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Post-breakage changes in particle properties using synchrotron tomography

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ABSTRACT

Granular recycled Construction and Demolition (C&D) materials reused in pavements, roads, and embankments experience particle breakage causing serious issues, such as settlement, during their service life. Particle breakage is of paramount importance for understanding the behaviour of particulate materials used not only in pavements, roads, and rail tracks, but also in the oil and gas industry and mineral processing. The engineering characteristics of a granular assembly is closely dependent on properties altered by breakage. Changes in particle properties of uniformly graded and spectrum of C&D specimens due to breakage under compressive loads were studied using three-dimensional Synchrotron Radiation-based Micro-Computed Tomography. The high-resolution 4D imaging was used to scan the inner body of the granular assemblies under compression. The resulting images were subsequently processed using a variety of techniques, including image thresholding, filtering, and segmentation, to identify and label each fragment in the assemblies. The fractal distribution of granular assemblies demonstrated that breakage becomes dominant in smaller particles rather than larger particles, where an increase in newly generated fine fragments brings about high coordination number surrounding the larger particles. More prominently, the results of particle morphology evolution showed a reversal trend as the stress increased. The C&D particles tended to generate more spherical fragments with higher aspect ratio, although by increasing the stress this tendency totally reversed. In addition, it has been found that the general trend of changes in particle shape obeys universality. In other words, for the materials tested; same generic evolution by increasing stress was observed irrespective of the material types or sizes.

1. Introduction

Recycled Construction and Demolition (C&D) waste materials are particulate materials produced during the construction and demolition of buildings and structures or commercial and industrial activities. C&D materials were recognized to have suitable geotechnical properties to be reused as pavement subbase/base materials in Victoria, Australia [1]. Recycling and reusing of waste materials leads to a decline in the demand for limited natural resources and simultaneously lowers disposal cost into the landfills. Among various types of C&D materials, crushed basaltic Waste Rock (WR), Recycled Concrete Aggregate (RCA), and Crushed Brick (CB) are of interest in this study (Fig. 1). Crushed WR originates from surface excavation of Quaternary aged basaltic rock, whose placement normally occurs near the surface to the west and north of Melbourne, Australia [2]. Waste Rock is by-product of excavation activities for residential subdivisional development and drainage lines as well as other subsurface infrastructure. Traditionally, WR, excavated during site preparation, would have been disposed as waste into landfill [3]. RCA and CB are by-products of construction and demolition activities of buildings and structures.

The response of particulate layers under traffic loading is normally characterized by the resilient modulus test. However, the true nature of the deformation mechanism of aggregates in pavement layers is still not fully understood [4] leading to continuous maintenance and rehabilitation work in the pavement industry. It has been accepted that the deformation of granular materials under loading is the consequence of three major mechanisms: consolidation, particle rearrangement, and breakage [5]. The consolidation mechanism is the alteration in compressibility of particle assemblies while the particle rearrangement mechanism includes sliding and rolling of particles. The breakage mechanism is the crushing that occurs when the applied load exceeds the strength of the particles. Crushing is a progressive process that can initiate at relatively low stresses, change the soil fabric and packing gradually, and cause serious issues such as settlement and reduction in hydraulic conductivity of the soil [6,7]. In addition, the engineering characteristics of a granular assemblage, including friction angle, shear

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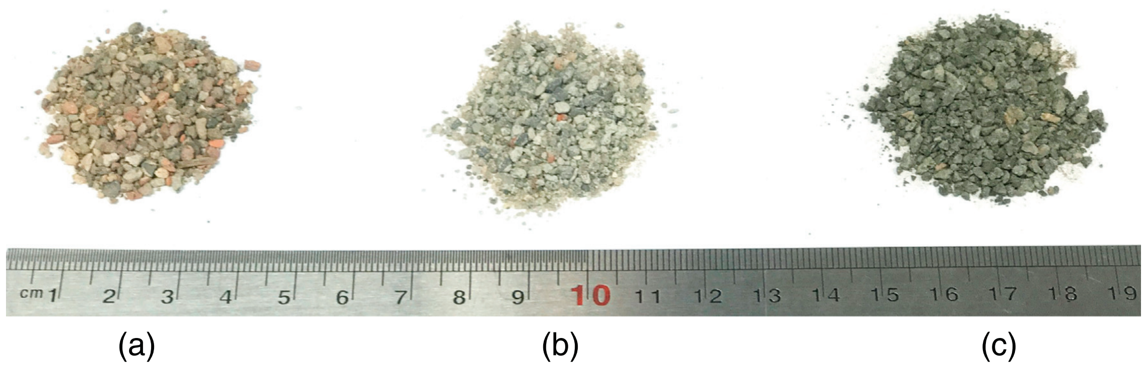

Fig. 1. C&D granular materials: a) CB, b) RCA, c) WR.

strength, and constitutive behaviour, have been shown to be dependent on properties altered by breakage [8]. Particle crushing causes dramatic changes in particle size and shape [9]. Considering the inherent links between particle size and shape, it is reasonable to hypothesize that wherever size matters, shape has to be important too [10,11]. A review of the latest literature reveals that although the measurement, description and application of particle shape have recently experienced a great leap forward, studies on particle shape in 3D are limited. The most likely reason for this shortcoming is the fact that 3D particle shape is more difficult to measure and quantify [12,13].

Recently, Discrete Element Modelling (DEM) has been used in a number of studies to explore the micromechanical breakage behaviour, which mostly provides information on the evolution of the particle size distribution during breakage [8]. Some studies have utilised agglomerate-based models to study breakage (e.g. [14,15]), but they were unable to quantify the particle shapes forming as a result.

Non-destructive testing methods have also recently become popular in fields such as material sciences and geomechanics to study granular materials at particle-scale. Among different methods, wave-based techniques such as X-ray Micro-Computed Tomography (μCT) are emerging as a powerful tool to study a wide range of materials in terms of deformation and density as exemplified in [16–20]. X-ray computed tomography has been used to observe the interior microstructure of samples without physically penetrating its surface. 3D CT images offer rich information about the entire specimen in contrast with point-wise data [18,21,22]. The recent advances in X-ray tomography, with synchrotron sources and sensitive detectors, have provided a powerful tool to obtain much finer spatial resolution of geomaterials, such as particle-scale characterization of sand undertaken by [23,24]. Nevertheless, investigations into the evolution of particle properties due to breakage, in particular morphology evolution, have been hampered due to the time-consuming image processing and segmentation procedure of CT images, where thousands of particles and newly generated smaller fragments have to be segmented and labelled accurately.

This study aims to gain a better understanding of soil behaviour in relation to particle-scale damage by examining the changes in the

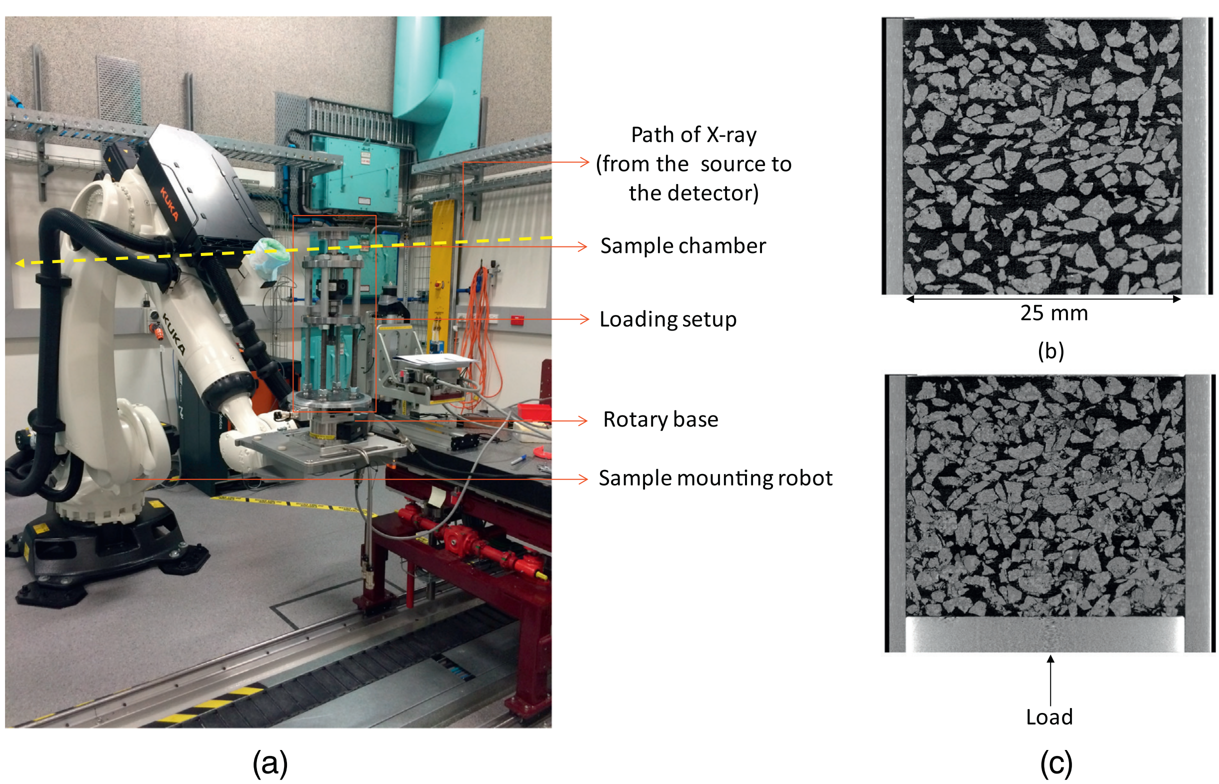

Fig. 2. Experimental setup: a) Compression apparatus, b) CT ortho-slices of a confined WR sample before and c) after vertical compression.