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Original Paper

Oblique impact simulations of high strength agglomerates

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ABSTRACT

Different types of particle compounds like concrete particles can be considered as a model material of high strength agglomerates. It is necessary to investigate and understand fracture behaviour of these agglomerates in order to avoid breakage during storage, handling and transportation. The aim of the research is to examine the comminution behaviour of high strength agglomerates during oblique impact loadings.

A two dimensional finite element analysis has been carried out to understand stress pattern distributions before crack initiation. Then a two dimensional discrete element method has been applied to study the fragmentation behaviour of the agglomerates. Concrete particles of B35 strength category have been chosen to represent the high strength agglomerates.

Analysis is done with oblique impact loadings at different velocities from 7.7 to 180 m/s. The stressing conditions comprise low flow rate transportation and handling to high speed impacts during fall down in bunker, stock piles, ship loading or stressing in crushers and mill operations. Particle size distributions and new surface generation have also been evaluated in the paper.

It is shown that at higher velocities, particle size distributions are identical to each other regardless of impact angle. Increasing impact velocity does not necessarily produce more new surfaces after certain velocity limit.

1. Introduction

In many cases comminution is a desired activity. For rocks and coarse particles it is necessary to have suitable fragment size distributions. In agglomerates, it is desired to have stable particle dispersions. In recycling/mineral processing it is adopted to liberate valuable aggregates from cheaper matrixes. The material has to be fractured in all these cases. Heterogeneous and discontinuous materials show a complicated failure during fragmentation. There are different loading methods to comminute particles, like impact, double impact, and compression. In this research, the loading conditions comprise low flow rate transportation and handling to high speed impacts during fall down in bunker, stock piles, ship loading or stressing in crushers and mill operations.

Different types of samples – mixture of sand cement particles [1–4], PMMA particles [5] and other agglomerates [6–11] are used to study the comminution behaviour of particles under different loading conditions. Schubert [12] has shown that the impact or double impact loading has higher fracture probability than the compressive loading. During impact experiments of particles, a cone shaped fragment can be observed at the impact site [1–3,5]. As the velocity of impact increases the size of the cone shaped fragment decreases and at larger impact velocities the cone shaped fragment will be commuted to become fines [3]. Damage patterns and mechanism vary with impact velocity [5] and behaviour of particles [3]. The tensile stress generated under impact is found to be responsible for producing diametrical cracks [4], cracks propagating from the impact side to the other side of the specimens.

Due to the nature of the two dimensional simulation, one would expect a wedge shaped fragment in place of the cone shaped fragment observed in 3D simulations and experiments. However, according to Schönert [14], who investigated the breakage of spheres and discs, the particle fracture mechanism is the same in both the samples. This demonstrates the relevancy of two dimensional simulations in relation to experimental and three dimensional analyses.

In some cases, target wall influences the fracture phenomena. During experiments, Shipway and Hutchings [10] have observed a considerable variation in the fracture loads for lead glass particles impacted against different wall materials. In soft walls, the particles formed plastic indentations whereas in the softest walls, the particles were completely embedded in the walls without fracture. They have observed a similar mechanism and stress condition for the failure of particles under impact and compression stressing against plastically and elastically deforming targets.

Both 2 dimensional [4,7,13] and 3 dimensional [8,11] discrete element method (DEM) simulations have been performed to inves-

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tigate the failure behaviour of particles. The two dimensional simulations are relatively faster than the three dimensional simulations for large number of particles. An increase in impact velocity results in a maximum wall force, shorter impact event (shorter time) and more broken bonds. Cracks initiate from the zone of contact and propagate towards the centre of the agglomerates. A localized damage zone has been observed adjacent to the contact [13]. A force–time curve can be used to describe failure mechanism of the agglomerates. Kienzler and Baudendistel [6] have performed continuum simulations of a sphere for the elasto-viscoplastic conditions and used stress patterns to relate the particle failure. Some authors [2,14] have used photo-elasticity method to observe the stress pattern distributions during particle fracture. The impact simulations for spherical materials are, mostly, carried out on engineering agglomerates. Thornton et al. [7] have reported that agglomerates either rebound, fracture or shatter depending upon impact velocities. The velocities used to impact the agglomerates [7,8] are much less than the velocities required for a comminution of high strength agglomerates.

Salman et al. [5] mentioned the same four types of fracture in oblique impacts as that of central impacts. It was inferred that a crack initiates because of the enhanced tension at the front end of the contact area. During breakage of agglomerates at different impact angles, Moreno et al. [11] observed that the impact angles govern the damage pattern with the same damage ratio (ratio of broken bonds to the total number of bonds present). They added, for the considered angles and velocities, damage was mostly on the rear part of the agglomerates. The extent of breakage increases as the angle (with horizontal axis) of target plate increases [9].

In this research, concrete particles are considered as an agglomerate of different sized primary particles having random properties with porosities. Most of the references mentioned above use the soft agglomerates, which break in free fall under gravity. However, the concrete material used here is very strong and stiff, and needs forced crushing. Though the concrete seems to be complex, it can be modelled with the principle of discrete element method [15]. The discrete element solution scheme assumes each of its constituents as a separate entity and applies force and momentum balances and constitutive models (force–displacement relations) at contact. The force and momentum balances are used to determine the motion of each particle arising from the contact and body forces acting upon it. The constitutive models are used to update the contact forces arising from the relative motion at each contact. The constituent particles are bonded with solid bridge bonds. The individual particle allows to delete the solid bridge bonds when it experiences the stress equivalent to the critical material strength ($\sigma \leqslant \sigma_{crit}$). This process shows fragmentation behaviour of the impact system.

1.1. Finite and discrete element modelling

This paper uses 2D finite and discrete element models described in Ref. [4] to simulate the oblique impact loading of particles. The finite and discrete element simulations have been performed with ANSYS [16] and PFC [15], respectively.

Finite element analysis is performed to understand the stress distributions before fracture initiation. In the finite element simulation, a particle (model) of radius 150 mm is impacted on the target at a velocity of 20 m/s. The specimen has 825 number of plane182 type elements. The surface to surface contact is assigned between the specimen and the target plate. Elastic modulus, density and Poission's ratio are 15 GPa, 2382 kg/m^3 and 0.28, respectively. The model material is assumed to have the stress–strain relationship as characterized by linear elastic behaviour and perfect plastic deformation without hardening.

The DEM model (disc) consists of large and small particles and bonded with hardened cement paste. 962 small particles having 1 mm radius are mixed with, 38 large particles, radii of 4 to 6 mm with a Gaussain distribution. The larger particles have normal and shear stiffness of 1×10^{10} N/m and density of 2870 kg/m^3, whereas the smaller particles have the stiffness of 1×10^7 N/m with density 1790 kg/m^3. The normal strength and shear strength of the model are 4.1 MPa. The parallel bond normal stiffness and shear stiffness are 1×10^{11} and 6.3×10^{10} N/m^3, respectively. The target wall has stiffness of 1×10^{20} N/m. These micro-properties are obtained from the calibration method as described by Schubert et al. [17]. The detail of parallel bond model (also called solid bridge bond) can be found in [15]. Gravity is also allowed to act on particles during the simulation. The default time step calculation used in PFC [15] is adopted. The linear spring mass contact model is chosen. The tentative arrangement of the hardened cement paste and aggregates for the DEM modelled specimen is shown in Fig. 1. The required number and size of particles are randomly generated and assigned bonding properties.

In oblique impacts the target plate angle should have some influence on fragmentation (on the wedge orientation and on initiation of cracks). In this work, the comminution behaviour of the particles was studied at 30, 45 and 60° oblique impacts. The central (normal) impact can be considered as a part of the oblique impacts having 0° inclined target. The friction coefficient 0.3 was assigned between the specimen and the target wall.

2. Result and discussions

2.1. Finite element simulation

Maximum principal stress distributions during 30 and 60° oblique impacts are shown in Figs. 2 and 3, respectively (negative sign shows compression and positive sign shows tension). The direction of impact is vertically downward. The compressive stresses are generated at the contact region, and the surface nearer to the contact area generates tensile stresses. Due to the loading angle, a wedge like compressed zone at the contact also has some inclination. The maximum tensile stress observed at the periphery of the contact region can be termed as a lateral tensile stress in 2 dimensional simulations. If the generated tensile stress at the perimeter of the compressive zone is equal to the tensile strength of the material then crack initiates at this point. The tensile waves are propagated on the periphery of the compressed region. This may suggest that the crack should follow this path. But in reality, after

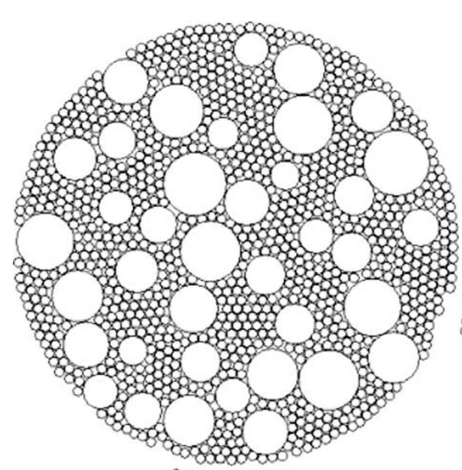

Fig. 1. Tentative arrangement of aggregates and hardened cement paste.