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Original Research Paper

Shear stress distribution within narrowly constrained structured grains and granulated powder beds

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ABSTRACT

An experimental study is presented here to understand the stress transmission characteristics under different geometrical arrangements of particulates inside a narrow chamber subjected to axial compression loading. The multi-grain systems considered here are face-centred, simple cubic and poly-dispersed structures, as well as inclusions embedded inside seeded, unseeded and cohesive powder bed of Durcal (calcium carbonate). The distribution of the maximum shear stress, direction of the major principal stress and shear stress concentration factor were obtained using photo stress analysis tomography (PSAT). The results show that the maximum shear stress distribution in the simple cubic structure is chain-like and self-repetitive, i.e., a single grain behaviour is representative of the whole system. This is not the case in the case of other granular packing. In the case of the inclusion surrounded by powder media, the maximum shear stress distribution in the inclusion occurs through ring-like structures, which are different from those observed in the structured granular packing. This tendency increases for an increase in the cohesivity of the surrounding particulates. In the granular systems, the direction of the major principal stress is mostly orthogonal to the direction of loading except in some particles in the random granular packing. In the case of inclusion surrounded by Durcal particulates, the directional of the major principal stress acts along the direction of the axial loading except in the ring region where this tends to be oblique to the direction of axial loading. Estimates of the shear stress concentration factor (k) show that, k tends to be independent of the structural arrangement of granular packing at higher load levels. In the case of inclusion surrounded by powder bed, k for the seeded granulated particulate bed is mostly independent of the external load levels. In the case of unseeded particulate (granulated) bed, a fluctuation in k is observed with the loading level. This suggests that the seeded granules could distribute stresses in a stable manner without much change in the nature of shear stress-transmitting fabric of the particulate contacts under external loading. An increase in the cohesion of particulate bed results in more plastic deformation as shown by the differential shear stress concentration factor. The results reported in this study show the usefulness of optical stress analysis to shed some scientific lights on unravelling some of the complexities of particulate systems under different structural arrangements of grains and surrounding conditions of the inclusions in particulate media.

1. Introduction

Particulate materials such as grains and powders are encountered in several industrial applications, for example, chemical, petroleum, pharmaceutical, food, geotechnical, minerals and materials processing sectors [1]. Granular materials consist of discrete solid particles that are arranged in a random or a particular structural form [2]. Such materials have a complex heterogeneous mechanical behaviour under different loading conditions [3]. Understanding the micromechanical behaviour of granular assemblies of different packing structure is important in engineering processes from molecular to bulk scales such as metals [4], crushing [5], permeability [6], erosion [7], composites [8] and granular physics [9–11]. The internal structural (fabric) arrangement of grains has a significant impact on their bulk behaviour under various mechanical loading environments [12–19].

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Micromechanical analysis of fine particulate systems, especially stress measurements in particulates, is performed by theoretical and computational studies [20]. The micromechanical behaviours of granular materials have been studied using discrete element method (DEM) [5,17,21–23]. However, DEM does not account for the stress transmission within the individual grains at a single particle scale [24]. Furthermore, in general, DEM simulations do not account for the interaction effects of a particular contact on the stress transmitted by its neighbouring contacts. Some studies have used coupled DEM-FEM (Finite Element Method) analysis to get information on the stress distribution within individual particles in particulate assemblies [25] but these studies are computationally expensive. Some experimental studies have used indentation methods on the outer surface of powder beds and interpreted the indentation depths to their material properties [26]. Experimental measurement of stresses inside particulate beds is difficult to conduct at the present time. However, recent studies show the usefulness of photo stress analysis tomography (PSAT) for obtaining the stress distribution within inclusions in particulate systems [1]. These studies have used optical stress analysis for understanding the mechanical response of fine particulates interacting with optically stress-sensitive inclusions and their surroundings [1]. They provide new understandings on the ability of particulates to distribute shear under mechanical loading. However, information on the shear stress distribution characteristics of some structures such as face-centred (FC), simple cubic (SC) and poly-dispersed systems within constrained walls (narrow channels in which distance between the walls is comparable to the size of the particle) are not yet well studied, but addressed in this paper. Furthermore, the shear stress distribution characteristics within inclusions surrounded by constrained granules made of fine powders through different manufacturing routes are not yet fully understood. For example, a new method of granulation was recently introduced as 'seeded granulation' [27]. In this process, large particles present in the feed act as seeds in the granulation. Seeded granules refer to the granules having the largest particle at the centre of the granule and unseeded granules do not have this feature. It has been shown that seeded granulation produces granules with narrower distributions of granule size, uniform strength, structure and density. Observations by X-ray micro-tomography and scanning electron microscopy (SEM) of sectioned granules show that under optimum conditions, each granule contains a seed at its centre [27–29]. Fig. 1 (a) and (b) shows X-ray micro-tomography images of the central cross section of two different granules re-produced here, which illustrate seeded and unseeded granules respectively. The white coloured material appeared at the centre of granule in Fig. 1(a) is a single crystal of Durcal (calcium carbonate) and this type of granule possesses higher strength and lower porosity than the granule in Fig. 1(b) (unseeded). The mechanism of formation of seeded granules is not yet fully understood due to the complex nature of shear response of particulates to external loading environments. In fact, we are still away from sensing stress distribution inside a powder bed at any point of interest. In granulation processes, the mechanics of particle interactions and the prevailing level of compressive and shear stresses at single particle level and bulk scales are affected by the operating conditions, scale of operation and

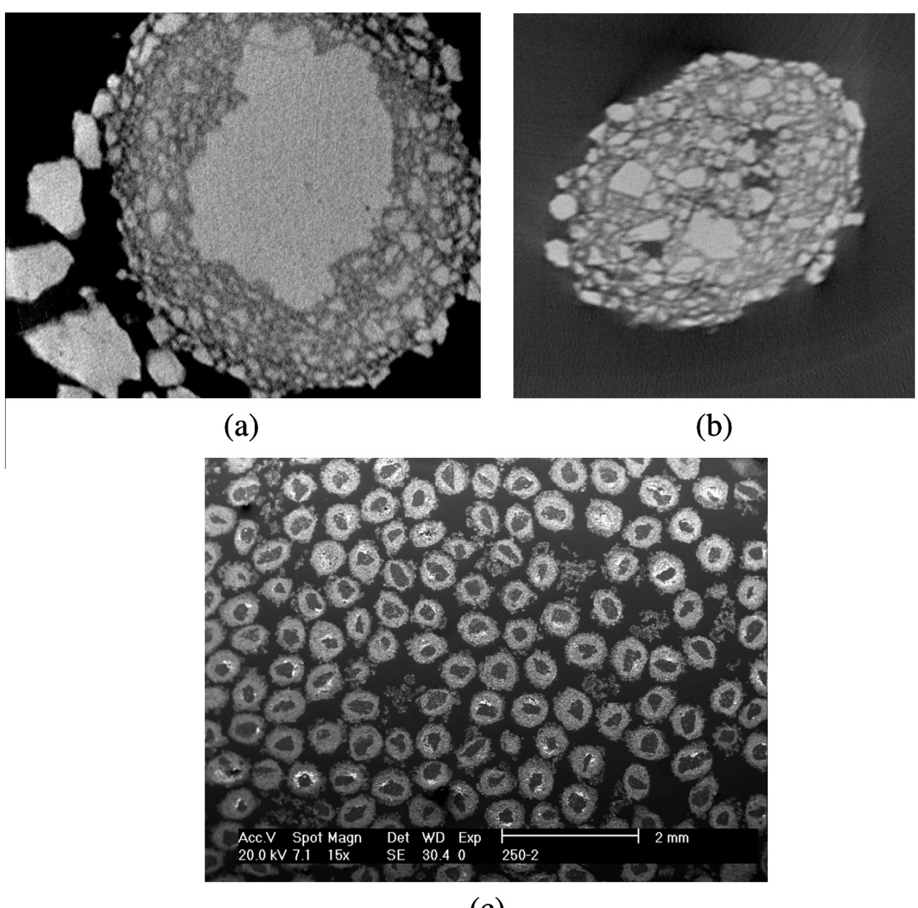

Fig. 1. X-ray microtomography images of the central cross section of Durcal granules: (a) seeded granule, (b) unseeded granule [27], and (c) SEM image of internal structure of about 100 seeded granules of $CaCO_3$ [29].