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Impact of particle shape on breakage of recycled construction and demolition aggregates

Tabassom Afshar [a], Mahdi M Disfani [b,*], Arul Arulrajah [a], Guillermo A Narsilio [b], Sacha Emam [c]

[a] Department of Civil & Construction Engineering, Faculty of Science, Engineering & Technology, Swinburne University of Technology, Hawthorn, Australia
[b] Department of Infrastructure Engineering, Melbourne School of Engineering, The University of Melbourne, Parkville, Australia
[c] Geomechanics and Software Engineer, Itasca Consultants S.A.S, Écully, France

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ABSTRACT

Granular recycled Construction and Demolition (C&D) materials used in pavement structures and embankments experience static and dynamic loading during their service life. As a result, particle crushing causing serious issues such as settlements may occur. Particle breakage depends on different factors such as particle mineralogy, loading condition, particle size, and particle shape. A new insight into the importance and effects of particle shape on the degree of crushing is presented. In this study, breakage of individual C&D particles with different mineralogy and microstructure was studied. The fracture characteristics were found to be highly dependent on the particle shape factor. The particle behaviour at different scales from a single particle to particle assembly is presented and discussed. Discrete Element Method (DEM) was also used to clarify evolution of cracks through the particles. DEM assisted in measuring breakage energy more accurately by partitioning and tracking the energy dissipation especially through the creation of new surfaces during fragmentation. Precise three-dimensional particle shapes were generated by a large number of bonded spherical sub-particles and used to model single particle crushing and particle assembly crushing. The results demonstrated that brittle C&D granular materials with higher degree of sphericity and lower flakiness index would show higher resistance to breakage.

1. Introduction

Recycled Construction and Demolition (C&D) materials are granular materials usually collected near curbsides, generated by construction and demolition of buildings and structures, or commercial and industrial activities. Recycling and reusing waste materials can help to decrease the demand for scarce virgin natural resources and simultaneously reduce disposal cost into the landfills. Waste Rock (WR) used in this study originates from surface excavation of basaltic rock, whose placement normally occurs near the surface to the west and north of Melbourne, Australia. Recycled Concrete Aggregate (RCA) and Crushed Brick (CB) are by-products of construction and demolition activities of buildings and structures. RCA, WR, and CB have been recognized as showing geotechnical properties equivalent or similar to typical quarry pavement subbase materials commonly used in Victoria, Australia [1].

Granular materials used in pavement structures, embankments, foundations, and even rail track structures experience static and dynamic loading conditions. Consequently, particle breakage in the shape of abrasion or asperity breakage and total fragmentation may occur [2]. Particle breakage causes various issues such as settlement or reduction in the hydraulic conductivity of the granular material. Furthermore, the elastic properties and the shear strength could also be adversely influenced [3,4].

Among a number of factors affecting degree of crushing, the inherent strength of the particles and effective stress state have been reported as the most important [5]. This is exemplified in the work undertaken by Indraratna et al. [6] who introduced an elastoplastic constitutive model to capture ballast degradation under monotonic loading. Table 1 summarises factors affecting pattern and probability of particle breakage. Particle shape is one of the governing factors in particle breakage phenomena. Jia and Garboczi [16] stated that particle shape is equally as crucial as particle size distribution in the characterization of particulate media; however, its importance has been largely overlooked due to difficulties in obtaining particle shape information. Santamarina and Cho [17] summarised particle shape irregularity into three main scales: *sphericity*, *roundness*, and *smoothness,* and explained how angularity causes difficulty in particle rotation while roughness hinders slippage. Le Pen et al. [18] and Sun et al. [19] also investigated ballast particle shapes in relation to particle sizes. To date, several studies have confirmed the notable effect of particle shape on packing characteristics

* Corresponding author at: Department of Infrastructure Engineering, Melbourne School of Engineering, The University of Melbourne, Parkville VIC 3010, Australia.
E-mail addresses: tafshar@swin.edu.au (T. Afshar), mahdi.miri@unimelb.edu.au (M.M. Disfani), aarulrajah@swin.edu.au (A. Arulrajah), narsilio@unimelb.edu.au (G.A. Narsilio), s.emam@itasca.fr (S. Emam).

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Table 1
Factors affecting particle breakage.

Factors	Example studies	Notes
Material type/mineralogy	Lobo-Guerrero and Vallejo [3], Bono, McDowell and Wanatowski [4]	Study of sugar and sand particles, respectively
Loading condition	Indraratna, Sun and Nimbalkar [6], Thakur [7]	Ballast breakage under cyclic and monotonic loading was studied.
Particle size	Marsal [8], Hardin [9] Rozenblat et al. [10]	• Breakage index was introduced with the focus on particle size distribution before and after loading. • Breakage probability of different particles with different sizes was investigated.
Shape	Tavares and King [11], Golchert, Moreno, Ghadiri and Litster [12] Antony, Moreno-Atanasio and Hassanpour [13]	• Particle fracture under impact loading was investigated to understand comminution process in mineral processing field. • Study was conducted on glass ballotini micro-particles with NaCl binder forming a greater agglomerate; totally different from soil particles. The focus was on issues related to chemical and process engineering. • Influence of non-spherical particles during shearing was investigated using DEM.
Coordination number	Mishra and Thornton [14], Lobo-Guerrero and Vallejo [3], Cil and Alshibli [15]	• Impact breakage of individual agglomerates • Breakage criterion only applied to particles having a coordination number smaller than three • Studies on three well-rounded sand particles in a compression column, highly affected by boundary conditions

of granular materials [20–22]. However, so far studies on effect of particle shape on particle breakage are still limited, particularly experimental studies.

Particle breakage and fracture is a detrimental phenomenon that can only be fully understood at the particle scale. Due to experimental limitations on measuring force chains and monitoring crack propagation at this scale, Discrete Element Method (DEM) has been widely used in the past few years. However, original DEM used circular/spherical balls to simulate particles [23]. Later, rolling resistance was added at contact points between balls to indirectly model angular particles [24]. Nevertheless, the rolling resistance behaves isotropically around the spheres; and cannot accurately represent the behaviour of elongated particles

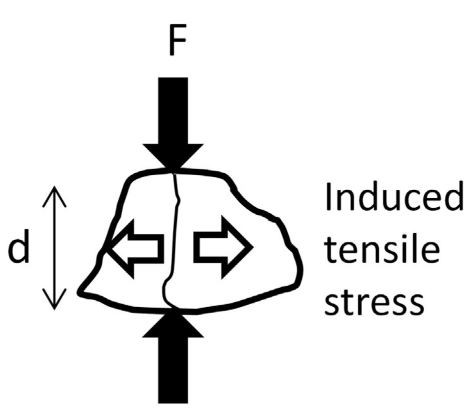

Fig. 1. Schematic description of the one-dimensional compression and induced tension.

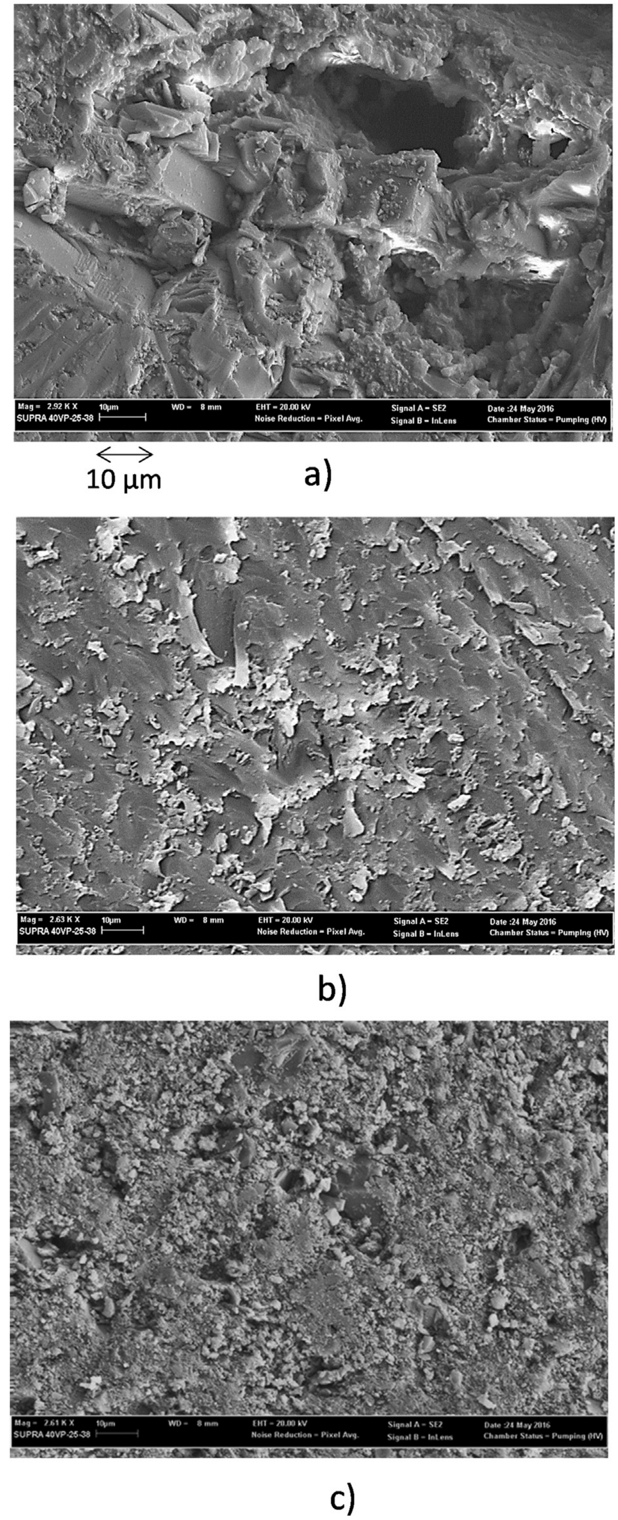

Fig. 2. SEM images of a) WR, b) RCA, and c) CB.

[25]. Clustering of balls, first introduced by Thomas and Bray [26], brought about some improvement in representing irregular particles. In recent years, crushable and irregular shaped particles have been simulated by replacing crushed particles with smaller fragments, and the selection of the failure criterion or the bond strength between sub-particles has been based on inherent tensile characteristics of the material [3,27–29]. Jaeger [30] studied breakage of rock particles between two flat platens and showed that tensile strength (σ) of rock particles is a