Powder Technology 277 (2015) 156–162

Contents lists available at ScienceDirect

Powder Technology

journal homepage: www.elsevier.com/locate/powtec

A numerical investigation on determining the failure strength of a powder compact in unconfined compression testing by considering the compressible character of the specimen

Hyunho Shin [a,*], Jong-Bong Kim [b,*]

[a] Department of Materials Engineering, Gangneung-Wonju National University, 7 Jugheon-gil, Gangneung, Gangwon-do 210-702, Republic of Korea
[b] Department of Mechanical and Automotive Engineering, Seoul National University of Science and Technology, 232 Gongneung-ro, Nowon-gu, Seoul 139-743, Republic of Korea

ARTICLE INFO

Article history:
Received 30 November 2014
Received in revised form 5 January 2015
Accepted 25 February 2015
Available online 4 March 2015

Keywords:
Failure strength
Unconfined compression test
Compressibility
Powder compact

ABSTRACT

The effect of the compressible character of a powder compact on the determined failure strength in unconfined compression testing is investigated numerically. The modified Drucker–Prager cap constitutive model (an elastic–plastic-work hardening model) is employed for a spray-dried Al_2O_3 powder compact. When the failure strength is obtained from the current cross sectional area determined solely by the axial strain based on the assumption of incompressibility of the specimen, it underestimates the failure strength of the compressible specimen significantly. The degree of underestimation is magnified if the powder compact possesses a more slowly increasing hardening curve and/or a larger cap aspect ratio. Based on these findings, we suggest that the compressible character of the specimen be taken into account, especially for a powder compact with a slowly increasing hardening curve and/or with a large cap aspect ratio; the current cross sectional area of the specimen needs to be determined by measuring not only the axial strain but also the radial strain of the specimen.

1. Introduction

The computer simulation of compaction behavior of particulate materials (e.g., ceramic, metal, and pharmaceutical powders) has received much interest from the viewpoints of optimizing their processing and of understanding the physics behind the processing [1–5]. In addition to shear yielding (failure) behavior, particulate materials exhibit hydrostatic pressure-dependent yielding behavior, while yielding of bulk metals does not show hydrostatic pressure dependency. In this sense, the Drucker–Prager (DP) constitutive model has been widely used as its yield (shear failure) surface is pressure dependent [6]:

$$f(p,q) = q - p\tan\beta - d = 0 \qquad (1)$$

where q is the Mises equivalent shear stress, p is the mean stress (pressure), $\tan\beta$ is the slope of the shear failure surface, and d is the intercept of the q axis. β has a physical meaning of the internal friction angle of particles. It is determined by the slope of the shear stress line in the shear stress–pressure domain and reflects the degree of interlocking and surface roughness of the particles. d is called cohesion which is the shear stress when the applied pressure is zero; it is the cohesive strength of the particulate material itself when no external pressure is applied.

While the DP model is an elastic–perfectly plastic model, the description of the work hardening phenomenon was achieved in later-developed models by introducing the concept of the cap to the DP model, as seen in the Drucker–Prager cap (DPC) model [7], the modified Drucker–Prager cap (MDPC) model [5,8], the geological cap model [9], and the continuous surface cap model [9,10]. In order to utilize the DP model as well as these advanced cap constitutive models that employ the DP-type shear failure yield surface, the determination of d and β is a prerequisite. In order to determine these shear failure surface parameters, the conventional triaxial test has traditionally been used, which measures the deviator stress at varying confinement pressures [11–13]. However, for powder compacts such as ceramic green bodies, metal pre-forms, and pharmaceutical tablets, the shear failure surface parameters have been determined very conveniently by employing two simple tests: the unconfined compression (UC) test [14–30] and the diametral test [14–31]. As seen in Fig. 1, the determined failure strengths by the two tests mark two points in the meridional plane, which are used to determine the intercept (d) and the slope ($\tan\beta$) of the shear failure surface. In this process, the measured failure strengths from the two tests are assumed to be located on the linear lines with the slopes of 3 and $3\sqrt{13}/2$, respectively, in the meridional plane (Fig. 1).

This study focuses on an issue that needs be clarified in UC testing of a powder compact in order to utilize the UC test as a tool to determine

* Corresponding authors. Tel.: +82 2 970 6434; fax: +82 2 979 7032.
E-mail addresses: hshin@gwnu.ac.kr (H. Shin), jbkim@seoultech.ac.kr (J.-B. Kim).

http://dx.doi.org/10.1016/j.powtec.2015.02.054
0032-5910/

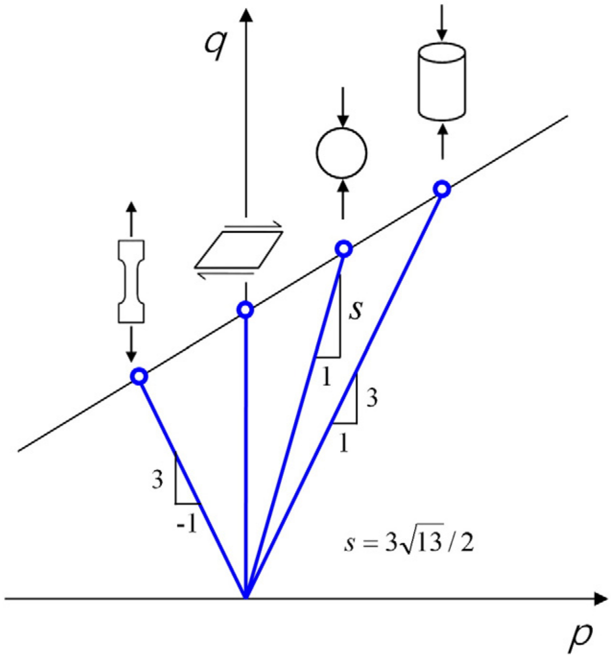

Fig. 1. Schematic illustration for the load paths for various tests.

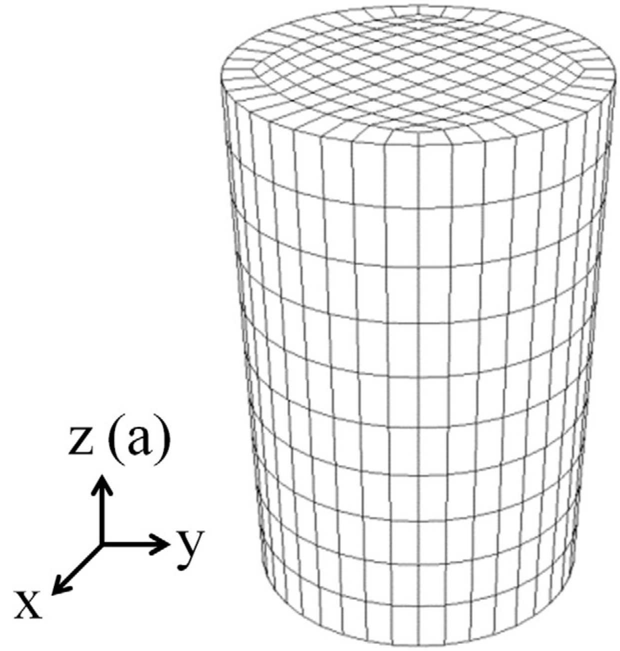

Fig. 2. Geometry and mesh of the model for the specimen with $L/D = 2$.

the shear failure surface of the powder compact. Powder compacts are generally compressible, which is unlike bulk metals where compressibility is negligible. Therefore, in essence, the compressible character of the powder compact has to be accounted for in the process of determining the failure strength in UC testing. However, no such effort has been reported explicitly in the literature for powder compacts [14–30] and for cohesive soils [11,32]. Therefore, here we uncover numerically (by finite element analysis) how much of the measured value of the failure strength based on the assumption of incompressibility of the specimen is different from the value accounting for the compressible character of the specimen. For this purpose, the modified Drucker–Prager cap constitutive model (an elastic–plastic-work hardening model) was employed for a spray-dried Al_2O_3 powder compact.

2. Numerical analysis

The length-to-diameter (L/D) ratio of the specimen considered in this study was 2 (10 mm in diameter and 20 mm in length). The full three dimensional space of the UC test specimen was discretized by eight-node linear brick elements, as seen in Fig. 2. The size of the elements was approximately $0.83 \times 0.83 \times 2.0\ mm^3$ and passed a separate mesh quality test. The specimen was loaded axially by controlling the displacement of the nodes at the top surface; the axial movement of the top surface was uniform. However, the axial movement of the nodes at the bottom surface was constrained. The radial movement of the top and bottom surfaces was not constrained; no friction between the specimen and the platens was considered. The specimen was not allowed to rotate during the axial loading by fixing the x-movement of a node located at the radial end of the specimen in the y–z plane. The specimen was not allowed to move in the x–y plane by fixing the movement of the center node at the bottom surface of the specimen in all directions. The reaction forces at the nodes located on the top surface of the specimen were summed and divided by the current cross-sectional area of the specimen to calculate the axial stress. In order to calculate the volume change of the specimen during axial loading, the volume of total elements in the specimen was extracted as a history output. A commercial finite element package Abaqus was used for the numerical analysis.

The specimen considered in this study is a spray dried Al_2O_3 powder (granules) compact which is widely used in the industry. The modified Drucker–Prager cap (MDPC) model [5,8] implemented in the Abaqus program package was used as the constitutive model. Fig. 3 illustrates the MDPC model schematically. In this figure, the cap is the locus of the iso-volumetric plastic strain points in the meridional (q–p) plane; the cap defines the work hardening yield surface. While the DPC model considers a circular cap [7], the MDPC model employs (1) an elliptical cap with aspect ratio R (Fig. 3) and (2) the transition surface defined by parameter α (Fig. 3). A detailed description of the employed model (MDPC) is given in our previous study [5]. The working principle of the MDPC model in UC testing is shown in the Appendix (Supplementary material) of this study.

The parameters of the MDPC model were selected in this study by referring to the parameters (properties) for Al_2O_3 shown in the literature [33–39] and the selected parameters are shown in parameter set no. 1 (Table 1). In the MDPC model, the relationship between the pressure (p) and the inelastic volumetric plastic strain (ε_v^{in}) needs to be specified. It controls the movement of the cap (work hardening behavior) of the specimen during loading. In general, the p–ε_v^{in} relationship (hardening law) of the powder compact varies significantly depending on the type and amount of the binder added to the particles, on the size and shape of the granules formed by the interaction of the particles and the binder, and on the degree of pre-compaction. The same is the case for the spray-dried Al_2O_3 as seen in Fig. 4. In this study, the reference p–ε_v^{in} curve was arbitrarily constructed (curve A in Fig. 4) which is located among various curves for spray-dried Al_2O_3 compacts available in the literature.

Another p–ε_v^{in} curve (curve B) was also constructed in this study by shifting curve A by -0.1 along the abscissa in order to consider a powder compact with a more rapidly increasing hardening curve. In the cap-type constitutive models [5,8–10], the p–ε_v^{in} relationship and the cap aspect ratio (R) control the compressible character of the specimen in the plastic deformation regime (the relationship between R and the compressible character of the specimen will be discussed in detail later). In order to uncover the behavior of the specimens with different compression characters, systematic variations from the p–ε_v^{in} relationship and the R value of the parameter set no. 1 were considered: curve B and a different value of R (0.25) were also adopted in the numerical analysis as seen in Table 1 (parameter set nos. 2–4).