

Article

Discrete Element Modeling of the Breakage of Single Polyhedral Particles in the Rotary Offset Crusher

Titus Nghipulile ^{1,2,*} , Mulenga Murray Bwalya ² , Indresan Govender ^{1,3} and Henry Simonsen ²¹ Mintek, Private Bag X3015, Randburg 2125, South Africa; indresang@mintek.co.za² School of Chemical and Metallurgical Engineering, University of the Witwatersrand Wits, Private Bag 3, Johannesburg 2050, South Africa; mulenga.bwalya@wits.ac.za (M.M.B.); henry.simonsen@wits.ac.za (H.S.)³ Discipline of Chemical Engineering, School of Engineering, University of KwaZulu Natal, Durban 4041, South Africa

* Correspondence: tnghipulile@nust.na

Abstract: Innovation in comminution is expected to continue unabated to address the inefficiencies that are inherent in comminution circuits. The rotary offset crusher (ROC) is a new comminution device with a promising performance potential in terms of throughput due to the enhanced speed of transportation induced by the centrifugal force of the discs. However, the processes driving the comminution of particles trapped in the conical space between the two discs of the crusher are not fully understood. To gain a better insight into the comminution process in this device, discrete element modeling (DEM) simulations were conducted to study the breakage of a single particle for the crusher operated under two different dynamic conditions, i.e., (1) a stationary top disc and (2) both discs rotating at the same speed. For both scenarios, the speed of the discs was varied between 550 and 2350 rpm. Experimental testwork was also conducted with the laboratory prototype to generate the data that were used to calibrate the breakage parameters of the $Ab \times t_{10}$ breakage model. Simulations were performed using polyhedral UG2 ore particles that were generated with the in-built particle generator in the DEM simulator. The simulated ROC, which is operated with both discs rotating, outperformed the ROC with a stationary top disc in terms of the specific input energy and throughput. The crusher with a stationary top disc is characterized by high shear forces (suggesting a higher wear rate), specific input energies greater than 1 kWh/t, and low throughputs (<50 kg/h). The ROC operated with a stationary disc is not recommended for hard rock applications due to expected excessive wear of crushing surfaces and higher energy consumption. The freewheeling discs are recommended, but there is scope to optimize the crusher performance in terms of the power draw, size reduction, and throughput by manipulating the difference between the speeds of the discs. There is also scope to optimize the crusher performance when it is simulated with many particles. Once the full performance potential of the ROC is established, it will then be important to benchmark it against the existing crushers in the minerals industry as well as other industries where crushers are used.

Keywords: rotary offset crusher; single-particle breakage; discrete element method; particle shape; polyhedron; comminution



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1. Introduction

It is well known that comminution devices are characterized by low energy efficiencies due to the random nature of force transmission to the particles [1] and the necessity to transform impact forces to tensional forces. The inefficiency results in the utilization of only a small fraction of the available energy for comminution while the rest is dissipated as noise, heat, and mechanical losses, as well as being used for elastic particle deformation [2–5]. Comminution research is thus expected to continue unabated to address the inefficiencies that are inherent in comminution devices and circuits. For many decades, comminution research has focused on the design and optimization of milling devices, with little attention

given to the crushing devices, and thus possibly missing out on the possible gains that can be achieved by improving crushing [6]. This paper discusses the comminution of a single particle in the rotary offset crusher (ROC), which is a new comminution device with a promising performance potential in terms of throughput due to the enhanced speed of transportation induced by the centrifugal force of the discs [7,8].

The main difference between the ROC and conventional crushers (e.g., cone crushers) is the orientation of the crushing chamber. It is acknowledged that in the cone crusher, particles gravitate in the crushing chamber, while in the ROC, the particles are centrifugally transported between the discs until they are discharged. Figure 1 highlights the key difference in the operating principles of the centrifugal force-driven ROC and gravity-driven cone crusher. The description of various parts of the ROC is provided in Table 1. The chamber geometry of the cone crusher is made up of a concave bowl housing a mantle that is supported by a shaft that rests off-center on a lever gear, causing an eccentric motion when the gear rotates. The eccentricity thus causes the mantle to cyclically move forward and backward relative to the concave, i.e., there is squeezing motion (forward movement of the mantle) and releasing motion (backward movement of the mantle). For the squeezing motion, the particles are compressed and, depending on the level of applied stress (relative to the critical stress of the process material), particle breakage or weakening happens. On the other hand, during the releasing motion, the material gravitates through the chamber. This type of flow is driven by gravity and governed by the motion of the mantle [9,10].

The laboratory-scale ROC employs a simple design with two parallel 500 mm diameter discs that are not mechanically linked and there is a provision to offset the axis of the upper disc. The shifting of the axis relative to the lower disc is a key factor behind the breakage mechanism of this crusher. Thus, in rotation, there is a geometrical expansion and contraction of the conical space between the two discs in each revolution. The frequency of the cyclic expansion and contraction of this space depends on the rotational speed of the discs (another important operating variable). In this design, only the lower disc is driven by the motor via the V-belt drive. The transfer of the rotational motion to the upper disc is via the particles that are trapped between the faces of the upper and lower discs. The particles in the crushing zone are crushed as the high-speed discs spin and their inter-spatial geometry is changed. The particles move centrifugally from the center of the bottom disc to the periphery as they become smaller until they are small enough to pass through peripheral gaps in the discs.

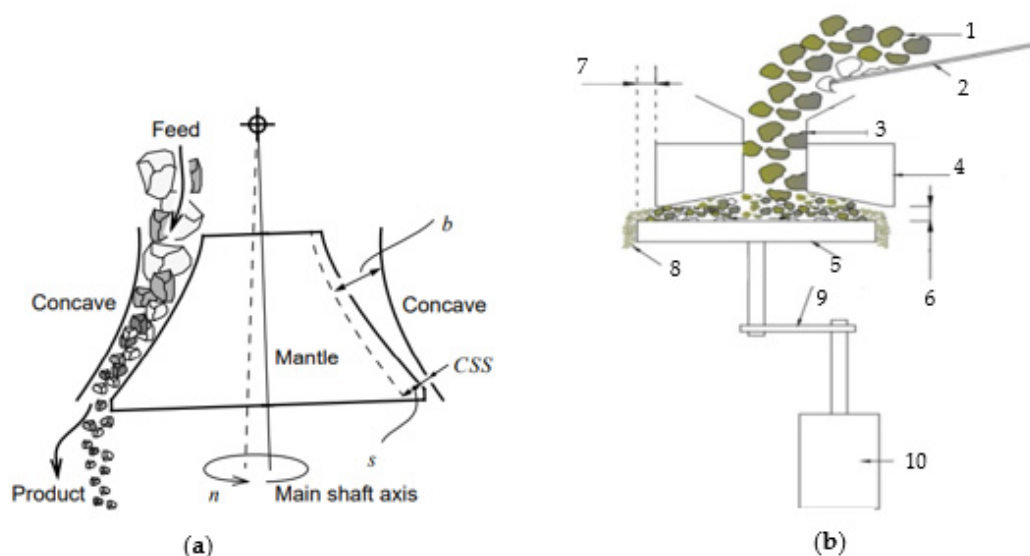


Figure 1. (a) Functional diagram for cone crusher [9] and (b) functional diagram of rotary offset crusher [8]. CSS stands for close side setting, n is the rotational speed, b is the gape, and s is the throw (difference between open side setting (OSS) and CSS).

Table 1. Description of parts for ROC.

Part Number	Description
1	Feed material
2	Conveyor belt
3	Feed chute
4	Top disc
5	Bottom disc
6	Vertical exit gap
7	Horizontal offset
8	Crusher product
9	Belt drive
10	Motor

The ROC closely resembles the helical disc mill used in the food industry [11]. The main distinct features of the helical disc mill include (1) having no offset between the vertical axes of the discs, (2) the top disc in the helical disc mill being stationary (not a free wheel), (3) not having a conical profile on any of the discs, and (4) having teeth on the crushing surface. The presence of horizontal offset between the discs as well as the freewheeling top disc in the ROC introduces some flexibility (i.e., preventing frequent jamming of the equipment when processing hard rocks). The crushing zone of the ROC has a smooth conical profile, which facilitates a succession of comminution events. However, it is acknowledged that various profiles (e.g., a curved profile with some corrugation in the form of ridges, squares, furrows, etc.) can be tried to enhance both the crushing forces and transportation rates. The corrugation of the crushing surfaces in the ROC is something that will need to be looked at in the future, with the selection and implementation of the profile performed after careful consideration given the expected high wear rate due to the sliding nature of particles between the discs. A more robust hydraulic system to ensure the maximum delivery of available energy to the particles nipped between the discs is also another area of improvement that could be looked at in the future. The implementation of the ROC in the mineral industry or any other industry would greatly depend on the potential performance advantages that it could offer in terms of energy consumption and throughput.

It is acknowledged that an adequate fundamental understanding of transportation and comminution processes in the crushing zone can help to establish the full potential of the ROC. In order to develop a deeper understanding of the performance potential of a specific equipment, it is critical to investigate how the variations in equipment geometry, shaft velocities, particle sizes, and material properties, among other variables, affect its performance [1]. It is possible to study the effect of various ROC operating variables (e.g., speed, horizontal offset, and vertical exit gap) and feed material characteristics (e.g., top size, strength, shape, and mineralogical composition.) on the crusher performance in terms of the size reduction ratio, power draw, throughput, and wear. However, it is difficult to obtain the measurements of the internal dynamic information on granular behavior with respect to rheology and breakage from physical experimentation with crushers [6].

Discrete element modeling of comminution devices has proven to be a viable approach that can provide the micro-properties and dynamic information of the material flow and fracture in the crushers (e.g., [6,12–21]). To gain a better insight into the micro-processes facilitating the comminution in the ROC, a discrete element method (DEM) simulation study was conducted using single particles to study the effect of the operating rotational speed of the discs on the size reduction ratio, ratio of the shear energy to impact energy (inferring the degree of dominance of the different breakage mechanisms), specific comminution energy, and throughput. The laboratory prototype was also used to conduct physical

experiments at 550 and 1000 rpm to allow the qualitative and quantitative validation of the simulation results. Discrete element modeling of the crushing device was performed using the simulated polyhedral particles to investigate the effect of the rotational speed (550, 1000, 1450, 1900, and 2350 rpm) on single-particle crushing when the crusher is operated under different dynamics, viz., (1) stationary top disc and (2) both discs rotating at the same speed. The $Ab-t_{10}$ breakage model [22,23] was used to study the crushing behavior of the single polyhedral particle. This model can predict the breakage behavior of particles, including non-spherical particles as demonstrated in previous studies [17,24–26]. The results generated from both physical and computational experiments provide preliminary insights into the performance potential of the current design of the ROC for hard rock application.

2. Materials and Methods

Prior to numerical simulation, some experimental work was conducted on the laboratory ROC using silica and UG2 platinum-bearing ore.

2.1. ROC Crushing Tests

Mono-size feeds ($-19 + 13.2$ mm) of silica and UG2 platinum-bearing ore were prepared from the bulk materials, which were pre-crushed to -19 mm using a laboratory jaw crusher. Standard procedures were used to determine the Bond crushability index (CWI) and Bond abrasion index (A_i), which are given in Table 2. Based on the classification of crushability indices [27], both materials have a ‘soft’ crushability index, with silica being slightly harder than the UG2 ore. The slight difference in the crushability indices can be attributed to the distinct mineralogical compositions of the two materials, i.e., silica constitutes $>99\%$ SiO_2 (quartz), while the UG2 ore contains a variety of minerals, as shown in Table 3. A higher A_i value obtained for silica confirms its relatively high abrasiveness [28], i.e., a high wear rate of the ROC crushing surfaces can be expected when processing silica. Since the crushing surfaces of the ROC are not yet lined with hardened steel or any other appropriate hard alloy, as is the case for crushers, the results of the Bond abrasion test can only be useful in future studies that would focus on the wear characteristics of the ROC discs.

Table 2. Material characteristics.

Parameters	Unit	Materials	
		Silica	UG2 Ore
Specific gravity (SG)	-	2.67	3.32
CWI	kWh/t	13.8	10.4
A_i	-	0.45	0.12

Table 3. Chemical composition of the UG2 ore, the remainder of the composition is mainly oxygen and sulfur, which were not determined.

Element	Concentration	Unit
Al	6.05	%
Ca	2.27	
Co	<0.05	
Cr	9.6	
Cu	<0.05	
Fe	11.2	
Mg	9.67	
Mn	0.15	

Table 3. Cont.

Element	Concentration	Unit
Ni	0.095	%
Pb	<0.05	
Si	16.3	
Ti	0.3	
V	<0.05	
Zn	<0.05	
Au	0.03	ppm
Pt	1.28	
Pd	0.91	
As	<0.01	
Others	~44.4	%

Single-particle crushing experiments were conducted with the laboratory ROC shown in Figure 2, which is located in the Minerals Processing Laboratory at the University of the Witwatersrand. A 3 kW three-phase induction motor that has a full-load speed of 1420 rpm powers the crusher. Two speeds (550 and 1000 rpm) of the 500 mm diameter cylindrical discs were tested. The variable speed drive (VSD) allows the speed adjustments. The vertical exit gap and horizontal offset were fixed at 4 and 10 mm, respectively. To account for inherent variation among individual particles of the same material and generate enough samples for particle size analysis, each test was repeated 10 times. The standard deviation of the mass for the ten particles individually fed to the crusher was maintained at ± 0.01 g as a way of using the particles with comparable densities that can infer comparable mineralogical composition (especially in the case of a multi-component UG2 ore).

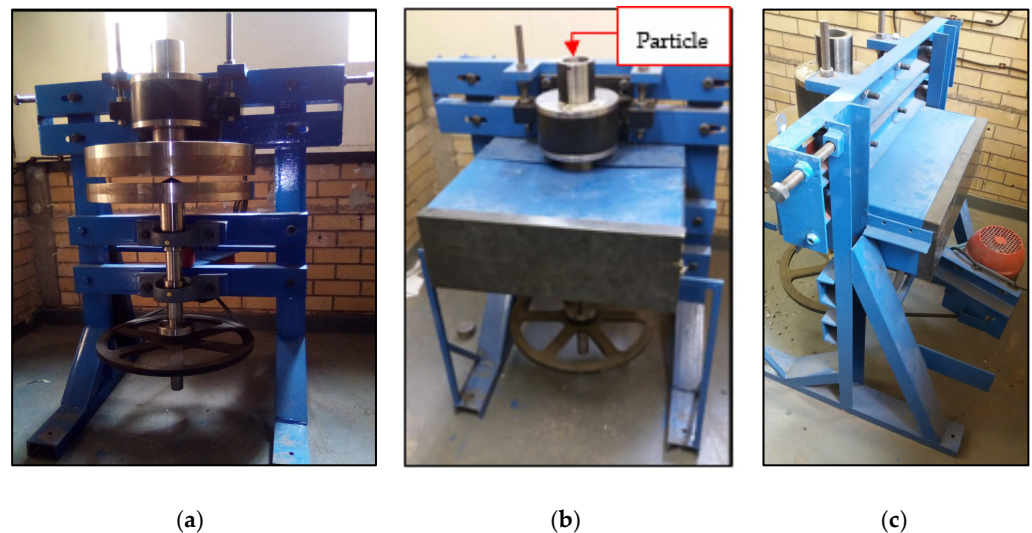


Figure 2. Laboratory prototype of the rotary offset crusher, (a) illustration of the discs (during operation to disc horizontally shifted to the right to provide the offset), (b) front-end of the crusher fitted with the sample collection box, (c) back-end of the crusher fitted with the sample collection box.

2.2. DEM Simulations

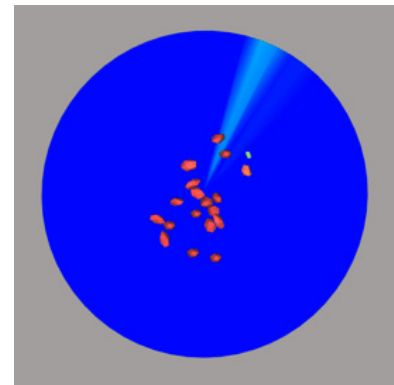
2.2.1. Calibration

Discrete element method simulations of UG2 ore particle breakage were carried out using the Rocky DEM[®] software version 2023 R2. The breakage of silica was not simulated.

The geometries of the various components of the ROC (lower disc, upper disc, and hopper) were imported into the DEM software using the widely exchangeable STereoLithographic (STL) format. Polyhedron particles (geometric mean size of 15.8 mm) were generated using the particle generator within the DEM software. Figure 3a illustrates the shape of real particles. It is evident from Figure 3a that the UG2 ore particles are non-spherical. Figure 3b shows the simulated polyhedral particles. The particle shape was not calibrated. The use of non-spherical particles to study breakage makes it possible to have realistic behavior since the real particles are irregular [25,26,29]. The hysteretic linear spring–dashpot model was used to model the normal contact force while the linear spring Coulomb limit law was chosen to model the tangential contact force.



(a) Real particle for UG2 ore (-19+13.2 mm)



(b) Illustration of simulated 15.8 mm diameter particles

Figure 3. UG2 ore particles (a) and polyhedral particles generated in the simulator (b). For single particle simulations, only one particle was fed to the crusher.

The particle density was measured on 30 individual rocks using the Archimedes method in Equation (1). The average particle SG was determined as 3.32. The bulk density was measured by filling a known volume with material and simply finding the weight of the material. The measurements were repeated ten times using the $-19 + 13.2$ mm particles and the average bulk density was found to be 1753 kg/m^3 . The average porosity, estimated using Equation (2), was found to be 48% (v/v).

$$SG = \frac{W_a}{W_a - W_w} \quad (1)$$

where W_a and W_w are the mass of the rock specimen in air and mass of rock specimen in water.

$$\text{Porosity} = \left(1 - \left(\frac{\text{Bulk density}}{\text{Particle density}} \right) \right) \times 1000 \quad (2)$$

Table 4 summarizes the DEM input parameters. The authors acknowledge a study limitation that the material properties (Young modulus and Poisson ratio) and the contact parameters such as friction coefficients were not experimentally determined. The default parameters in the DEM software were used. It is recommended that future studies on the DEM simulation of the device should improve on this limitation. However, it is the authors' view that the indicative results are adequate to provide general performance trends. The parameters for the $Ab \times t_{10}$ breakage model, which enables the particle replacement method [24], were calibrated through the particle fracture response data in terms of fragment distribution, which were generated using the single-particle experiments conducted with the laboratory ROC. The breakage function in the DEM software was changed to ensure the simulated size distribution is similar to the experimental size distribution in terms of P_{80} sizes. The breakage function that yielded similar P_{80} sizes was adopted in all simulations. The selection function coefficient of 0.002 kg/J compares to what was

calibrated for copper ore when the same breakage model was also used [24]. The minimum fragment size in the DEM was set at 300 μm to cut down on the computational cost.

Table 4. DEM input parameters (P-P is ore particle and ore particle interaction and P-B is ore particle and boundary interaction).

Parameter	Unit	Description/Value
Material (ore and boundary) properties		
Material	-	UG2 platinum-bearing ore
Ore SG	-	3.32
Mean feed size	mm	15.8
Breakage model	-	$Ab \times t_{10}$ model
Selection function coefficient	kg/J	0.002
Minimum size of fragments	mm	0.3
Poisson ratio	-	0.3
Young modulus of ore	N/m ²	1×10^8
Young modulus for boundary	N/m ²	1×10^{11}
Density of boundary	kg/m ³	7850
Contact parameters		
Static and dynamic friction (P-B)	-	0.3
Static and dynamic friction (P-P)	-	0.7
Coefficient of restitution (P-B)	-	0.3
Coefficient of restitution (P-P)	-	0.3

2.2.2. Studying Crusher Dynamics Using DEM

After the calibration of the DEM parameters was completed, the following simulations were conducted to study the particle breakage in the ROC. Simulations of single-particle breakage were performed for a variety of speeds (550, 1000, 1450, 1900, and 2350 rpm) while the horizontal offset and vertical exit gap were fixed at 10 and 4 mm, respectively. This was performed for the following two scenarios: (1) stationary top disc (this closely represents the experimental setup with the top disc not rotating when a single particle is fed to the crusher) and (2) both discs rotating at the same speed, i.e., the top disc was not friction driven as was the case with the laboratory prototype.

3. Results and Discussions

3.1. Breakage of Single Particles of Silica and UG2 Ore in the Laboratory ROC (Experimental Results)

Experimental versus simulated PSDs for the UG2 ore are shown in Figure 4. Experimental product size distributions of UG2 ore are compared to those of silica (single-component material) in Figure 4. It can be observed that for each material, the size distributions for the 550 and 1000 rpm speeds are comparable for the particle sizes above 100 μm . The product P_{80} sizes are about 2 mm, suggesting reduction ratios of at least 8 (calculated based on the assumption that the feed size is 15.8 mm, i.e., the geometric mean of the feed size class ($-19 + 13.2$ mm)). Feeding one particle to the ROC does not accelerate the top disc. This suggests that the parent particle and subsequent fragments in the crushing zone were forced against a stationary body (top disc) while radially moving to the periphery. It is worth mentioning that the crusher design with a stationary top disc (assuming the disc is not a free wheel) is not suitable for hard rocks as two problems are likely to happen, viz., frequent jamming and high wear rate (due to the expected higher degree of dominance of the abrasion mechanism). The free wheel ensures some degree of

flexibility, which can facilitate the release of the arrested particles along the comminution cavity and thus prevent jamming.

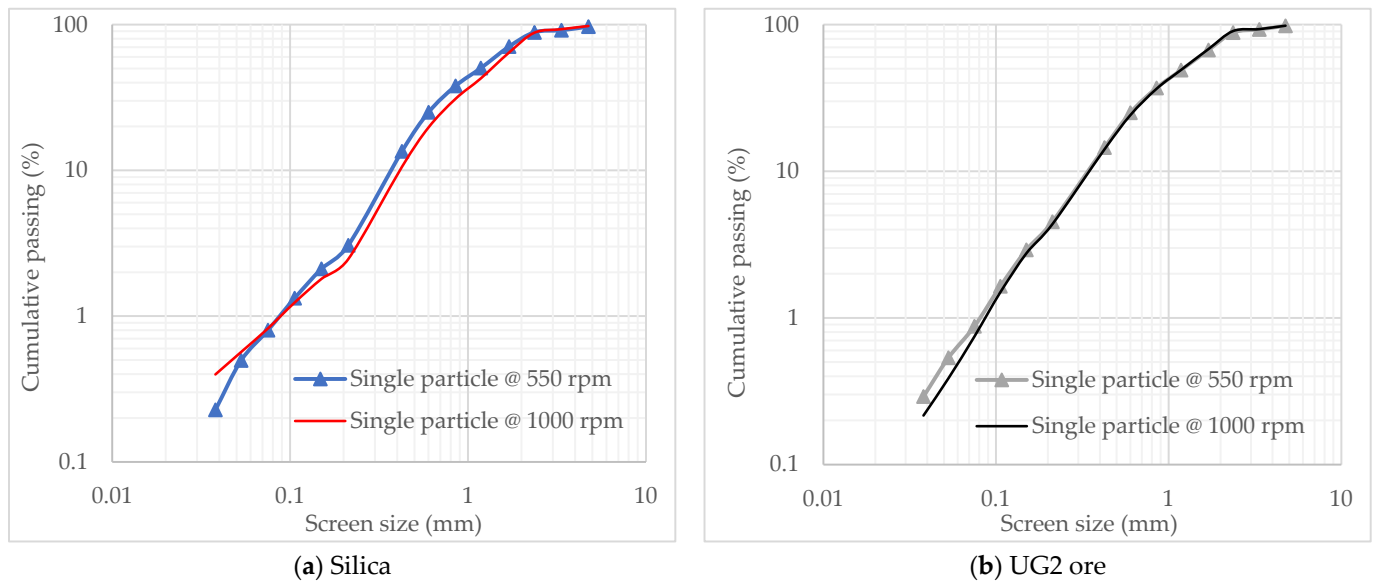


Figure 4. Product size distributions after crushing $-19 + 13.2$ mm particles, (a) silica and (b) UG2 ore.

The summary of the product sizes (in terms of P_{80}) is shown in Table 5. It is evident that for each material, the P_{80} sizes for 550 and 1000 rpm are comparable, and that the silica P_{80} sizes are slightly coarser than the UG2 ore for both 550 and 1000 rpm. The trend in the P_{80} sizes of silica and UG2 ore can be attributed to the difference in their Bond crushing work indices in Table 2.

Table 5. P_{80} sizes after crushing $-19 + 13.2$ mm of silica and UG2 ore.

Speed (rpm)	P_{80} (mm)	
	Silica	UG2 Ore
550	2.17	2.14
1000	2.26	2.09

The torque values during operation can provide some insights into the crusher dynamics. The typical signal is presented in Figure 5 (for the test with UG2 ore at 1000 rpm). It is evident that there is a slight increase in the torque when a single particle is fed to the crusher. From Figure 5b, it is clear that the peaks in the torque signal for the different particles correspond to a common value of approximately 5 Nm (suggesting comparable breakage energy for the individual particles). Breakage of a single particle is instantaneous, with no successive peaks in the torque signal during the processing of each particle. The progeny particles produced move radially along the comminution cavity until they are nipped again between the two discs. Any subsequent nipping is followed by further breakage (mainly abrasion due to the rotation of the disc and compression as the particle(s) is forced against the stationary top disc). The simulation results discussed in Section 3.2 provide insights into the intensities of the compressive and shear stresses for a variety of operating speeds when the crusher is operated with a stationary top disc as well as when it is operated with a rotating top disc.

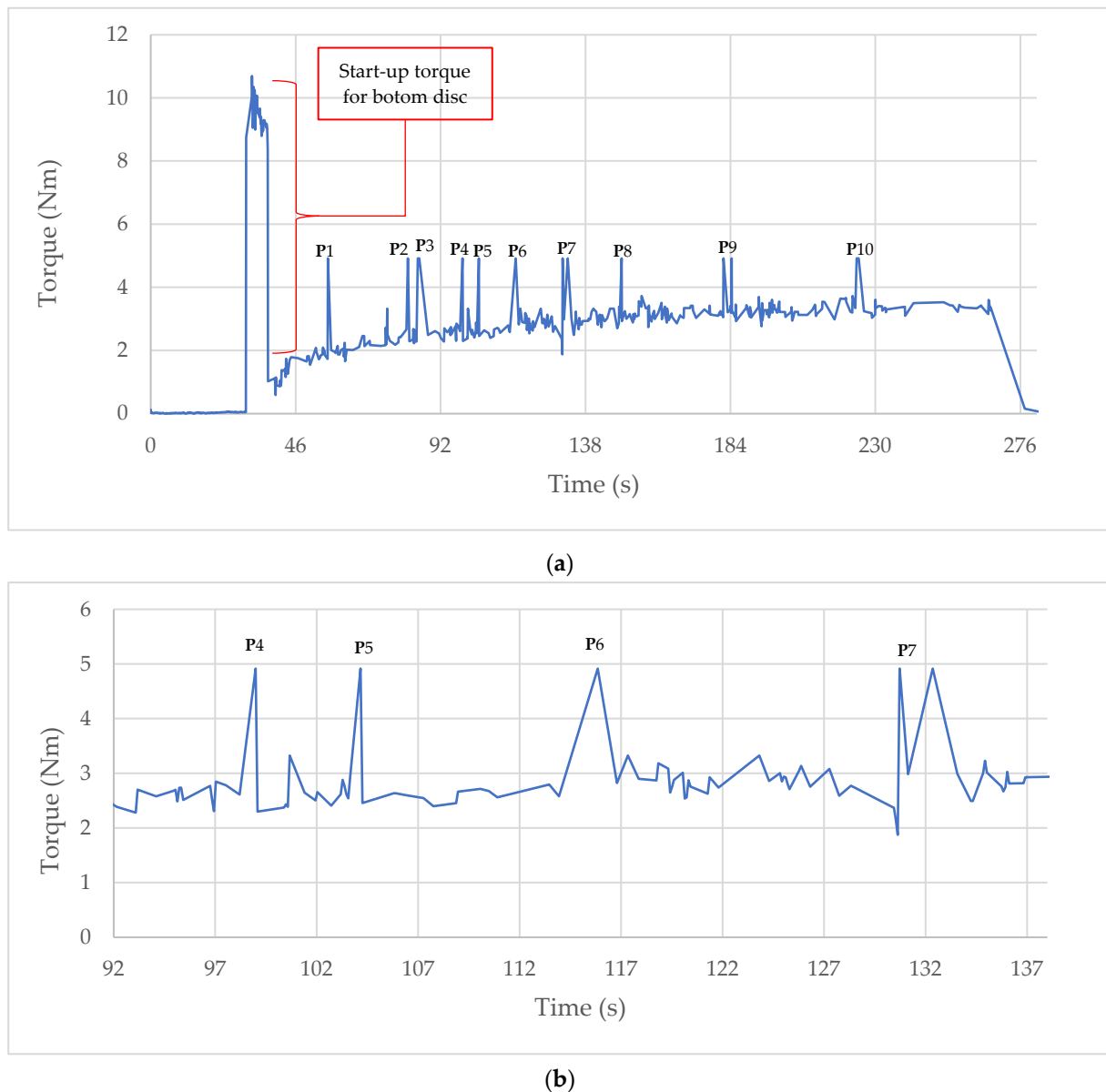


Figure 5. Torque signals for the ROC in operation (speed was 1000 rpm, vertical exit gap of 4 mm gap, horizontal offset of 10 mm), successively fed with single particle of UG2 ore, (a) full signal and (b) signals for time ranging between 92 and 137 s (particles 4 to 7). P stands for particle.

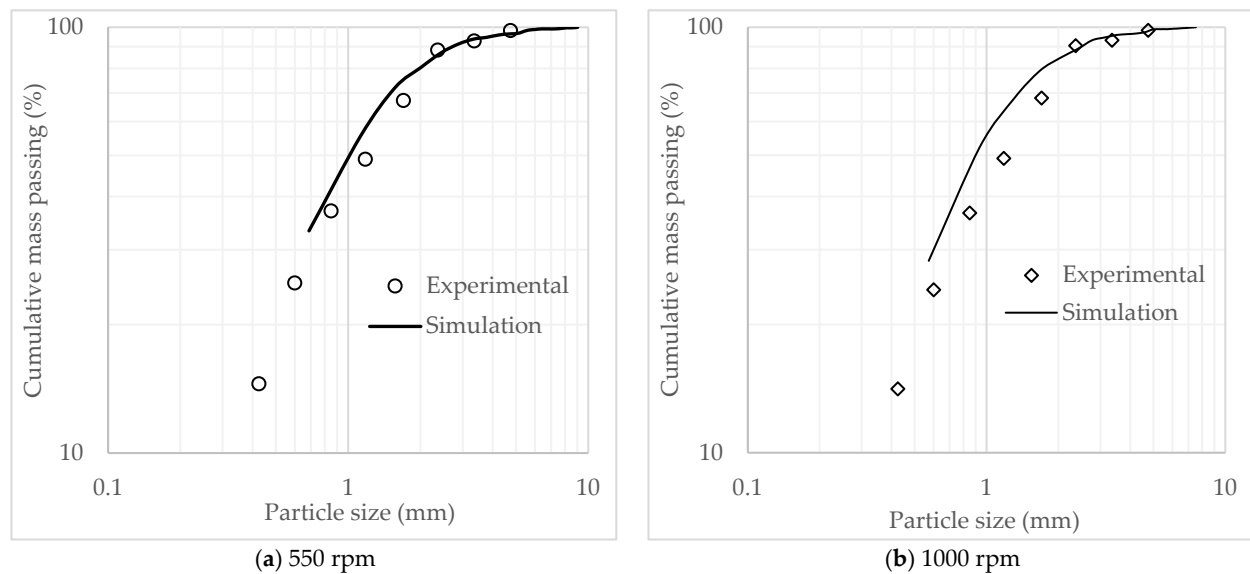
3.2. Numerical Simulation of Single-Particle Breakage

3.2.1. Validation of Simulated Breakage Response

Table 6 summarizes the percentage errors between the experimental and simulated P_{80} sizes and throughputs. Figure 6 shows the experimental and simulated PSDs. The simulated product size distribution is truncated due to the computation limit of the minimum particle size that was simulated. Lichter et al. [29] made the same observation for the cone crusher simulation. There is a slight overestimation of the fineness of the progeny size distribution. The errors between the experimental and simulated P_{80} sizes were less than 10%. The errors between the average experimental and simulated throughputs were 3% and 10.3% for 550 and 1000 rpm, respectively. The analysis and interpretation of the simulation results were performed cognizant of the discrepancies in Table 6.

Table 6. Experimental and simulated d_{80} sizes and throughputs.

Speed (rpm)	P_{80}			Q		
	Experimental (mm)	Simulated (mm)	Error (%)	Experimental (kg/h)	Simulated (kg/h)	Error (%)
550	2.14	1.99	6.71	35.3	36.4	3.0
1000	2.09	1.92	7.85	39.5	43.6	10.3

**Figure 6.** Experimental versus simulated ROC product PSDs crushing the UG2 ore.

The DEM simulations were conducted for two scenarios, i.e., (1) stationary top disc and (2) both discs rotating at the same speed.

3.2.2. Effect of Crusher Dynamics on Normal and Tangential Forces

(a) Both discs rotating at same speed

The fragmentation process of a single particle along the comminution cavity is simple to describe, with the size of the particles progressively reduced because of the compressive and shear stresses imposed on the particles nipped between the discs. Sequential arresting (nipping) and release (moving further along the comminution cavity of the crusher until they become arrested between the discs again) happens until the progeny particles are small enough to escape from the crushing zone. Figure 7 illustrates the progressive comminution when the two discs are both rotating at 1450 rpm. Similar diagrams could be shown for the other simulated speeds; the main difference is only in the residence time at which breakage events are occurring. Figure 8 shows the normal and tangential forces acting on the particle(s) because of bottom disc–particle interactions for various speeds. Similar trends could be shown for the forces due to upper disc and particle interactions. It is evident that the fracture events of the particle(s) correspond to the ‘rise’ in the normal and tangential forces. For the speed of 1450 rpm in Figure 7, it can be seen that a body breakage of the particle happens when the simulation time is 0.295 s. This time, in turn, corresponds to the highest normal and tangential forces of 4.6 and 1.4 N, respectively, as shown in Figure 8. Prior to 0.295 s, as evident for the simulation time of 0.25 s in Figure 7, chipping of small fragments from the parent particle was happening.

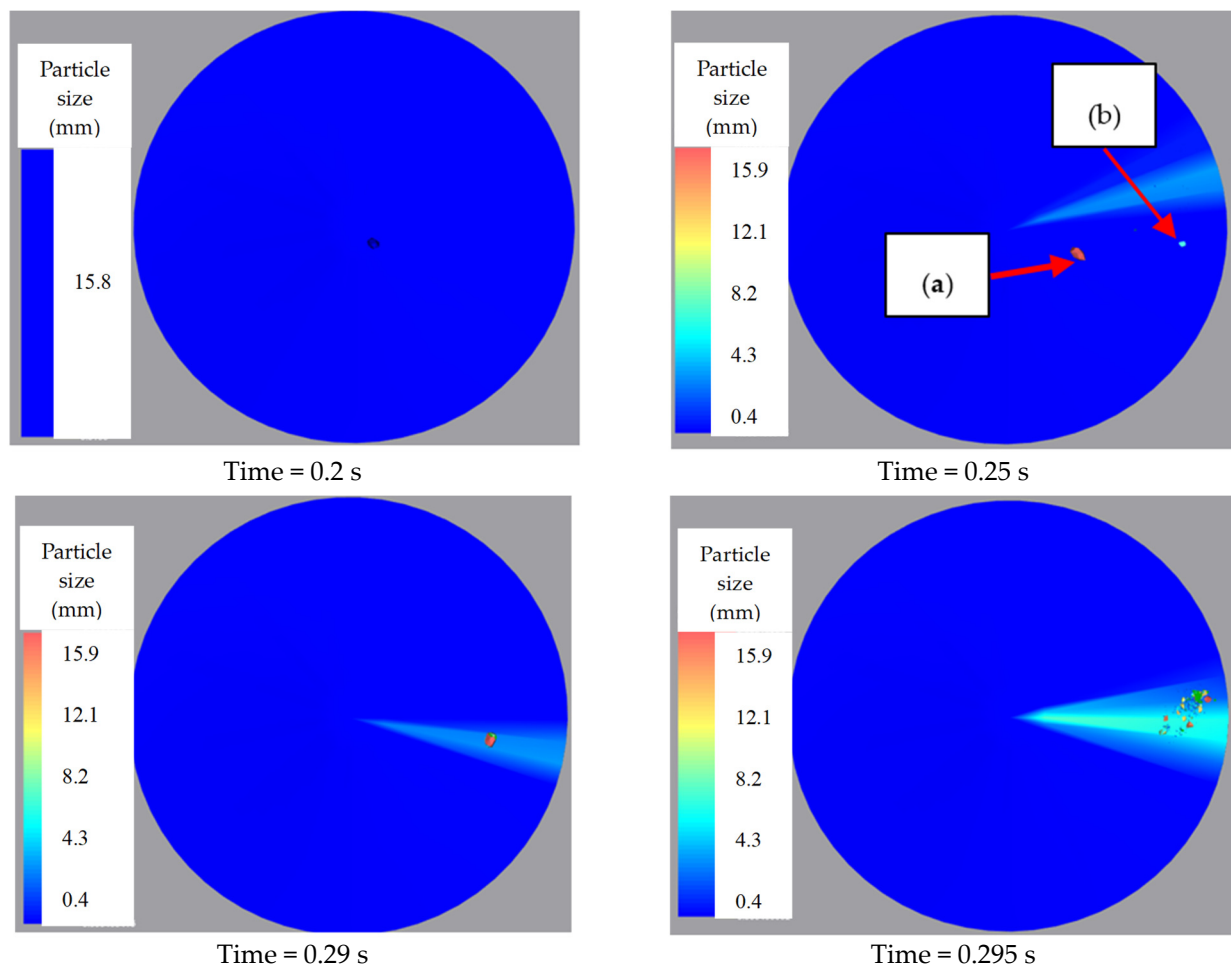


Figure 7. Spatial images of progressive particle breakage along the comminution cavity when ROC is operated with both discs rotating at same speed (1450 rpm), (a) parent particle (most of it) and (b) chipped fragment from the parent particle.

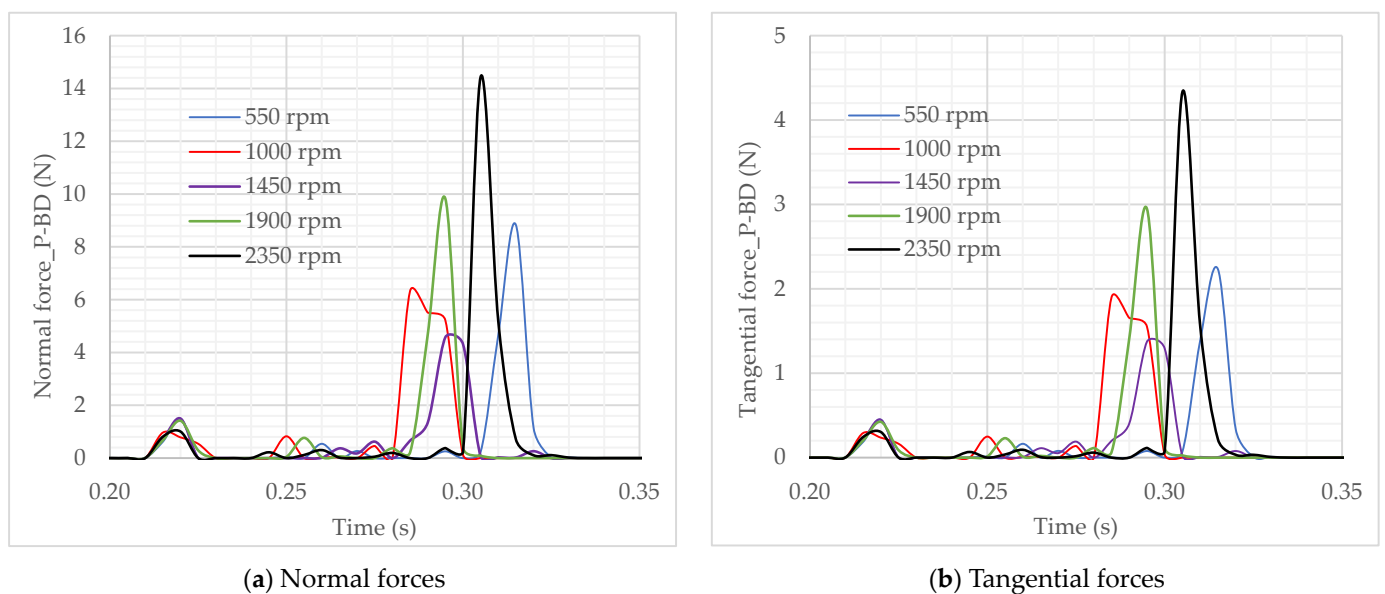


Figure 8. Normal (a) and tangential (b) forces due to bottom disc and particle interactions for various speeds for the simulated ROC with both discs rotating at the same speed.

(b) Stationary top disc

The normal and tangential forces acting on the particle(s) as a result of bottom disc–particle interactions are shown in Figure 9 for various speeds. Similar trends could be shown for forces due to the upper disc and particle interactions.

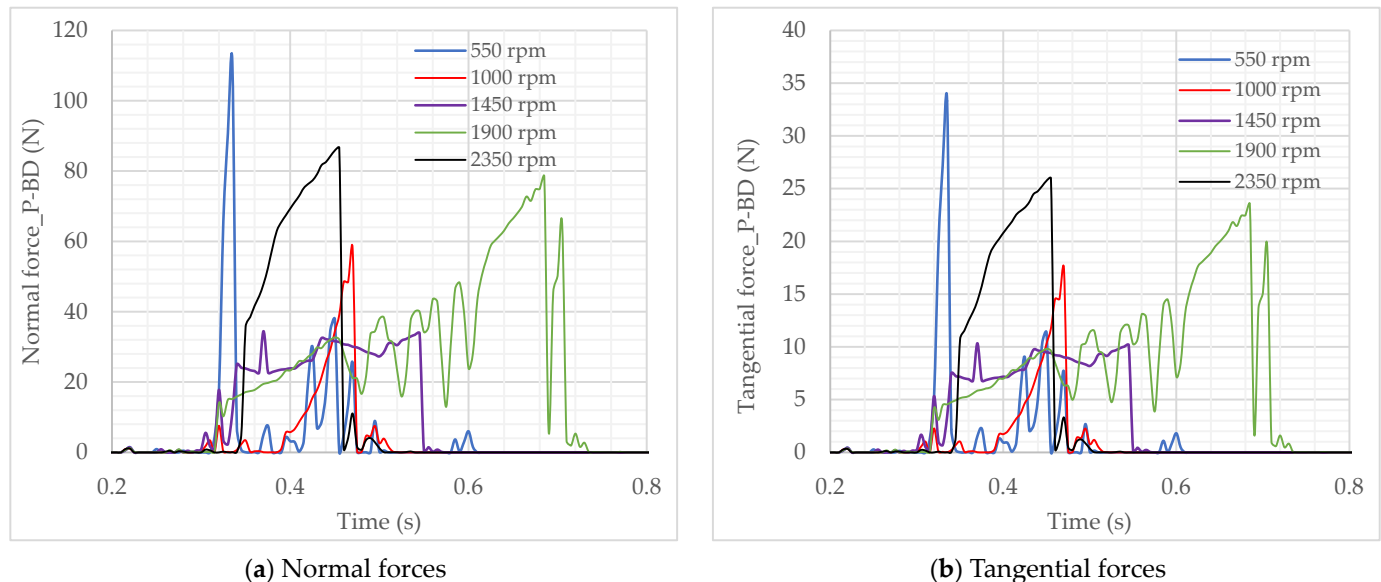


Figure 9. Normal (a) and tangential (b) forces due to bottom disc and particle interactions for various speeds for the simulated ROC with stationary top disc.

Compared to Figure 8, it is evident from Figure 9 that with the stationary top disc, the residence time is relatively longer (e.g., approximately 0.73 s for 1900 rpm speed). It is also evident that both the normal and tangential forces are relatively higher when the crusher is operated with a stationary top disc. Since these forces can be used to infer the wearing characteristics due to the geometry–particle contacts, the results suggest that the wear of the crushing surfaces can be reduced by manipulating the crusher dynamics, with a stationary disc crusher expected to be associated with higher wear rates. Optimization of the operating speed can be conducted to reduce the shear stress due to disc–particle contacts while promoting interparticle comminution within the device. One area of research that would be looked at in the future is the understanding of the number of stress events and accumulated damage in the particles for a variety of crusher dynamic conditions.

3.2.3. Effect of Crusher Dynamics on Size Reduction and Specific Comminution Energy

(a) Size reduction ratio

Figure 10 shows the reduction ratios, in terms of 80% passing sizes, for the two scenarios, i.e., (1) stationary top disc and (2) both discs rotating at the same speeds. When the top disc is stationary, the crusher reduction ratios tend to be comparable for various speeds, as can be observed in Figure 10. A similar trend could not be observed for the simulated ROC operated with both discs rotating at the same speed. For this crusher dynamic, the reduction ratio increases slightly with the speed until 1000 rpm, beyond which it consistently decreases with the speed. For this limited simulation dataset, the results suggest the 1000 rpm speed to be the optimal speed for maximizing the reduction ratio when the two discs are rotated at the same speed. The reduction ratios of at least 8 for both scenarios compare well to those observed from the experimental data in Figure 4.

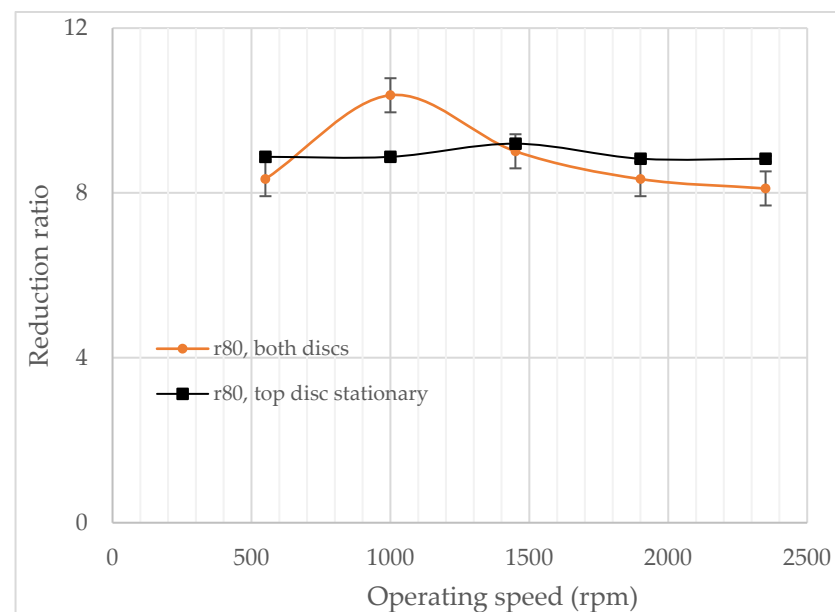


Figure 10. Reduction ratio against crusher speed.

(b) Energy consumption

The impact (compressive), shear, and dissipated energies due to particle–particle, particle–bottom disc, and particle–top disc interactions are presented in Figures 11 and 12 for case 1 (stationary top disc) and case 2 (both discs rotating at same speed), respectively. From Figure 11, it is evident that the shear energies due to particle–bottom disc (P-BD) and particle–top disc (P-TD) interactions are higher than the corresponding impact energies. This highlights that the ROC with a stationary disc is characterized by high shear actions, which, in turn, could contribute to high operating costs (due to frequent replacement of crusher liners). The impact energies due to particle–discs interactions are highest at 1450 rpm. This is also the speed at which the shear energy due to particle–top disc interactions is highest. A slightly higher reduction ratio at this speed (see Figure 10) can be attributed to the increased compressive and shearing actions.

From Figure 12, it is evident that the shear energy due to geometry–particle contacts increases with the speed, which suggests that the degree of the shear breakage mechanism increases with the speed. Compared to the crusher design with the stationary top disc (see Figure 11), the shear and dissipated energies are significantly lower when both discs are rotating at the same speed. The impact energy due to P-BD interaction decreases with a gradual increase in the rotational speed of the discs until 1000 rpm, beyond which it is relatively constant. The impact energy due to P-TD is showing a different trend, with it increasing with the speed until 1450 rpm, beyond which it decreases with the increasing speed. The shear energy due to particle–particle interactions is also highest at 1450 rpm. For optimization purposes, it is desirable that the crusher is associated with many particle–particle (P-P) events (interparticle comminution) and a shearing action due to disc–particle interactions.

The specific comminution energy was calculated from the sum of the impact and shear energies using the following equation.

$$E_{cs} = \frac{(E_{\text{impact}} + E_{\text{shear}})}{3.6 \times M_p} \quad (3)$$

where 3.6 is a conversion factor, E_{impact} is the sum of the impact energy due to particle–particle, particle–bottom disc, and particle–top disc interactions, E_{shear} is the sum of the shear energy due to particle–particle, particle–bottom disc, and particle–top disc interactions, and M_p is the mass of the particle.

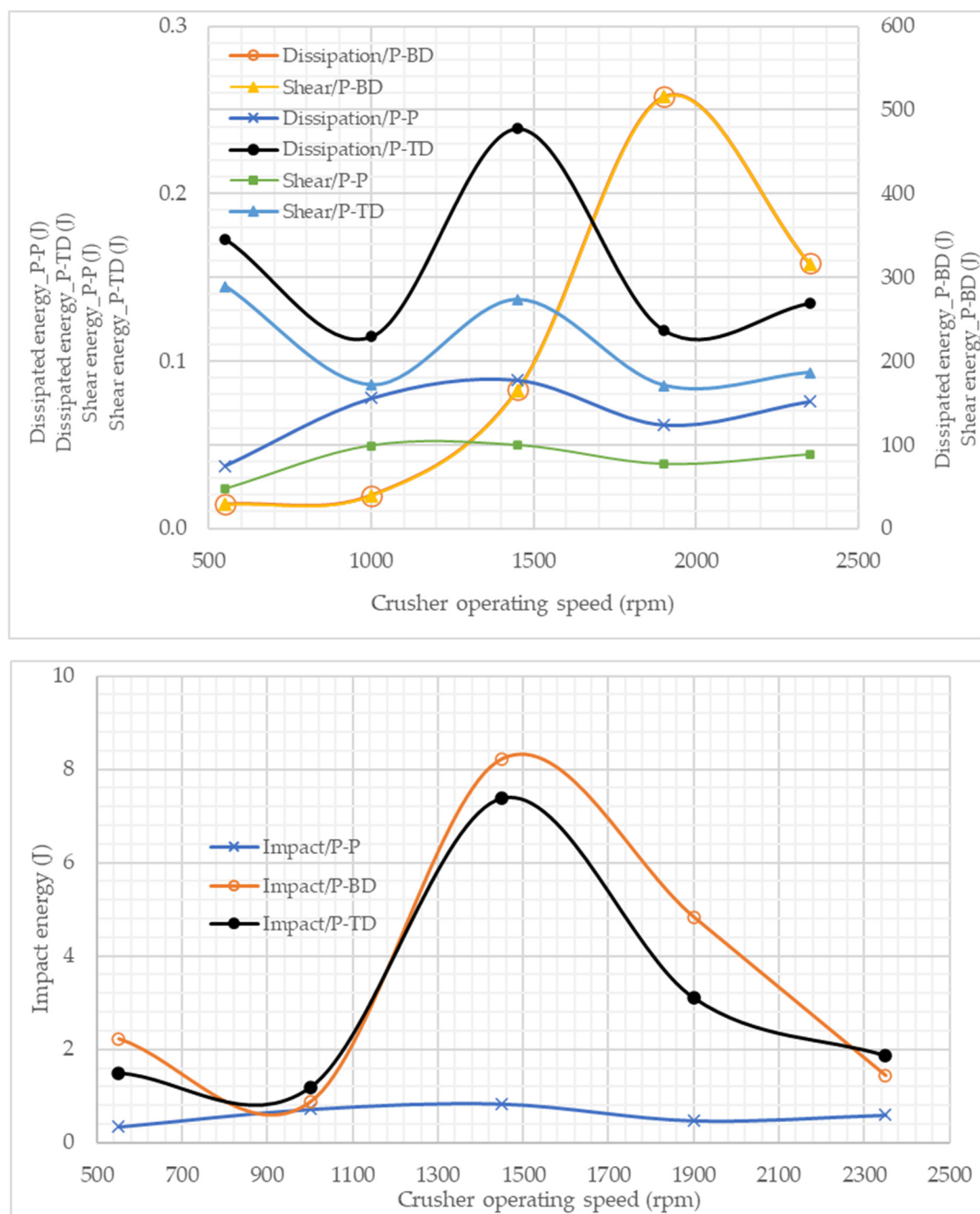


Figure 11. Impact, shear, and dissipated energies due to interactions when the ROC is operated with a stationary top disc. P-P, P-BD, and P-TD denote particle–particle, particle–bottom disc, and particle–top disc interactions, respectively.

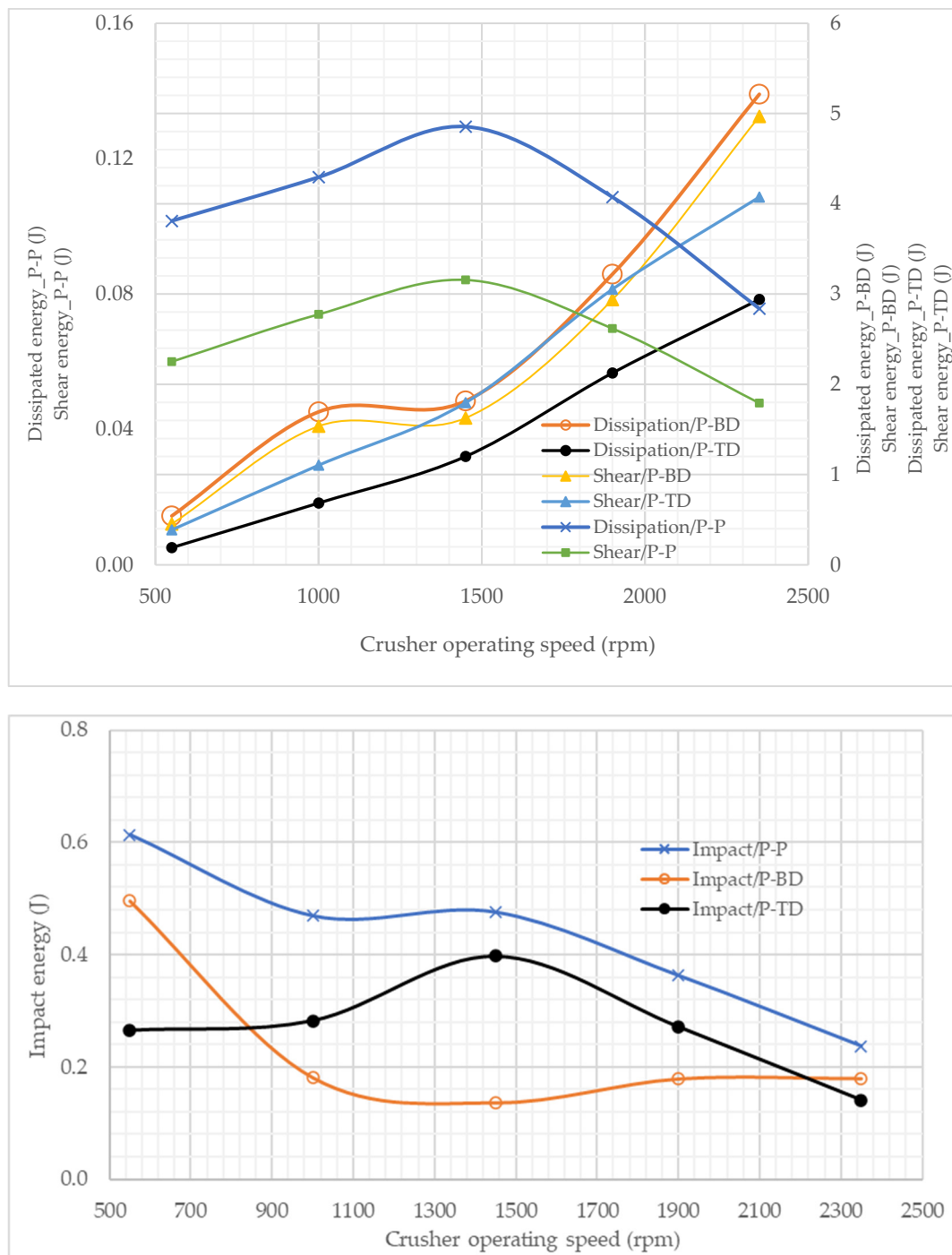


Figure 12. Impact, shear, and dissipated energies due to interactions when the ROC is operated with both discs rotating at the same speed. P-P, P-BD, and P-TD denote particle–particle, particle–bottom disc, and particle–top disc interactions, respectively.

Equation (3) was modified to include the dissipated energy (i.e., the energy that is not recovered and is absorbed in the dashpots) in order to calculate the total specific energy as follows.

$$E_{s,\text{total}} = \frac{(E_{\text{impact}} + E_{\text{shear}} + E_{\text{dissipated}})}{3.6 \times M_p} \quad (4)$$

where $E_{\text{dissipated}}$ is the sum of the dissipated energy due to particle–particle, particle–bottom disc, and particle–top disc interactions.

The ratio of the specific comminution energy to the total specific energy was defined as energy utilization (E_u), as shown in the following equation to evaluate the efficient utilization of the available energy for breakage.

$$E_u = \frac{E_{cs}}{E_{s,total}} \times 100 \quad (5)$$

The comminution energy, total specific energy, and energy utilization are summarized in Table 7. As expected, the ROC with a stationary top disc is characterized by higher specific energies, which are attributed to the high shear energy of that stationary disc. For the ROC with a stationary top disc, the energy utilization is approximately 50% for all speeds. This implies that half of the input energy of the system was utilized to effect breakage. Changing the system dynamics (e.g., allowing both discs to rotate) can be said to provide some performance advantages since the specific energies were reduced significantly to below 1 kWh/t and the energy utilization (especially at low speeds) also increased. The reduction in the specific energy is attributed to the reduced shear energy due to disc–particle interactions as a result of the increased flexibility in the crusher.

Table 7. Summary of net comminution and total energies.

Speed (rpm)	Comminution Energy				Total Specific Energy (kWh/t)	Energy Utilization (%)	Shear/Impact Ratio
	Impact (J)	Shear (J)	TOTAL (J)	Specific (kWh/t)			
Case 1—stationary top disc							
550	4.058	29.145	33.203	1.844	3.471	53.133	7.2
1000	2.778	39.659	42.437	2.357	4.571	51.568	14.3
1450	16.434	165.466	181.899	10.103	19.313	52.315	10.1
1900	8.401	515.661	524.062	29.109	57.768	50.389	61.4
2350	3.891	316.420	320.311	17.792	35.388	50.276	81.3
Case 2—both discs rotating at the same speed							
550	1.375	0.902	2.277	0.126	0.173	73.162	0.7
1000	0.933	2.714	3.647	0.203	0.341	59.378	2.9
1450	1.010	3.508	4.518	0.251	0.426	58.951	3.5
1900	0.814	6.062	6.876	0.382	0.685	55.766	7.4
2350	0.558	9.090	9.648	0.536	0.993	53.966	16.3

The shear/impact ratios, as shown in Table 7, were calculated from the shear and impact energies and they are plotted against the energy utilization in Figure 13. It is evident that the shear/impact ratio increases with the rotating speed, and it is inversely proportional to the energy utilization. To maximize the energy utilization, it is recommended that the ROC is operated at low speeds. At higher speeds, the ROC is comparable to a laboratory pulverizing device, with abrasion comminution being dominant over compressive comminution. Thus, to advance the ROC from the status of a laboratory pulverizer to an innovative comminution device requires further design innovations. Apart from the importance of disc profiling, the device could have vertical vibratory motion to the top disc to increase the compressive stress and thereby shatter the particles, which could partly reduce the slabby particles discharged from the crusher. Furthermore, interparticle comminution has to be promoted when the crusher is fed with many particles by choke feeding it with the feed with a suitable size distribution. Increasing the height of the feed opening/gape of the crusher's comminution cavity to promote interparticle comminution, as shown in Figure 14, is recommended.

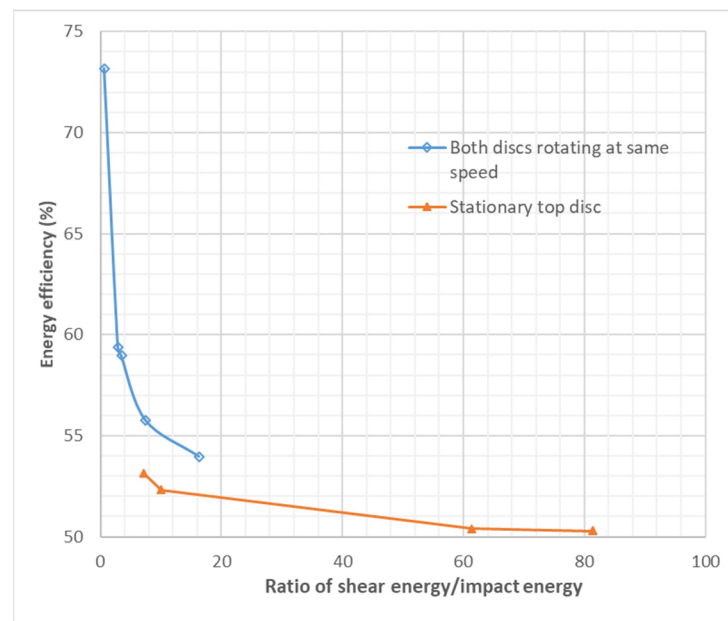


Figure 13. Relationship between discharge rate (throughput), reduction ratio, and crusher operating speed.

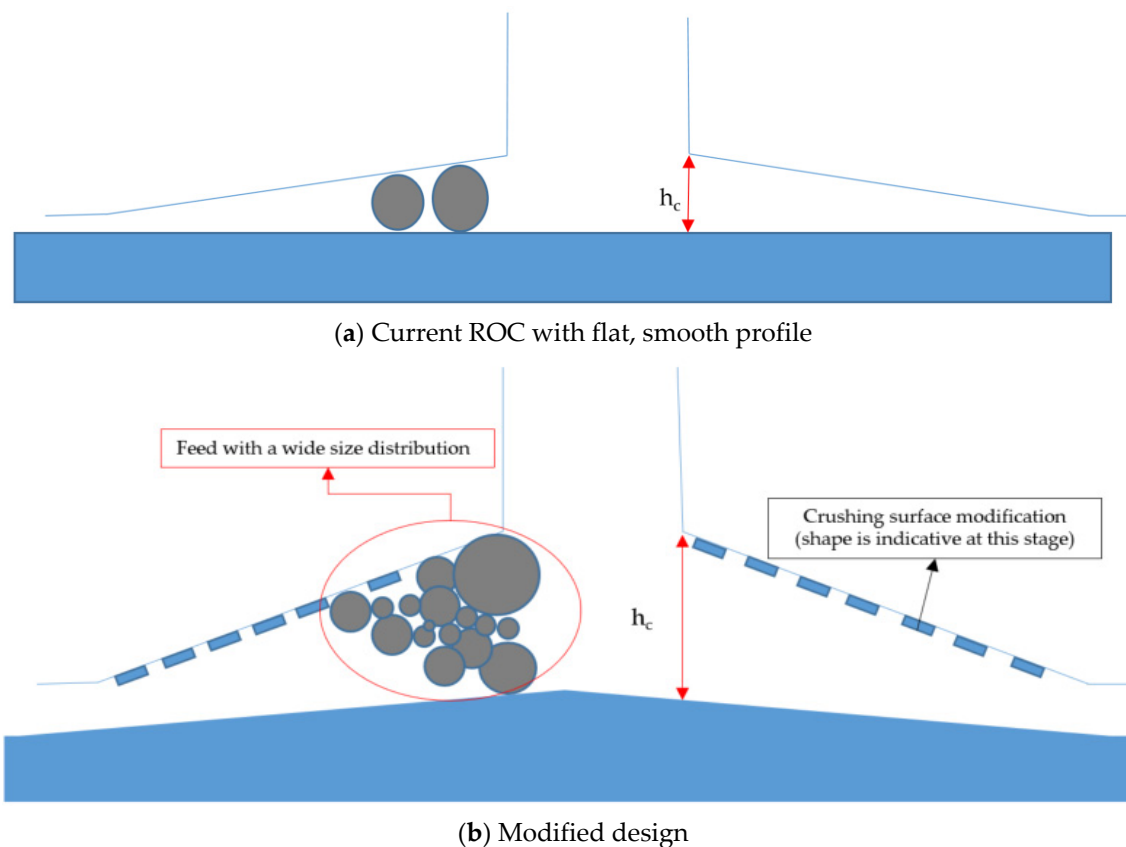


Figure 14. ROC crushing chamber, (a) current design and (b) modified design to be used in future work.

3.2.4. Effect of Crusher Dynamics on Throughput

The throughput of the crusher was evaluated using the following equation.

$$Q = \frac{M_f}{\tau_c} \quad (6)$$

Where Q is the throughput in kg/h, M_f is the feed mass, and τ_c is the residence time in the crushing zone.

Figure 15 plots the throughput (and the reduction ratio) against the crusher operating speed. The difference in the crusher's dynamic due to the speed differential affects the rate at which the progeny particles are discharged from the crushing zone. While comparable reduction ratios were achieved for the two crusher designs, the difference in dynamics allows the fast transmission of the compressive and shear stresses on the particles (hence, faster throughput) when both discs are spinning at the same rate. A stationary top disc negatively affects the crusher throughput, with throughputs less than 50 kg/h and which seem insensitive to the rotational speed. When the crusher is simulated with both discs rotating at the same speed, the progeny particles tend to be discharged faster, with throughputs greater than 130 kg/h. The authors acknowledge that further simulation studies involving the calibration of geometry–particle interaction parameters and particle shape could provide more insights into the performance potential of the crusher in terms of throughput. It is thus recommended that once the crushing chamber is redesigned to promote interparticle comminution, material transport should be thoroughly investigated in order to benchmark the ROC against other crushing devices.

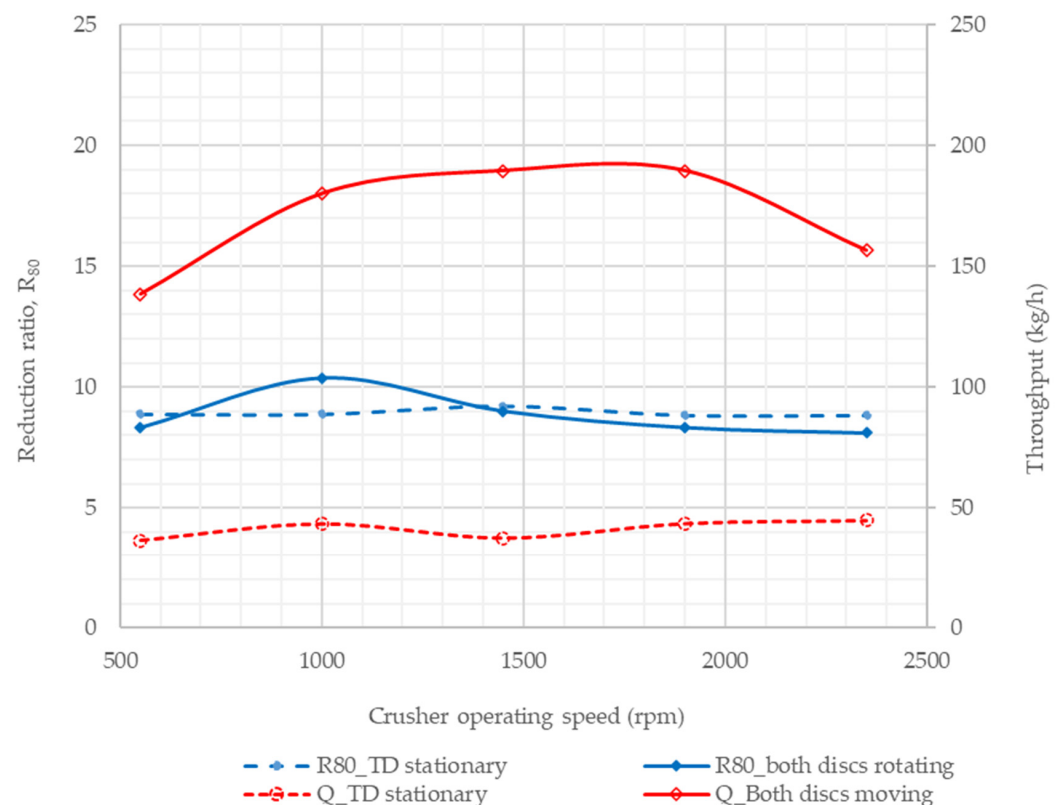


Figure 15. Relationship between throughput, reduction ratios, and crusher operating speed.

3.3. Discussions

The inherent inefficiency associated with comminution devices necessitates the search for size reduction solutions. The novel crushing device, the rotary offset crusher, with a promising performance potential but with complex dynamics as demonstrated by the data generated from physical and computational experiments, was studied. The experimental results showed the reduction ratios are indifferent for 550 and 1000 rpm, as shown by the self-similar size distributions in Figure 4. This contradicts the previous results reported for the ROC (with both discs rotating) fed with many particles, which showed a consistent increase in the reduction ratio with the rotational speed for the speeds in the range of 330 to 830 rpm [8]. It is acknowledged that the crusher dynamics for the current and

previous studies are different since with many particles, the freewheeling top disc is also accelerated to a speed closer or equal to that of the bottom disc. The instrumentation setup on the experimental crusher yielded operational data (e.g., torque in Figure 5), which provided insights into the dynamics of the crusher. The ‘rise’ in the torque signal indicates the breakage event.

More micro-dynamic information about the crusher was provided by the DEM simulations. This includes the normal and tangential forces acting on the particles (e.g., in Figures 8 and 9). It is evident from Figures 8 and 9 that when the crusher is operated with a stationary top disc, the residence times are relatively longer. This suggests low throughputs, as depicted in Figure 15. Optimization of the ROC throughput is highly dependent on the rate of rotation of the discs [8], with the difference in the speeds of the discs proving to be an important variable, which should be considered in future studies. It is evident that the stationary disc crusher has high normal and tangential forces compared to the ROC with both discs, which are rotated at the same speed. Since higher forces suggest a higher wear rate (higher operating costs), it is recommended that the crusher not be operated with the stationary disc. The crusher with both discs rotating should rather be optimized further in the quest to increase interparticle comminution and reduce the crushing surface wear while not compromising on the throughput.

While Figure 10 suggests comparable reduction ratios for the two crusher designs, the impact and shear energies due to the geometry–particle contacts are relatively higher (see Figures 11 and 12) when the ROC is operated with a stationary top disc. This translates into high specific energies, which is another motivation to disqualify the implementation of such a design. On the other hand, the specific energies for the ROC with both discs rotating are less than 1 kWh/t, as shown in Table 6. Realistic energy consumption of the device will be quantified further in future work when the crusher is choke fed with many particles.

The ratio of the shear energy and impact energy against the energy utilization in Figure 13 has shown that high energy utilization (>53%) can only be achieved with the ROC operating with both discs rotating. However, the crusher should not be operated at speeds above 1000 rpm if an energy utilization of >60% is desired (as shown in Table 6). Operating the crusher at higher speeds, as recommended in a previous study [8], may not be the best option since this can be associated with a high wear rate, but not necessarily an improved crushing efficiency.

There is still some scope for crusher optimization when it is fed with many particles. Options that are suggested for future studies in the quest to enhance the degree of dominance of the interparticle comminution mechanism and maximize material transport are listed below.

- Modifying the volume of the crushing zone to increase the height h_c [7] (e.g., to 40 mm) so that the bed of particles is promoted, as illustrated in Figure 14.
- Operating the ROC with the feed that has a wide size distribution to allow the smaller particles to fill the voids between the coarser particles. The top size of the feed material should be optimized to promote interparticle comminution.
- High feed rate to ensure the maximum delivery of particles to the crushing zone. Material transport in the feeding zone of the crusher can potentially be a bottleneck to enhance crusher throughput.
- Modification of the shape of the profile on both discs to ensure particles are sliding downward (as shown in Figure 14).
- Possibility of imposing vibratory motion on one or both discs to deliver compressive stress to the particles in the crushing zone.

Once the full potential of the ROC has been established, it will be benchmarked against existing crushers such as the cone crusher, high-pressure grinding rolls (HPGRs), and vertical roller mills (VRMs). It is acknowledged that the implementation of the ROC will depend on the demonstration of performance advantages in terms of throughput and energy consumption. The characteristics, such as shape and size distributions, of the crusher product would also influence the adoption of this technology in the minerals industry.

4. Conclusions

Discrete element modeling of single-particle breakage in the ROC has been conducted, with the experimental data providing the required validation of the simulation models. Based on the single-particle simulation, a throughput above 130 kg/h is achievable when both discs are rotating at the same speed. This is contrary to the ROC with a stationary top disc, which has throughputs below 50 kg/h. Specific energies are above 1 kWh/h due to higher normal and tangential forces when the crusher has a stationary disc. On the other hand, to have specific energies below 1 kWh/t, the crusher should be operated with both discs rotating at the same speed. However, to obtain a true picture of the ROC's performance potential, future simulations with multiple particles will be required.

The results clearly show that operating the ROC with a stationary disc is not recommended, as such an operation will be associated with higher operating costs due to the high frequency of liner replacement and high power draw. Both discs should be allowed to rotate, but the speed differential between the discs can be optimized to reduce wear while not compromising on throughput and size reduction. For easy control during operation, it is recommended that both discs have separate drivers, rather than relying on friction to drive the freewheeling top disc. There is still some scope for crusher optimization when it is fed with many particles. Once the full potential of the ROC has been established, it will be benchmarked against other crushing devices such as the cone crusher, HPGRs, and VRMs.

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