Ball Impact and Crack Propagation - Simulations of Particle Compound Material

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Abstract

Particle/ particle compound is the combination of various sized particles with non uniform properties and can be considered as one of the most complicated engineering materials. The properties of the particle compound vary in large range depending upon applications, methods of manufacturing and ratio of its compositions. Even if the method of manufacturing is the same, the properties may be different because of arrangements of ingredients. The different types of engineering agglomerates and concretes are some of the examples of the particle compounds. Similarly, the proper recycling of particle compound is very important in order to utilize, e.g. the coarser particles as the aggregate as valuables.

The 2 Dimensional Finite Element Analysis is carried out with central impact loading condition to understand the stress pattern distributions before cracking rather than to stick in numerical play. The Discrete Element Method (DEM) is adopted for further analysis.

To study the crack propagating mechanism in particle compound, the concrete ball of diameter 150 mm with properties of B35 is chosen for the representation. Concrete ball shape is geometrically easier for the analysis. The assumption can be made that after some stages of loading the box shaped concrete will be similar to the ball shape after losing its edges.

This paper discusses the continuum and discrete approach for the analysis of crack propagation in particle compound with reference to the concrete ball. The analysis is done with central impact loading conditions in different velocities ranges between 7.7 m/s to 39 m/s. The correlations between theoretical simulations and practical experiments are also discussed.

Keywords:
fracture pattern, crack propagation, crack simulation, air cannon, numerical simulation
Introduction

The aim of this research is to study the crack initiation and propagation in the building materials of spherical model like concrete ball while subjected to impact. The efficient way of cracking allows to get the valuable aggregates as the recycled products. In Germany in 1995, the annual occurrence of building rubble was about 30 Mt [1]. Most of the recycling products are still used as low quality materials. To produce the high quality products from recycling with the minimum of same product quality as the primary materials had, the efficient method must be adopted. The crack initiation and propagation in the concrete ball was dealt in the paper by Tomas et. al. [2]. Different research papers are available in the investigations of liberation of aggregate from the matrix [3,4] though the model material is different than the concrete ball. Single particle crushing experiments were done to investigate whether impact, double impact or compression stressing is more suitable for efficient cracking to get the better utilization of the valuables from the comparatively cheaper matrix. Spheres with only a diameter of 10 mm consisting of sand particles embedded in hardened cement paste were used as a mineral model material by Kiss and Kiss et. al. [3,4]. Arbiter et. al. [5] produced spheres - a mixture of flint-shot sand particles and high early strength cement and water – with a diameter of 74 to 124 mm for free fall tests with stressing velocity of only up to 7.6 m/s. The goal of this was mainly to observe the crack formation and fracture patterns.

All these specimens used do not correspond to a real concrete composition in civil engineering [6]. The stressing conditions in recycling practice [7] are also quite different from it. It is shown from Schubert [8] that if the feed is stressed by impact or double impact, the material has a higher fracture probability than for compression stressing.

Though, literatures are available for cracking in concrete structures with the application of finite element analysis, very few of these papers deal with the crack initiation and propagation in the concrete sphere when its subjected to impact. The cracking in the spherical model materials are carried out mainly in engineering agglomerates rather than in the concrete material. The concrete is also considered as the particle compound material like other engineering agglomerates. The cracking phenomena is different in sphere as compared to other regular structures in impact. The stresses for the elasto-viscoplastic conditions with FEM simulations for the sphere was investigated by Kienzler and Baudendistel [8]. But many literatures are available with the DEM simulations for the similar case of agglomerates. The DEM simulation for the impact breakage of spherical agglomerates were carried out by Kafui and Thornton [9] and Thornton et. al. [10, 11]. Mishra et. al. [12] shows the different parameters influencing the breakage of agglomerates in impaction. Similarly, the solid particle failure under normal and oblique impact in aluminium oxide of diameter 5.15 mm was studied by Salman and et.al. [13]. The impact and compression tests for the soda lime glass spheres of diameter range 0.4-12.7 mm was presented by Salman and et. al. [14]. With DEM simulation the effect of impact angle on the breakage of agglomerates was carried out by Moreno and et. al. [15]. Because of material heterogeneity, it is noted that the deformation and fracture of
concrete is associated with very complicated failures, as characterized by initiation, propagation and coalescence of microcracks [16,17].

Numerical Simulations
The initiation of the crack can be considered as the effect of stresses generated inside the concrete ball. Hence, the study of stresses inside the ball will provide the insight to the crack initiation and propagation. The best way to analyse the generation and distribution of stresses during impact in the concrete ball is through the continuum approach. The 2 Dimensional continuum analysis is carried out with central impact loading condition to understand the stress pattern distributions before cracking rather than to stick in numerical play. In reality, the continuum approach is not suitable for the analysis of particle compound as continuum theory assumes the material as continuous, homogeneous and isotropic which are totally inapplicable with particle compound. However, the continuum analysis is done with finite element analysis software called ANSYS.

For the ANSYS model, a 2 Dimensional concrete ball of radius 150 mm is allowed to impinge on the target by the velocity of 50 m/s. The ball has 825 number of plane182 type elements. The contact is surface to surface contact. Elastic modulus is 15 kN/mm$^2$, density is 2382 kg/m$^3$, poission’s ration is 0.28. The model material is assumed to have the stress-strain relationship as shown in figure 1.

To understand the stress pattern distribution inside the concrete ball, the single velocity, 50 m/s, impaction is sufficient. Hence, only one impact velocity is mentioned for the continuum analysis, here, in this report as with the same parameters with only change in velocities causes the change in numerical value of the stresses rather than the stress patterns.

![Figure 1](image)

Figure 1. shows the assumed material type for the FEA for ball.
Figure 2. shows the mess of the half concrete ball and the stress distribution in impinging direction, i.e. in Y direction.

Figure 3. shows the Major principal stress distribution..

Figure 4. shows the displacement in impinging direction, i.e. in Y direction.
Figure 2 shows the maximum compressive stress is generated at the bottom of the ball and the dark coloured zone beside the cone shows the tensioned region. Initially, the stress waves are propagated from the first contact zone and moves towards the top of the ball, low stressed zone, as a result different stressed zones are built up in the system.

Figure 3 shows the first principal stress developed during the impaction. It is clear from the figure that, in the cone shape boundary between light coloured and dark coloured zone has the transition between compressive to tensile stress. Hence, this region can have dominant effect for the crack generation.

Figure 4 shows the displacement in the impenging direction. The zones which are nearer to the contact area has less displaced as compared to the farther zones, which is a normal expectation during the impact of any ball.

In the stress figures, figure 2 and 3, there is more disturbances in the impacted zone, which is similar to the shape of cone or half ellipse. From this, it can be guessed that, this is the point where there will be first disturbance while impacting and hence, crack should first appeared in this region in more or less as the shape of the disturbed region, which is valid and can be seen in DEM simulation.

After getting the idea of stress pattern distribution through continuum approach, the next step is followed with Discrete Element Analysis. The limitations posed by continuum analysis during assumptions are freed in Discrete Element Analysis. Discrete Element Method (DEM) treats the particle compound as the constituents of different individual small balls as the particles. In Discrete Element Method all the constituents are considered as distinct element and simple law of motion and contact law are applied to each element. The DEM is simulated through the ITASCA software[18], which considers each element as rigid ball having own stiffnesses. The Discrete Element Method allows us to visualise and track the crack propagation.

The DEM model is considered to be constituents of gravel as large particles and sand as small particles and bonded with hardened cement paste. The 962 small particles having 1 mm radius are mixed with, 38 big particles, radii of 4 to 6 mm with gaussian distributions of large particles. The larger particles have normal and shear stiffness of $1 \times 10^{10}$ N/m and density of 2870 kg/m$^3$ whereas the smaller particles have the stiffness of $1 \times 10^7$ 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 $1 \times 10^{11}$ N/m$^2$ and $6.3 \times 10^{10}$ N/m$^2$ respectively. The gravity is also allowed to act in balls during simulation. The default time step calculation is adopted. The model is projected with the different predefined velocities. The linear spring mass contact model is chosen.

Since, the ITASCA DEM[18] uses the micro properties for the modelling, its very difficult to get the exact micro properties, though the predefined equations are also available. For this concrete case, these predefined equations don’t work as per requirements. Hence, the next, trial and error method is adopted to find out the resonable micro properties.
The DEM simulation with different velocities are shown in the figures.

Figure 5 a
Figure 5 a shows the DEM model of the concrete ball

Figure 5 b
Figure 5 b shows the tension field present inside the modeled concrete ball with dark in colour and gray colour shows compression.

Figure 5 shows tentative arrangement of the hardened cement paste and gravels. The bigger balls represent gravels where the smaller represents the sand. They are bonded together with hardened cement paste.

The concrete ball has made to strike on the target plate with different velocities and the corresponding crack patterns are shown in the figures 9 to 11 with their respective comparison with the experimental crack pattern. The comparative studies of DEM simulated crack and experimental crack are similar in nature with almost the same path followed in both the cases.
Figure 6 shows the simulation of the concrete ball fractured after impaction with velocity of a. 7.7 m/s, b. 21 m/s and c. 39 m/s.

Figure 7 shows the force experienced by the wall during impaction in DEM simulation.
The force experienced by wall during impaction by DEM simulation is shown in the figure 7. It can be seen from the figure that almost the crack is initiated at the same force, which is shown by the first small peaks for different velocity in the graph. The rise in peak shows the forced gain by the ball because of applied velocity and the sudden fall in peak shows the crack propagated inside the ball and the energy is consumed for generating the new surface.

Experiments
The impact experiments are carried out with our pneumatic cannon [2] as shown in figure 8, which works with accelerating principle by air pressure. The pneumatic cannon allows adjustment of different stressing conditions in different velocities as a function of air pressure. The test rig consists of two main parts, air pressure unit and accelerating unit. The operating principle of pneumatic cannon is as follows. Firstly, the test sample is loaded with the cartridge in the accelerating tube. The test sample may be the one which is to be crushed, generally, a concrete ball or waste materials. After loading, the accelerating tube is closed carefully and the compressor is allowed to fill the air in the pressure tank. Once, the required pressure reaches the tank, the valve is opened and immediately, the sample along with the cartridges accelerates in the tube and impinges in the target made up of strong steel alloy and crushes. All pressures and velocities are monitored simultaneously and recorded in the computer for analysis. The test rig can amounts for maximum pressure of 3 MPa with sample mass of 1 – 4 kg. The sample material can be accelerated up to 300 m/s. The crushing process can be observed through the high speed camera at 200 pictures per second.

A large number of balls were impacted to get the consistent result. The concrete ball of 150 mm diameter of B35 strength category were chosen for the experiment. The generated fragments after impaction were collected in the bin as situated in the cannon at outlet side. Each ball was coloured with different colours in different sides before impaction. After, each impaction the fragmented parts were collected and assembled according to the color. The assembled fragmented parts are shown in figure 9 b, 10 b and 11b for different velocities of 7.7 m/s, 21 m/s and 39 m/s respectively. It is clear from the figure that, every assembled ball has lost its conical or semi elliptical shape on the impacted side. This shows the disturbed region has the conical shape as predicted by continuum method. The increase in impact velocity causes the increase in contact diameter with the target and expand in the cone like region. This conical lost region is the one, called cone of fines. The meridian cracks and secondary craks are also seen in the figure. The meridian cracks move in the direction of the impact like orange pieces. The secondary cracks are not in parallel to the meridian craks. Generally, the secondary craks are perpendicular to the meridian craks but not all secondary cracks. The impact speed causes the cone of fines to expand more and lose in remaining cone. Hence, it can be seen that as the cone of fines increases the remaining cone decreases.

The current analysis is done with central impact loading conditions in different velocities ranges between 6 m/s to 50 m/s with sample mass of 4 kg. The concrete balls are of B 35 model concrete having compressive strength 35 N/mm², water
cement ratio 0.5, aggregate cement ratio 5:1, storage time greater than 180 days, 150 days from it wet stored [6].

Results and Discussion

In the figures, 2 and 3, it can be seen that, there are more disturbances in the impacted zone, which is similar to the shape of cone or half ellipse. From this, it can be guessed that, this is the point where there will be first disturbance while impacting and hence, crack should first appeared in this region in more or less as the shape of the disturbed region. This can be seen valid with the help of Discrete Element Method.

When the stress generated by the impaction at the maximum possible contact circumference is greater or sufficient than the material absolute difference in values between the tensile and compressive strength the contact deformation initiates the small circular crack of radius of impaction and small meridian cracks. The tension region shows in the boundary of the contact diameter initials the crack. Again as the crack goes inside and if the stresses are still greater than the material stresses (as the binding force between the materials) of the materials at the weakest points, the crack propagates inside the ball with further meridian cracks, as shown in figure 12 by Tomas and et al. If the weakest points lie perpendicular to the meridian cracks then the secondary cracks are generated. The circular crack is initiated from the point where there is maximum change in stress values from tension to compression.

Once, the crack is initiated through the impacted edges, again, the crack will follow
the path to form the wedge shaped fragment and shows the sharp cutting edge effect. The crack follows the weakest point of the concrete ball to make the elliptical or conical region in the ball from the side of impaction. The sharp point tip of the fragment further penetrates inside the remainig cone of the ball. In this process the share stress will also be generated in the interface of two cones in opposite direction of the enhancement of the crack. During the propagation of circular crack inside the concrete ball, the meridian crack will also propagate and unbalanced stresses will be generated which introduces the secondary cracks. The intensity of occurrence of this phenomenon depends upon the stress generated inside the ball during impaction which governs by the impact velocity of the ball.

The simulation from the Discrete Element method shows the crack propagation path followed the same path as predicted by finite element method in the initial stage. As the continuum method doesn’t allow the calculation in discontinuous region, hence, the propagation of crack can be predicted by discrete element method. The results obtained from the Discrete Element Simulation is compared with the practical results and shown in figures 9 to 11. The fragments from the simulated results show the almost same type of fragments as found from the experiment. It can be seen that figure 6 a, b, c show the same nature of cracking during impaction.

Figure 9 a and b show the crack pattern observed during DEM simulation and experimental simulation respectively with velocity 7.7 m/s.
Figure 10 a and b show the crack pattern observed during DEM simulation and experimental simulation respectively with velocity 21 m/s.

Figure 10 a and b show the crack pattern observed during DEM simulation and experimental simulation respectively with velocity 39 m/s.

Figures 9, 10, 11 show the fracture patterns follow the identical path during simulation and experiments.
Figures 12 shows the fracture types as proposed by Tomas and et al [2].

Conclusion

The DEM simulation shows the similar cone type disturbed region as shown by FEM for the crack initiation. Depending upon the impact velocities the cracks are furthering inside along with meridian cracks and secondary cracks. The diameter of the contact region depends upon the impact velocities.

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References


