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Transparent confined compression tests on particle beds: Observations and implications

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ABSTRACT

Particle breakage is quite common in a variety of engineering circumstances, and the underlying mechanism as well as its effects on overall responses of particle assembly still demand further investigation mainly due to the difficulty in monitoring the progressive size reduction process. This paper presents a series of confined compression tests for two kinds of quasi-brittle spherical particles, namely Al_2O_3 and ceramic granules. A broad range of particle sizes and feed gradations were considered, and a transparent sample container was purposely adopted for a direct observation of particle disintegration. Typical macro- and micro-scale test results are presented, including the development of overall load-bearing capacities versus the compaction displacement, disintegration modes of single particles as well as the description of fragment size distributions. Two characteristic indexes t_{sqrt} and B_r' are proposed to quantify the fragment size distribution and particle breakage degree, respectively. It is also found that under the same specific input energy, distributions of fine products from samples of different feed gradations remain basically the same. The findings facilitate a better understanding of the macro- and micro-scale progressive particle breakage behaviour under one-dimensional compression, and some concluding remarks are provided in the final part of the paper.

1. Introduction

As a conglomeration of discrete solid particles, granular materials are widely utilised in a variety of industrial circumstances, particularly within the disciplines of civil, chemical, pharmaceutical and minerals engineering. As a consequence of particle-particle or particle-equipment interactions, particularly under high compression and shear loads, particle breakage may arise undesirably or intentionally. Absolutely, the breakdown of particles would influence the internal micro-structures, such as the gradation profile, the void ratio, the spatial distribution of grains and voids, etc., and in turn affect the overall behaviour of particulate materials. For instance, grinding and milling of minerals are commonly adopted for the purpose of size reduction of coarse particles through mechanical action [1,2]. In the field of geoscience and geotechnical engineering, the stress-strain behaviour and strength of soils are greatly affected by the degree to which particle fragmentation takes place under external loads [3–5]. It is therefore of great importance to engage in a more in-depth discussion of particle breakdown during the macro-scale deformational and stability analyses.

Quite lots of experimental studies into the breakage behaviour of particle materials have been presented in literature, which can be mainly classified into two types [6]: single particle breakage and inter-particle breakage. For the former type, a variety of testing methods, such as single particle compression, tension, bending, impact and cut tests [7–10], have been proposed and adopted to investigate the deformation and disintegration mechanism and the effects of underlying factors. Amongst various experimental approaches, compression test of a spherical particle between two rigid platens is most commonly adopted in practice for testing the modulus, hardness and strength of particle materials, such as the tensile strength of brittle spheres [11–13]. A concise review on the single particle compression tests is given by Antonyuk et al. [8].

A single particle compression test can be helpful for determining the single granule properties and the minimum energy requirement for breakage [8,14]. On the other hand, more complex fragmentation behaviour of particle beds can be expected owing to the friction and collision between adjacent particles, leading to migration process between particle classes [15], particularly when the differences in particle size, shape, arrangement structure, mineralogy factor and adhesion behaviour are incorporated [16–18]. Extensive experimental studies [2,19–22] have also been conducted on various particle beds by many researchers, using testing methods of lab scale or pilot scale, such as one-dimensional compression, tri-axial compression, roller compression, shear, as well as types of crushers and mills.

Even though different types of testing methods have been established for particle conglomerations, and a huge amount of reference data can be found in literature, only limited attention has been

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previously given to the progressive breakage or failure modes of particle beds and their effects on macroscopic deformation and load-carrying capacity, particularly when various gradation curves and complex stress paths are incorporated. Statistical analyses of the liability and the degree of particle breakage for different feeds as well as the morphological analyses of fragment surface from a microscopic viewpoint also deserve more attention. Concentrating on these aspects, this paper presents a series of quasi-static confined compression tests using two types of granular materials, aluminum oxide (Al_2O_3) and ceramic granules, considering different feed profiles as well. Specifically, the sample container, indenter and support platen were all chosen to be transparent which allowed a direct observation of the progressive particle breakage behaviour during the compression tests. Both macro- and micro-scale breakage behaviour of particle beds, and sieve analysis results are provided to discuss the effects of feed material types, size and gradation distributions. Two characteristic indexes t_{sqrt} and B_r' are proposed for better description of fragment size distributions. The paper ends with some concluding remarks from the test study.

2. Experimental study

2.1. Test preparations

Spherical particles sintered using aluminum oxide (Fig. 1(a)) and ceramic material (Fig. 1(b)) respectively were selected in this study. The ceramic particles were prepared using kaolin, clay and some other ingredients. Different particle sizes were considered and the size grading is shown in Table 1.

To observe the progressive particle breakage process directly and conveniently, a cylindrical container and an indenter made of transparent high-strength (Uniaxial tensile Strength = 65.9 MPa) plexiglass were adopted in the confined compression tests (Fig. 2). The support platen was also made of the same type of plexiglass material, transparent enough for sample observation after the end of compression. The dimensions of the container are 80 mm in inner diameter, 130 mm in outer diameter, and 70 mm in height. The surfaces of all these components are smooth enough and the vertical compression can be realized by prescribing the vertical displacement of the indenter during the tests. The capability of such a choice has been approved by the test results. For each test sample, the particles of prescribed sizes were mixed thoroughly according to the mass ratio and gradually fed into the container; After sufficient compacting and levelling the surface of the particle layers, the pressure indenter was placed and its vertical displacement was controlled by the loading platen in INSTRON-8506 servo-control compression machine. A constant loading rate of 0.7 mm/min was applied ensuring a quasi-static loading condition, and the particle beds were gradually compressed to a certain apparent stress level at which significant particle breakage was observed through the transparent container. The development process of reaction force versus compression displacement was recorded using a data logger.

(a) (b)

Fig. 1. Particles for the compression tests. (a) Al_2O_3 granules. (b) ceramic granules.

Table 1
Particle size grading of Al_2O_3 and ceramic granules (unit: mm).

Al_2O_3 granules	Size grading	I	II	III	IV	V
	Diameter range	1–2	2–3	4–6	6–8	10–13
Ceramic granules	Size grading	I	II	III	–	–
	Diameter range	4–6	6–8	8–10	–	–

2.2. Test cases

In order to analyse the effects of feed profiles, a series of mono- and multi-dispersed confined compression tests were conducted using the two kinds of spherical particles, as given in Tables 2 and 3. For each case, mono- or multi-dispersed, corresponding feed particles of the same mass were adopted in the test study, and two duplicate samples were included. One can note that besides three mono-dispersed cases for either type of particle materials, four (seven) multi-dispersed cases were also considered for the ceramic (Al_2O_3) particle material respectively by adjusting the gradation proportions of feed particles. Commonly, the gradations of feeds were designed that the amount of relatively fine particles was sufficiently large to achieve a roughly uniform packing whilst containing the bigger particles within the test sample.

3. Results and discussions

3.1. Load-displacement response

3.1.1. Mono-dispersed particle cases

Fig. 3 summarizes the reaction force versus compression displacement curves from the test results of mono-dispersed particle beds. It is shown that an increase trend with respect to the compression displacement is shown by all curves for both types of particles, and reasonably the support load capacity by Al_2O_3 particle beds (Fig. 3a) is significantly smaller than that by ceramic particle beds (Fig. 3b), which is mainly attributable to the relatively lower strength of Al_2O_3 particle material. For the situations of the same feed size, the reaction force at the final stage by ceramic particle beds is approximately 5–8 times as large as that by Al_2O_3 particle beds. Moreover, it is found that most of the test curves can be subdivided into three consecutive segments. The first segment, initiating from the origin point, indicates the early stage when particle beds are being compressed to a denser state, with deformation mainly from particle rearrangement and no observable breakage.

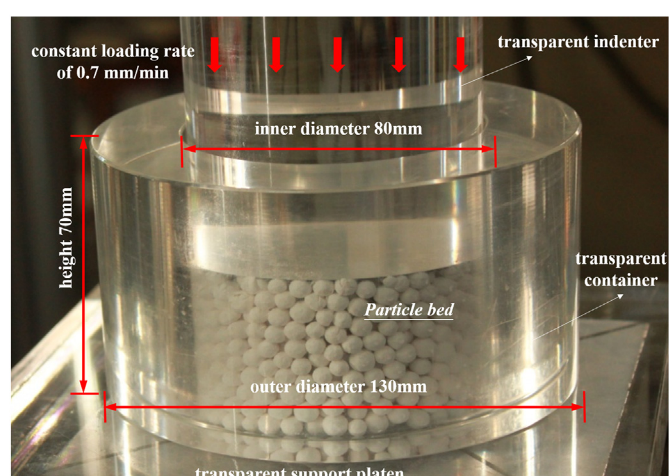

Fig. 2. General arrangement of the confined compression tests (Al_2O_3 particle bed as an instance).