



Comparing particle breakage in an uniaxial confined compression test to single particle crush tests—model and experimental results



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ABSTRACT

The correlation between single particle breakage parameters and the behavior of particulate beds under compression is a subject that has attracted much interest in the field of particulate solids. This knowledge can assist in simplifying the design of various units for handling and conveying of particulate solids and can be used in computer simulations (DEM) to shorten the computational time. In addition, it is convenient to compress a particulate bed in order to obtain the single particle strength distribution. The current work deals with the development of a mathematical model, correlating the ratio of broken particles in a confined bed compression to single particle strength. The model is based on Janssen's axial-stress model for a particulate bed, single particle strength distribution and force distribution in a granular media. The developed model not only allows us to predict the ratio of broken particles during uniaxial compression but also allows us to determinate the single particle strength distribution by conducting two uniaxial confined compression tests. Narrow fractions of GNP, zirconium and sodium chloride (NaCl) in the size range of 2–5 mm were tested using two rigid cylinders of 25 mm and 45 mm in diameter, with varying compressive forces and bulk heights. The single particle strength parameters were taken from single particle compression tests performed in the laboratory. The developed model shows good agreement with the experimental results within a certain range of the particulate bed geometry and compressive loads.

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1. Introduction

Strength distribution of single particles is a very important parameter in the field of particulate solids. It should be taken into account in the design of units for handling of particulate solids, storage and conveying. Such a strength distribution can be determined by a series of single particle crush tests. This requires numerous experiments and a relatively complicated experimental system. The cumulative distribution functions which represent the strength distribution of a particle in a single crush test were investigated thoroughly in the past [1–4].

The prediction of the percentage of broken particles during uniaxial confined compression has a design importance as it is. In addition, a correlation between the single particle crush test and the uniaxial confined compression test can be used to determine the strength distribution of a single particle from a compression of a particulate bed, which is very convenient, because it requires a smaller amount of experiments and a relatively simple experimental system.

The correlation between the single particle crush tests and the uniaxial confined compression test raises a number of difficulties. During uniaxial compression, the particulate bed develops a grid of random

force chains. The forces between the particles are transmitted through these chains. During compression the force chains change, disappear and new chains are formed [4]. The measurement of forces which are transmitted, stresses developed in the particles and the deformation the particles undergo, on each particle, is impossible using today's experimental methods. Therefore, in order to build a model that correlates the behavior of a single particle in a crush test to its behavior in a bed during compression, a statistical approach might be applicable. One of the ways to describe the nature of force chains is by finding experimentally the distribution of forces applied on particles in a layer of particulate bed [5].

In addition, during the bed compression, some unique processes occur, including attraction forces between particles, friction with the die walls and activation of forces in several points on the particles. These processes should be taken into account for the establishment of the correlation. A wide research effort has been devoted to understand the pressure–volume relationship during compression of the particulate bed [6–9,11] and the nature of particulate bed configurations [10].

Some approaches for establishing the correlation between the single particle crush test and the uniaxial confined compression test can be found in the literature. Adams (1994) considered the uniaxial confined compression as a purely dissipative process. The Mohr–Coulomb stress criterion was applied to the failure of individual particles leading to load–deformation relationship. Adams's theory provides a correlation

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between the average shear strength of a single particle, which is obtained by experiments on a bed, to the single particle crush strength using a single empirical proportionality factor [11]. A different approach was used by Couroyer et al. who attempted to relate the bulk crushing strength (BCS) to the single particle crushing strength distribution using distinct element analysis (DEA) [12].

The current work presents a new approach for the correlation between the single particle crush tests and the uniaxial confined compression test, by formulating a theoretical model that is based on Jansenn's axial-stress model for a particulate bed, single particle strength distribution and force distribution in a granular media. An experimental system which was developed for crush tests of single particles was upgraded in order to enable uniaxial confined compression tests. Three different materials, sodium chloride (NaCl), zirconium and GNP, were tested to validate the model. The developed theoretical model shows good agreement with the experimental results within certain limitations.

2. Development of the model

2.1. Theoretical development of the model

As mentioned previously, the objective of the model is to predict the ratio of broken particles during uniaxial confined compression tests using particle strength distribution parameters obtained in single particles crush tests. The model was established on two basic phenomena. The first was the existence of force chains which develop in a particulate bed during compaction. Fig. 1 qualitatively presents the nature of those force chains [4]. The three consecutive images are photos of a two dimensional bed, consisting of photo-elastic particles, subjected to three different pressures on the top layer (from the lowest pressure in the top image to the highest pressure in the bottom image). The dark patterns observed in the particles are stress intensity zones. The higher the stress developed in the particle the darker is the zone. In the third image the force chains are marked by dashed lines. The following commonly accepted conclusions can be derived from this photo-elastic observation.

1. The force chains have a random configuration with random force intensity.
2. Some particles do not participate in the force chains.
3. There is a voidage in the bed, which is not occupied by the particles.
4. Some particles are junctions of force chains, and transform forces through several points of contact.

An additional study of beds containing a combination of photo-elastic particles and regular particles [4] that can undergo breakage has showed that after the breakage of a particle, it stops bearing the force chain, and the load that it has carried is distributed between the neighboring particles or its broken pieces. This process causes the force chains to change during compaction. Furthermore, force chains change their intensity, some disappear, and new force chains are being formed. Fig. 2 presents a set of photos consisting of four consecutive images of the same combined bed subjected to different loads. In this case, two non-photoelastic particles that can break are added (black circles). When the 60 N load is applied, moments before the breakage of the regular particle, four distinct force chains can be observed. At the 70 N load, the particle is broken, and rearrangement occurs. Chain 1 disappears, and chain 5 is formed. The intensity in chains 2, 3, and 4 is changed. At the 110 N load, a second breakage of the same regular particle occurs, and a new chain, 6, is formed.

The second basic phenomenon is the particle's ability to withstand a limited force before it breaks. This maximum force that a particle can withstand is defined as the particle strength. Even in a very narrow sized fraction population of particles, the strength of those particles can be distributed widely. This can be explained by the fact that each particle differs geometrically from the other, and has a different system of micro cracks. In addition, the experimental systems for measuring the

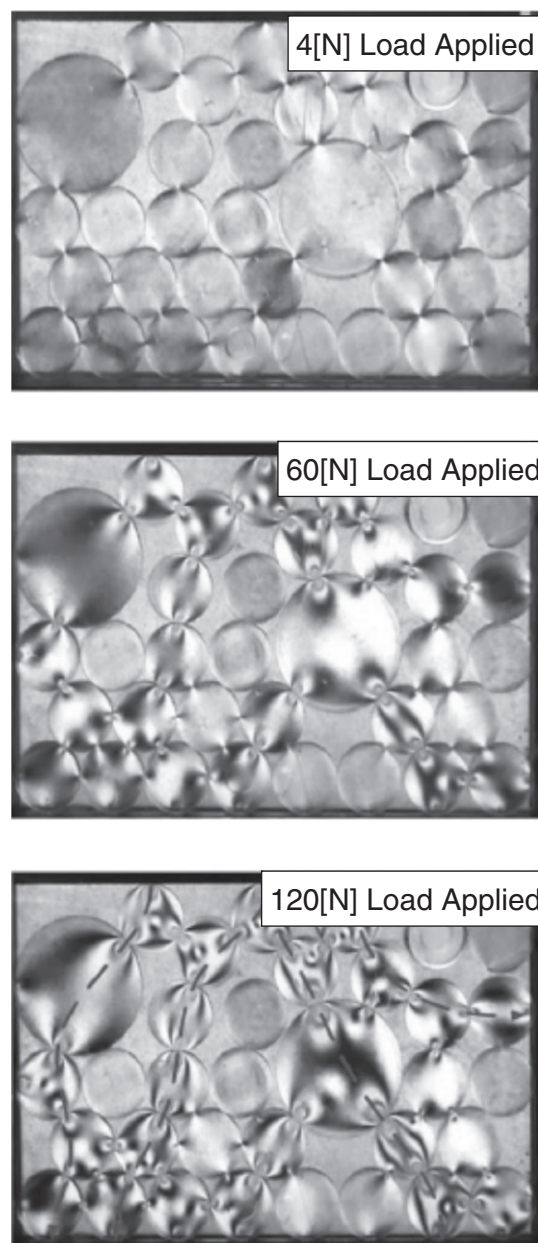


Fig. 1. Photo-elastic study.

strength of particles in a crush test is based on two parallel surfaces, one of which is static, and the second which moves towards the first, when the particle is located between them until it is crushed. Such an experimental method does not assure that the initial orientation of the particle and the point in which the force is applied on the particle, will not differ from test to test. Therefore the strength of the particle in a specific size fraction is a statistical distribution that can be described by a cumulative distribution function [1–4].

The main idea behind the model is to correlate these two basic phenomena. By quantifying the force chains distribution in a particulate bed and the strength of the particles in the particulate bed, one can predict the forces applied on the particles with certain particle strength, and therefore derive the ratio of broken particles in the bed during compression.

The compaction of a particulate bed can be divided into stages [14]. Fig. 3 depicts a compaction curve for a particulate bed of zirconium particles. The figure presents the density of the bed and the measured ratio of the broken particles at a number of discrete points as a function of the

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