Global Journal of Researches in Engineering: a Mechanical and Mechanics Engineering
Volume 17 Issue 2 Version 1.0 Year 2017
Type: Double Blind Peer Reviewed International Research Journal
Publisher: Global Journals Inc. (USA)
Online ISSN:2249-4596 Print ISSN:0975-5861

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GJRE-A Classification: *FOR Code: 120499*

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Design, Construction and Performance Analysis of a 5 Kg Laboratory Ball Mill

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Abstract- In this study, a 5 kg laboratory ball mill has been designed, constructed, and its performance analysed. This was achieved by using Bond's equation to calculate the specific and shaft powers required to drive the mill at the specified capacity, and also to size the mill. After the fabrication of the ball mill, grinding test was conducted with the mill, using limestone as the feed material. This was followed by the particle size analysis of the ground product from the mill in order to determine the performance of the mill. The design results show that the minimum shaft power required to drive the ball mill is 0.2025 horsepower, the length of the mill at a fixed mill diameter of 210 mm is 373 mm, and the required shaft length and diameter are 712.2 mm and 30 mm respectively. The results of the particle size analysis, before and after the grinding test, show that the values of F_{50}, F_{80}, P_{50}, and P_{80} of the limestone that was fed into the mill are 650 microns, 1950 microns, 47.5 microns and 85 microns respectively. The fabricated ball mill is efficient in its performance as the value of P_{80} of the products from the mill (85 microns) is less than P_{80} (100 microns) used in the design of the ball mill.

Keywords: laboratory ball mill, bond's equation, shaft power, milling efficiency.

I. Introduction

Size reduction, or comminution, is an important operation in mining and mineral processing. It is important because it can be used to: (i) produce a finer, more marketable product, with specific size distribution; (ii) expose or liberate a valuable mineral so that it can be extracted from the ore; or (iii) increase the surface area available for subsequent processing (Kelly, 1992). Size reduction is accomplished through the process of crushing and grinding. Crushing, which is the first mechanical stage of comminution, is accomplished by reducing the size of run-of-mine ore down to 25 mm (1 in) using equipment that compress the ore against rigid surfaces. The equipment can also reduce the size of the ore by impacting it against surfaces in a constrained path. Grinding is the final stage of comminution. It accepts feed from the crushing stage, which ranges in size from 5 – 25 mm, and reduces it to a size of about 10 – 200 microns.

The principle purposes of grinding are: (i) to obtain the correct degree of liberation in mineral processing; and (ii) to increase the specific area of the valuable minerals for hydrometallurgical treatment, i.e. leaching. Grinding can be accomplished by using rod mills or ball mills. Rod mills are generally used as coarse grinding machines while fine grinding is performed in ball mills, using steel balls as the grinding medium.

A ball mill consists of a cylindrical vessel mounted on a stand at both ends which allows rotation of the vessel around the center axis. The mill is driven by a girth gear bolted to the shell of the vessel and a pinion shaft moved by a prime mover. The prime movers are usually synchronous motors equipped with an air clutch or gear transmission. After the mill is charged with the starting material (rock, ore, etc.) and the grinding ball media (balls), the milling process takes place. The milling process occurs during rotation as a result of the transfer of kinetic energy of the moving grinding media into the grinding product.

The design of a ball mill can vary significantly depending on the size of the required mill, the equipment used to load the starting material (feeders), and the system for discharging the output product. The size of a mill is usually characterized by the "length-to-diameter" ratio, which frequently varies from 0.5 to 3.5. The starting material can be loaded either through a spout feeder or by means of a single or double helical scoop feeder. Based on the discharge system, ball mills are commonly classified as overflow discharge mills, grate discharge mills, and center periphery discharge mills. Several ball mills have been invented for laboratory size reductions, pilot scale reductions, and industrial grinding purposes. All these inventions have been done to proffer solutions to the problem of size reduction in mineral processing.

Irrespective of the ball mill inventions mentioned above, which have been developed to solve the problems encountered during size reduction in mineral processing, laboratory ball mills are seldom available in Nigerian markets. Most times, these ball mills are imported from other countries. Again, with the need for Nigeria to revitalize her manufacturing sector in order to increase productivity that will help to boost Nigeria's Gross Domestic Product (GDP), there is the need to encourage the design and production of locally made ball mills, which will be used in the country's educational sector and the solid mineral sector. These have prompted the drive to design and fabricate this laboratory ball mill, hence, supporting the industrialization of the country.

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II. Design Methodology

a) Milling Sizing

The Bond's method was used in sizing the laboratory ball mill. This method is based on two power calculation approaches used in ball and rod mill design processes due to its simplicity and workability. The first approach, which is specific power calculation, determines the power required to grind an ore from a given feed size to a specific product size. The second approach, the shaft power calculation, determines the power required for a given mill capacity. These approaches are explained in the next section.

i. *Specific Power Calculation*

The mill power per tonne of 80% feed and product passing a particular screen size is estimated by using the Bond's equation given below:

$$E = W_i\left(\frac{10}{\sqrt{P_{80}}} - \frac{10}{\sqrt{F_{80}}}\right) \quad (1)$$

where:

W_i = workindex of material to be ground by the mill;
P_{80} = 80% of product passing a given sieve size;
F_{80} = 80% of feed passing a given sieve size.

The P_{80} (product) and F_{80} (feed) characteristics required in Bond's equation were defined to enable the calculation of the specific power required by the laboratory ball mill.

Feed Characteristics

The laboratory ball mill was designed for grinding limestone, meaning that the work index required for the specific power calculation was assumed to be the work index of limestone, which is 11.6 KWh/t, with a specific gravity of 2.6 g/cm^3 or 2600 kg/m^3. The feed size (F_{80}) of the ball mill was assumed to be 2 mm (2000 microns). This is the size of the ore particles that are retained on a 10 mesh sieve.

Product Characteristic

The product characteristic is defined as the target fineness at P_{80} (80% of the products passing a given sieve size). The value of P_{80} depends on the use of the ground limestone. Target uses of ground limestone are:

a. Agricultural uses – for production of fertilizers, coated seed applications, buffering agents in beef cattle diets, and dietary applications in egg production of hens.
b. Industrial uses – raw material for cement production, filler in paper making, industrial coatings and suspension applications.
c. Mineral Processing and oil production uses – for mining, drilling, and geotechnological applications.

For all these uses, the size of the ground limestone is within 100 microns. Thus P_{80} for the ball mill design was assumed to be 100 microns.

Efficiency Factors

In practice, the Bond's equation is modified by multiplying the right hand side of the equation by correction factors (C) to allow for milling conditions. The modified form of Bond's equation is given as:

$$E = C \times W_i\left(\frac{10}{\sqrt{P_{80}}} - \frac{10}{\sqrt{F_{80}}}\right) \quad (2)$$

where:

$$C = C1 \times C2 \times C3 \times C4 \times C5 \times C6 \times C7 \times C8 \times C9$$

Considering the important correction factors, we have that:

C1 (the correction factor for wet and dry grinding) is equal to 1.3 for dry grinding;

C2 is the correction factor for open circuit grinding and is a function of the degree of control required on the circuit product. The values of C2 are shown in Table 1. Since for the ball mill design we are using 80% passing, the required value of C2 for the ball mill will be equal to1.20.

C3 is the correction factor for mill diameter and is given as;

$$C3 = \left(\frac{2.44}{D}\right)^{0.2} \quad (3)$$

However, it is important to note that C3 =0.914 if the mill diameter is greater than 3.81m. The cylindrical vessel used in producing the ball mill was got from a steel pipe that has an internal diameter of 210 mm. This means that the ball mill has a fixed internal diameter of 210mm, meaning that C3 will be:

$C3 = \left(\frac{2.44}{D}\right)^{0.2}$, Where D = 210mm = 0.21 m

$$C3 = \left(\frac{2.44}{0.21}\right)^{0.2} = (11.619)^{0.2} = 1.6332$$

C4 is the correction factor for feed size and is given as:

$$C4 = 1 + \left[\frac{(W_i - 7) \times \left(\frac{F_{80}}{4000\sqrt{\frac{13}{W_i}}} - 1\right)}{\frac{F_{80}}{P_{80}}}\right] \quad (4)$$

This equation applies only if $W_i > 14$kWh/t or/and if feed is $F_{80} > 4$mm. Since for the ball mill design, $W_i < 14$ kWh/t and $F_{80} < 4$ mm, we have that C4 will be:

$$C4 = 1 + \left[\frac{(11.6 - 7) \times \left(\frac{2000}{4000\sqrt{\frac{13}{11.6}}} - 1\right)}{\frac{2000}{100}}\right]$$

$$C4 = 1 + \left[\frac{4.6 \times -0.5277}{20}\right] = C4 = 1 + \left[\frac{-2.4274}{20}\right] = C4 = 1 - 0.1213 = 0.8786$$

$C5$ is the correction factor for product fineness and is given as:

$$C5 = \frac{P_{80} + 10.3}{1.145 \times P_{80}} \quad (5)$$

Equation 5 is used to calculate C5 if $P_{80} < 75$ microns. However, if $P_{80} > 75$ microns, C5 is assumed to be 1.0. For the ball mill design, $P_{80} > 75$ microns (100 microns), this implies that the value of C5 = 1.0.

$C6$ is the correction factor for high efficiency separators (cyclones) and is assumed to be equal to 1.0.

Therefore, the correction factor, C, for the ball mill design is given as:

$$C = C1 \times C2 \times C3 \times C4 \times C5 \times C6 = 1.3 \times 1.2 \times 1.6332 \times 0.8786 \times 1.0 \times 1.0 = \underline{2.2385.}$$

Estimated Mill Specific Power

Using equation 2, the specific power required to reduce the size of the limestone from F_{80} = 2000 microns to P_{80} = 100 microns will be:

$$E = 2.2385 \times 11.6 \left(\frac{10}{\sqrt{100}} - \frac{10}{\sqrt{2000}}\right) = 2.2385 \times 11.6 \left(1 - 0.2236\right) = 2.2385 \times 11.6 \left(0.7764\right) = 20.160 \text{ kWh/t.}$$

Considering that the laboratory ball mill is of small capacity, the specific power was converted to kWh/Kg instead of kWh/t. This was done as follows:

1000 kg = 1 tonne, therefore, 20.160/1000 = 0.02016 kWh/kg (The Mill's Specific Power).

Mill Capacity (Production Target)

Production target or mill capacity looks at the amount or tonnage of ore a mill can grind in an hour. Based on the capacity of existing laboratory ball mills, the mill was assumed to have a capacity or target production of 5 Kg/h.

ii. *Shaft Power Calculation*

Using the calculated specific power or energy (E) for the desired mill diameter, the required shaft power for the desired mill capacity was estimated from the following equation:

$$P = QE \ (in \ KW) \quad (6)$$

Where P = shaft power; Q = mill capacity. Thus the shaft power of the mill is

$$P = 5 \ (kg/h) \times 0.02016 \ (kWh/kg) \ 0.1008 \ kW$$

This implies that the shaft power required to drive the ball mill is 0.1008 kW.

The motor horsepower is computed from the power required to grind the material from a given feed size to a given product size. This is the power of the shaft given in horsepower.

Since 1 kW = 1.341 horsepower, 0.1008 kW in horsepower will be given as:

0.1008 kW × 1.341 = 0.135 horse power.

Using a factor of safety of 1.5for the design, the motor horsepower required will be = 1.5 × 0.135 = 0.2025 horse power.

Therefore, a motor with a horsepower that ranges from 0.5 to 1.0 horse power can be selected for the mill.

iii. *Mill Sizing Parameters*

The important mill sizing parameters required for the ball mill design are: the mill speed (critical speed at which the mill should operate), the filling degree, and the length of the ball mill. These parameters for the mill have been derived as follows:

Critical Speed

Critical speed is the speed at which the contents of a mill would simply ride over the roof of the mill due to centrifugal action. The critical speed (rpm) is given by the following equation:

$$critical \ speed(N_c) = \frac{42.3}{\sqrt{D-d}} \quad (7)$$

where: N_c = critical speed; D = mill diameter; d = charge diameter (diameter of balls).

Mills operate at a speed of a given percentage of the critical speed, i.e.:

$$Mill \ speed = N\% \times critical \ speed \quad (8)$$

Ball mills, according to Schlanz (1987), are normally operated at around 70 to 80% of critical speed. A speed of 75% of critical speed was assumed for the laboratory ball mill. Based on this assumption, the mill speed of the ball mill was estimated as follows:

$(N_c) = \frac{42.3}{\sqrt{D-d}}$, where D = 0.21m and diameter of the steel ball, d = 0.06m

$$(N_c) = \frac{42.3}{\sqrt{0.21-0.06}} = \frac{42.3}{\sqrt{0.15}} = \frac{42.3}{0.3873} = 109.22 \text{ rpm}$$

Therefore the mill speed, using equation 3.7, is given as:

Mill speed = 75% × 109.22 rpm = 81.914 rpm.

Filling Degree

The filling degree gives the amount of feed and charge balls that occupy the volume of the ball mil in

percentage. It can be estimated by using the curve shown in Fig. 1. As can be seen from Fig. 1 and assuming a H/D ratio of 0.618, the filling degree of the laboratory ball mill is 35%.

$$P = 7.33 \times C \times J \times Vcr \times (1 - 0.937J) \times \left[1 - \frac{0.1}{2^{9-10Vcr}}\right] \times s.g \times L \times D^{2.3} \quad (9)$$

where: C = 1 if overflow mill is assumed or 1.16 if grate mill is assumed; J = volume load in %; Vcr = % of critical speed; s.g = bulk density of the ball charge in t/m^3; L = mill length (in m); D = mill internal diameter (in m).

Length of the Ball Mill

According to Schlanz (1987), the mill shaft power can be related to the mill dimensions. This is given as:

All values in equation 9 have either been determined or can be specified. Thus at the value of the calculated shaft power, the length of the mill can be determined. This is done as follows:

P = 0.1008 kW; J = 0.35; Vcr = 0.75; s.g of steel = 7.85 g/cm^3 = 7.85 t/m^3, D = 0.21m, L =?

$$0.1008 = 7.33 \times 0.35 \times 0.75 \times (1 - 0.937 \times 0.35) \times \left[1 - \frac{0.1}{2^{9-10\times0.75}}\right] \times 7.85L \times 0.21^{2.3}$$

$$0.1008 = 1.9241 \times 0.67205 \times 0.9646 \times 0.21676L$$

$$0.1008 = 0.27037L; \qquad L = \frac{0.1008}{0.27037} = 0.3728\text{m} \approx 373\text{mm}$$

b) Shaft Design

A shaft is a rotating member usually of circular cross-section (solid or hollow), which is used to transmit power and rotational motion. Elements such as gears, pulleys (sheaves), flywheels, clutches, and sprockets are mounted on the shaft and are used to transmit power from the driving device (motor or engine) through a machine. The rotational force (torque) is transmitted to these elements on the shaft by press fit, keys, dowel, pins and splines. The shaft rotates on rolling contact or bush bearings.

According to Yung and Nyberg (2010), two basic approaches are considered in shaft design. In the first approach, the shaft is made large enough (and therefore strong enough) to drive the specified load without breaking. Mechanical engineers, according to Yung and Nyberg (2010), define this approach as the ability to transmit the required torque without exceeding the maximum allowable torsional shearing stress of the shaft material. In practice, this usually means that the minimum shaft diameter can withstand at least two times the rated torque of the motor. In the second approach, the minimum diameter needed to prevent torsional deflection (twisting) during service is calculated. To engineers, this means that the allowable twisting moment, or torque, is a function of the allowable torsional shearing stress (in psi or k Pa) and the polar section modulus (a function of the cross-sectional area of the shaft) (Yung and Nyberg, 2010). The two approaches have been used to develop equations for determining minimum shaft sizes. These equations can be obtained from the Machinery's handbook.

i. *Shaft Diameter*

The size of the shaft (shaft diameter) required to drive the ball mill can be estimated by using the equation stated below:

$$D = \sqrt[3]{\frac{1.33 \times 10^6 \times P}{N}}\ mm \quad (10)$$

where: P = shaft power of the mill = 0.5 hp; N = 75% of critical speed of the mill = 81.914 rpm. Therefore, the shaft diameter will be:

$$D = \sqrt[3]{\frac{1.33 \times 10^6 \times 0.5}{81.914}} = 20.098\ mm$$

Due to availability, safety and machine cost savings, a shaft of diameter of 30 mm, greater than the minimum required size, has been selected for the ball mill.

ii. *Shaft Length*

Shafts must be designed so that deflections are within acceptable levels. Too much deflection can cause noise and vibration problem. It can also result to the degradation of gear performance. Since the ball mill is subjected to torsional stress and bending stress, at a maximum allowable torsional angular deflection (θ) of 0.0045 rad/m, the required length of the shaft can be calculated by using the torsional angular equation given below:

$$\theta = \frac{T \times L \times 32}{G \times \pi \times D^4} \quad (11)$$

where: T = applied torque =1.231 Nm; L = length of the shaft; G = modulus of rigidity = 2.45 x 10^9 Pa ; D = diameter of the shaft = 30mm.
Solving for L from equation 3.11, we have that:

$$L = \frac{0.0045 \times 2.45 \times 10^9 \times 3.142 \times 0.03^4}{1.231 \times 32} = 0.712205\ m$$
$$\approx 712.2\ mm$$

A shaft length of about 700 mm, close to the calculated value, was used in the fabrication of the ball mill. This shaft length comprises both the mill and the shafts at both ends of the mill.

c) Pulley Size Calculation

The size or diameter of the pulley required to drive the ball mill (the driven pulley) is an important factor that will determine if the ball mill will operate at the required speed (75% of its critical speed). The equation used to calculate the diameter of the mill shaft pulley is given as:

$$diam.of\ driven\ pulley = \frac{diam.of\ driver \times rpm\ of\ driver}{rpm\ of\ driven\ pulley} \quad (12)$$

Where: diameter of driver pulley (motor pulley) = 200 mm; rpm of driven pulley (motor speed) = 25 rpm; rpm of driven pulley (75% of critical speed of the mill) = 81.914 rpm. Solving for the diameter of the driven pulley, we have that:

$$diam.of\ driven\ pulley = \frac{200 \times 25}{81.914} = 61.04\ mm$$

A pulley of 62.5 mm diameter, close to the calculated value, was used in order to prevent the belt groove from intersecting with the mill shaft.

d) Construction Procedure

i. *Working Drawings*

The ball mill fabrication was done based on the dimensions given in the working drawings that are shown in Fig. 2 and Fig. 3.

ii. *Materials Selection*

Shown in Table 2 are the materials selected for the fabrication of the laboratory ball mill.

iii. *Fabrication*

Mill Cylindrical Vessel

The steel pipe procured to serve as the mill chamber was cut to the required mill length (375 mm). Three rectangular bars, equidistant from each other, were welded to the steel pipe internally as lifters (Fig. 4). Two steel rings with diameters of 210 mm to be welded on both ends of the mill chamber were machined on a lathe. Six holes equidistant from each other, having a pitch diameter of 184 mm, were given to the steel rings. The six holes on the rings were threaded before the rings were welded to the steel pipe (Fig. 5).

Flanges

The shaft required for the ball mill fabrication was cut into two with lengths of 175 mm each. Two steel round plates, 210 mm in diameter, were used as flanges. The shafts were welded to the flanges. This was done by first boring a hole having the same diameter as that of the shaft (35 mm) on the flanges. The shafts were then fit into the bored holes and welded (Fig. 6). Registers were made on the flanges with a circular step equal to the inside diameter of the rings to receive the rings at the ends of the mill cylinder (Fig. 7). Registering of the flanges was made to accuracy, to enhance concentricity during assembly and operation. These flanges were further drilled to align with the rings and then fastened with M8 bolts (Fig. 8).

Machining

The complete ball mill chamber assembly was mounted on the lathe and scribed with a four-jaw chuck and dial indicator. The machining was done in stages: (i) the shaft was machined down to 30 mm, the diameter of the bearing; (ii) the flanges were machined to a thickness of 6mm; (iii) the welded edges between the barrel and the ring was smoothen by turning; (iv) the body of the mill was further machined for concentricity and to remove dynamic imbalance. All these were done to make sure the mill runs concentric without wobbling during operation (Fig. 9).

Ball Mill Stand

The 76.2 x 76.2 mm angle irons were measured, marked and cut to lengths of four pieces of 460 mm and two pieces of 260 mm. The edges of each of the angle irons were cut to an angle of 50° so that the mill legs will be spread to an angle of 100° when welded. The pillow blocks (bearing housings) were centralized on the 260 mm length angle irons. The holes for fastening them were marked, punched and drilled with a 10 mm drill bit. The shafts were fit into centralized bearing housings up to a distance of 30 mm from the flange covering the mill. The remaining angle irons of 50.8 x 50.8 mm were cut to a length of 550 mm (i.e. length from one end of the first pillow block to the end of the other pillow block internally). Their edges were drilled for mechanical fastening of the stand using bolts and nuts.

These angle irons were welded together to form two stands with their legs spread at an angle of 100° from the base (Fig. 10). These legs were also drilled. The 2" x 2" angle irons were fastened to the legs formed using M8 bolts and nuts. Hence, the mill stand is formed as shown in Fig. 11. After the fabrication of the mill stand, the mill vessel was mounted on the stand and the pillow blocks fastened with M16 bolts and nuts (Fig. 11)

Feed and Discharge Opening

A square hole of 80 x 80 mm, after levelling of the mill vessel and the stand, was cut out from the vessel using an electric hand filing machine. This hole serves as the feed and discharge point of the mill (Fig. 12). A dynamic imbalance was observed in the vessel (i.e. the part with the hole always stayed down when the vessel steadied after rotation). This is an advantage for discharging the ground product. The square metal piece that was cut out from the mill was welded to a bigger flat plate of 2 mm thickness to serve as the cover of the

feed/discharge opening of the mill (Fig. 13). A hinge was attached to this plate to assist the opening and closing of the mill without removing the cover entirely.

Motor Seating

The motor seating (Fig. 14) was made through the following steps:

- Points for tightening the motor were marked on the 250 x 115 mm plate. These points were punched and drilled using a 9 mm diameter drill bit. A slot was made on one part of the plate and the end closed by welding a plate piece to it (i.e. the slot for the threaded M16 shaft);
- Small pipes and shaft were used to make a hinge carrying the threaded M16 shaft on the other 170 x 60 mm plate. This was done in order to assist in the tensioning of the belt between the motor and the mill when connected;
- These plates with their components were welded to the leg of the mill stand.

Completed Mill Assembly

Shown in Fig. 15 is the complete mill assembly (without the drive belt) after construction of the mill.

e) Grinding Test

The aim of the grinding test is to determine the performance or efficiency of the designed and constructed laboratory ball mill. Since the mill was designed to operate at P_{80} of 100 microns, efficiency can be achieved if the product of the mill has a particle size of which 80% is 100 microns. If the product particle size is > 100 microns, the mill is said to be inefficient.

To carry out the grinding test, the inner chamber of the mill was cleaned to remove foreign particles that would act as impurity in the required product. The as received limestone ore was manually crushed into particles within the size range of 2 mm. A representative sample of the crushed limestone (270 g) was fed into the ball mill with the required amount of steel balls, after which the grinding operation was performed for about 30 mins. After grinding, the ground ore was discharged from the mill together with the steel balls. The ground product from the mill was then analysed to determine its particle size distribution. The results obtained are presented in the next section of this work.

III. Results and Discussion

a) Laboratory Ball Mill

As can be seen from Fig. 15, the constructed laboratory ball mill met all the specifications required in the design. The mill has a mill diameter of 210 mm, a length of 375 mm, a speed of 81.914 rpm and a 0.5 hp motor to drive the mill. The ball mill also has three lifters, an opening for ore feeding and discharging of ground products, and a solid stand to counter wobbling during operation.

b) Grinding and Particle Size Analysis Results

Shown in Fig. 16 is the picture of the crushed limestone that was fed into the fabricated ball mill for the grinding test. As can be seen in Fig. 17, the picture of the limestone after the grinding test shows that a very fine ground product was obtained after the test.

i. *Feed Particle Size Analysis Results*

The results (weight retained in grams for each sieve size, % weight retained for each sieve size, and cumulative weight % passing for each sieve size) of the particle size analysis of the feed ore or limestone are shown in Table 3. These results were used in plotting the particle size distribution curve of the feed material (Fig. 18). As can be seen from Fig. 18, the plot of the cumulative % passing of the feed limestone against particle size (in microns), the values of F_{50} and F_{80} of the feed are 650 microns and 1950 microns respectively.

This means that about 50% of the feed limestone passes through a sieve size of 650 microns while 80% of the feed material passes through a sieve size of 1950 microns. It is also important to note that the value of F_{80} from the particle size analysis of the feed is almost the same as the value assumed for F_{80} in the ball mill specific power design (F_{80} = 2000 microns).

ii. *Product Particle Size Analysis Results*

The results (weight retained in grams for each sieve size, % weight retained for each sieve size, and cumulative weight % passing for each sieve size) of the particle size analysis of the limestone product from the grinding test are shown in Table 4. These results were used to plot the particle size distribution curve of the ground product (Fig. 19). As can be seen from Fig. 19, the plot of the cumulative % passing of the product limestone against particle size (in microns), the values of P_{50} and P_{80} of the ground product are 47.5 microns and 85 microns respectively. This means that about 50% of the ground limestone passes through a sieve size of 47.5 microns while 80% of the ground product passes through a sieve size of 85 microns. Since P_{80} is 85 microns, which is less than 100 microns (the value of P_{80} used in designing the mill), it means the laboratory ball mill is working within the required size reduction and thus is efficient.

IV. Conclusion

Based on the results of the design, fabrication, grinding test and performance check of the produced laboratory ball mill, the following conclusions have been drawn:

1. The fabricated ball mill met all the specifications required in the design. It has a mill diameter of 210 mm, length of 375 mm, and a speed of 81.914 rpm.
2. The minimum shaft power required to drive the laboratory ball mill when filled with ore and grinding media is 0.2025 horsepower.

3. The minimum shaft dimensions for the ball mill are: 30 mm for diameter and 712.2 mm for the length of the shaft.
4. The performance of the laboratory ball is effective as the P_{80} of the products from the mill is less than the P_{80} (100 microns) of the design. The ball mill is efficient for grinding limestone.
5. The laboratory ball mill can also be used to grind other ores.

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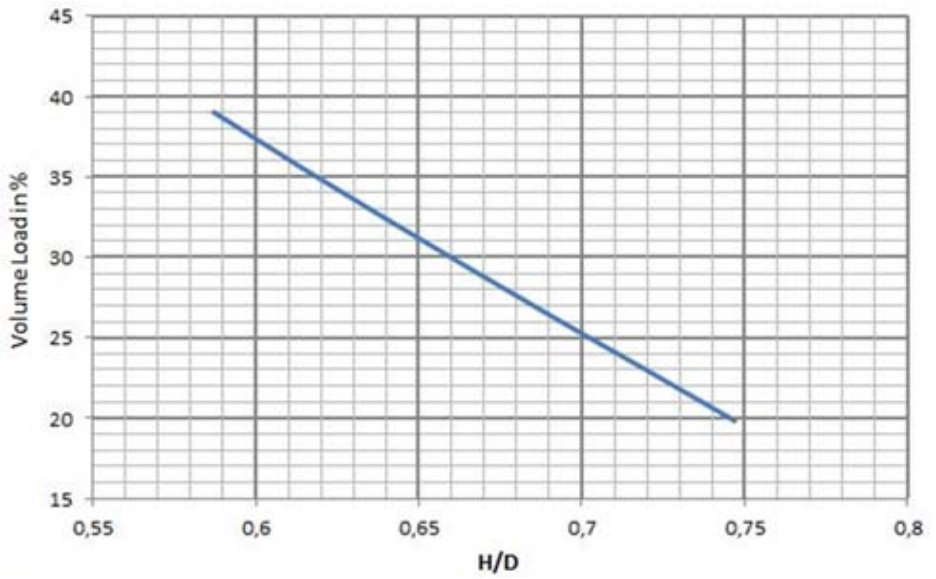


Fig.1: Filling degree as a function of H/D ratio (The Cement Grinding Office, 2012)

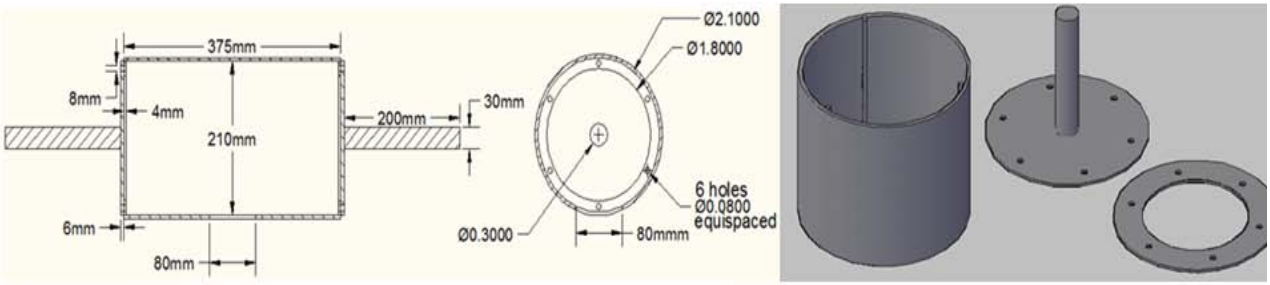
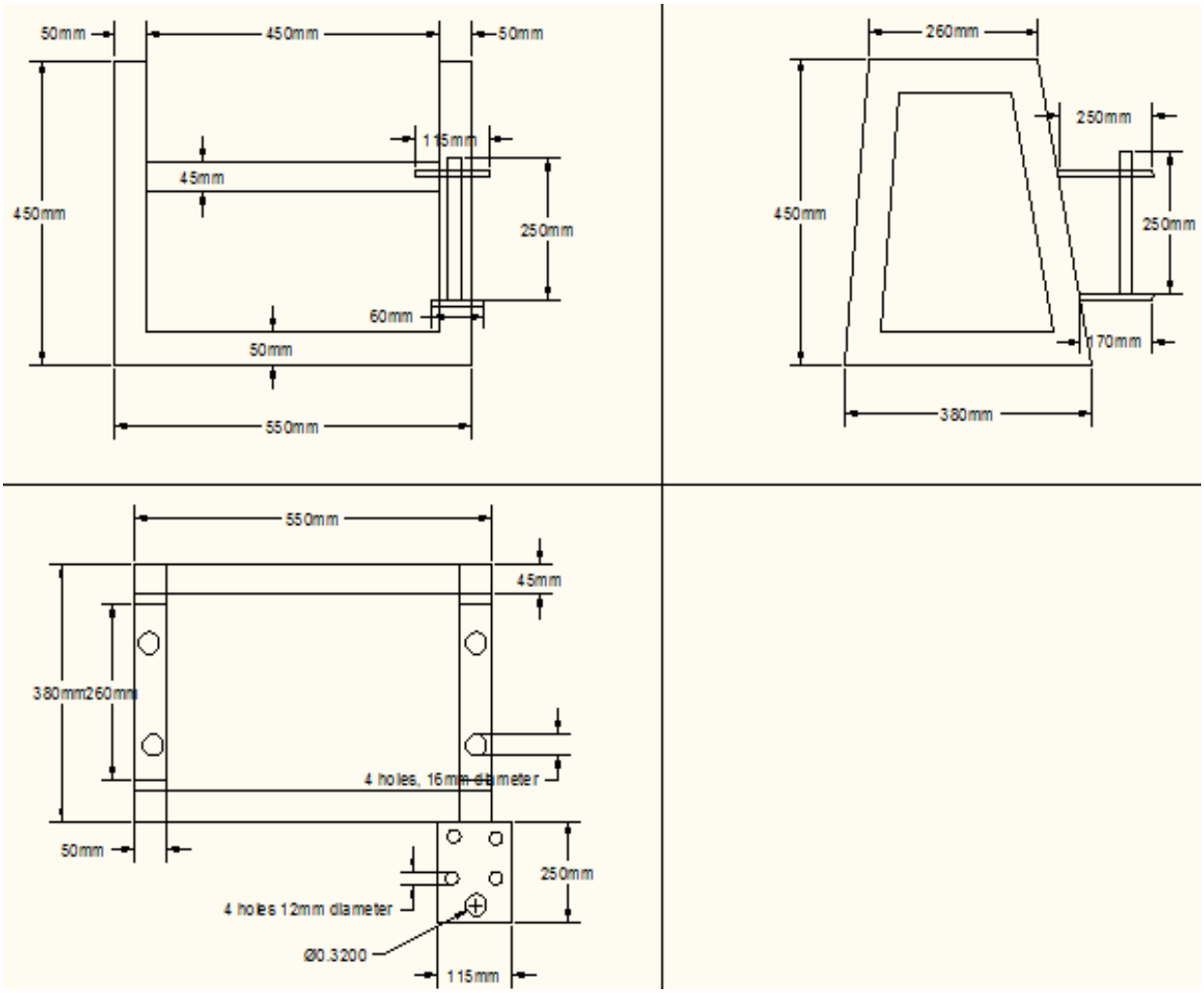


Fig. 2: Detailed working drawing of the vessel for the mill



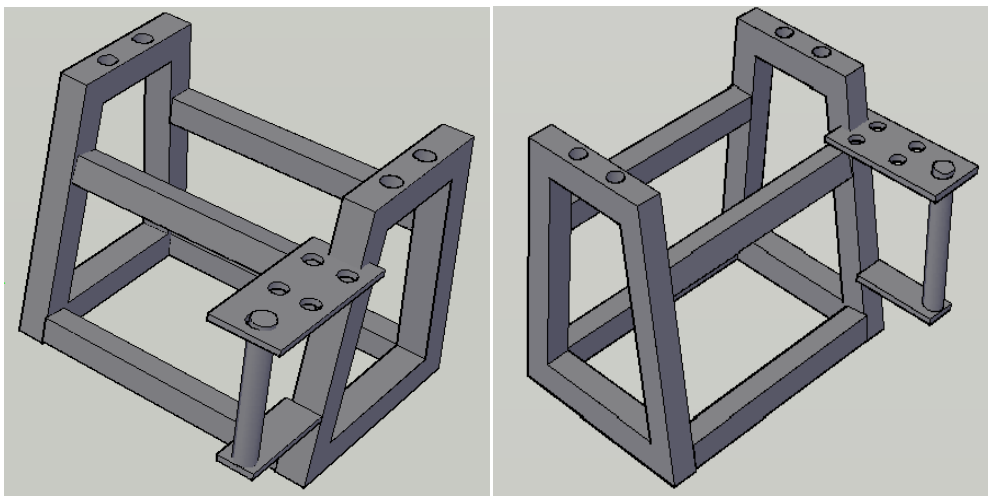


Fig. 3: Detailed working drawing of the stand to the mill

Fig. 4: The steel pipe cut to 375mm and the welded lifters

Fig. 5: Marking the rings using the dividing head; machined rings welded to the pipe

Fig. 6: Shafts welded to the round plates to make the flanges

Fig. 7: Registers made on the flanges

Fig. 8: Flanges fastened to the pipe using M8 bolts

Fig. 9: Different views on how the pipe and flange assembly were mounted on the lathe machine and the scribing of the mounted assembly

Fig.10: Different views of the welded legs of the stand

Fig. 11: Mill mounted on the stand

Fig. 12: Feed and discharge hole cut on the vessel

Fig. 13: Square cut out part welded to a curved plate to serve as feed hole cover

Fig. 14: The different views of the assembled stand and a clearer view of the motor seating

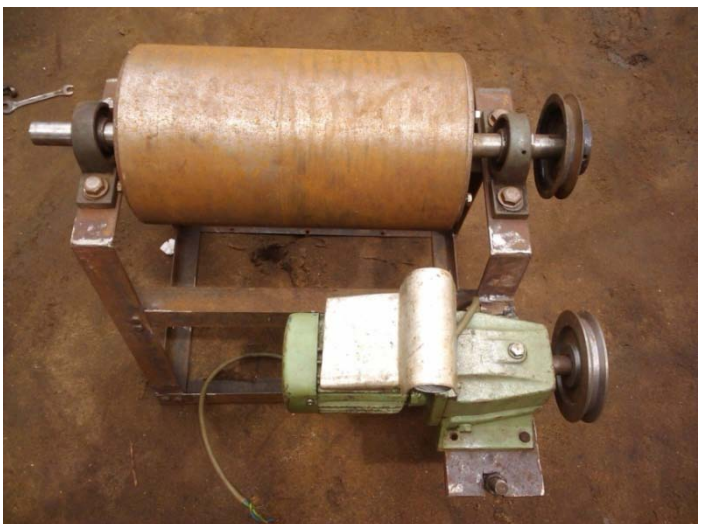


Fig. 15: Complete mill assembly without drive belt

Fig. 16: Feed material

Fig. 17: Limestone product (a) after grinding (b) after sieving

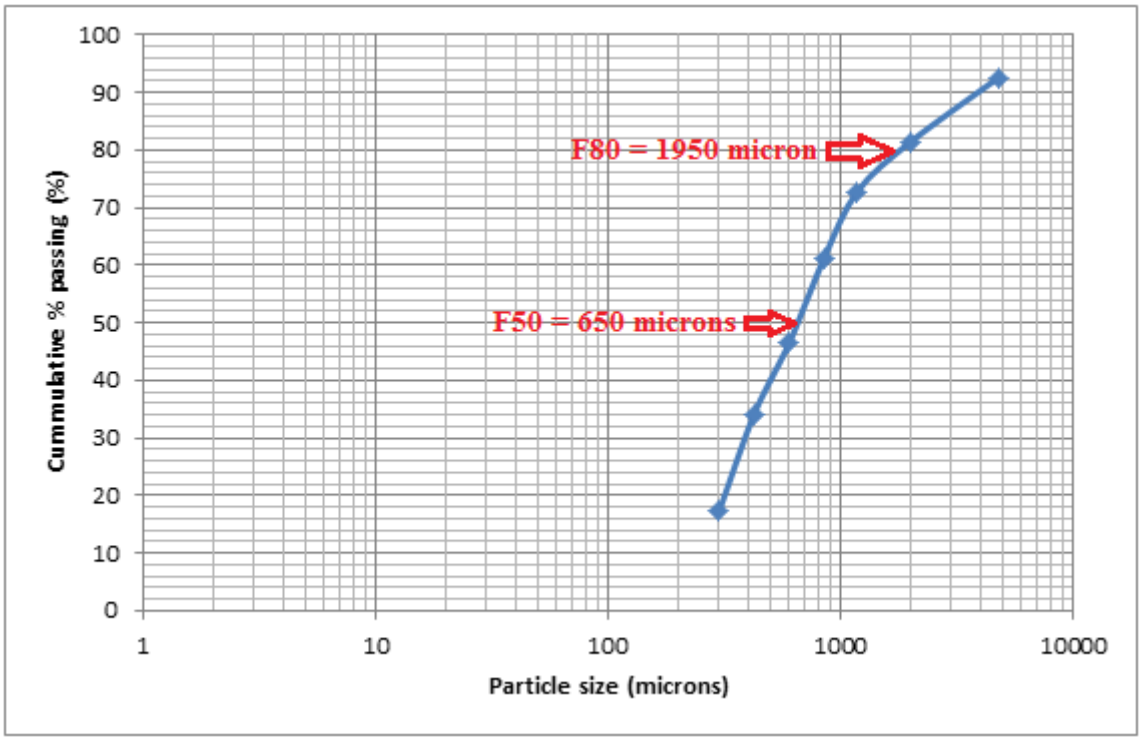


Fig. 18: Graph of Cumulative % passing to Particle size for feed size

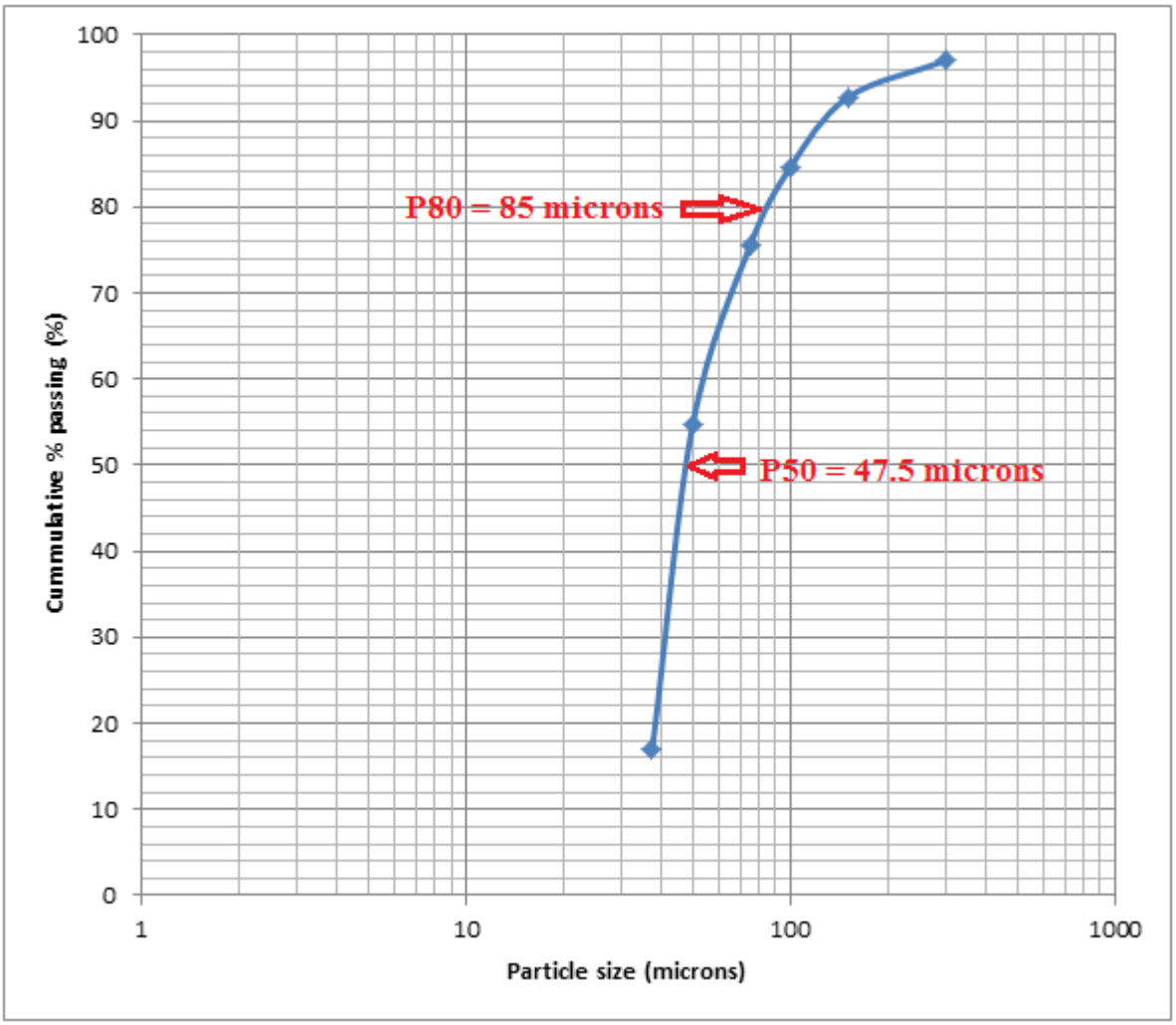


Fig.19: Graph of Cumulative % passing to Particle size for product size

Table 1: Correction factors for open circuit (Schlanz, 1987)

Product passing size	Reference C2
50	1.035
60	1.05
70	1.10
80	1.20
90	1.40
95	1.57
98	1.70

Table 2: Work pieces

SN	Part of machine	Item description	Quantity	Picture
1.	Mill chamber	Steel pipe – diameter, 210 x 400 mm.	1	
		Flat bar – 5x10x370 mm.		
		Steel balls – diameter, 25mm	3 20	
2.	Flanges	Round plate – diameter, 210 x 8 mm.	2	
		Round rings – diameter, 210 x 6 mm.	2	
		Steel shaft – diameter, 35 x 350 mm.	1	
		Pillow block – 30mm inner race	2	
3.	Electric motor	Electric gear motor – single phase, 0.5hp, 70rpm.	1	
		Pulleys – 125mm diameter; 62.5mm diameter, both with B belt groove	2 ; 1	
		Key – Gib-head key of 7x6x50 mm.		

4.	Motor seating	Flat plate - _____ Threaded shaft __mm M16 nuts Hinges Short pipes Shaft	2 1 2 2 2 1	
5.	Mill stand	Angle iron, 76.2x76.2 mm (3" x 3"). Angle iron, 50.8x50.8 mm (2" x 2").	5 6	
6.	Fasteners	M8 bolts and nuts M16 bolts and nuts Electrodes	24 4 ½ pack	

Table 3: Feed particle size analysis with the cumulative percent passing

Sieve size(microns)	Weight retained(g)	% weight retained	Cumulative% passing
4750	20.210	7.485	92.515
2000	29.956	11.095	81.420
1180	23.275	8.617	72.803
850	31.085	11.513	61.290
600	40.050	14.274	46.457
425	33.140	12.274	34.183
300	45.510	16.855	17.328
pan	46.784	17.327	0.000
	270.00	100.000	

Table 4: Product particle size analysis with the cumulative percent passing

Sieve size(microns)	Weight retained(g)	% weight retained	Cumulative% passing
300	8.077	3.04	96.96
150	11.289	4.24	92.72
100	21.515	8.09	84.64
75	24.360	9.16	75.48
50	54.922	20.64	54.84
37.5	100.565	37.80	17.04
Pan	45.338	17.04	0.000
	266.070	100.00	