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A case study of grinding coarse 5 mm particles into sand grade particles less than 2.36 mm

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ABSTRACT

This paper presents the viability study of utilising a rod or ball mill to grind a '5 mm grit' to 100% passing 2.36 mm and fit in with a desired particle size analysis. The aim is to introduce this grit into the concrete grade sand produced at the Hanson owned Axedale Sand & Gravel quarry to reduce generated waste and improve the process efficiency. A ball mill and rod mill were used to grind the samples at an interval of 5 and 10 minutes. From the laboratory experimental analysis, it was found that a ball mill with 5 minutes grinding time in closed-circuit using a classifier to remove undersize and reintroduce oversize to the mill would be a viable option in an industrial setting. A Bond Ball Mill Grindability Test was undertaken to determine the grindability of the 5 mm grit, which served to determine the power (kWh/t) required to grind it to 100% passing 2.36 mm. The bond ball mill grindability test showed that the grit had a work index value of 17.66 kWh/t. This work index gives an actual work input of 13.54 kWh/t, meaning that for every ton of feed material introduced to the mill, 13.54 kWh of work input is required to grind it to 150 microns.

Keywords: Grinding, fine grade sand, ball mill, bond index.

1. Introduction

Concrete grade sand is a fine sand, generally exhibiting a particle distribution of less than 2.36 mm. The sand requires a range of sizes so that it forms a consistent base. If the sand has a narrow size range, pits will form in the matrix developing a weak or pervious spot (Dilbas et al., 2019) because particles of the same size form a square pattern with gaps (Fig. 1a). However, with the introduction of wide range of particles sizes, these gaps are mostly filled and make a denser and stronger matrix (Fig. 1b). This matrix used to manufacture concrete, so a strong matrix with a range of particle size is important (Cepuritis, 2013).

Additionally, particles in a concrete matrix should not be too coarse. A coarser sand base will produce a coarser finished product, which is generally not desirable (Deniz, 2016). It increases the chance of chipping or fracturing as larger particles are more likely to get chipped off over the same time that smaller sand particles are eroded due to wear. This will also cause the concrete mass to wear more readily, because the chipped particles will essentially break the seal formed/applied when it is first laid.

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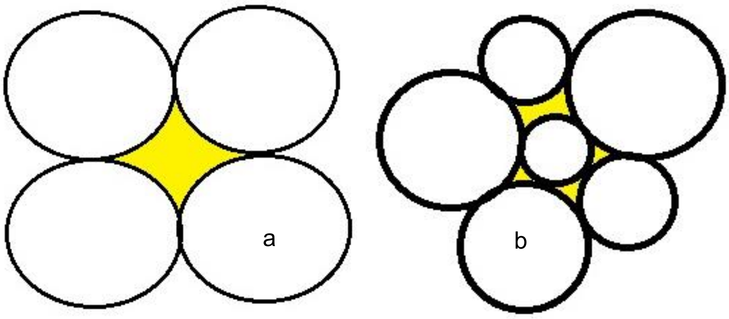

Figure 1. Gap created when same sized particles connect (a); void space created when varying sized particles connect (b)

On the other hand, a mix with a high presence of fine particles leads to a high-water and high-cement demand in the concrete manufacturing process. Addition of the water will lead to bleeding and segregation contributing to gentle interfaces within granular materials. The superplasticizers and fine additions, which are added into the composition are justified to accomplish the desirable workability and to have an appropriate viscosity (Karima Gadri, 2017).

A lot of previous studies has been carried out by various researchers (Hu and Wang, 2011, Ferraris, 1999, Geiker at al., 2002) on the effect of various aggregate size partitions on the rheological properties of concrete. It was found that different fine and coarse aggregates with an equivalent modification in shape features produce fine aggregates that require two to three times water demand in the mix than the coarse aggregates (Cepuritis, 2016). Coarse crushed aggregates are used in a mixture with natural sand. Numerous Norwegian concrete manufacturers have discovered that the presence of mass fractions from 10-50% of the entire sand content may provide somewhat decent fresh concrete rheological properties. Nevertheless, the ultimate phase to use 100% crushed sand is still quite challenging (Rolands Cepuritis, 2016).

To achieve desirable distribution of fine and coarse aggregates, which then deliver suitable rheological properties and workability of the product, grinding can be applied to generate the required particle size distribution. The mineral processing industry commonly uses rod and ball mills as particle size reduction equipment. So, in this paper an attempt has been made to find the viability of using a ball or rod mill to grind “5 mm grit”, to obtain 100% of final material less than 2.36 mm and to compare this product with the optimal size range of concrete grade sand. The bond ball mill grindability test has also been performed to find the bond work index.

2. The study area

Hanson Australia is a company specialising in producing industrial materials to an extensive network of building and engineering industries across the country. A broad range of standard, premium, high performance and decorative concrete is produced. Aggregates covering widely used stone and rock in addition to an extensive variety of standard and specialty sands are also supplied (Hanson Australia, 2017).

Axedale Sand & Gravel is currently the major supplier of concrete grade sand for Hanson in Melbourne and Western Victoria. As a by-product of sand processing, an unwanted 5 mm grit is yielded as a part of the resource being quarried. Due to the resource being particularly coarse in nature and also too coarser for concrete grade sand, this grit is cast aside to a stockpile as a waste stream. Over time, this stockpile has grown large enough that it is beginning to impact on the footprint of the processing site.

The concrete sand at Axedale is a matrix of particles ranging between 6.7 mm to fines less than 75 microns. The 5 mm grit is too coarse to be used in concrete grade sand. Therefore, it would be beneficial to minimise the waste by generating valuable product, which at the same time improves sustainability of the plant. The present research is to find the viability to convert this coarse grit and reintroduce it as fines in the final product. While the sand product is of high quality, an investigation into the possibility of utilising the waste grit to fill deficiency of fine material, 300-600 microns, by grinding would provide an increased production of concrete grade sand, increasing the efficiency of the operation. Table 1 shows the optimal particle size distribution of concrete grade sand.

Table 1. Particle size distribution of product and grit target

Screen size μm	Cumulative Passing %	
	Current product	Grit target
6700	100	100
4750	100	97-100
2360	90	90-100
1180	69	64-77
600	49	45-60
425	39	30-50
300	29	24-36
150	12	8-14
75	4	0-4

3. Laboratory Testing and Analysis

The test work was completed using a laboratory scale rod mill, ball mill and an approved bond grindability test ball mill (Boemer, 2017). The charge for each mill is set, with the rod mill containing 30 rods of varying diameter, and the ball mill containing over 100 balls of varying diameters.

Test work was completed using a laboratory scale rod mill, ball mill and an approved bond grindability test ball mill (Boemer, 2017). The charge for each mill is set, with the rod mill containing 30 rods of varying diameter, and the ball mill containing over 100 balls of varying diameters.

A representative sample was received from the quarry (Fig. 2). The sample arrived in a run of mine state, so there was no moisture loss. Prior to the sample preparation, a laboratory drying oven was used to dry the sample.

The particle size analysis was undertaken using a sieve stack. The samples were placed on the sieve shaker for twenty minutes to allow all the undersize to pass through. The screens used in the process had apertures of 6.7 mm, 4.75 mm, 2.36 mm, 1.18 mm, 600 μm, 425 μm, 300 μm, 150 μm and 75 μm (Figs. 3a, b).

To split the material and generate a representative sample, a laboratory riffle splitter was used (Fig. 4). The riffle splitter separates the sample into two separate fractions. Each fraction was then weighed to ensure that there was no more than 10% difference in the masses. If the mass difference was more than 10%, the material was recombined and split action was performed again to ensure that each of the samples is as representative of the original sample as possible.

Each of the two separate fractions were split again using the above mentioned method to create four representative fractions. Each sub-sample was screened to perform a particle size analysis and to ensure that each part is a truly representative. A schematic diagram of the test work is shown in Fig. 5.

Figure 2. Grit stockpile at Axedale Sand & Gravel (a); dry grit sample from Axedale Sand & Quarry (b)

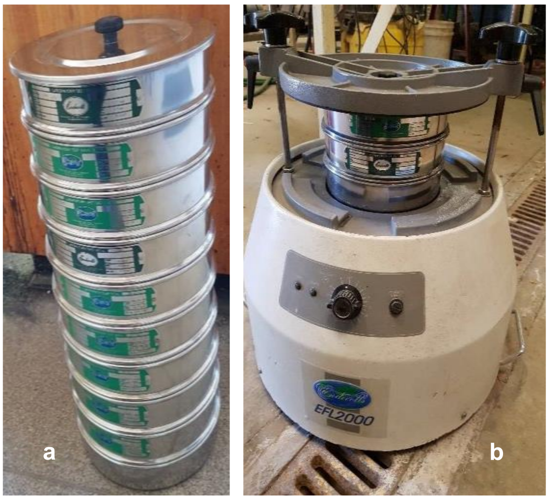

Figure 3. (a) Sieves used in the size analysis and (b) Sieve shaker

Figure 4. Riffle splitter used to separate the material into equal portions

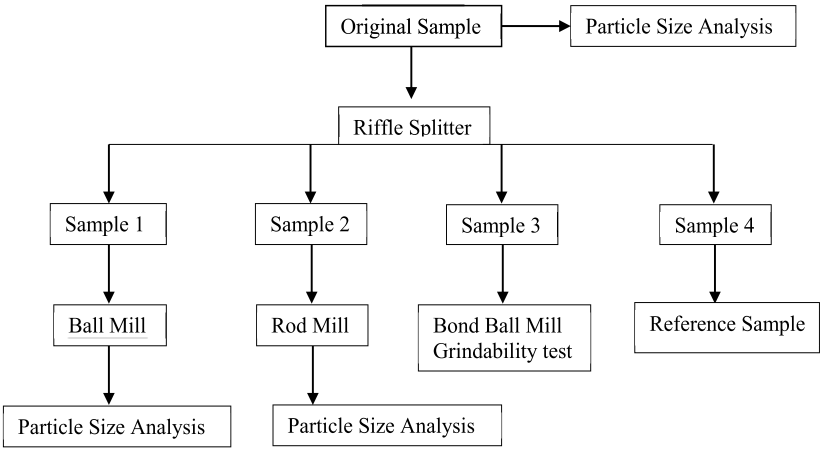

Figure 5. Flow chart of the methodology

The procedure used in this study is as follows:

- Sample 1 was ground in the laboratory ball mill (Fig. 6). Grinding was completed in different stages (5 min, 10 min, 15 min 20 min and 25 min) and particle size analysis was undertaken throughout the grinding to determine the point at which 100% sample passes through the 2.36 mm sieve.
- Sample 2 underwent the same process as sample 1, except this time laboratory ball mill was utilized (Fig. 7). Grinding was continued until 100% of sample 2 passed the 2.36 mm sieve.
- Sample 3 was used to complete a Bond Ball Mill Grindability test (Bond, 1961; Berry and Bruce, 1966; Menendez, 2017). This test was completed using the dry grinding and dry screening methods (Merkus, 2009).
- Sample 4 was kept as a reference sample.

Figure 6. Laboratory ball mill (left); grinding media and feed (right)

Figure 7. Laboratory rod mill (left); grinding media and feed (right)

Both rod and ball mill rotated at 41 rotation per minute (RPM). Hence, fhe grinding stages of 5 min, 10 min, 15 min 20 min and 25 min were selected to achieve the rod and ball mill rotations in order to have a practical determination of particle size distribution which could translate to an industry achievable setting. Additionally, extended grinding time may be required as it was known that the sand can have hard property and Bond work index between 11 kWh/t to 27 kWh/t (SME, 2011).

4. Results and Discussion

4.1. Rod Mill Test

A representative sample was ground using laboratory rod mill. The sample was milled for 5 minutes, 10 minutes, 15 minutes and 20 minutes interval.

The Table 2 shows the mass and percentage of material above the specified 2.36 mm upper boundary left in the sample after each rod mill cycle, and the amount of revolutions the rod mill completed during each cycle. The rod mill rotated at 41 RPM (revolutions per minute). The testing was undertaken with each cycle covering the grinding time specified in the Table 2.

Table 2. Mass of size fractions +2.36mm in the product of rod mill grinding

Grinding Time, min	Revolutions	Mass of Particles +2.36 mm	
		g	%
Feed	0	645.2	53.48
5	205	46.1	3.82
10	410	13.2	1.09
15	615	4.69	0.39
20	820	4.89	0.38
25	1025	1.48	0.12
27	1107	1.07	0.084

The particle size analysis after 20 minutes of grinding in the rod mill demonstrated the overabundance of fines in the product and it showed significant reduction in the oversize (+2.36 mm) material. The test-work results also exhibit the overabundance of fine fractions in the product and shows that 10.01% of material were passed through the 75 micrometres (µm) screen.

The desired amount of fines, -75 µm, in the sample is between 0 to 4%, so 10.01% is still too high. Additionally, the data points established that 97.96% of material passed the 1180 µm screen, while the desired percent passing this screen is between 64 to 77%.

After 5 minutes grinding of the sand sample in the rod mill the evaluation of particle size distribution shows that the product is well within the preferred size range for all size ranges for all the sizes except for a slight under abundance of 600 and 300 µm particles (Fig. 8). The required cumulative passing of material under 600 µm is between 45 to 60%, while after 5 minutes of grinding, it reached 41.97%. The product generated by 5 minutes grinding achieved 22.39% cumulative passing for 300 µm, while the desired size range was 24 to 36 %. There was a slight overabundance of -75 µm particles, meaning that excess fines were discovered in the initial sample, which is difficult to completely avoid, if adequate reduction of the coarse material is desired. The anticipated cumulative passing rate of 75 µm is 0 to 4%. The feed demonstrated 0.77% passing for 75 µm, and as expected, the amount of fines increased and reached 5.28% passing after 5 minutes of grinding.

After 10 minutes of grinding, the product particle size analysis showed oversupply of 1.18 mm material. The required cumulative passing for this screen size is between 64 to 77%, whereas after 10 minutes of grinding, overgrind has clearly evident, as the product was containing 92.71% of -1.18 mm particles. The mid-sized fractions (600-300 µm) were well within the preferred size range. Nevertheless, there was an overabundance of material from 150 µm and finer. Therefore, the size range of particles produced by 10 minutes milling is a preferred size distribution for the coarser part of the product 1.18 mm. Unfortunately, the finer part of the product, -1.18 mm, contains an undesirable amount of fines.

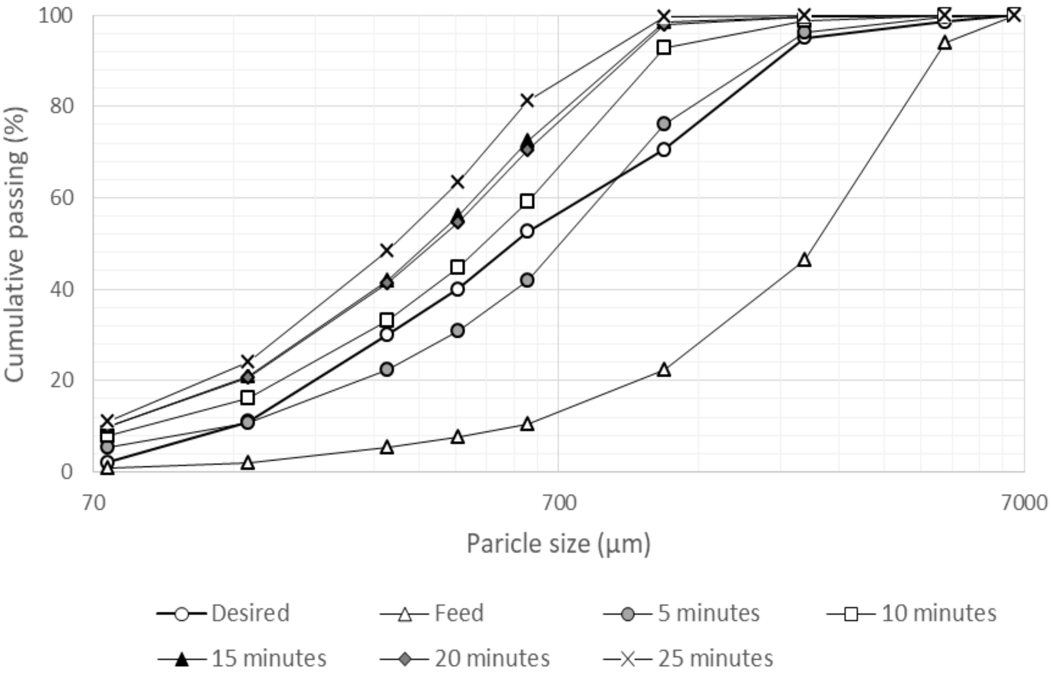

Figure 8. Particle size analysis, rod mill grinding

The desired P80 for the concrete grade sand produced at the Hanson is 1600 µm (Table 3). The grinding in the rod mill for 5 minutes achieved P80 of 1200 µm. Increasing milling time for 10 minutes reduced the P80 by 50%.

Table 3. The grain size at P80 by the rod mill test

Run	Overall Time, minutes	P80, µm
Desired		1600
1	5	1200
2	10	900
3	15	750
4	20	750
5	25	580
6	27	560

As expected, the longer residence time resulted in overproduction of fines (Figs. 8, 11 and 13). While the portion coarser than 2.36 mm material is reduced with increasing grinding time and at the same time an undesirable large portion of fines is generated. The particle size analysis of product generated by 5 minutes grinding in the rod mill, or 205 revolutions, closely emulates the desired particle size range for concrete grade sand set by Axedale Sand & Gravel (Table 1).

4.2. Ball Mill Test

The Table 4 shows the mass of material above the specified particle size of 2.36 mm in the starting sample and product produced by grinding in the ball mill.

Particle size analysis for ball mill tests were completed (Fig. 9) and P80 of products determined (Table 5).

At 5 minutes grinding of the sample using the ball mill, there was an insufficient generation of mid-sized particles in the product. The cumulative passing at 600 µm was 36.52%, whereas the desired range is between 45 to 60%. It demonstrated that 5 minutes milling is not a sufficient residence time in the ball mill to reduce the grit to the desired size range.

Table 4. Mass of size fraction of +2.36 mm in the product of ball mill grinding

Grinding Time, minutes	Revolutions RPM	Mass of Particles +2.36 mm, g	Mass of Particles +2.36 mm, %
Feed	0	702.66	53.48
5	255	261.28	20.01
10	510	163.65	12.60
15	765	123.45	9.52
20	1020	101.75	7.87
25	1275	86.58	6.71

An increase of the residence time to 10 minutes product material which proved to be a good fit against the required particle size distribution target. The product of every size range above 150 µm is within that considered by the customer as acceptable parameters. There was an overabundance of fines production after 10 minutes of milling, but it was not large when compared to the fines after 10 minutes in the rod mill. The rod mill exhibited 7.77% cumulative passing 75 µm, whereas the ball mill exhibited only 1.2% more at 8.97%.

The experimental data-points demonstrate that a residence time of 5 minutes in the ball mill results in a suitable reduction of the coarse portion of the feed, while not allowing an over representation of fines.

Table 5. The grain size at P80 by the ball mill test

Run	Overall Time, minutes	P80, micron
Desired		1600
1	5	2360
2	10	1600
3	15	1000
4	20	800
5	25	600

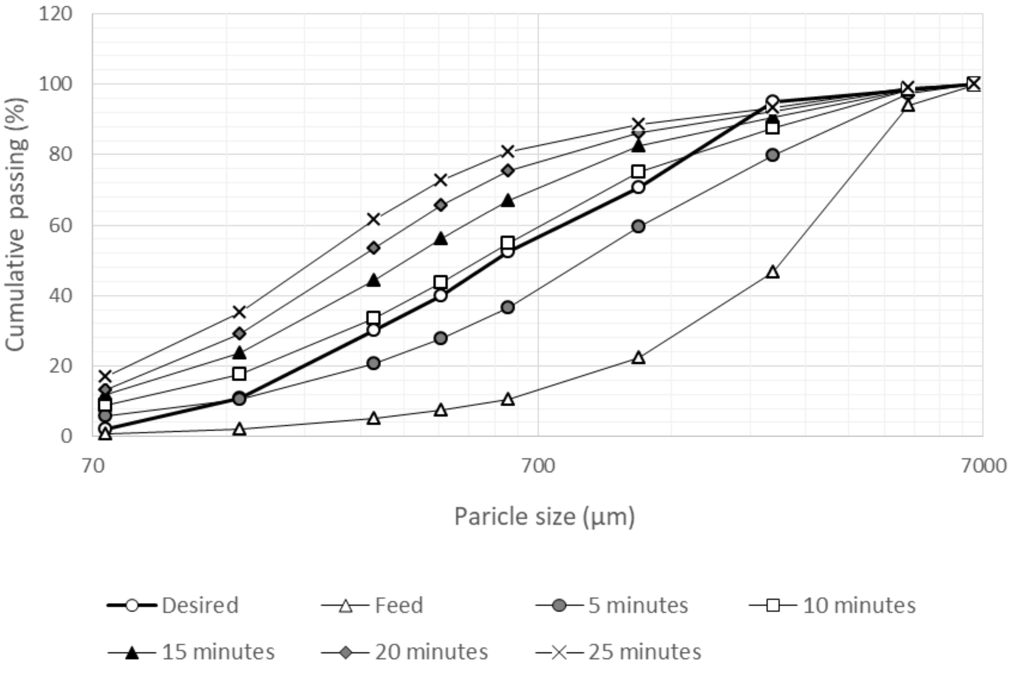

Figure 9. Particle size analysis, ball mill grinding

4.3. Bond Ball Mill Grindability Test

The grindability of an ore is a measure of the amount of product which is produced per revolution of the grinding mill, defined as the maximum desired particle size for the next stage in the process. Ore that is harder to grind will increase the costs associated with the processing stage, as the throughput will be decreased, and the energy consumption will increase for a given mill size. In addition, the grindability of the ore, and the desired product size and size distribution, affect the selection of purchasing equipment.

The Bond Work Index (BWI) of the material is determined from the grindability of the ore and is a direct measure of the power required to grind the material.

The sample particle size was reduced to 100% passing 2.36 mm by crushing using a cone crusher. A particle size analysis demonstrated that P80 of Bond test-work feed and Bond test-work product is 2500 μm and 107 μm respectively (Fig. 10).

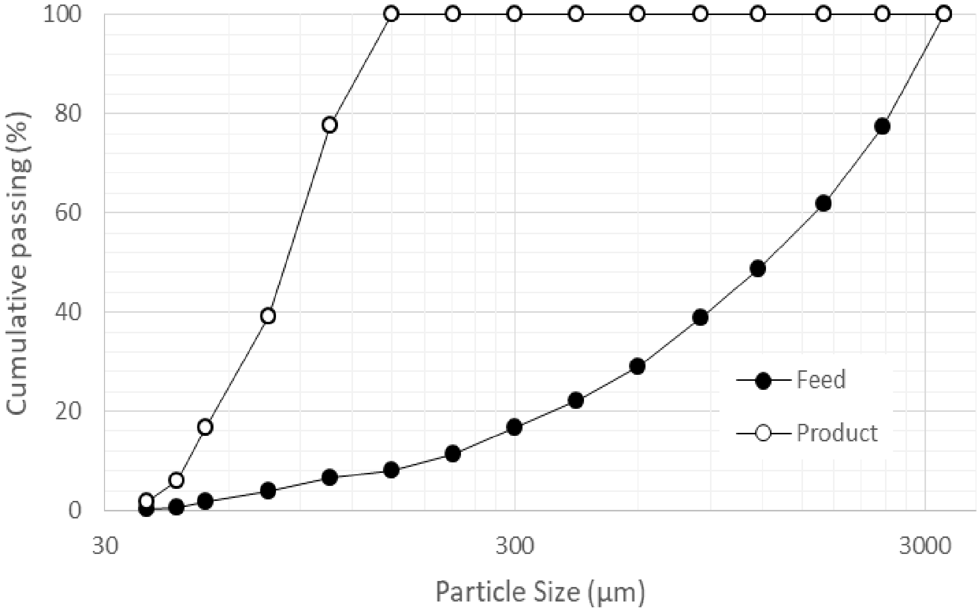

Figure 10. Particle size analysis, Bond Work test-work feed and product

The BWI was calculated using the following equation (Bond, 1961, Bond, 1985; Lynch, 2015):

$$Work\ Index\ (W_i) = 1.1\left[\frac{44.5}{(P_1)^{0.23} * (G)^{0.82} * \left(\frac{10}{\sqrt{P}} - \frac{10}{\sqrt{F}}\right)}\right]$$

Where:

W = Work Index in kWh/tonne

P_1 = Mesh of grind size (μm) used for screening the ground product

G = Grindability in net grams produced due to grinding per revolution of the mill

P = Size in μm through which 80 % of the ground product passes

F = Size in μm through which 80 % of the feed passes

The test-work identified that the material has a BWI of 17.66 kWh/t. This Bond Index value, when compared to the values determined by various other researchers and collated by (Michaud, 2015) (Table 6), match the BWI values of many similar materials to this grit found at Axedale Sand & Gravel. Comparing the average BWI of Axedale grit and Gravel, it ranges from 17.5 kWh/t in the "Tenova Bateman mills" test, to 18.0 kWh/t in the SME handbook. However, the SME handbook of mineral processing does state that from 6 tests completed on gravel, the BWI ranged from 11 kWh/t to 27 kWh/t (SME, 2011). This puts the BWI of 17.66 kWh/t gained through this test-work in the expected range for a sand and a gravel product. Importantly, according to classification by JKTech Laboratory Services (JK Tech, 2017), a BWI value of 17.66 kWh/t is considered a hard property.

Table 6. Bond work index by minerals - Gravel (Michaud, 2015)

Material	Reported by Fred Bond	Equipment and pipelines	Tenova Bateman mills	SME handbook of mineral processing		
	kWh/t	kWh/t	kWh/t	kWh/t	Range	No. of tests
Gravel	17.7	17.7	17.5	18.0	11-27	6

The actual work input can be calculated (Barry and Wills, 2016):

$$W = 10W_i\left[\frac{1}{\sqrt{P_{80}}} - \frac{1}{\sqrt{F_{80}}}\right]$$

Where:

W_i = Bond Work Index in kWh/tonne

W = Actual work input in kWh/tonne

P_{80} = Size in μm through which 80% of the ground product passes

F_{80} = Size in μm through which 80% of the feed passes

An actual work input of 13.54 kWh/t was found. This means that for every tonne of feed introduced to the mill, 13.54 kWh is required to grind the material to 150 μm.

Figures 11-12 present experimental results for grinding the coarse sand by ball and rod mill for 5 and 10 minutes.

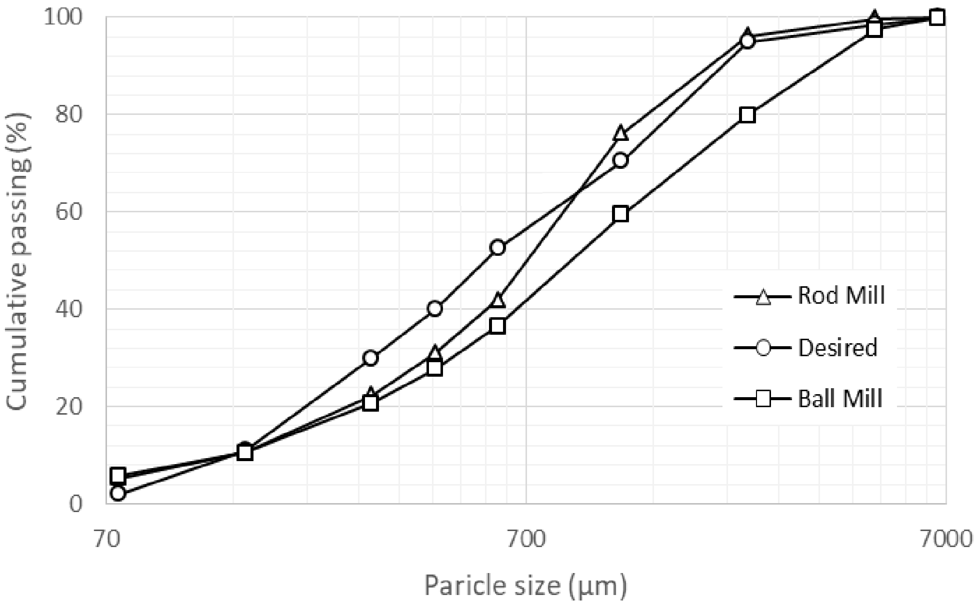

Figure 11. Particle size distribution after 5 minutes grinding in ball and rod mill

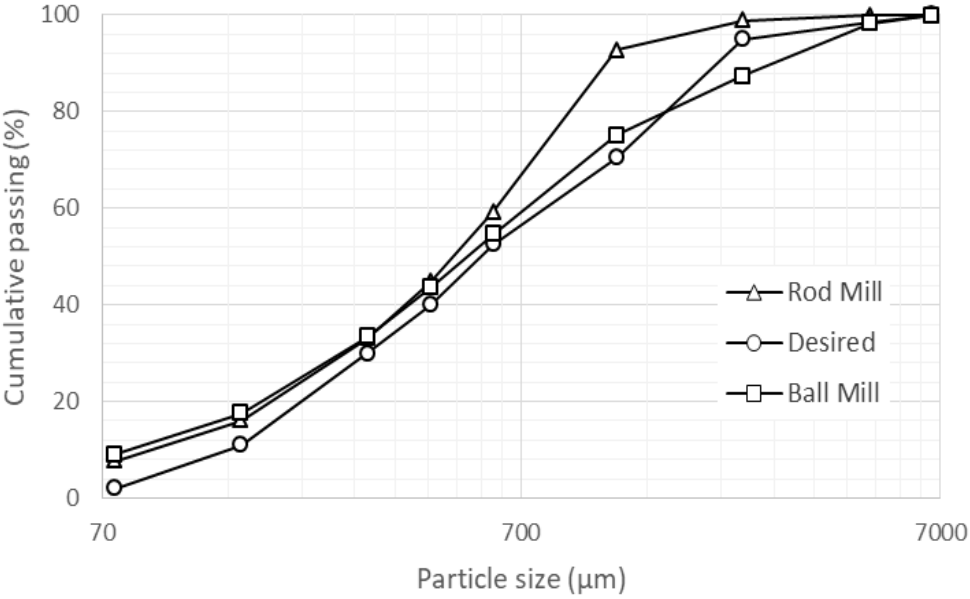

Figure 12. Particle size distribution after 10 minutes grinding in ball and rod mill

4. Comparison of Ball Mill and Rod Mill Results

The rod mill curve shows a much higher percent passing of coarser particles than the ball mill. At 2.36 mm the rod mill reported 96.18% passing, while the ball mill reported only 79.90% passing. This is attributed to the action of the rod charge, taking priority of coarse particles grinding over finer particles, which is known as selective grinding. The ball mill curve demonstrates a less pronounced drop, showing a lower gradient curve. The random grinding action of the balls charge produces a higher portion of fines, but it doesn't over grind the coarse portion.

At 5 minutes, the rod mill mirrors the desired coarse particle size range but is underrepresented in the mid-sized particle range. The ball mill product underperformed in both the coarse and the mid-sized particle range. Rod and ball mills, both produced an overabundance of fines, with the ball mill reported 5.71%, whereas the rod mill reported 5.28% passing at 75 μm. The desired range for particles passing 75 μm is between 0 to 4%.

The coarse particles in the rod mill are significantly reduced at a greater rate than the ball mill (Fig. 13). It was found that 92.71% of rod mill product passed the 1180 μm screen, whereas only 75.1% of ball mill material passed the 1180 μm screen. This discrepancy is greatly reduced by using a 600 μm screen, with 59.26% of rod mill and 54.67% of ball mill products passed through the same screen.

The ball mill demonstrates a lower gradient with a more evenfall than the rod mill particle size analysis, which initially shows a straight line then a higher gradient line. This supports a conclusion on the rod mill selective crushing technique, and that the ball mill creates an even reduction of a feed.

The P80 of the ball mill product after 5 minutes grading is 2360 μm compared to a P80 of 1200 μm in the rod mill, which confirms that less input work was was applied to the coarse particles in the ball mill than the rod mill.

The particle size distribution of the ball mill product mirrors that of the desired down to 150 microns, where an over representation of fines can be seen. The desired cumulative passing percent range was between 8 to 14%, whereas the cumulative passing was 17.52%. The rod mill particle size analysis also closely mirrors the desired down to 150 µm, except for the 1180 µm outlier where 92.71% of material passed, whereas the desired size range was between 64 to 77%.

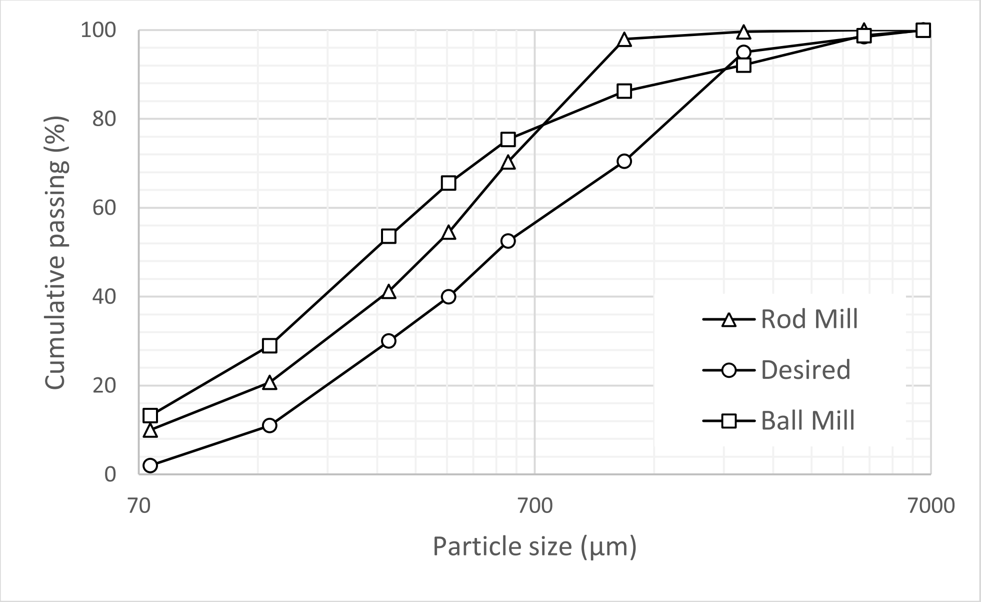

Figure 13. Combined cumulative % passing at 20 minutes

The P80 of the ball mill product is 1600 µm and is equal with the P80 of the desired particle size range. The P80 of the material generated by grinding the initial sample in the rod mill was lowered to 900 µm.

The ball mill with a residence time of 10 minutes is the closest fit to the desired particle size range. The investigation results clearly demonstrate that 10 minutes grinding time (510 revolutions) produces a required particle size range down to the fines below 150 µm. A ball mill with 5 minutes of grinding time (205 revolutions) in closed-circuit using a classifier to remove undersize and reintroduce oversize to the mill would therefore be a viable option in an industrial setting. This would minimize the generation of undersize material, improve throughput and improve the operational efficiency.

By calculating the bond work index, it was found that the actual work input required to grind the material to 150 microns is 13.54 kWh/t.

5. Conclusions

This paper presents the viability study of utilising a rod or ball mill to grind a “5 mm grit” to 100% passing 2.36 mm and fit in with a desired particle size analysis. Experimental results showed that 5 minutes grinding time (205 revolutions) using the laboratory rod mill produces a particle size range closely emulating the desired size. 10 minutes of grinding produces a closer simulation to the desired in the coarse and mid-sized particles, however an overabundance of fines was present. In an industrial setting, a classifier used in closed-circuit to remove undersize and reintroduce oversize to be reground is the most viable option for a rod mill.

The ball mill results demonstrated that 10 minutes grinding time (510 revolutions) produces a desired particle size range down to the fines below 150 microns. A ball mill with 5 minutes of grinding time in closed-circuit using a classifier to remove undersize and reintroduce oversize to the mill would be a viable option in an industrial setting. This would minimize the generation of undersize material, improve throughput and improve the operational efficiency significantly. By calculating the bond work index, it was found that the actual work input required to grind the material to 150 microns is 13.54 kWh/t.

Results obtained from test work are directly relevant to the material from Hanson Australia's Axedale Sand and Gravel site. Material at any site exhibits different characteristics, ranging from impurities to inherent joints or fractures, to any other site. Therefore, results from this test work can be used as a general guide of how any material from other similar operations will act, but they should not be used to base decisions without performing any test work.

Further work in this project would involve application of the results in the field. Material from the quarry should be tested on an industrial pilot plant to finalise the test-work. This will give confidence in application of the procedure at the Axedale Sand & Gravel processing plant.

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Conflict of Interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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