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Investigating crushing-induced particle shape change in granular material

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ABSTRACT

High-pressure uniaxial compression tests were conducted under strain-controlled conditions using spherical glass beads. The study focused on investigating the compression behavior and particle fragmentation phenomena, particularly observing changes in particle size and shape resulting from fragmentation. The examination of particle shape, specifically sphericity and roundness, was emphasized. The samples comprised glass beads with uniform particle size and shape initially. It was observed that pressures exceeding 20MPa triggered particle fragmentation, leading to significant compression behavior. Notably, a softening phenomenon characterized by rapid fluctuations in compressive stress, despite a monotonic increase in strain, was observed during fragmentation. This phenomenon indicates the particles' catastrophic failure, unable to withstand the contact forces they previously sustained. Observations of particle shape revealed trends toward asymptotic distributions in cumulative curves for particle size, sphericity, and roundness. Moreover, changes in the cumulative curve of roundness were more pronounced compared to particle size and sphericity.

Keywords: Particle crushing; particle size; particle shape, 1d compression test.

1. Introduction

Particle crushing occurs when soils experience compression or shear, leading to the generation of smaller particles and changes in particle size distribution (PSD), affecting material properties, such as deformability, strength characteristics, and permeability (Bandini and Coop, 2011; Liu et al., 2015). Understanding the mechanisms of particle crushing and its impact on mechanical properties is crucial.

The evolution of PSD and mechanical characteristics induced by crushing has been extensively studied. Early investigations (Lee and Farhoomand, 1967) emphasized the susceptibility of coarser and angular particles to crushing. Hardin (1985) quantified the extent of crushing using the breakage parameter B_r and observed its variations with applied compressive and shear stresses. Experimental studies by Coop (1990) furthered understanding under high-pressure conditions. Kikumoto et al. (2010) introduced the grading index I_G to represent the evolution of PSD during crushing, correlating I_G with the reduction in the reference void ratio, such as that at the critical state.

Particle crushing impacts not only particle size but also shape. Crushed particles exhibit reduced sphericity, convexity, and aspect ratio (Altuhafi and Coop, 2011)), while impact loading can lead to more regular particle shapes (Xiao et al., 2022), indicating diverse effects of crushing mechanisms, influencing macroscopic deformation and strength characteristics.

The significance of particle shape on mechanical properties has been highlighted (e.g., Cho et al., 2006; Rouse et al., 2008). Recent studies (Ali et al., 2023a,b; 2024) have shown significant effects on both microscale particle rotation and contact and macroscale stress-strain relationships, with angular particles exhibiting higher critical state stress ratio compared to rounded particles.

Kikumoto et al. (2010) and Nghia-Nguyen and Kikumoto (2023) developed constitutive models aimed at describing the behavior of crushable soils by incorporating the evolution of PSD resulting from crushing and its impact on the critical state line. Their model operated under the assumption that despite the exposure of new particle surfaces due to crushing, the surface material maintains consistent frictional characteristics, thus assuming no alteration in the critical state stress ratio. The formulation of the model was based on previous research, including a DEM analysis of biaxial tests (Muir Wood and Maeda, 2008). Their analysis revealed the lowering of the critical state line in the specific volume direction induced by particle crushing. However, their analysis solely accounted for variations in PSD, treating all post-crushing particles as spheres and ignoring any alterations in particle shape.

Given the limited understanding of the evolution of particle shape due to crushing, comprehensive studies are necessary. Natural soil experiments, while valuable, face challenges in precisely replicating initial particle shapes. Therefore, conducting reproducible experiments under simplified conditions to observe the evolution of particle size and shape and its impact on mechanical behavior is crucial for advancing constitutive modeling. This study utilized perfectly spherical and single-sized glass beads devoid of internal voids to examine the changes in particle size and shape during 1d compression. High-pressure 1d compression tests up to 80 MPa were conducted to meticulously observe the evolution of particle size, shape, and compression behavior at different stress levels.

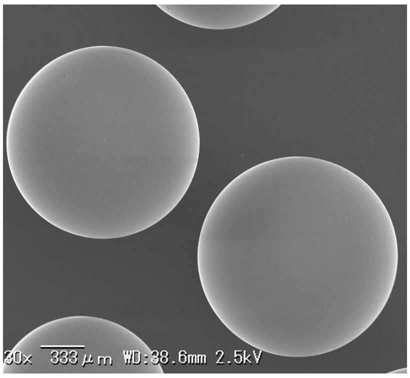

Figure 1. SEM image of spherical glass beads

2. Material and method

2.1. Testing material: initial size and shape

Specimens of glass beads, with a specific gravity G_s of 2.51 and particle sizes ranging from 1.0 to 1.4 mm, were prepared for the study. Figure 1, captured at 30x magnification using a scanning electron microscope, confirms that the particles are perfect spheres with smooth surfaces and are devoid of internal voids or microcracks. Unlike natural crushable soils, which typically consist of irregularly shaped particles with intragranular voids, such as volcanic soils or marine calcareous sands, industrial glass beads were chosen for their consistently uniform spherical particle shapes without any intragranular voids. They exhibit minimal variations in size, shape, and strength compared to natural sands. This uniformity reduces variability in crushing strength, making glass beads ideal for systematic investigation. However, due to their hardness, loading devices capable of applying high pressures were required to observe crushing phenomena.

The sample was assembled in an oedometer ring with a diameter of 30 mm and a height of 20 mm. Spherical glass beads were densely packed to achieve a void ratio of e = 0.63, corresponding to a relative density of D_r = 90 %.

Particle shape has been characterized by various parameters. In this study, changes in particle shape were assessed using sphericity S and roundness R. Sphericity S is defined as the ratio of the perimeter length of the equivalent circle P_{EQPC} with the same area as the actual particle to the actual perimeter length P_{real} of the particle, which quantifies the particle's bulkiness.

$$S = \frac{P_{EQPC}}{P_{real}} = \frac{2\sqrt{\pi A}}{P_{real}} \tag{1}$$

Roundness R is defined as the ratio of the average radius r_i of curvature of all the corners (number of corners n) to the particle's maximum circumscribed circle radius R_c, quantifying the degree to which the particle resembles a circle.

$$R = \frac{\sum_{i=1}^{n}\left(\frac{r_i}{R_c}\right)}{n} \tag{2}$$

Similar particle shape parameters were also utilized by Xiao et al. (2022). In this study, we examined how the crushing of spherical particles under various stress levels influences changes in particle shape through variations in these parameters.

2.2. High-pressure one-dimensional compression tests

To investigate the deformation behavior, particularly crushing, under one-dimensional compression conditions of glass beads, we utilized a displacement-controlled high-pressure compression apparatus. This apparatus comprises a loading frame, a load cell for measuring axial loading force, and two displacement transducers for measuring axial displacement. Both the load cell and the displacement transducers are connected to a data logger. Compressive stress was computed by dividing the applied load by the cross-sectional area. The average value of two displacement transducers was divided by the initial specimen height to determine axial strain. The eccentricity of the loading plate was minimized, ensuring consistent measurements from the two displacement transducers. Loading proceeded by applying axial strain at a constant displacement rate until reaching the predetermined axial stress. In this experiment, axial stress was applied up to a maximum of 80 MPa, considering the specimen's cross-sectional area and the device's loading capacity.

Given that particle size and shape analysis require post-testing specimen retrieval, we repeated the tests with variations only in the maximum compressive stress to investigate the gradual evolution of particle size and shape due to crushing. As this requires sufficient test reproducibility, the initial PSD and packing density of the specimens were strictly controlled to remain consistent throughout. Initial testing under a maximum axial stress of 80 MPa revealed significant particle crushing. Subsequent tests gradually reduced the axial stress until stress levels where the specimen exhibited minimal crushing behavior were reached. Consequently, it was established that there was minimal particle crushing at loading stresses around 20 MPa for uniformly spherical glass beads. Hence, testing was conducted at stress levels of 20, 40, and 80 MPa.

2.3. Method to assess the evolution of particle size and shape distribution

When granular materials are subjected to significant external loads, the constituent particles tend to crush, resulting in the generation of smaller fragments or fines. Traditionally, this crushing phenomenon has been confirmed by examining changes in the particle size through sieve analysis. However, in this study, the aim is to identify not only particle size but also changes in particle shape. To achieve this, QicPic, which can simultaneously and rapidly measure the particle size and shape distribution of numerous particles, was utilized. QicPic is a dynamic image analysis system developed by Sympatec GmbH, which operates by allowing glass bead particles to fall freely in small quantities through a feeder and capturing high-speed images of the falling particles at 500 frames per second. It can analyze over one million particles in a few minutes. The captured images are converted into binary images, and particle size and shape are analyzed individually for each particle. Though the captured images are two-dimensional, statistically reliable results are obtained as the device analyzed

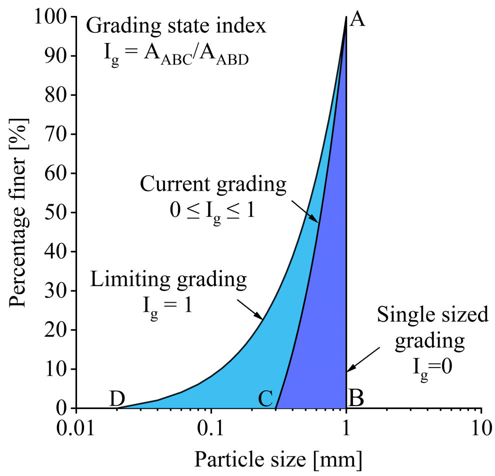

Figure 2. Schematic diagram of grading evolution due to particle crushing and definition of a grading index I_G (Muir Wood, 2007; Kikumoto et al., 2009)

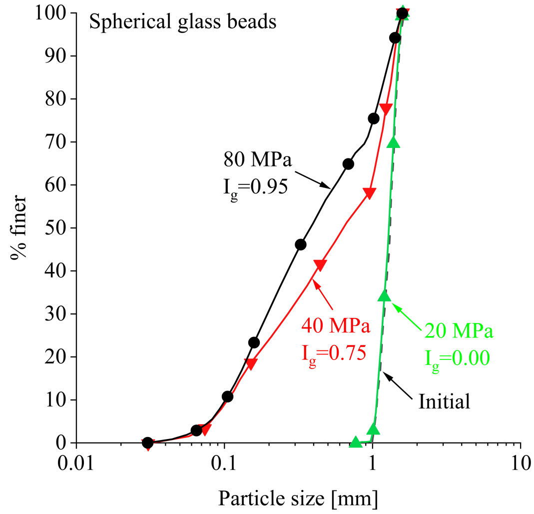

Figure 3. Grading curves of spherical glass beads compressed at different stress levels

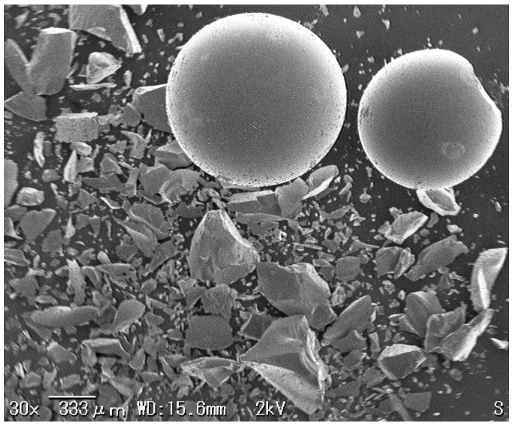

Figure 4. SEM image of crushed spherical glass beads compressed at 80 MPa

significantly numerous particles. The reproducibility of particle size and particle shape measurements by the QicPic has been confirmed to be sufficiently high when analyzing the same sample repeatedly. Compared to the sieve analysis, the QicPic tends to evaluate the maximum particle size slightly larger and the particle size of fine fractions slightly smaller. Furthermore, due to the limited image resolution of the QicPic dynamic image analysis device, the focus of shape analysis was on particles with a diameter of 0.1 mm or larger.

By analyzing numerous images captured by QicPic, various indices of individual particle images, particle size, and particle shape can be obtained. In this paper, the changes in particle size and shape due to particle crushing are discussed based on the cumulative curves of particle size, sphericity *S* and roundness *R*.

Muir Wood (2007) and Kikumoto et al. (2009) proposed the grading index I_G as an indicator of the progress of particle crushing. I_G represents the relative position of the current PSD between single-sized grading and limiting grading, increasing monotonically from 0 to 1 due to crushing. Here, the limiting grading refers to the ultimate PSD reached at the end of particle crushing due to continuous compression or shear, which is said to exhibit self-similarity in the mixing ratio of particle sizes at any scale, known as fractal grading (MacDowell et al., 1996). I_G is defined as the ratio of the areas enclosed by these particle size cumulative curves represented by AABC (navy blue area) and AABD (sum of light blue and navy blue area), as shown in Figure 2.

In the experiments, the PSD of the initial samples was adjusted to ensure that all particles had a similar particle size ranging between 1.0 and 1.4 mm corresponding to single-sized grading having I_G = 0. Additionally, the concept of limiting grading was originally associated with a state where no further particle crushing occurs, typically achieved by shearing under high confining stress. However, in this experiment, which involves high-pressure 1d compression, the potential for further particle size changes due to shear cannot be precisely quantified. Therefore, in this study, the PSD from the test case exhibiting the most significant PSD change due to particle crushing (the testing case using angular glass beads with the application of an 80 MPa compression stress) was provisionally designated as the limiting grading with I_G = 1.

3. Results and discussion

3.1. Compression behavior and grading change

Figure 3 presents the particle size distribution (PSD) for spherical glass beads, as measured by the QicPic apparatus. There was negligible crushing exhibited at 20 MPa. However, the sample compressed at 40 MPa has experienced a considerable amount of crushing, and even more crushing was observed at 80 MPa. A significant quantity of fine particles is evident at 80 MPa as shown in the SEM image taken after the experiment (Fig. 4). Notably, even at this pressure, intact spherical particles are observable, albeit with some scratches resulting from friction with other particles. A particle with partial splitting can also be seen.

The combination of compression curves and grading indices (Fig. 5) offers a clearer insight into the crushing process at various stress levels. Spherical glass beads exhibited a brittle response, characterized by distinct strain softening, where compressive stress reduces even as volumetric compression continues, as depicted in Figure 5(a). Beyond a certain stress threshold, a significant change in slope in the compression curve of spherical glass beads occurred in the stress range of

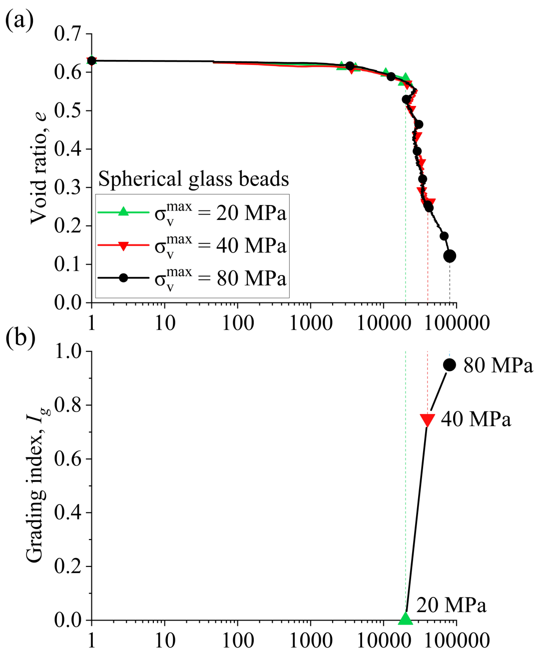

Figure 5. Test results for spherical glass beads compressed up to 20, 40, and 80 MPa: (a) compression curves; (b) grading state indices

27-30 MPa, coinciding with the distinct sound of glass beads crushing during the compression tests. As displacement continued to increase, the recorded load progressively decreased following the breakage sound. Several instances of catastrophic crushing were observed during the test, marked by a negative slope in the compression curve. It's worth noting that this behavior is relatively rare and observed in only a few brittle materials. Importantly, the grading state index for spherical glass beads (Fig. 5(b)) at 80 MPa reached at 0.95.

3.2. Crushing-induced shape change

Crushing-induced alterations in the particle shape of granular materials occur as stress forces particles to deform, flatten, elongate, or break into smaller pieces. Given that changes in shape can significantly impact void ratio, particle interlocking, and material porosity, this phenomenon holds significant importance, playing a pivotal role in influencing macroscopic soil behavior.

The evolution of shape changes was observed for spherical glass beads as vertical stress levels increased to around 40 MPa. The spherical glass beads experienced a dramatic reduction in sphericity with an increase in stress (Fig. 6). Minimal evidence of crushing and shape variation in the specimen compressed at 20 MPa was observed. However, at higher stress levels of 40 MPa and 80 MPa, more significant crushing-induced shape changes became apparent. A considerable number of less spherical particles, ranging in size from 0.1 to 0.3 mm, were generated, while many intact particles with high sphericity values remained within the specimen. Considering roundness, the initial roundness of the specimen was almost 1, and due to the negligible crushing observed at 20 MPa, the shape parameter remained almost identical (Fig. 7). However, at stress levels of 40 and 80 MPa, a significant amount of crushing

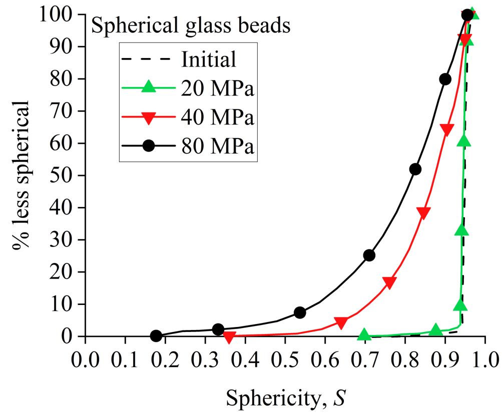

Figure 6. Evolution of sphericity of spherical glass beads

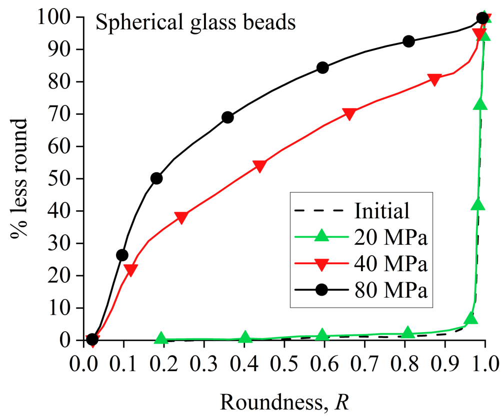

Figure 7. Evolution of roundness of spherical glass beads

occurred, resulting in the generation of numerous smaller particles ranging from 0.1 to 0.4 mm.

It is worth highlighting that both spherical and angular glass beads, with identical initial sizes, underwent testing. However, the outcomes for angular glass beads are not presented in this context and will be featured in our upcoming publication. The findings of this study bear practical significance in the assessment of foundation stability, the design of filters for large dams, and the improvement of aggregate crushing plant efficiency. By understanding how diverse shapes of granular materials react to high-pressure conditions and recognizing potential limiting gradings, engineers can make more informed choices concerning material selection and construction methodologies.

4. Conclusions

An extensive investigation was conducted into the deformation behavior of granular media under high-stress one-dimensional compression conditions and the accompanying changes in particle size and shape resulting from particle crushing. This comprehensive approach utilized a high-pressure compression apparatus in conjunction with the QicPic system.

Experimental tests focused on homogeneous materials devoid of voids within the particles, utilizing uniform spherical glass beads to ensure experiment reproducibility while changes in particle shape were systematically observed. Changes in particle shape due to particle crushing were confirmed through the analysis of sphericity and roundness.

Distinct changes in stress-strain characteristics were observed during high-stress compression of the spherical glass beads, particularly around 40 MPa, where particle crushing becomes significant. Clear strain softening behavior and a notable increase in compressibility were observed. Although strain softening behavior is typically observed in shearing tests, its occurrence under one-dimensional compression conditions with strain-controlled compression was demonstrated, particularly in the context of brittle particle crushing.

A significant decrease in both sphericity and roundness of the spherical glass beads was observed with increasing vertical stress. This decrease was evident in the particle sphericity cumulative curve and particle roundness cumulative curve, with a particularly pronounced reduction in roundness. Previous studies (Ali et al. 2023a,b; 2024) have suggested that lower roundness may lead to an increase in ultimate strength, while ultimate strength exhibits nonlinear changes with respect to sphericity. This implies that changes in particle shape distribution, such as those observed in our experiment, may capture previously overlooked effects of particle crushing.

Moving forward, future plans include conducting similar observations and incorporating test results for samples with different particle shapes, further enhancing understanding of particle crushing phenomena and their implications.

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