Sample preparation

The artificially crushable materials were made by mixing silty sands and cement according to their ratio of mass, in which silty sand was the main matrix material and cement could provide bonding between soil particles. Silty sand with a faint yellow color and low moisture content was extracted from one construction site in the Chengdu city area. The particle size distribution curve of the silty sand is shown in Fig. 1; w_L is 43%, w_P is 22%, G_s is 2.712, and the natural water content is 3.88%. The silty sand was dried and sieved through a 0.5 mm mesh, serving as the main matrix material mixed uniformly with bonding materials of cement by mass. Artificially crushable materials with different strength can be made by varying the ratios of the masses of these two materials. In the current study, the mass ratio of cement to silty sand is determined by trial and error to ensure that the crushable materials are sufficiently strong to explore their crushing properties subject to cyclic loading. The cement used was 325R Portland cement produced in Chengdu.

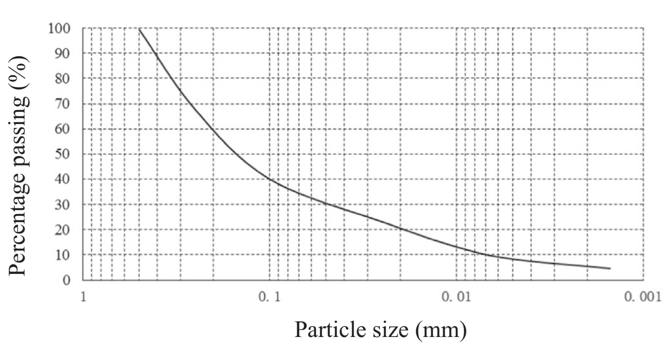

Fig. 1. Particle size distribution curve of silty sand.

The produced crushable materials were spherical particles with a 2-cm diameter. The materials were formed by mixing water, silty sand and cement. The ratio of silty sand, cement and water was determined to be 100:40:56 by trial and error in this study. The steps in the process of preparing the crushable particles are as follows: (i) according to their mass ratios, the silty sand and cement were first uniformly mixed, and water was then added to this mixture to form a uniform slurry by stirring; and (ii) lubricating oils were then smeared uniformly on the plate and placed in hemispherical indentations with diameters of 2 cm to remove the particles easily after they were formed into spherical shapes. Particles with diameters slightly greater than 2 cm were formed using a uniform slurry and placed into the hemispherical indentations, as shown in Fig. 2(a). Another plate was then pushed down closely along the bolts located in the four corners to force out redundant slurry. The two plates were then squeezed tightly and fixed using the C-shaped clamps, as shown in Fig. 2(b). After 24 h, the particles were removed, placed in water to cure for 30 days, and then kept in sealed plastic bags to undergo subsequent tests, as shown in Fig. 2(c).

When preparing crushable materials, the following aspects should be considered: (i) the size of the particles formed by the slurry should be strictly controlled and appropriate to form the same diameters for all particles; (ii) the setting duration of the mixed slurry should be constant to ensure the formation of particles such that the initial setting time does not affect the quality of the formation of these particles; (iii) the fixed bolts must be properly controlled in the process of squeezing the two plates to avoid the creation of weak surfaces in the particles; and (iv) attention should be paid to removing the particles because of their low strength at that time to avoid changes in their shapes.

Although microcracks and microvoids exist in the particles, all particles should be uniform at the macroscale. To assess their uniformity and integrity, four groups of 20 particles were selected, with masses of 6.407, 6.386, 6.400 and 6.440 g, respectively. The average group mass was 6.408 g with a maximal error of 0.5%. Another four groups of 20 particles were also selected, with diameters of 20.00, 20.10, 20.06 and 20.07 mm, respectively; the average diameter was 20.06 mm with a maximal error of 0.3%. These results indicate that the crushable particles satisfied the requirement of uniformity and integrity. Three sets of crushable particles were tested under uniaxial compression at a loading rate of 0.4 mm/min, and the forces at failure were 0.592, 0.602 and 0.606 kN, with an average force at failure of 0.60 kN, indicating that there were no notable weak planes or local defects in the artificial particles; thus, the particles were relatively homogeneous. Their split patterns under uniaxial compression loading are shown in Fig. 3(a) and (b).

2.2. Testing apparatus and method

The apparatus employed is the GCTS test system produced in the U.S.A., which is shown in Fig. 4. According to the soil test specifications released by the Ministry of Water Resources of China in 1999 [33], the maximal particle size *d* should satisfy the following requirement: the ratio of d/D is smaller than 5.0 when the diameter of sample *D* is approximately 10 cm. Thus, we used cylindrical samples with a diameter of 100 mm and height of 200 mm and an initial void ratio of 0.875. The cyclic loading applied, with a frequency of 1.0 Hz and a sinusoidal waveform, is shown in Fig. 5. To reduce the influence of membrane penetration on the volumetric deformation, a thin layer of rubber was placed between the samples and outer latex membranes when assembling them. After the samples were assembled, they were saturated with *B* values of at least 98% and consolidated under confining pressures of 100, 125, 150 and 175 kPa. The cyclic deviatoric