An investigation of impact breakage of rocks using the split Hopkinson pressure bar

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Synopsis

Discrete element methods (DEM) are being used to provide detailed impact histories of the particles in comminution devices, such as mills. To match this immense detail of information, far more informative breakage tests than those that are generally conducted are now required. The split Hopkinson pressure bar apparatus is used in this study, as it allows the calculation of breakage forces and absorbed energies.

The geometry of rock particles has been identified as significant, so this project undertook to identify the influence of shape on the breakage pattern of blue stone. Comparisons are then made between the breakage pattern of angular rocks and rounded, milled rocks for single impact fracture and consecutive impact loading at low energy.

Results of this experiment indicate that although breakage for both geometries occurs over a similar energy range, rounded particles have the greater probability of fracture because they absorb more of the impact energy for a given loading. Size distributions of progeny show that five pebbles or more are sufficient to predict the distribution of most particles in small energy regimes. Cumulative impact testing shows that considerably more energy is required to break a rock through cumulative damage than through a single impact—this is of considerable importance in the light of the indications from DEM simulations that most breakage in a mill will be from cumulative damage rather than single impact breakage.

Introduction

Comminution machines are used for liberating the valuable minerals through rock fracture and size reduction. It has been previously established that the main forms of breakage in such devices are abrasion, chipping and crushing[1]. Mathematical models have been adapted to simulate these breakage patterns in modern machines, but in order to simplify the analyses certain assumptions have been adopted.

To further optimize the current design of comminution devices, more detailed experimental data is required to give greater understanding of the mechanisms of rock breakage, which can then be incorporated into breakage models. As more characteristics of breakage are identified, improved breakage methods may then be adopted to increase the efficiencies of comminution plants.

This study was undertaken to investigate energies required for several different aspects of rock breakage and sought to obtain statistical data and identify patterns that could be used to further develop discrete element method (DEM) simulations of breakage machines. The split Hopkinson pressure bar (SHPB) was used for applying the breakage forces, as it allowed the accurate calculation of input and absorbed energies—based on stress wave theory.

Objectives

In existing breakage models, the energy absorbed during an impact event is idealized to be independent of rock geometry. In addition, the degree of breakage for a given impact is considered to be a characteristic of every independent loading. As such, this work set out two primary objectives to address these specific areas.

First, it was sought to determine the energy required for single impact breakage of homogenous pebbles and then comparatively analyse the specific energy absorbed between two geometries. Rocks in their angular form and rounded ones obtained from tumbling—to simulate rocks in an AG/SAG mill—were the shapes chosen.

The second aim looked to investigate the effect of cumulative impacts on breakage. By striking a rock multiple times until it breaks, it was hoped to compare the energies absorbed and breakage product for single impact breakage against those for multiple loading at sub-critical impact energies, below which fracture would not occur for one loading.

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To tackle the objectives of this preliminary study, statistical data were to be compiled from an analysis of specific energies and product sizes of:

- Rounded versus angular crushed specimens
- Cumulative damage at sub-critical energies versus single impact breakage.

Experimental technique

Split Hopkinson bar summary

Although many adaptations have followed his work, the original design of split Hopkinson bars is accredited to Bertram Hopkinson[2] who just before the First World War developed a technique to measure pressures from dynamic loading events such as the impact of bullets. By a study of the shapes of stress waves propagating through metallic bars and the use of momentum traps to capture reflections, he was able to accurately measure the forces associated with velocities of impact. Figure 1 shows the typical configuration of SHPB as set up at the Blast Impact and Survivability Research Unit (BISRU) at the University of Cape Town.

The technique has been experimentally used to determine characteristics of rock breakage for single samples or beds of particles[1,5]. It was considered ideal for this study because it provided data that could be used accurately to calculate forces associated with particle fracture as well as energies associated with impact.

The typical set-up of split Hopkinson bars involves a compression gas gun, a striker and two bars in series with a specimen loaded between them, illustrated in Figure 2. Both bars are fitted with strain gauges, which generate pulses of voltage in direct proportion to the stresses along them. The gas gun launches the striker, which impacts against the first bar, known as the incident bar and transmits a stress through the specimen to the second bar, called the transmitted bar. By a measure of the time taken by the striker to cover the small trap gap illustrated, the initial kinetic energy of the striker can be calculated as a confirmation of the impact energy.

The impact on the incident bar generates a stress wave, part of which reaches the transmitted bar, while the remainder is reflected back through the incident bar. Instantaneous stress and strain in the specimen can then be calculated using one-dimensional stress wave theory[6] and, through further calculations the force, power and energy for the impact can be obtained. Figure 3 gives an example of a read-out captured by the strain gauges.

Figure 1—Split Hopkinson pressure bar

Because the transmitted pulse is directly proportional to the stress through the specimen, the breakage force is calculated from this wave. The energy input for the impact is found by squaring the integral of the incident wave curve, which gives the total strain energy through the incident bar. The energy absorbed by the specimen is then found by assuming a conservation of energy for the impact. The difference between the incident wave strain energy and the sum of the transmitted and reflected wave strain energies is taken to be absorbed by the specimen.

During loading stress pulses travel back and forth through the bars several consecutive times, which can cause multiple loadings of the specimen per impact event, if the specimen remains in contact with the bars. To overcome this potential problem, a momentum trap was used, which is a device designed to capture the reflected pulse before it is retransmitted through to reload the specimen.

Experimental procedure

In order to establish a similar breakage pattern for the analysis, homogenous blue stone (rock commonly used as aggregate in construction and road layer works) was used as the test material. The rock was obtained from a local quarry, Holcim Aggregate and Readymix (Alpha Mamre Quarry), in size ranges of 20–57mm.

In order to produce rounded pebbles, part of the specimen was taken to the University of Stellenbosch and tumbled wet for five hours in a 0.5 m diameter by 1 m long mill with steel balls in an approximately 30% total volume loading. The test was designed to provide low stress abrasion, so as to round out the pebbles without prestressing them. Those chosen by inspection to have become fairly oval were then taken as the rounded samples. Individual pebbles of both types were weighed to select pebbles in a mass range of 17 to 21 g.

Testing summary

From prior experimental work, it had been established that loading at 18 joules (J) and above constituted a high energy range, which almost always caused single impact breakage. 14 to 15 J was determined as a middle energy range, which usually caused first impact breakage, while 12 J and below was deemed to be a low energy range that caused breakage only on consecutive loading of specimens. Experimental tests were therefore structured in the following two types.

- *Test type 1*—Single impact breakage of angular and rounded samples at middle to high energy ranges. In order to form a statistical comparison between the breakage behaviour of angular and rounded rocks at the middle energy range, at least 3 dozen of either type of rock were broken. Breakage was defined as any

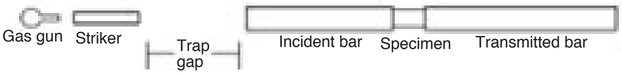

Figure 2—Schematic of the SHPB

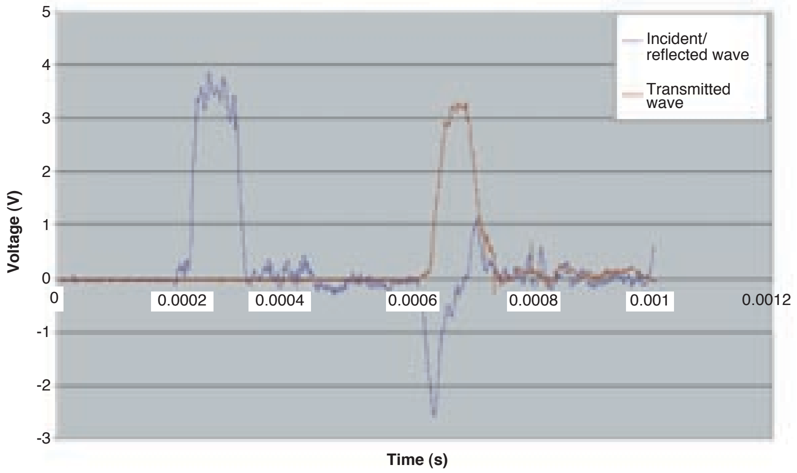

Figure 3—Strain gauge output from typical breakage impact

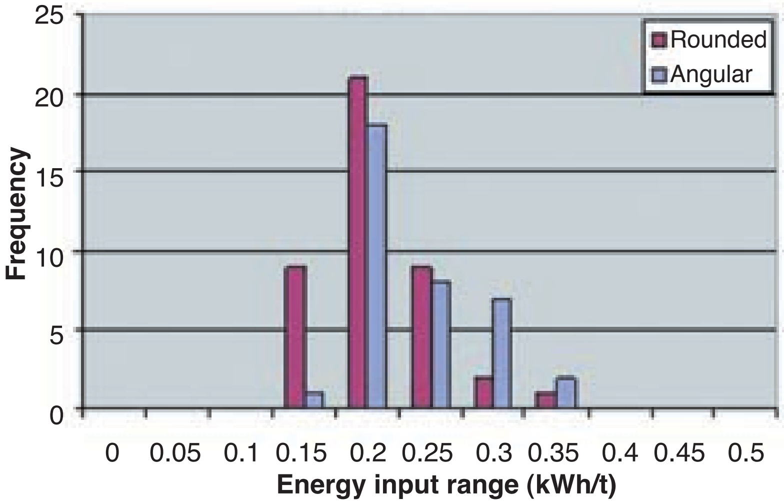

Figure 4—Graph of the number of occurrences of particular energy input ranges

loading that caused a chip in the rock greater than a third of its initial size. Any rocks that failed to fracture on the first strike were consigned to Test type 2.

- *Test type 2*—Cumulative impact breakage of angular and rounded pebbles at middle to low energy ranges. To investigate the effects of cumulative breakage on both types of rock, these breakage tests were performed at the low energy range. Samples were loaded consecutively until breakage or for up to ten hits for the low energy range, while those inherited from single hit breakage for the middle energy range would be loaded for up to five hits.

The progeny from impact was sized according to the descending screen sizes of 22.4, 16.2,11, 8, 5.6, 4, 2.8, 2 and 1.4 millimetres, where anything below 1.4 mm was considered fines.

Results

A total of 78 blue stone pebbles, 36 angular and 42 rounded, were subjected to single impact breakage. The specific energy input and absorbed by specimens for each impact was calculated and compiled into graphical form as shown in Figure 4.

As shown, for both samples input energies ranged from 0.15 to 0.35 kWh/ton. From a statistical analysis, the mean input energy ranges for the angular and rounded samples were found to be 0.214 and 0.184 kWh/ton, with standard deviations of 0.049 and 0.045, respectively. The small disparity within the two averages was compensated for by the standard deviations, which meant that both types of specimens were subjected to breakage at closely similar energy ranges.

Figure 5 shows that the energy absorbed by individual particles of both orientations fell within a much smaller range than the input energies. Either rock type absorbed between 0.01 to 0.1 kWh/ton of energy for single impact breakage, with a mean of 0.053 for rounded rocks and 0.046 for angular ones. The standard deviations were 0.013 for rounded and 0.017 for angular pebbles, considerably lower than those from energy inputs as the absorbed energy range fell within a much smaller bandwidth. The standard

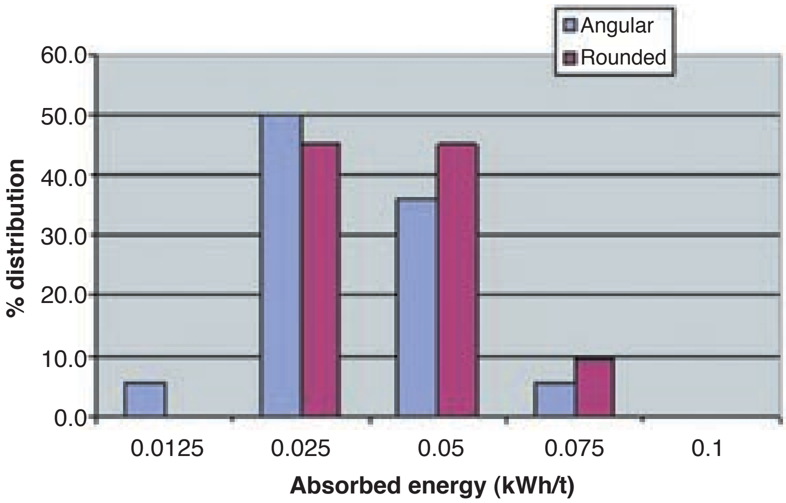

Figure 5—Number of occurrences of amounts of energy absorbed by individual particles during single impact breakage

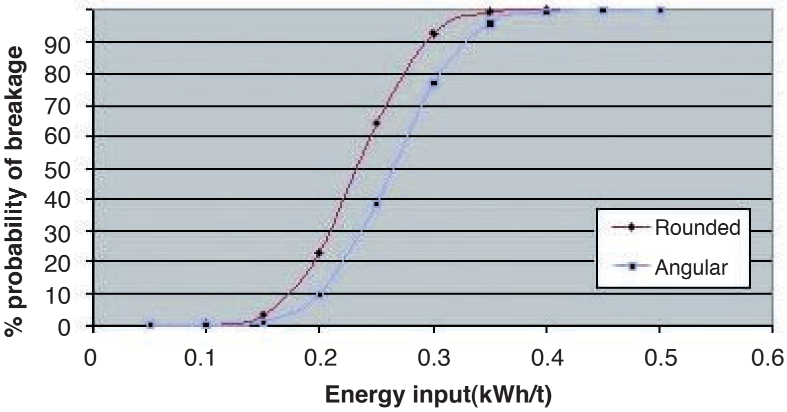

Figure 6—Cumulative breakage probability curves for angular and rounded geometries

deviations indicate that statistically there is no difference in the mean for energy absorbed for single hit breakage between rounded and angular rocks.

However, a cumulative probability function strongly suggests that there is a real difference between the two geometries, with rounded specimens having a greater percentage likelihood of fracture. Thus shown in Figure 6, as input energy increased, the probability of fracture increased in response.

The product size distributions for all test particles in each of the energy input ranges were compiled in an attempt to identify the number of test particles for a particular energy range that was required in order to obtain a reasonable prediction of the average behaviour of all particles. All size distributions particles from each range were compiled into one graph, and the combined mass distribution and average mass distribution drawn on the same axes, together with the standard deviation. Error bars of one standard deviation either side of the mean were used to show the discrepancy. The results showed that, for small energy ranges of either geometry, five or more particles were required to predict the average breakage distribution of the entire range. An example of this is given in Figure 7 where the size distributions of 9 breakages in the energy input range of 0.1 to 0.15 kWh/t were compared with their combined size distribution and the average of five breakages, and only slight error was observed.

Finally, to establish the effects of cumulative damage at lower energies, the breakage statistics of the entire set of tests was compiled into the single bar graph shown in Figure 8, where total energies from the multiple hits were summed up. The rounded rocks, due to their nature of absorbing more energy, broke even at low energies, although as observed, under cumulative damage required fewer hits to breakage than their angular counterparts. Angular rocks in some cases failed to break for up to ten hits. The pattern noted then was that cumulative damage at low energies could cause breakage, but due to their geometry more hits would be required for angular rocks.

It was noted that rounded specimens absorbed an average energy per impact for multiple loading that was similar to the energy absorbed during single impact

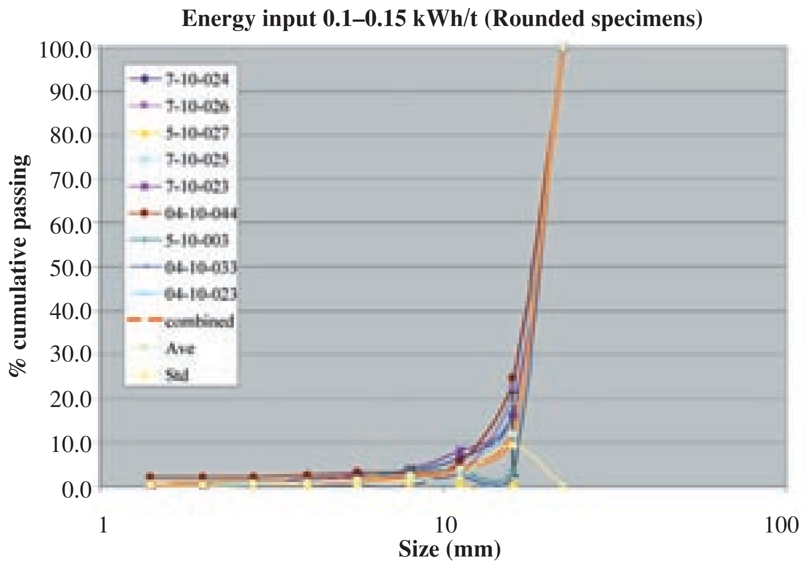

Figure 7—Comparison chart of size distributions for rounded specimens

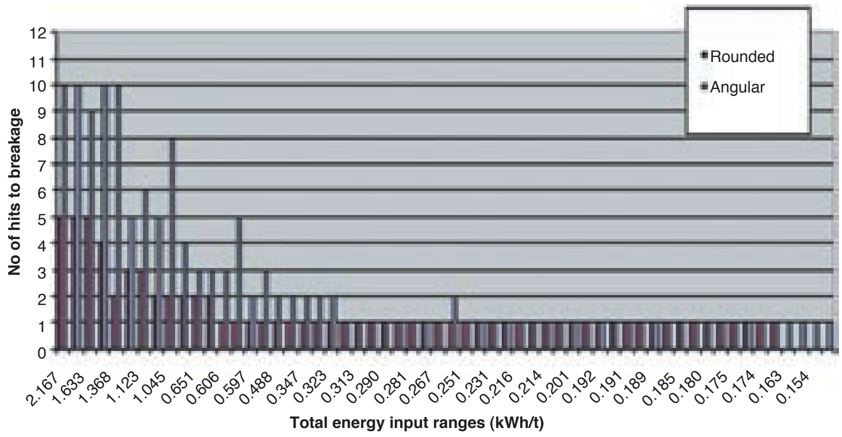

Figure 8—Summary of number of hits to breakage of all specimens

breakage, whilst angular particles were found to absorb an overall average per impact that was less than the amount absorbed for one hit fracture. Figure 9 and Figure 10 show the percentage distribution of input energy ranges and absorbed energy ranges, respectively. Rounded specimens required less energy for breakage during multiple loadings, and had a tighter distribution. As may be expected, the angular particles had a far wider distribution of cumulative energies to breakage.

Conclusions

Over the energy ranges that were used for testing, due to their geometry, rounded specimens of blue stone are observed to absorb greater amounts of energy during impact. Thus, for a typical impact loading, rounded specimens have a greater probability of breakage than angular specimens based on their shape. For angular specimens, chipping is noted to occur more frequently as the geometry of the rock tends to allow for fragments to break off during loading.

The results of cumulative impact testing show that at sub-critical loading energies, consecutive loading can lead to eventual breakage. The results indicate that due to their nature of absorbing greater energy during impact, rounded specimens fracture in fewer hits than angular ones, where the cumulative energy absorbed at final fracture is similar to the energy absorbed for single impact breakage multiplied by the number of hits to breakage. For angular specimens however, this cumulative absorbed energy is found to be significantly less, for the same number of hits.

The rounded rocks required slightly less energy to break, but there were insufficient specimens in this initial work to establish if this is statistically significant. The angular rocks undoubtedly have a wider distribution of breakage energies than the rounded rocks. Only in the region of 30% of the input energy is absorbed by the rocks for these test conditions, but there are indications that this is dependent on the duration of the impulse. Considerably more energy is required to break rocks through multiple hits than through single impact. This has significant consequences for

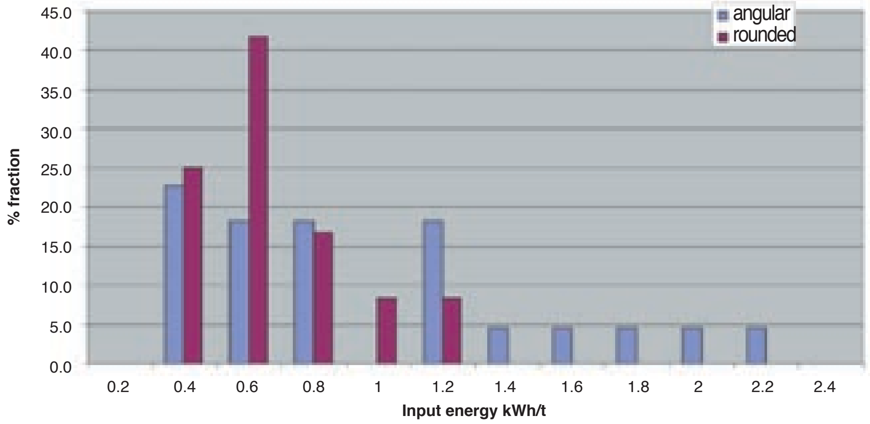

Figure 9—Cumulative impact testing input energy ranges

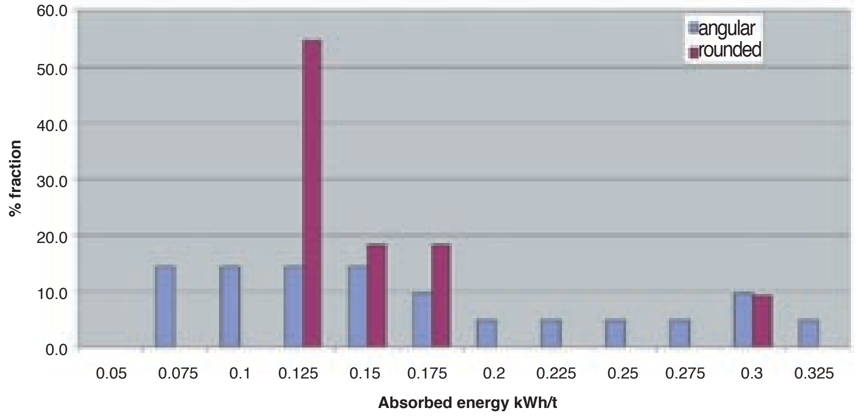

Figure 10—Cumulative impact testing absorbed energy ranges

meaningful modelling of comminution processes, as it has been identified that even in large mills most breakage arises from multiple impacts rather than single fracture events.

The SHPB has been found to be useful in studying breakage in greater detail than is generally the case, and should be able to provide data of sufficient detail to populate the more advanced comminution models that are emerging from computational modelling techniques, such as DEM.

Recommendations

During testing, it was noted that strikers of similar weight to the one utilized but with different dimensions such as wider diameter and shorter length failed to cause fracture even at higher energy inputs. The reason for this was identified as the impulse of the loading generated by the striker, or the duration of the impact force that the specimen was subjected to for a shorter striker. Therefore further investigation will be conducted on the effects of impulse on breakage characteristics.

For this work, only fracture tests were performed. There may have been other contributing factors to breakage that were overlooked such as chipping and cracking. This is another area that may warrant further study.

Acknowledgements

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