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Addition of pebbles to a ball-mill to improve grinding efficiency

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ABSTRACT

Ball-mills are used widely for secondary grinding. Loveday (2010) reported on laboratory tests in which small pebbles (7–25 mm) were used in various proportions with balls. The optimum proportion of pebbles, by volume, was found to be about 25%. Substantial savings in power and ball consumption were achieved, with no loss in grinding capacity. However, continuous pilot-plant tests were disappointing, because the consumption of small pebbles was too high.

The idea of using a mixture of balls and pebbles, at a mill speed suitable for ball-milling, was revisited in this investigation, using a normal spectrum of pebble sizes (19–75 mm). Batch tests in a pilot-scale mill (0.57 m diameter) were used to compare ball-milling to various ball/pebble mixtures. The mill power was measured online by monitoring lateral torque on a freely suspended motor and gearbox. Initial tests were done using pebbles from previous tests on gold ore, in combination with balls, to mill silica sand (0.6–1.5 mm)

The size distributions of the balls and the pebbles were calculated to simulate steady-state addition of balls (37.5 mm) and partly-rounded pebbles (19–75 mm). There was a reduction in pebble consumption, as expected, when using larger rounded pebbles, to about 6% of total production. *The grinding capacity, when using a mixture containing 25% pebbles, was the same as that with balls alone, resulting in a 13% saving in energy and an implied saving in ball consumption of 25%.*

It was concluded that the use of a composite load for secondary grinding is a very attractive option. Further tests were done, using samples from a platinum mine, namely the feed to a secondary mill (ball-mill) and rounded pebbles from a primary AG mill. Grinding capacity was maintained over the range 0–30% pebbles, by volume, with savings in energy and ball consumption increasing progressively. At 25% pebbles, the saving in energy was 18% and the pebble consumption was about 7% of total production.

The theory of pebble wear was developed during this investigation, for application to batch grinding tests. The size distribution of the pebbles was measured after each test and the theory was used to calculate the pebble wear rate (mm h^{-1}) and the specific wear rate (kg h^{-1} kg^{-1}) for all screen fractions. The wear rate of pebbles in the presence of balls was higher than that for pebbles alone. When the proportion of pebbles in the mill charge was low (up to 30%), the larger pebbles wore away significantly faster than expected, based on a constant surface wear rate. This could be due to size segregation in the mill.

1. Introduction

The grinding circuit used for processing of gold, platinum and base metal ores typically consists of SAG primary mills, followed by ball-mills. The power drawn by the ball-mills is about the same as that of the SAG mill for high capacity milling circuits. Table 1 is an example of data for this type of circuit.

Attention has been focused on the control of the primary mill, as variations in the proportion of competent rock in the feed, can cause significant variations in the throughput and consequent variations in product sizing. Closed-circuit crushers for SAG mills, or their replacement with HPGR's, has been used to reduce this problem. The control of ball-mills is relatively simple in comparison (i.e. addition of balls to maintain power and control of the cyclones and pulp density). Pebble-milling is used on some mines for secondary grinding, to reduce operating costs. However, the availability of pebbles is essential and pebble storage is required. The pebble mills need to be much larger than ball mills, to draw the same power, and hence it is not easy to change from one type of milling to the other. Most mining companies have opted for the 'safe' option of ball-mills for secondary grinding.

Loveday (2010) reported on batch tests in a laboratory ball-mill (300 mm diameter), to investigate the replacement of a portion of

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Table 1
Example of design power and costs for a SAG/ball-mill circuit in Peru, with a 34.6 million t/a capacity (Vanderbeek et al., 2006).

	SAG mills	Ball mills
Number of mills	2	4
Diameter × length (m)	12.2 × 6.7	7.3 × 10.7
	Power (kW h/t)	
Mills	8.71	8.71
Pebble crushers	0.64	
Ancillaries	0.5	1.56
Total	9.85	10.27
	Cost ($/t)	
Power	0.345	0.359
Balls	0.203	0.176
Liners	0.132	0.042
Total	0.680	0.577

the balls by an equivalent volume of small pebbles (crushed stone, 7–25 mm). At the optimum volume of pebbles (25%), the rate of production of fines, (which included the material worn off the pebbles), was the same as that of the ball load, despite a 12% reduction in power, due to the lower density of the pebbles. It was also noted that the implied 25% reduction in ball consumption was also a very significant cost saving. A few batch tests were conducted in a mill 1.2 m diameter and 0.31 m long, to test the viability of the pebbles at a larger scale. These tests confirmed the results, but subsequent pilot-plant tests in a continuous 1.8 m diameter mill were disappointing, as the pebble consumption was too high and the pebble fragments contributed to a coarser product.

The current investigation involved various aspects of pebble milling, using a full range of pebble sizes (i.e. the size distribution normally discharged from pebble ports in a SAG mill and periodically crushed in a recycle crusher). The experiments were limited to rounded pebbles, as pebbles in this form were considered to be preferable to rock recovered by screening the feed to a primary mill. This paper is focused on a specific application, namely the partial replacement of balls (about 25%) and grinding at a conventional speed for ball-milling (69% of critical speed). The term "composite milling" is used to describe the use of a mixture of balls and rounded pebbles. The larger pebbles last longer and hence pebble consumption is reduced, but the efficiency for fine grinding was questionable.

Simple (open-circuit) batch grinding is used by laboratories to produce samples for flotation tests. There is no short-circuit of coarse material in a batch test and the ground material has a size and mineral distribution which is similar to that of a closed-circuit mill (i.e. the cyclone overflow). A simple batch test can also be used to measure relative ore hardness (Berry and Bruce, 1966). However, in order to test autogenous and semi-autogenous grinding, pilot-scale tests are required to accommodate the pebbles. The use of batch pilot-scale tests makes it feasible to use limited quantities of ore and pebbles (Loveday and Naidoo, 1997; Loveday and Dong, 2000; Loveday, 2004; Pillay and Loveday, 2015).

2. Experimental

Tests using pebbles with diameters up to 75 mm require the use of a pilot-scale mill. The University of KwaZulu-Natal has two pilot-scale batch mills, 0.57 m and 1.2 m in diameter, and it was decided that the 0.57 m mill would be used, to reduce the labour involved in loading, unloading and sizing of pebbles and fines. The mill was attached to a drive shaft, (supported on bearings), and driven by a freely-suspended gearbox and motor. The torque on the drive assembly was measured on-line and the average value was used to calculate power. (The surging of the mill load caused the torque to oscillate.)

Mill charge fillings of 30% and 40% were tested. Previous experience has shown that either filling could be used, and hence a 30% charge was used in preliminary tests, to reduce ore consumption and labour. The charge volume was further subdivided into media (50%) and pulp (50%). The aim of most tests was to produce the final product sizing and hence a relatively low solids content of the pulp was used (30% by volume), to avoid viscosity problems, which had been experienced in previous investigations.

The size distributions of the pebbles and balls were calculated to simulate steady-state in a mill operated continuously (i.e. a 'seasoned' load). Any feed size distribution can be transformed into a 'seasoned' size distribution. The ball size distribution was calculated to simulate a periodic top-up using 37.5 mm balls. If one assumes a constant wear rate (mm/h), the size distribution of balls has equal numbers in each linear interval of size. Hence, the steady-state mass in these intervals is proportional to the cube of the average diameters of the intervals. The same principle can be applied to transform any pebble feed size distribution into a 'seasoned' pebble size distribution. Each pebble feed size produces a steady-state distribution, analogous to the ball-mill calculation. A spreadsheet was used to accumulate weighted data for all feed pebble sizes. This method makes the simplifying assumption that the pebble wear rate is independent of pebble size. This assumption was examined later. The calculations required a lower limit for balls and pebbles. In the case of pebbles, they were observed disappear below 13 mm. A relatively small mass was present at the exit sizes for balls and pebbles.

A series of tests was conducted using rounded pebbles of silicate ore (gold ore and rocks from a local quarry). The density of the pebbles was about 2650 kg m^{-3}. The feed material for grinding was quartz sand with size range 0.6 to 1.5 mm, which was available in bags as a pool filter medium. After each experiment, the pebbles and balls were removed from the mill and washed on a 3.3 mm screen, as a convenient size for separating 'pebbles' and 'fines'. Previous experience has shown that there is virtually nothing in the size range 1–5 mm, as this size is ground rapidly. Fine material was then flushed out of the mill, also through the 3.3 mm mm screen, and allowed to settle in drums. Excess water was siphoned off, prior to repeated use of a sample splitter, to obtain a sample of slurry containing about 200 g of solids. Wet screening at 75 µm was then used to remove most of the fines, prior to dry screening of the +75 µm material. All tests were done in duplicate and both samples from the final sample split were screened.

The pebbles were screened and weighed after each test and reused in subsequent tests, after adding make-up pebbles to restore the required size distribution. The pebbles were considered to be derived from the ore and hence the calculation of the rate of production of fine material included the 'bonus' production of material abraded off the pebbles. The initial mass of sand added was reduced in some tests on composite milling, so that the average mass of fines in the mill was about the same as the base case of ball-milling.

When encouraging results were obtained using silicate pebbles, arrangements were made to obtain samples from a platinum mine, consisting of rounded pebbles (150 kg) from a primary mill and a settled slurry of the feed to a ball-mill (a dry mass of 340 kg). After drying, the ball-mill feed sample was blended and sub-sampled into 21 kg lots (for milling tests). Each bag was sampled, followed by wet and dry screening (as above). The particle size analysis revealed that the bags of feed material had on average 37% passing 75 µm, with a standard deviation of 0.7%. It was concluded that the blending and sub-sampling of the mill feed was acceptable.

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