

A STUDY ON THE COMMINUTION CHARACTERISTICS OF DIORITE

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DECLARATION

I hereby declare that the content presented in this document is completely a masterpiece of my own original investigation, and all results acquired for the research were studied and obtained at Botswana International University of Science and Technology (BIUST). I therefore grant affirmation that the dissertation was never submitted to any other independent academic institution or university for a Degree certification or a MEng.

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ABSTRACT

The focus of this thesis was on the comparison in breakage behavior of heterogeneous diorite rock obtained at two separate quarry locations in Botswana. There are many problems associated with inefficient size reduction of quarry stones. Generally, when the material is left over sized, it will fail in its downstream operation because during separation/ screening the product will not pass to lower screens and it will require a secondary crushing activity resulting in a waste of energy and slimes challenges. Hence proper control of the desired product size range of material is of paramount importance in this industry. Current research efforts in comminution are mainly focused on issues pertaining to energy efficiency. Numerous intrusive activities that occurred during solidification and crystallization lead to development of many inherent material defects that substantially altered intrinsic characteristics of the igneous material thus presenting processing and material selection a very difficult task for many applications. Samples were collected from the central district region (Master quarry) and the north-east district (Panda quarries). Geochemical analysis was carried out via laboratory scale in-situ x-ray diffraction equipment as the initial step to identify composition for elemental contrast purposes. It was observed that a high crystalline phase percentage was identified for Panda rocks while a large amorphous phase constituted the Master diorite rock. An optical microscopy analysis aided in revealing surface characteristics of the samples. The grain distribution, grain orientation and grain size were determined to be the essential factors used to characterize material properties such as fracture toughness and hardness. The diorite rock from the central district showed an average grain distribution with an aphanitic texture or rather porphyritic texture due to fewer grain distribution appearances within a fine-grained matrix while the rock from the north-eastern region was mainly dominated with large crystal grains with a grain size slightly above 1 mm (Anthony & Smart, 2014). Unified crushing circuit comprising of the Jaw crusher, Gyratory crusher and a laboratory planetary ball mill was arranged to further investigate the mechanical properties of each rock species. It was found that the Master quarry rock type was much resistant to breakage as compared to the Panda rock type, a result that can be attributed to poor force distribution and transmission within the material and

also numerous material defects like voids and porosity factors. It was also found from the particle size distribution (PSD) analysis of the Jaw crusher product that for each sample of the Master diorite rocks, the device required 41.58 KWh t^{-1} power to effect breakage while the Panda diorite rocks required only 38.33 KWh t^{-1} of power to break. The Master diorite rock sample is to a greater extent recommended for civil engineering works and infrastructural construction such as steel reinforcement. The structural intactness of components within the Panda rocks, and a characteristic high percentage (40%) of dark amphibole, this rock type is recommended for road construction and infrastructural work.

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CHAPTER 1

1.0 Introduction

A quarry is an open pit mine that focuses mainly on excavation, size reduction and classification of construction aggregates and gravel. The Botswana economy is fast growing as evidenced by the massive construction works in both towns and villages in terms of new roads, schools, infrastructure, buildings and malls. Needless to say, products from the local quarry mines are playing a significant role as raw materials in the construction works. Hence, quarry mining activities play an important part not only in contributing to the Gross Domestic Product (GDP) from the mining sector but also to the flourishing construction industry in Botswana.

Quarry mines are situated mainly in the south-eastern as well as northern district towns and villages in Botswana, such as in Gaborone (Bela Bela quarry), Mahalapye (Quarry mine), Palapye (Maope quarry), Serowe (Master Quarry) and Francistown (Panda Quarries). The mines employ a sizable number of unskilled and semi-skilled employees from the neighboring communities as well as professional mining, civil, mechanical, electrical and instrumentation engineers, health and safety officers and medical personnel for their clinics. Hence, they do assist the government in as far as employment creation is concerned. With Botswana International University of Science & Technology (BIUST) adding to the already growing number of graduates in the country, it is high time we take a closer look at such industries like the quarry industry, in contributing to the solution of reducing unemployment.

Comminution of quarry stones, especially of an igneous rock nature that are characterized by a high hardness, requires excessive amounts of energy input to fragment the rock into particulate material of manageable size. Therefore, research efforts need to be directed at the size reduction processes of such material in order to reduce operational costs in-terms of energy requirements used by the size reduction equipment. Such research efforts also save the purpose of increasing the lifespan of equipment and minimizing the effects of machine wear problems arising due to improper loading or feeding techniques.

“The process of Comminution which involves size reduction, classification (screening and separation) and Milling is one of the most important industrial processes that utilize large amount of electric energy. The electric power consumption by this process is estimated to a value from 5 to 20% of overall world electric power.” (Deniz, 2011) Therefore, there is a great need of providing adequate size reduction methods engaged in mineral processing and relevant grinding strategies that will combat or otherwise reduce power consumption within a Comminution operation plant processing diorite igneous ore material with high densities and hardness (David , 2007). Understanding the types of material defects associated with the ore mineral can critically help reduce the amount of electric power spent via a comminution operation process, it is also vital in the interpretation of particle size distribution (PSD) diagrams obtained from crushing and grinding equipment in order to combat problems arising from overfeeding or choking of the device with feed that has differing hardness properties.

There are many problems associated with inefficient size reduction of quarry stones. Generally, when the material is left over sized, it will fail in its downstream operation because during separation/ screening the ore material will not segregate to lower screens and it will require a second crushing activity and when it is subjected to a closed circuiting operation to convert it to finer particles it will result in a waste of energy and slimes challenges. Hence proper control of the desired product size range of material is of paramount importance in this industry. Current research efforts in comminution are mainly focused on issues pertaining to energy efficiency.

Size reduction is enhanced by the presence of natural defects in crystalline materials embedded within the crystal unit, such as dislocation densities and numerous interstitial defects. Hence, the size of particles ranging from Nano-meter scale to micro-meter scale will be lost to the tailings stream in a large-scale processing plant if the feeding and energy input of the crushing circuit is not regulated. Botswana has large reserves of quarry materials for applications in civil engineering activities, construction and materials science studies. Control must then be imposed on energy utilization in this sector to conserve the amount of power utilized in these industries. Important operational parameters of the equipment such as the feed rate, capacity calculations, throughput and gap size of the equipment need to be extremely understood when working with

materials with variable comminution behavior or grindability which is a measure of resistance to crushing and grinding and is thus related to the material's physical properties as well as its rank, chemical, and petrographical compositions (Deniz, 2011).

Diorite rock is an intrusive rock material intermediate of gabbro and granite rocks in terms of composition. It is found mainly in mountainous landscapes where it occurs in substantial amounts as batholiths (vitalij, et al., 2003). With rock composition of about 5-50% dark minerals (melanocratic) and a white appearance, the plutonic rock composite closely relates to andesite in appearance and textural similarities, consequently containing mostly hornblende (amphibole), plagioclase and/or pyroxene (augite) and approximately 52% - 63% silica content (Sen, 2014).

1.1 Comminution

According to Deniz (2011) when commenting on Coal, a heterogeneous substance which consists of organic matter, moisture and various mineral matter materials mentioned that for Several crushers such as jaw crusher, gyratory crusher and roll crushers which use physical effect of compression to hard and brittle igneous rocks and because of tremendous expenditures of money and equipment necessary to investigate the size reduction of large-dense particles hardly any scientific investigations were being carried out so far and Therefore, these crushers are still classified by empirical rather than by scientific approaches (Deniz, 2011). Due to a rise in the quarry mining industries in Botswana processing diorite rocks for different construction duties, a study on the Comminution characteristics of heterogeneous diorite ores was hence mandatory to scientifically understanding their response following crushing and grinding activities. Raw materials acquired as run-of-mine (ROM) ore lumps are essentially converted to manageable feed sizes for successive separation and reduction stages. According to Kapadia & Weber (2019) "At every stage, over size ore pieces which are not crush into proper size, again conveyed towards re-crushing by process circuit and the under-size particles are sent to upcoming size reduction operations." Because of the inherently high densities and hardness of igneous materials, re-crushing and conveying may be a costly operation especially when it has to be repeated for several times therefore products of size reduction obtained from equipment may be continually subjected to screening and isolation in the middle of coarse and fine size reduction stages to avoid costs of over-crushing and disadvantages resulting from over-crushing activities. Following every crushing operation largely find application and utilization in the civil and

construction engineering industries therefore mechanical property estimations for each rock fragments distributed within the screens aids engineers understand the behavior of every igneous rock being fragmented. The separation methods are however based on the differences in the physical properties of various minerals such as shape, susceptibility to size reduction, specific gravity, electro-magnetic susceptibility, surface chemical property, etc (Kapadia, et al., 2019). For size reduction processes compressive stress and impact stress are usually associated with primary and secondary processing of the material while shear stress is applied when milling or grinding particles to a fines and it is called the tertiary processing stage here the mineral constituents that are very much attached to the mother ore are grind using shear stress to encourage particle-particle interaction and hence liberation. For all the comminution processes grinding is the most energy intensive when compared to crushing thus milling time and the revolution speed of the mills must be operated with caution.”

1.2 The research problem associated with comminution processing

Energy regulation and calibration in a processing plant is one of the most difficult aspects to control because there are many factors that contribute to energy dissipation and losses in the mining environment. According to Wills & Napier-Munn (2016), energy is normally lost to the environment due to machinery movement and/ or absorption as most of the equipment overheats during operation. For the comminution techniques, both physical and chemical methods of separation are usually employed where necessary to either liberate minerals of commercial interest or rather fragment them to finer particles therefore substantially large quantities of energy will be absorbed by the ore material because naturally minerals exist in physical and chemical combinations with each other via strong atomic bonds which in most cases will tend to stretch before fragmentation occurs hence presenting a further difficulty in measuring the exact amount of energy required break the material (Gupta, et al., 2016).

In the process of size reduction, it was generally discovered that particle size of the fragmented rock species is inversely proportional to the surface area of the generated particles. Therefore, a measure of the particle size before and after breakage can be used to indicate the extent of energy expended in the comminution process.

The equation that was derived by Bond, which calculates the specific energy of grinding as:

$$E_G = 10w_i \left[\frac{1}{\sqrt{P}} - \frac{1}{\sqrt{F}} \right] kWh/t \quad \text{Eq. (1.1)}$$

Where:

F = 80% passing size of the feed in μm , P = 80% passing size of the product in μm and w_i is the Bond Work index (Barry , et al., 2016).

When considering the equation for calibrating the amount of energy or power required fragmenting the material ore into finer particles, there are limitations that would naturally lead to development of errors because when measuring the mass retained in each sieve or screen some material will always be lost due to improper handling.

1.3 Research questions

What are the main material selection criterions that are put in place to coordinate products of a quarry mine reduction circuit plant according to various applications and usages? How does processing route for a diorite size reduction plant help combat problems resulting due to production costs and the work required to operate the equipment?

1.4 Particle Size Distribution (PSD) representation method

After ore fragmentation through various methods of comminution the material feed aggregates will retain a complex and irregular shapes therefore their particle size cannot be directly defined because of a variable particle size, dimensions etc.,. Particle size distribution is an average expression that indicates the particle proportion as a percentage of the total feed amount and the average retained particle size within the same size group to be measured and the separation or screening is done using sieve stacks like that on figure 1.1. Usually the aggregate Volume, area, length, and quantity are used as standard particle dimensions when quantifying the relative particle amount and the Volume Mean Diameter (VMD) is often used for frequently for establishing fracture toughness comparison of different kinds of feed materials (Jennings , 1988). Statistical distributions and curves are usually employed to quantify the behavioral

pattern for the fragmentation of the feed material where the amounts of particles existing on size intervals are contrasted with their respective sieve aperture openings. The cumulative percentage distribution for passing aggregates of the sieve are commonly calibrated because it expresses the amounts of material below a specific sieve while alternatively the cumulative percentage distribution for particles retained on the sieve or the oversize material are also calibrated. During sieve analysis tests particle diameters are commonly measured indirectly using the equivalent spherical diameter equation that expresses the particle size of the measured particle by the diameter however various principles of measure exist for particle size distributions analysis that significantly differ in their quantification approach such as the laser diffraction method that will classify material aggregates based on response to light therefore whether same or different light diffraction patterns were recorded when the material was passed under light intensity source (Danha, 2013)



Figure 1.1 showing sieve arrangement stacks that are used for Particle size distribution analysis after a size reduction process (picture taken with a camera)

1.5 Aims and Objectives of the dissertation

My main aim in undertaking this experimental study was to understand the factors that affect the size reduction process in the quarry industry in Botswana with an intent to conceptualize these operational parameters and hence improvement on the outcome of the results.

To achieve this aim, I need to fulfill the outlined objectives:

- i. Study and understand the material science concepts of quarry rocks and to understand their associated material defects.

- ii. Make a comparison of diorite rocks from major quarries that statistically represent a larger area across the country.
- iii. Appreciate material characterization using x-ray diffraction technology (XRD) and optical microscopy for grain distribution or rock morphology.
- iv. Completely familiarize with common problems incurred when using a Jaw crusher, gyratory crusher and ball mills in a combination and learn their common limitations.
- v. Study particle size distribution of diorite rocks with lab sieving.
- vi. Evaluate energy consumption for crushing processes; power required reduction of ratio for both gyratory and jaw crushers.
- vii. Analyze products of milling activities with laboratory sieves for diorite rocks in order to learn about particles distribution patterns.

1.6 Outline of the dissertation

CHAPTER 2

This chapter introduces a background study on the properties of igneous materials and factors that influence the fragmentation behavior of these types of rocks during breakage. It also touches on the relevance of igneous rock provenance to the methods applied in comminution. The chapter covers the majority of materials defects associated with igneous rocks and how their relative densities have a profound impact on the microstructural properties of the material such as elasticity, hardness and fracture toughness. The basic operation and performance of common comminution devices are also mentioned, how their adaptation to an activity can highly combat wear problems that might arise due to improper loading. Milling and screening sections are also discussed since they play an important role in controlling material size of feed to the crushing device during an operation.

CHAPTER 3

This chapter focuses on the materials and methods relevant to my investigation on properties and structural compactness of diorite obtained from two different quarries. Hence such aspects as

sample collection, sample preparation, characterization, comminution and classification activities are discussed in this chapter.

CHAPTER 4

Chapter 4 is devoted to the results and discussion of characterization, classification and comminution experimental results. An in-depth analysis of the two diorite rock types obtained from Serowe (Central district) and Francistown (Northern region) is carried out in this chapter.

CHAPTER 5

This chapter presents a set of conclusions and recommendations emanating from my results and discussions section. From my laboratory experimental study of the comminution characteristics of Diorite, a number of conclusions and recommendations were derived. One of which was that both the Panda and Master Quarry diorite rock types are suitable for road construction engineering and civil work due to the inherently large grain size constituents and a well-defined composition that add to the hardness of the material. From the size class of interest, +4.75 mm and +3.35 mm it was observed that large quantities of the material was collected in the above sieve range class when processing the Panda diorite relative to the Master diorite, a behavior that might have resulted due to structural intactness of components within the Panda rock material because of its properties dark amphibole dominated about 40 % of the XRD scan results while plagioclase occupied approximately 32 %.

CHAPTER 2

2.0 Literature Review

2.1 The Comminution of igneous rocks

There are various mechanisms that differ by their deformation mechanics, employed in the size reduction of rocks. The mechanics are classified into: impact stress inducing, compression against rigid surface and shear or attrition depending on the operation being carried out. Crushing is normally achieved by application of impact force acting rapidly on a material or compressive force on feed material within the equipment. However, this process is highly dependent on the nature of rocks being comminuted, the chemical bonding within the rock structure that accounts for the inherent physical properties inherent hence, I will now discuss about the nature of this type of rocks as it is a factor that affects its comminution behavior.

Igneous rock minerals have a crystalline structure in which homogeneous chemical compounds exists with a regular repeating arrangement of atoms systematically ordered within a crystal lattice. Minerals would usually form a three – dimensional structure with a multi-phased structural orientation in a neatly homogeneous configuration. Crystalline materials exist either as amorphous structures, multi-phased crystals or a single-phased crystal structure depending on the crystallization conditions that were prevalent at the nucleation and formation stages (Barry , et al., 2016). The energy within the material results as a consequence of the type of chemical and physical bonding exhibited by the atoms constituting its crystal lattice. Besides diorite, some other common examples of crystal materials include diamond, quartz, topaz, selenite and gypsum which occur mainly as polycrystalline minerals. Naturally, they are formed underground in volcanic conditions as a result of cooling magma or lava hence solidification process may give result to a crystal mineral or an amorphous one depending on the temperature of the liquid magma, pressure at solidification and the cooling rate.

Some rocks have their crystal lattice held within highly defective grain boundaries, a phenomenon that occurred during crystallization of the mineral. This gives rise to weaker physical properties e.g toughness. Due to this, grain boundary cracks are easily developed and can propagate with limited resistance when an impact force is exerted. The long – range order of atoms give the rocks their varying mechanical properties such that even grain sizes and grain distribution on the surface of the mineral contributes significantly towards the general properties manifested by the material and so, for polycrystalline materials grain characteristics are always proportional to their breakage behavioral patterns.

Feed material preparation is another important aspect in size reduction technique since the influence of pressure, temperature and cooling rate contribute significantly as a major factor of the mineral rock solidification (Rhodes, 2006) is well documented. Therefore, alterations can be made on the feed material in order to control the amount of energy the material can absorb before fracture can occur. Mineral provenance is also vital when assessing environmental impact of the material to be mined. This is so because economic profitability, excellent performance and effectiveness in operation are not the only factors to consider in mineral processing. Health and safety of the end user, local community as well as personnel working on the quarry site is also of paramount importance.

During the initial deformation stages when the run – off – mine material is loaded in the machinery for breakage the external and internal forces exerted on the material are not equally disseminated. This is due to dimensional differences of particle aggregates, grain – orientation and compositional constituents within the polycrystalline rocks and as a result the stress distribution affects the mechanical breakage of each individual mineral in the rock (Wills, et al., 2006). Igneous rocks are not perfectly homogeneous and symmetric in their atomic array rather they are always defected. They have microstructural properties of the crystal lattice that do not reveal all the important information about atomic vacancies existing within the material and interstitial sites or void positions that might capacitate instabilities during breakage. Presence of impurities imbedded inside the structure is another problem that has challenged material

scientists doing research attempting to perfect certain single crystals for applications such as in airplane turbine blades.

Crystal defects manifested by ores in their numerous occurrence and relative densities have a profound impact on microscopic properties such as elasticity, fracture toughness and crack propagation within the rock matrix and how the host mineral ore respond generally to breakage factors. These structural deformities normally concentrate applied strain energy at unique points of the lattice hence leading to an asymmetric fracture of the mineral rock. Figure 2.1 reveal common material defects that are associated with mineral ores therefore interstitial foreign atoms positioned between crystal grain boundaries of the unit cell and substitution impurity atoms of an approximate size such as silicate atoms that generate defectiveness and create stress – field imbalance regions that usually change the coordination of atoms surrounding them when there is an applied force. This leads to compressive stress or tensile stress that usually results to unequal force distribution throughout the material and/ or development of multiple lattice distortions throughout the crystal matrix (Barry , et al., 2016).

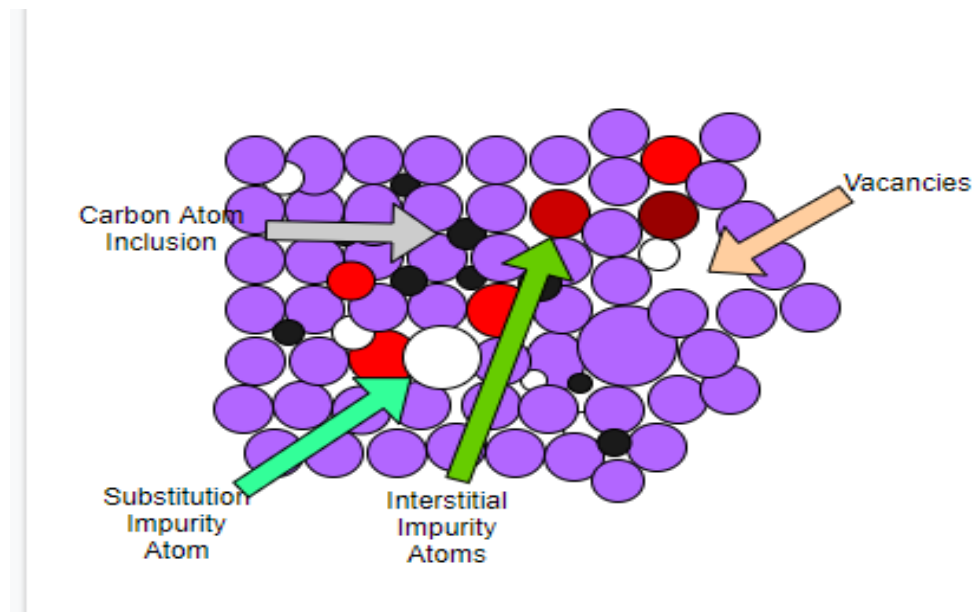


Figure 2.1 showing a crystalline mineral ore structure with many impurities and associated material defects such as cracks, vacancies, shrinkages etc. (Wills, et al., 2013)

Unregulated solidification temperature, pressure variations, and cooling rates of igneous rocks together with temperature resulting from particle attrition during crushing, creates excess strain energy within the rock structure. This effect, however, disturbs the near homogenous array of molecules and atoms and creates crack nucleation or propagation from any direction hence presenting a difficulty when controlling the particle size of interest. Investigations have demonstrated that crystallization temperature of the magmatic minerals is directly proportional to the number of vacancies, and the phenomenon is illustrated by equation 1.0:

$$N_V = N_S e^{\left(-\frac{E_V}{K_B T}\right)} \quad \text{Eq. (2.1)}$$

Where; N_V represents the number of vacancies, N_S the number of regular lattice sites, K_B Boltzmann Constant and where E_V Is the Energy required to cause plastic deformation.

Energy accumulation at lattice sites exerts stresses inside the material resulting in initiation of crack propagation (David , 2007). Previous studies reveal that the square root of the crack length is directly proportional to the applied stress increments acting at 90° to the direction of crack growth. As the applied load continues to increase, the tip of the crack also experiences majority of applied pressure thus rupture of atomic bonds occurs at these points leading to breakage by permanent plastic deformation that can be either trans-granular fracture or intergranular fracture.

Polycrystalline materials are commonly characterized as materials which are brittle and possessing a lower elasticity or low toughness depending on their surface characteristics. They are usually occurring with poor energy absorption characteristic of the material such that fracture can occur easily due to such a phenomenon. Trans-granular fracture occurs when there is difference in orientation of cleavage planes within the crystal matrix resulting in abrupt failure that spreads throughout the crystal lattice. Fragmentation expose the surface area of grains hence a coarse – textured surface morphology that can be easily observed under an optical microscope (Wills, et al., 2006). Inter – granular crack propagation occurs along the grain boundaries and the critical crack length where fracture occur is significant in determining the energy required to produce material failure of the crystal matrix as shown by equation 2.2

$$E = 2K_{\beta} \left(\frac{1}{\sqrt{D_n}} - \frac{1}{\sqrt{D_i}} \right) \quad \text{Eq. (2.2)}$$

Where: E And K_{β} are the energy input and Bond work index constant. D_n And D_i Are the final and initial diameters of the sample respectively.

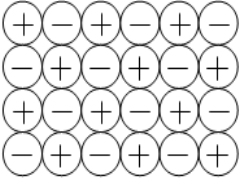
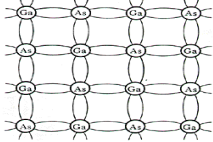
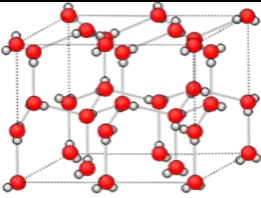
Even when uniformly loaded, igneous rocks though brittle have a little elasticity characteristic that allows them to absorb small quantities of strain energy prior to failure an aspect that presented numerous problems especially when estimating the required energy amount of fragmentation using equation 2.2. Elasticity of any material is therefore related to the type of chemical bond the material is comprised of either metallic bond, ionic bond, covalent bond or van der Waals bonding because bonding affects how atoms interact with each other as can be seen in Table 2.1, also the crystal grain structure of the resultant rock after crystallization and solidification. Grain structure and properties for any material are unique and differ in size range from the Nano-meter scale to the Micro-meter scale.

Grains and phase constituents are positioned in different orientations with respect to other adjacent grains that maybe of the same mineral or a different kind, which is a common property for all polycrystalline materials. When subjected to loading, some crystalline materials can however absorb strain energy without any fractures occurring internally but rather because atoms and molecules interact via small movements and the matrix re-arranges its position to assume new ones thereby sliding past each other and only the crystal lattice shape is distorted, a characteristic or behavior natural to piezoelectric materials and perovskites.

Grain boundaries density also can strengthen some materials and improve their physical properties as they tend to impede dislocation movements thus improving the fracture toughness of the material. Crystals with smaller grains – size tend usually to respond to induced strains differently when compared to a coarse – grained mineral crystal under the same conditions (Sands, 1969). They tend to produce a higher strength and it is important during heat treatment processes to control cooling rates because they determine the grain size outcome. Rapid cooling produces a finer grain structure pattern while slow cooling produces larger grains and

so toughness can be expected in fine – grained crystals while coarse – grained crystals are generally hard and very brittle.

Table 2.1 shows the crystal unit cell structural properties for various materials together with their associated bonding type found in the structure (Callister , 2007).

Bond Type and Structure	Bond	Properties	Example
 Ionic bond	Electron/ ionic attraction	▪ Hard ▪ High Melting point ▪ Soluble in polar liquids ▪ Electrical insulators	▪ Alkali Halides ▪ Oxides (Na₂O)
 Covalent bond	Shared Electrons	▪ Very hard ▪ High melting point ▪ Insoluble in nearly all liquids ▪ semiconductors [9]	▪ Diamond, C.
 Molecular bond	Van der Waals Forces	▪ Soft ▪ Low melting and boiling points ▪ Soluble in covalent liquids ▪ Electrical Insulators	Methane (CH₄)
 Metallic bond	Electron Sea	▪ Ductile ▪ Metallic luster ▪ High electric and thermal conductivity	Sodium (Na)

2.2 Principles of comminution

For any industrial work and/ or mining activity, size reduction is employed as the first stage/ step of processing, in which run-of-mine (ROM) material is crushed and reduced to smaller manageable sizes. Large scale crushing operations performed mechanically through Jaw crushers, gyratory crushers and roll crushers are employed to attain desired material size range required for downstream processing (Barry , et al., 2016).

Different breakage mechanisms are adopted for specific ores depending on the material properties. Large boulders that are also too dense may need to be taken first to percussion rock breakers before feeding them to any size reduction equipment. The selection of machinery between the many alternatives remains a difficult task since it intricately takes into consideration the mineral deportment. Comminution patterns and characteristics is a measure of material resistance to breakage at the size reduction stage and also grinding, which is significantly related to the feeding patterns and controlled by the amount of material the crushing device can handle at a time.

Material justification in terms of characterization of components within each mineral is of great significance because the component – rank in the hardenability series easily estimates the geochemical composition and the amount of energy, time and pressure it was involved in the mineral formation (Barry , et al., 2016). Throughout history, several crusher machines such as Jaw crusher, gyratory crusher and/ or roll crushers have significantly increased in pricing due to continual improvement of crushing components in order to combat problems arising because of wear, thus because of funds and economic affordability of equipment for various local plants involved in scientific research, to some extremes have been struggling to replace their old machines. Controlled parameters for a mineral size reduction process may include variations of grinding time, ball mill speed in revolutions per minutes, feed material strength or density, feed size amount or choke feeding.

Research has tremendously improved size reduction efficiency not only through development of new advanced technological equipment with improved energy utilization but also via designed

optimal unit patterns that render the whole comminution process a friendly operation. Growth in scientific statistics and logistics in recent years indicate new calculations for simple data presentation of variables have improved performance efficiency even in former technology. This is a concept that is important in mineral processing technology reducing energy consumption of the plant and therefore the cost of expenditure in electrical bills. It has been estimated on average annually that billions of tons of material are mined, crushed and fragmented to the required size, a process that utilizes thousands of kilowatt/hours energy of electricity in one year. This information therefore renders the size reduction of mineral ores an activity that is highly energy intensive process altogether.

2.3 Size reduction equipment

2.3.1 Jaw Crusher Design and specification

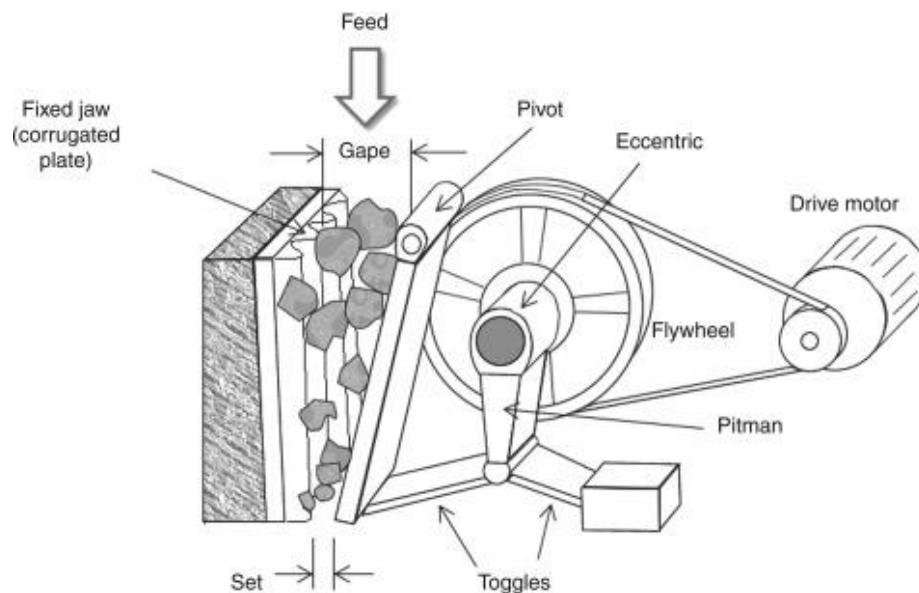


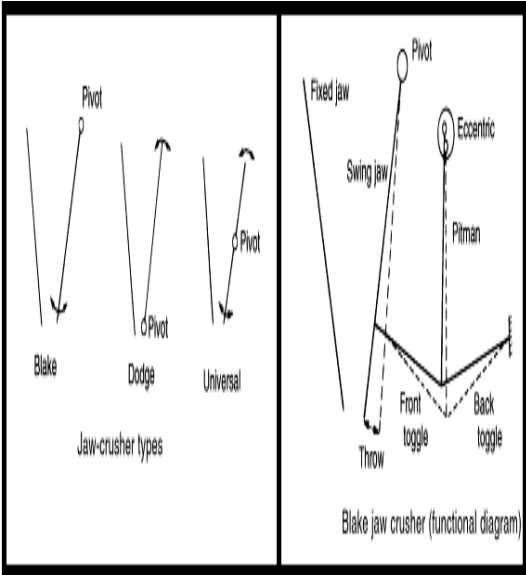
Figure 2.2 shows a double-toggle jaw crusher (Gupta, et al., 2006)

Jaw crushers similar to that presented by figure 2.2 are designed with an intricate mechanical network of hardened high carbon steel overlaid on a heavy block and fastened with bolts. Many types of Jaw crushers exist in the current market differing to a large extent by component assembly, area of application (size), and model of design (operation). The principal operation of the device borders around compression breakage exerted by a movable Jaw plate against a stationary Jaw plate (Gupta, et al., 2006). Fundamentally, they comprise of two main jaws that can be differentiated according to usage and model.

The jaws form an acute angle opening into the crushing chamber where the material is received for crushing. One Jaw is fixed while the adjacent jaw is pivoted such that it produces an elliptical motion as it exerts pressure on the fed ore material and the position of the pivot determines the model of the crushing device. The discharge aperture zone of the jaw crusher is located at the bottom while its opening is at the top. Depending on the position of the pivot on the revolving jaw, three common jaw crushers find their specifications and their operational speed ranges between 100-350 rev/min also based on the model type and area of application.

Only three (3) types of Jaw crusher designs are commonly used; (a) Blake-type crusher: - where the movable Jaw plate is pivoted at the top end near the *gape* or *feed* opening, (b) Dodge-type crusher: - with a movable jaw plate fulcrum position near the bottom of the crushing chamber closer to the *set* discharge zone and also, (c) The Universal crushers: - with fulcrum position middle of the reciprocating Jaw plate such that compressive impact apply both at the top and bottom of the crushing chamber, as illustrated by the Table 2.2.

Table 2.2 Different types of Jaw crusher models common to local industrial applications (Wills, et al., 2013)

Name	Equipment Classifications	Specifications	Uses
1. Blake		Variable discharge opening and fixed feeding area. Pivot position at the top.	Industrial usage and laboratory.
2. Dodge		Pivot located at bottom with fixed discharge opening and variable feeder area	Laboratory use only.
		Receiving and delivery areas are variable as	Industrial usage and

3. Universal		pivot is at the middle.	laboratory.
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The basic operation and performance of a Blake jaw crusher takes from its simplified mechanical design. The reciprocating motion provided via the *eccentric* shaft will selectively allow particles smaller to the *set* diameter to be discharged while large lumps are trapped within the crushing chamber. In order for successive compression and breakage to occur particle interaction and attrition forces are exerted on the feed material until it fragments to size less than that of the discharge zone (Legendre, et al., 2014). Therefore, the undersize material will move to the next stage for further processing. The scalping screens that control the amount of feed material will thus only receive material within the stipulated size range less than the gape opening as illustrated in figure 2.3. This creates an efficiently smooth operation of the circuit environment, a development that also avoids overloading of the equipment and improves its efficiency and lifespan (Gupta, et al., 2006).

2.3.2 Jaw crusher sizing and selection

Important factors to consider when selecting a jaw crusher for a specific task are easily followed by application of basic equations that identifies loading size as well as the gape size computation in meters (*m*) on the device (Deniz, 2011).

$$\text{Vertical height of crusher (y)} = 2 \times \text{Gape (x)} \quad \text{Eq. (2.3)}$$

$$\text{Width of Jaw (z)} > 1.3 \times \text{Gape} < 3.0 \times \text{Gape} \quad \text{Eq. (2.4)}$$

$$\text{Throw} = 0.0502(\text{Gape})^{0.85} \quad \text{Eq. (2.5)}$$

Jaw crusher size are normally described using the gape and width dimensions across all process engineering from small laboratory crushers to large industrial crushers, expressed as *gape x width* (Marcus et al. 2017)

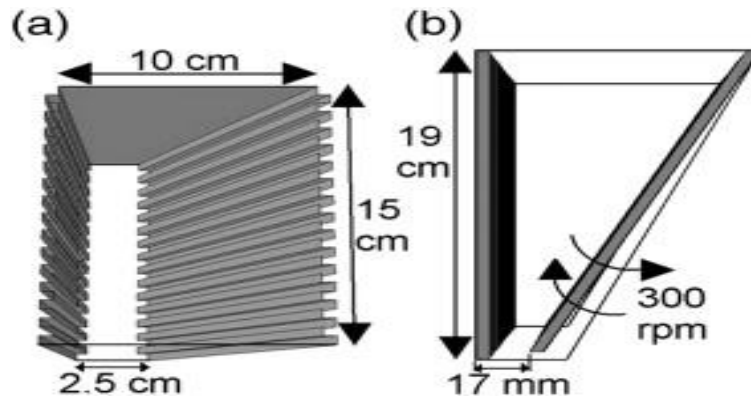


Figure 2.3 Laboratory Jaw Crusher top and side views, 100 mm x 1500 mm (Deniz, 2011)

2.3.3 Jaw crusher size reduction circuits design

Jaw crushers are naturally employed in engineering laboratories usually as primary crushing devices for investigation on mechanical properties of the material as well as in large industries for mineral processing in various operations (Legendre, et al., 2014). Depending on the required particle size, they are usually connected in series with other crushers either in an open-circuit connection or a closed-circuit connection which consist of primary crushers, secondary crushers and tertiary crushing depending on the material to be processed as illustrated by figure 2.4. The last crusher in a unified size reduction treatment plant always operate under closed circuiting conditions in order to screen and re-crush material products to ensure homogeneity of parts and thus easy management on required particle size of interest (David et al. 1991).

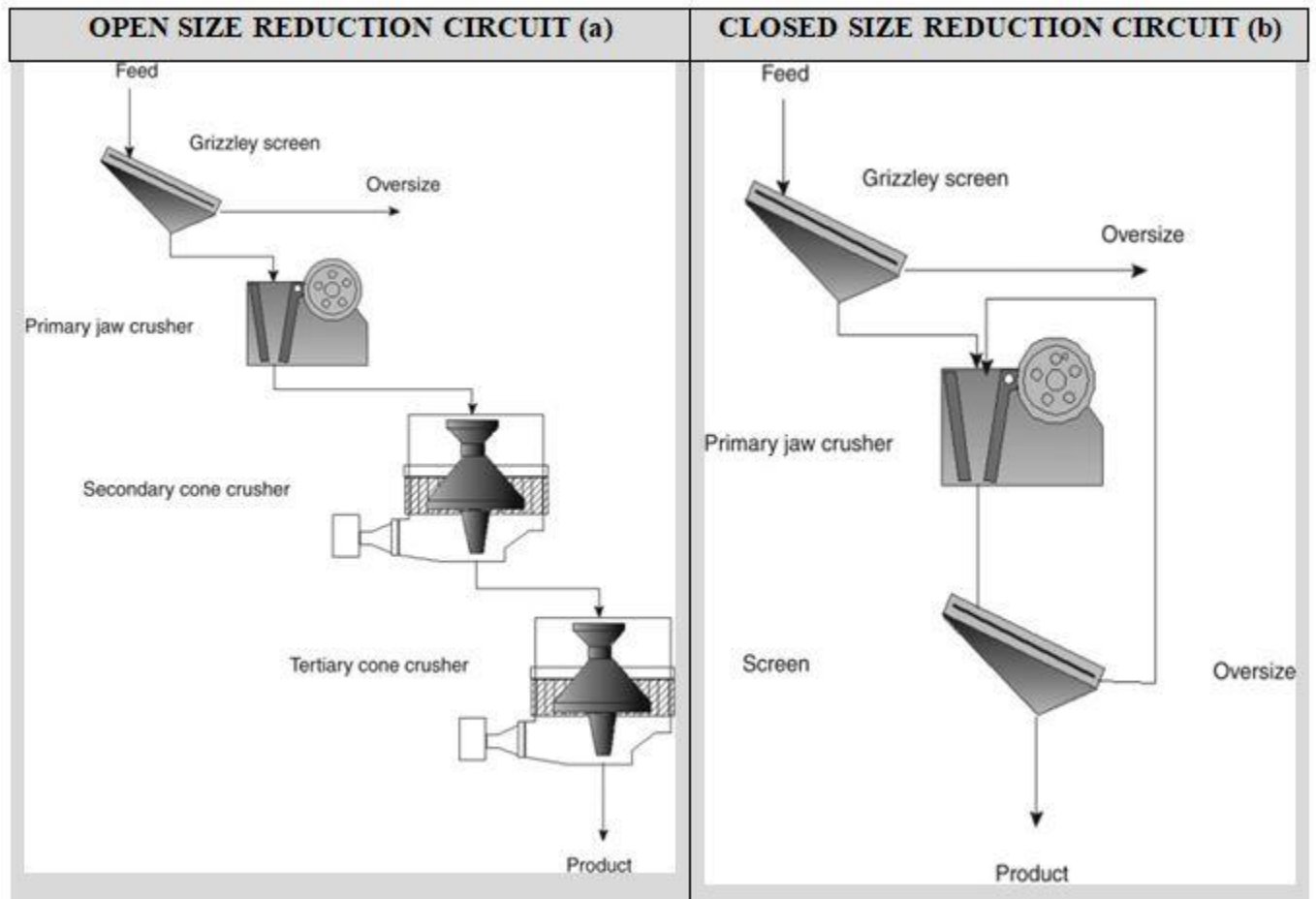


Figure 2.4 Open and closed size reduction circuit connection with primary crushing, secondary crushing and tertiary crushing stages (Gupta, et al., 2016)

Installation on industrial crushers can either be underground or above ground depending on the mode of feeding and application. Crushers installed underground are normally choke feed to liberate fine particles via the action of inter-particle attrition and compression (David , 2007). Choke feeding demand careful feed control when in operation and it is thus desirable in industry where valuable minerals are liberated. Surface installation is normally applied in construction and quarry industries where large mass material is crushed to achieve only the required particle size (Sabba Rao, 2017).

2.3.4 Gyratory crusher sizing

The schematic diagram of Gyratory crushers is explicitly shown by the figure 2.5 and here it can be clear that the basic operation of the device adopted from its design and structure. However, Gyratory crushers are also known as cone crushers and they find application in metallurgical engineering in scientific laboratories or larger scale processing industries. Their application can vary depending on size and usage. The Tables 2.3, 2.4 and 2.5 respectively reveal the common dimensions associated with typical cone crusher equipment. They find application in university laboratories for test experimental investigations as well as in industries where they may be inter-changeably utilized in a size reduction unified processing plant either as primary crushers or secondary crusher depending on the activity and/ or their size. Cone crushers are flexible to be used in an open and closed circuiting environment to receive the run-of-mine (ROM) ore material (Gupta, et al., 2016)

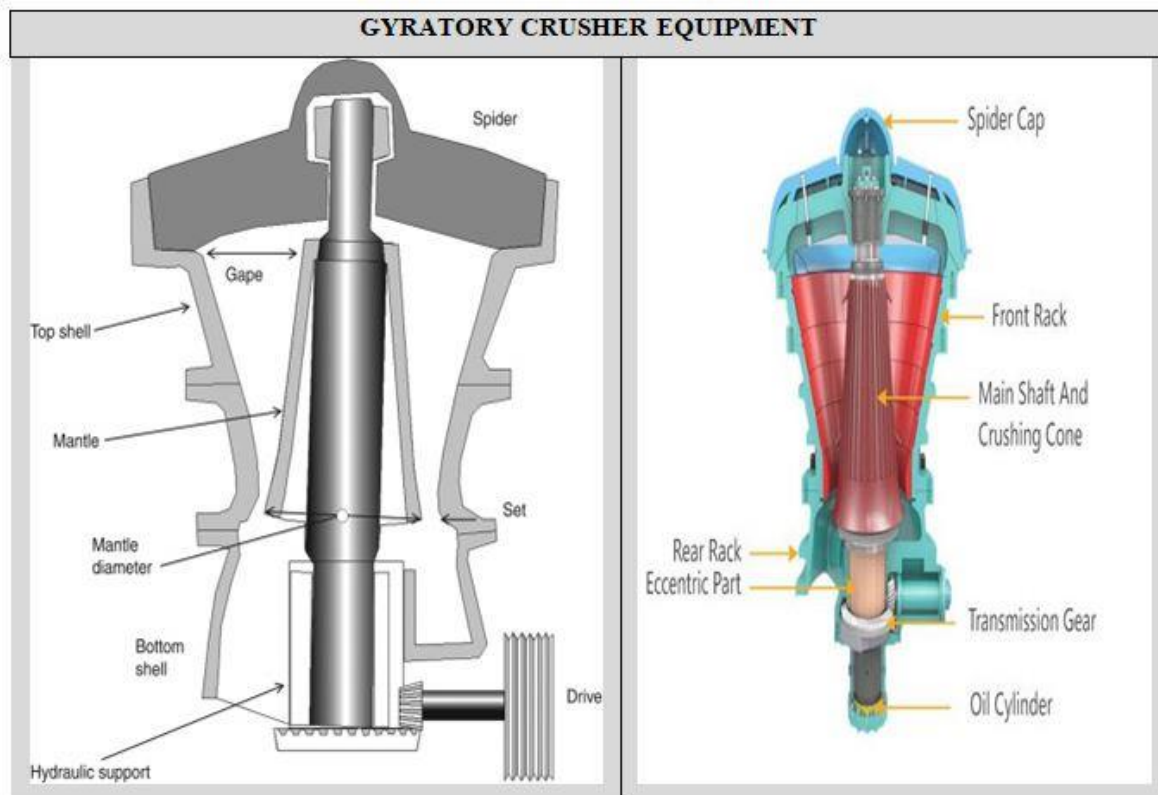


Figure 2.5 Schematic diagram of the longitudinal section of a Gyratory crusher together with common design component specifications and labeling. (Wills, et al., 2006)

Gyratory crushers are available in a wide size range compared to the Jaw crushers because its design allow usage in various applications due to a high reduction ratio, from the laboratory usage to large quarry mining industries. Force is transmitted via a long spindle that run midway throughout the device as depicted in figure 2.5 such that a conically shaped grinding mechanism in screw effect is produced progressively from top to bottom of the crushing chamber. The crushing chamber components comprise elements such as the spider and also the mantle or crushing cone, functions that assist to provide rotational movement for the spindle like the beveled edge transmission gear that provide maximum torque. The size and dimensions of a gyratory crusher is always proportional to the amount of power required to produce a quantified amount of torque along its shaft as can be seen in Tables 2.3, 2.4 and 2.5 and the data of Appendix A, Table A3 - A5. The main shaft or crushing cone rotates with a revulsion speed ranging between 85 – 150 rev/min in a spiral path, the speed and energy input significantly depends on the size of the machinery as well as the feed material amount inside the crushing chamber.

Depending on the area of application, feed material specifications and desired particle size can be adopted in crushing circuit environment either within the intermediate of the plant as an open circuit crusher device or rather as the last section of the crushing unit as a closed-circuit crusher device, thus it presents an added advantage of efficient reduction ratio as seen below:

- Primary crusher 3:1 to 10:1
- Secondary crusher 6:1 to 8:1,
- Tertiary crusher $\approx$ 10:1.

Gyratory crushers are most efficient size reduction devices (Wills, et al., 2006). Their design specifics explain the basic operations of the crushing equipment. Cone crushers consist of a conically shaped crushing chamber that decrease in diameter from the *gape* section to the discharge zone or the *set* opening. A spider suspends a central rotary-mantle with a breaking head that form the crushing chamber of the device. The bottom end of the spindle provides compressive blow movement via a revolving bevel edge tooth drive which

is powered electrically such that the mantle of breaking head continually force particles against the fixed metallic jaw plate on its walls, as can be seen on Figure 6. Due to scientific research evolution on stress dissemination within the crushing unit, manufacturing companies have adopted numerous crushing unit designs with different nip angles, control variables and eccentric shaft length designs. Such that for larger gyratory crusher the nip angle range between 21° and 24 ° for straight edge chambers while for curved surface crushers it range between 27° – 30° and also with difference of rotational speed as can be seen in the tables below (Wills, et al., 2006).

Table 2.3 Design Long shaft primary gyratory crusher (Barry , et al., 2016)

Characteristics	Small	Large
Size	63.5 – 711 mm	1829 – 2294 mm
Set range	25.4 – 44.5 mm	228 – 305 m
Rev/min	700	175
Power (kW)	2.2	298

Table 2.4: Design Long shaft primary gyratory crusher (Barry , et al., 2016)

Characteristics	Small	Large
Size	762 – 1524 mm	2133-2794 mm
Set range	50.8 – 152 mm	178-305 mm
Rev/min	425	275

Motor rating (kW)	149	750
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Table 2.5: Design Long shaft primary gyratory crusher (Barry , et al., 2016)

Characteristics	Small	Large
Size	203.2-813 mm	635-5538 mm
Set range	31.7 mm	-
Rev/min	750	480
Motor rating (kW)	16.8	83.9

2.3.5 Gyratory Crusher Circuits

The feeding mechanization of a gyratory crusher is usually such that a scalping screen is placed at the feed hopper in order to control the feed material particle size that enter the crushing chamber thus control size management of the feeder. This is also to prevent portions of wooden pieces and scrap metals in the (ROM) dump on the conveyor belt carrying pit extracts. Gyratory crushers operate on surface installation conditions in which a primary crusher receive feed material with size range between 1 m – 1.5 m in diameter and fragments them to a product size range between 10 cm to 15 cm (Hayden, 1998). Further material treatment may be required in downstream processing where secondary and tertiary crushers are employed and especially for mineral extraction where particle size below 6 mm – 2 mm may be ideal (Wills, et al., 2006).

2.3.6 Rotational speed for cone crushers.

According to reported research findings, it is clear that “speed of rotation required to producing particles less than size d should not be less than that given by the expression: (Barry , et al., 2016)”

$$v \geq \frac{665 (\sin \theta - \mu \cos \theta)}{\sqrt{d}} \text{ (rpm)} \quad \text{Eq. (2.6)}$$

Where: θ = angle of inclination of the cone to the horizontal

μ = coefficient of friction of the material.

d = size of crusher product (cm)

Material products treated using gyratory crushers require careful adjustment with regard to operational speed in revolutions per minute (rpm), of the device and well as control in feed amount to the equipment. Speed circulation in the device is inversely proportional to the feed size material. To attain product size of interest alertness must be adhered when tempering with speed control variables of the eccentric shaft as well as the size of material feed to the crusher (Musa, et al., 2009).

2.4 Grinding mills

2.4.1 Rod and ball mills

Tumbling mills (Figure 2.6) make use of the most important characteristic that takes into consideration the hardness of an ores material fed to the device in order to grind the feed into smaller aggregates. Different types, designs and varieties of grinding mills are available in our local market for many material processing industries and they are available with ranging sizes depending on applications. These include, to name a few the rod mill, ball mill, pebble autogenous and semi-autogenous mills. Ball mills are famous for usage in laboratory tests for milling activities and they operate with an induced motion that will largely results in collision breakage of particles within the milling cylinders and impact

strains from hard ceramic or steel metal balls. The schematic presentation of the rod and ball mill is relevantly depicted by figure 2.6. Normally the operating speed and grinding time are related to the final particle size of the product therefore, they can be used for pulverizing activities when conducting materials investigations and other Nanotechnology tests experiments (Ballantyne et al. 2018).

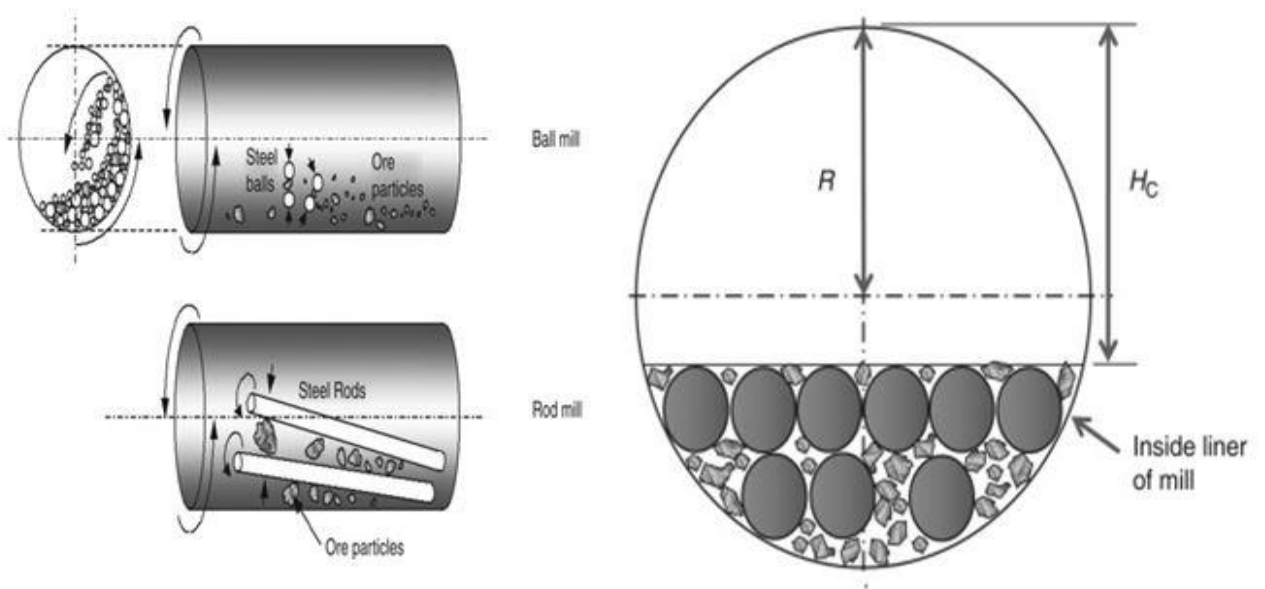


Figure 2.6 Schemeatic representation for the mechanism of a Rod mill and Ball mill grinding equipment. (Danha, 2013)

There are generally two design types of grinding mills; the tumbling mills and stirred mills. The breaking mechanism of a mill is via impact or compression due to sudden applied force; attrition or abrasion which may be due to forces acting along the surface of device. Milling of feed material is a treatment that can either be applied on dry or wet conditions. Steel rods, milling balls and ceramic are the usual material used for the grinding media construction; these grinding media can assume a varied range of sizes depending on the required particle size. Breaking media size can vary widely from about 20 mm for fine grinding to 150 mm for coarse grinding.

The particle reduction efficiency of grinding mills is very high with particle feed size around 5 – 250 mm to product size range of about 25 and 300 μm (Gwiranai, 2013). Stirred mills are usually mounted horizontally or vertically in their respective areas of application with an agitator to provide rotational motions. Of all the size reduction process operations grinding is the most energy requiring operation in mineral processing technology:

“It was shown that the average energy consumption in $kWh\ t^{-1}$ was 2.2 for crushing, 11.6 for grinding, and 2.6 for flotation (Barry , et al., 2016).”

Mineral liberation in grinding mills is largely through shear stress and abrasion of the particles within the grinding chamber (Barry , et al., 2016). Tumbling mills performance are largely affected by feed particle size, amount of feed material, adopted milling motion and amount grinding media in the equipment. Grinding is a continuous process in which feed material is fed via one end of the mill and is discharged at the other. Controlling feed size amount and the nature of feed material it is possible to control the outcome of the mill therefore product size of interest (Gwiranai, 2013).

Tumbling mills consists of a horizontal cylindrical shell with a replaceable liner and a charge of grinding medium, depicted in Figure 2.7. The dimensions of a grinding mills are directly proportional to the efficiency and or performance of the device such that its diameter is related to the amount of feed material it can accommodate (Danha, 2013) Therefore, the larger grinding mill will have high impact force exerting to a material toe and hence greater probability of breakage as it is the case in figure 2.8. Tumbling mills use dense crushing bodies which are large, hard and heavy in relation to the ore material under processing but smaller with respect to mill size. Also, the mill running speed together with the liner designs are important as they determine nature of product outcome.

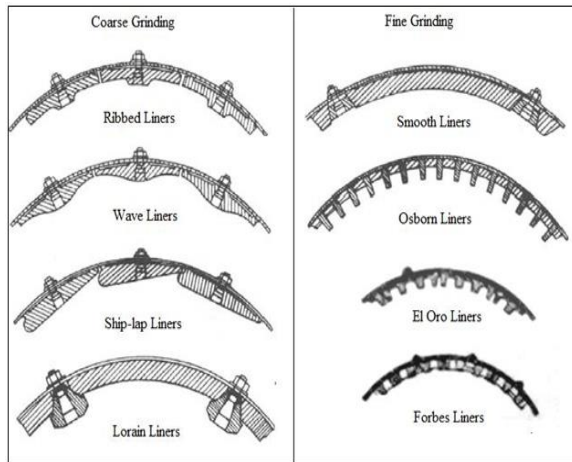


Figure 2.7 Show mill shell liners and the charge rotary motion projectory (Danha, 2013)

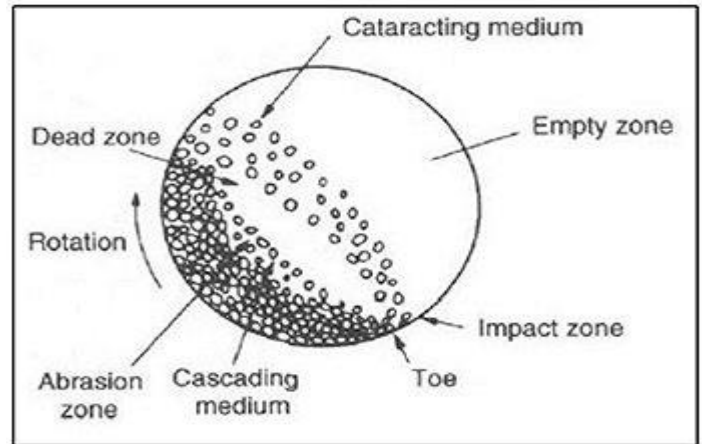


Figure 2.8 Showing the movement of particles inside a mill with the dead zone and impact zone well displayed (Danha, 2013)

When considering the grinding device it is clear that the charge rotational trajectories within the tumbling mill followed by both charge and grinding media can easily be traced. The shell liners of Figure 2.7 with various surface specifics present sufficient evidence to suggest that breakage of the material occurred also via particle-particle interaction and impact stress as the bulk feed material is lifted from the toe all the way to the dead zone. The shell liners play a major contribution in predicting breakage outcome of the resulting products and the characteristic properties of the feed material (Sabba Rao, 2017). Particle breakage behavior also tend to vary with liner design and rotary speed and therefore with a smooth liner only abrasion will occur as grinding media roll down to the toe of the mill.

2.4.2 Autogeneous and Semi-autogeneous grinding mills

Mineral processing technologies consume large amounts of energy with about 36% of electricity a country use per annum. Common grinding equipment such as ball mills, autogeneous (AG) grinding mills and semi-autogeneous (SAG) grinding mills occupies an important part in our local mine processing circuit routes. AG/SAG mills provide many engineering advantages because they can be easily maintained as well as easy installation at the site. The largest tumbling mill in mineral processing engineering is the semi-autogenous grinding mills where size reduction of ores is accomplished by a combination of impact, attrition and abrasion forces during mill rotation (Gupta, et al., 2016), hence force between particles, particles and mill wall and fall material at the mill toe to contribute to material fragmentation and also, the mill can be adopted to processing large coarse material feed within the comminution circuit (Raymond , 2004). The SAG mills shown in figure 2.9 have varied size range depending on area of application as well as product size of interest. SAG mills with an approximate diameter of about 12m, are amongst the largest mills in our current market, they comprise of variables and settings of rotational speed together with different loading capacities in the range between 28MW when refining copper-molybdenum-silver. But in general, the SAG mill operates with an average power draw of approximately 12.5MW for a feed rate performance of about 6000 t/h in a continuous processing environment (kawatra, 2006).

When working with either AG/SAG mill it is very important to be observant and cautious when working with the device settings because they are sensitive especially at high energy levels and therefore making process simulation and optimization a challenge to maintain within reasonable balance (kawatra, 2006). Tumbling mills similar to those of figure 2.9 can be used either in an open or closed processing circuit condition for treatment such that for open circuiting, the ore material is processed with the focus on analytical solutions to help predict product size distribution whereas in a closed circuits, operation is mainly focused on producing a product with specific size especially in pharmaceutical experiments (Gupta, et al., 2016)

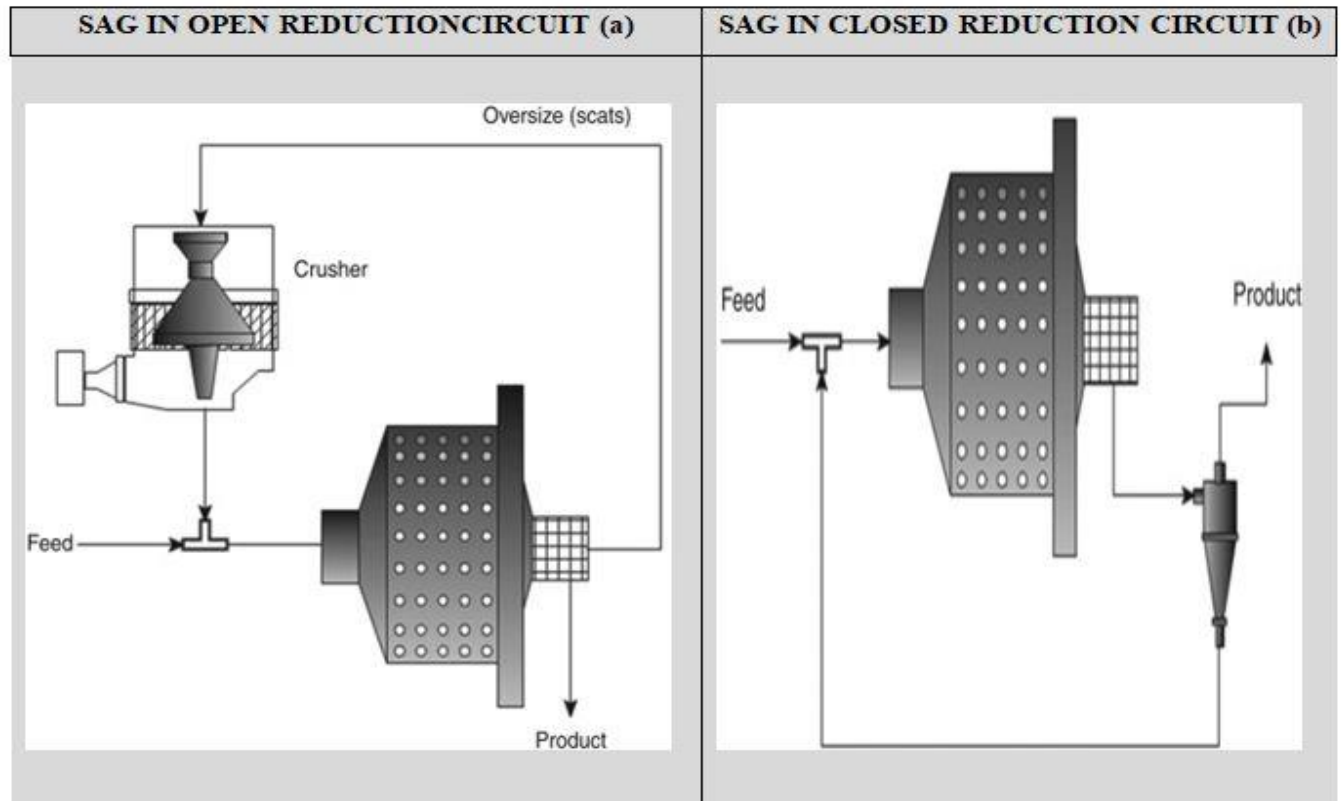


Figure 2.9 showing a semi-autogenous grinding (SAG) mills which are normally charged with small grinding ball to assist the downsizing process. The SAG mills are connected in an open and closed circuit respectively (Gupta, et al., 2016).

2.5 Size classification

2.5.1 Screening

Mineral are found in compounds of rocks dispersed in a chemical matrix with other substance of lower grade, for example Bauxite, may comprise of aluminum oxide together with other silicates or oxides of other metals. Rock Ore matrix, with such dispersions of various mineral composite that widely differ in their physical properties such as hardness, friability and crushability has provided metallurgist an additional engineering advantage during liberation since these material characteristics aid in choosing the relevant comminution processing techniques. Some ores however, may require a series of crushing and re-crushing treatment before the final material composite is completely isolated from the gangue material, therefore screens are designated after every crushing activity/ operation in order that particles with

different sizes and shapes are separated (Angela , et al., 2007). Particles smaller than the aperture opening will pass via the screens such that only large materials and lumps of rocks exceeding the aperture opening will remain on the screen for further crushing. The uses of separation screens similar to those of figure 2.10 in a size reduction circuits provide an effective path that easily concentrates material of interest while simultaneously rejecting the unwanted gangue constituents (Gwiranai, 2013).

Screening operations together with sieving can be used in a single treatment plant but their applications are widely varied, mechanical screens or grizzly, in mineral processing are involved in large scale production of the mining industries where they are installed to receive large tonnage of ore dumping from considerable heights by wagons, tipper cars and other bulk material handling systems like conveyor belts. Sieves are only engaged in small scale treatment for laboratory investigations that are attempting to address issues of composition and other particulate behaviors (kawatra, 2006). In general, both combination of grizzly and sieve analysis, in a dry condition size reduction maybe be partitioned together provided the downsizing does not exceed 75 μm limitation because below the size range limit finer particles tend to develop other agglomeration properties where blinding of the aperture opening initiate thus rendering erroneous analysis. In such cases water is employed to aid easy passage of particles and thus unlocking the sieve mesh apertures (Dhingra, et al., 1995).

For mineral processing industries, screens/grizzlies are designed with three basics:

- a) Screen Surface properties and aperture design patterns
- b) Type of screen (application)
- c) Screen movements

2.5.2 Screen Surface properties and aperture design patterns

Industrial screens are made with durable material such as manganese steel, with high toughness to withstand impact loading from tipper cars of the ore mixed with rabbles and with special

consideration on the materials chemical properties because due to unprocessed ore containing numerous corrosive salts from underground, it may limit the lifetime of the screen and thus its effectiveness (Angela , et al., 2007).

Generally grizzly screens are fabricated with coated steel rails, steel rods or bars designed into grid or any other pattern of interest. Before the receiving hopper of any crusher device screens are set to critically control material size and quantity of ore the crusher can handle, with an aperture spacing range between 5 – 200 mm. Like sieve analysis, screens require mechanical movements and or vibrations that aid its efficiency during operation and so they are usually installed in horizontal flat position or plane with a small angle of inclination to allow ore material to flow across the screen. Therefore, this angle of inclination may range from 30° – 40° to a maximum of 45° depending on the cohesiveness of the ore to the screen. Therefore, large angles will be effective for sticky ore that tend to agglomerate and have high resistance to flowing (Wills, et al., 2006).

The hopper opening for feed material is an important component of any crushing device. Designing the screen aperture size must take into consideration the relative receiver opening for the crusher as well as the maximum screen height above the hopper, which is normally in the range around (x0.9 hopper opening in magnitude). Therefore, material type, geometry and duty of application for a screen are significant because for plain carbon steel, stainless steel and other steel alloys, sheet screens are usually fabricated with perforated circular, square or rectangular hole patterns while hard plastics like polyurethane and other types of rubber maybe used where mechanical wearing remain a major challenge for production (Pasi , 2015). Figure 2.10 shows symmetry design of perforations or apertures adopted for use in separation screens. These aperture size dimensions can be calculated with the help of certain equations like equation 2.7 for diagonal spacing and equation 2.8 for square spacing during symmetric holes design and drilling. Therefore they are usually specifically punched directly from a manufacturing industry with numerous design such as decked patterns where screens are doubly stacked with an upper screen design having the larger holes to suit a specific separation process of certain feed materials. This is meant to separate coarse and intermediate particles which will be re-crushed and re-screened while the lower screen will allow finer particle to pass through to the crusher. For such screen designs, screening is applied for particle size in the range 100mm – 2mm and

crushing normally continue until a required particle size of interest has been attained (Gavhane, 2009).

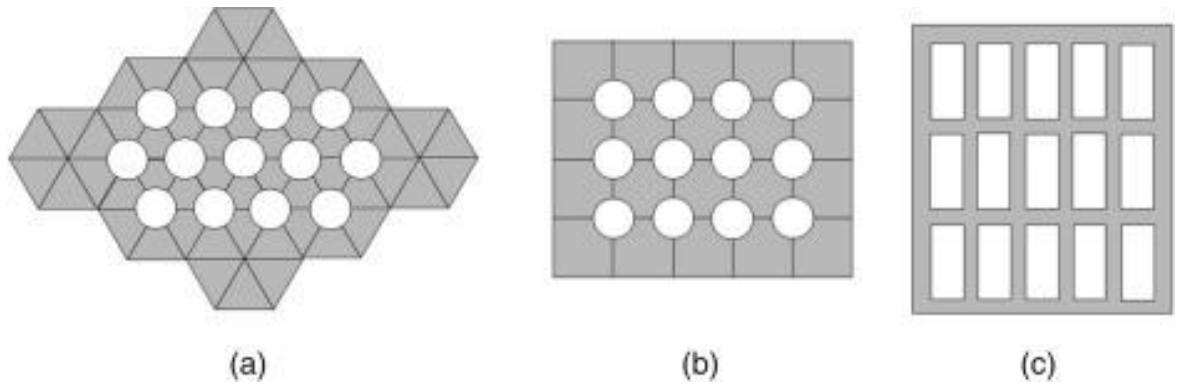


Figure 2.10 Basic perforated plate patterns for (a) Circular 60° pattern (b) Circular square pattern (c) Rectangular aperture patterns (Barry , et al., 2016)

According to investigations, the percentage of open area within the plate is vital since it determines the amount of material that can pass through screen. Figure 2.11 shows the design geometry of holes and holes spacing that can allow easy engineering calculations for the screen and also, the calculations of the relative amounts of open area to closed area within a given screen plate.

For diagonal spacing (Figure 13):

$$A = \frac{\left(\frac{\pi}{8}d^2\right)}{\cos 60\left(\frac{1}{2}\right)(s+d)^2} = \frac{0.907 d^2}{(s+d)^2} \quad \text{Eq. (2.7)}$$

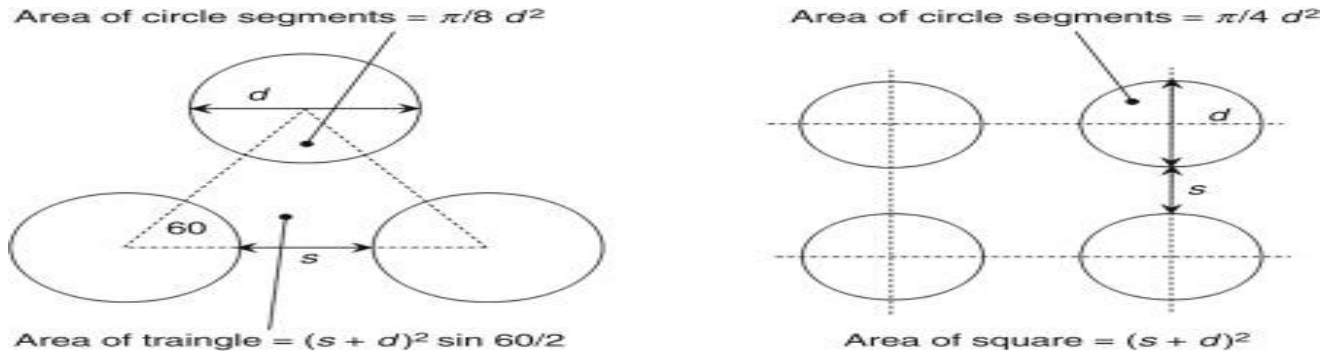


Figure 2.11 geometry of open area for diagonal and square placement of Circular openings (Wills, et al., 2013).

For square spacing (Figure 13):

$$A = \frac{(\frac{\pi}{4}d^2)}{(s+d)^2} = \frac{0.785d^2}{(s+d)^2} \quad \text{Eq. (2.8)}$$

Screening procedure in mineral processing is an empirical operation for control and product management. Many specialized mining activities have adopted diverse material treatment routes and circuiting techniques that yield product sizes of interest at lower cost and methods that are also reliable as well as time efficient. Figure 2.12 below depict some common examples of circuit routes designs commonly employed in quarry mining for processing construction material rocks with a variable size ranges (-90 +50mm) and where separation screens are importantly utilized.

It is crystal clear from the figure 2.12 that numerous processing techniques can be adopted when processing materials especially with variable mechanical properties such as fracture toughness, crack propagation resistance etc. For materials having high densities and hardness factor a three-stage mineral processing flow diagram can be adopted for the path a rock aggregate pass

through before reaching required size of interest and also a one-stage processing flow diagram are used in treatment plant where the medium crushed is soft and less resistant to fragmentation hence the mineral rock ore goes via single crushing stage before attaining the required particle sizes (-12.5mm) (Deniz, 2011). Each processing stage have specific energy distribution associated with it such that the energy dissipation is proportional to the number of crushing units involved within the unified circuit, therefore the three-stage operation will tend to utilize more energy in comparison to the one-stage operation and also consume more time comparatively. Depending on other factors like rock composition, moisture content and petrographic deposition of the minerals associated to the host mineral ore, comminution operations may be highly influenced by the type of feed material, quality of rock chemical composition and characteristics (Musa, et al., 2009).

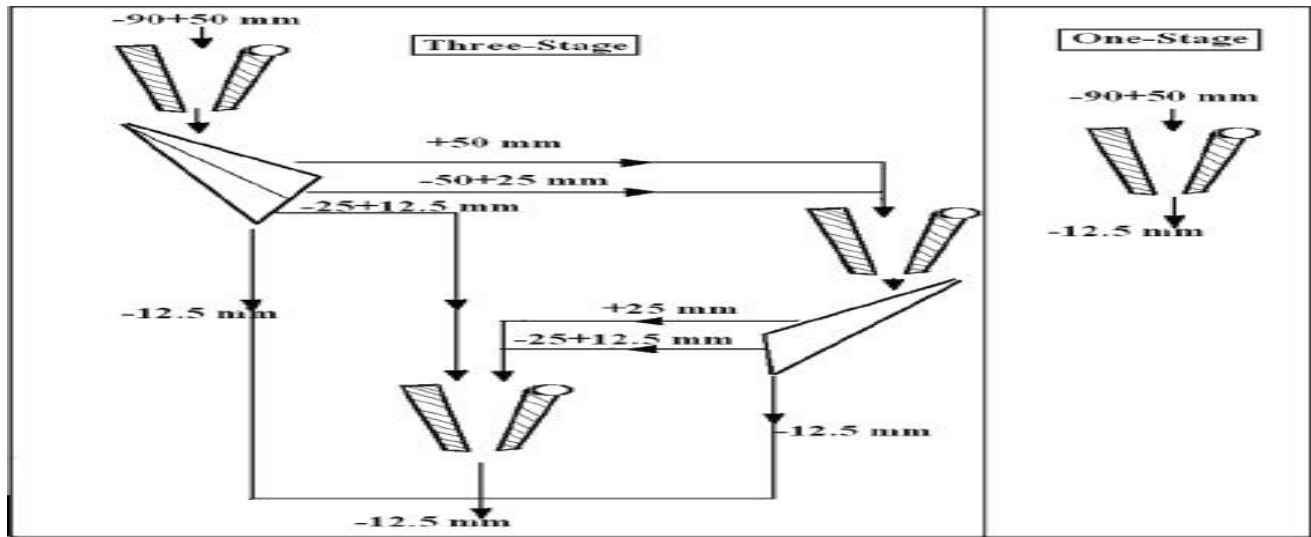


Figure 2.12 flowchart of crushing activities with three-stage and one stage reduction (Deniz, 2011)

2.6 Mineralogy, Grain Size and Grain Distribution

Intrinsic properties of the rock such as microstructure, mineralogy and hardness contribute a major role to the key components for predicting durability of the rock material especially relative to its application. Important parameters are normally engaged for estimations of performance when the rocks material is subject so physically straining environment or where there is exposure

to chemically aggressive conditions. Structural defects are naturally inherent for almost all materials and they significantly lower the strength of material because of pores and cracks within the mineral crystals (Lindqvist, et al., 2007). Therefore, because of these defects regions of stress concentration can develop thus resulting into brittle failure and fragmentation especially that damage and expose the surface of the rocks to corrosive and chemically aggressive environment. However, combination of compatible mineral crystals making the rock is known to influence the stability of the material hence improving its durability predominantly in construction engineering (David, et al., 2009).

Our focus was especially inclined into understanding the mechanical wear resistance and fragmentation of the rocks by inspection on the strength, fracture toughness and hence the modulus of elasticity for these individual constituent mineral crystals. According to the investigation quartz and feldspar are found to be resistant to weathering whereas mafic minerals like amphibole and olivines are less resistant nonetheless other factors like thermal expansion on individual minerals must be considered because minerals possessing large variation in thermal expansion will usually grant a low resistance to thermal wear (Lindqvist, et al., 2007). High clay diorite rock complex are traditionally weak and less durable due to weak mechanical properties of clay, therefore clay compounds absorb the water of crystallization in the structure or organic compounds embedded within the crystal lattice (Bogoch, et al., 2002).

Grain size and grain size distribution are most important because a large size range yield better properties in that they enable higher strength of the rock and resistance to fragmentation compared to where the grain distribution is more equal-granular notwithstanding small, randomly oriented micas in the matrix will also increase the fracture toughness of the rock as numerous grain boundaries impede crack propagation for sudden brittle failure (Barry , et al., 2016). Different grains oriented in diverse direction exerts some influence on adjust grains and the extent highly depend on the properties for that mineral crystal relative to its environment, whether they are similar in structure or widely different.

Quartz – feldspar interface for instance will differ in their inherent strength, Young's moduli, surface energies and other phase aspects therefore phase contact will significantly have greater influence to mechanical properties generally extending as the properties of the rock as compared

to where there is only a grain contact like amphibole – amphibole where the surface tension will be relatively similar in regard (Lindqvist et al. 2007).

CHAPTER 3

3.0 Materials and Methods

3.1 Materials

Two separate dry samples of diorite ore were obtained from two quarry mines in Botswana, namely Master Quarry in Serowe and Panda Quarry in Francistown. The particle size ranges of the samples were between -15 mm + 12 mm. After sample collection, I proceeded to carry out sample preparation in order to homogenize my sizeable material for the subsequent experimental investigations.

3.2 Methods

3.2.1 Methodology

Diorite materials are igneous rocks that are exceptionally high in density $\rho = 2.85\text{g/cm}^3$ and hardness. The selection criterion for the processing methodology of the material when considering the size, capacity and capability of university crushers to fragment and break the material to finer aggregates came as great challenge. Initially the diorite mass was subjected to a splitter for easy sampling on the material and for both quarry products each step was executed with precision to establish comparison in the outcome of the test experiment. A mass with particle diameter range between -200 mm +100 mm was fed as large lumps to the lab Jaw crusher a mass not exceeding 1398.10g for master diorite while for the panda diorite 2260.91g of the material was fed to the primary crusher. The products were then sifted to allow only a product size strictly under +13.2 mm sieve aperture size where the feed mass of 1398.10g and 2260.91g were sampled. The illustration of figure 3.1 show how the experimental procedure for all the laboratory activities were carried out to crush and grind the diorite rock samples therefore the separation stage was employed after every crushing activity such that the material product of the Jaw crusher was strictly below +13.2 mm while the oversize material in the range -20 mm and +13.2 mm were re-crushed before it was fed to the gyratory crusher. The Gyratory crusher however was used in a series connection as the secondary crushing device and received feed mass with aggregate of approximately -13.2 mm and + 6.3 mm. A planetary ball mill was used

as a tertiary crusher device to study the effects of impact, attrition and abrasion forces during mill rotation for aggregates in the sieve size range of +4.75 mm (Gupta, et al., 2016).

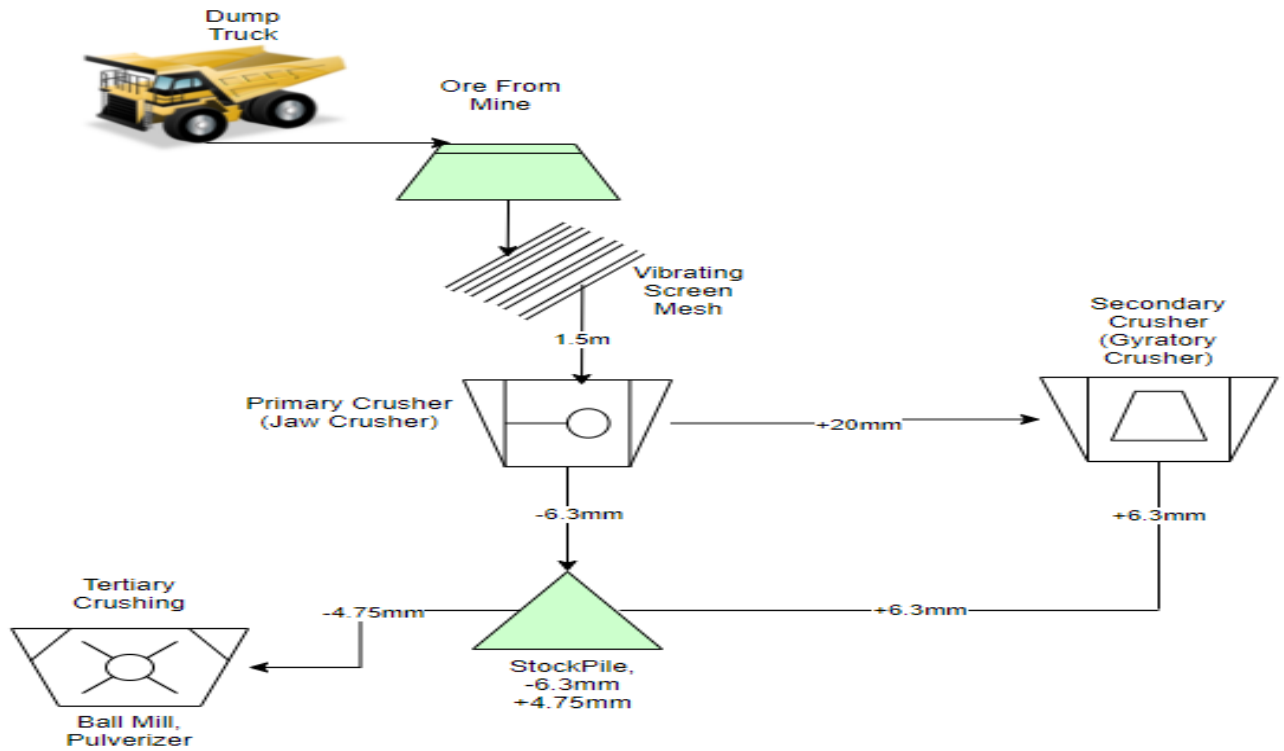


Figure 3.1 showing the size reduction processing route that was adopted for experimental tests on the heterogeneous diorectic ore material of master quarries and panda quarries.

3.2.1 Sample preparation

Using a shovel, canvas sheet, measuring tape, note-pad and a pencil; the process of sampling at each quarry site was carried out. Grab sampling method, where rock specimens were simply picked from a mineral stock pile to statistically represent a larger population whose properties were studied to attain information for the whole mass. This Technological sampling method was vital and understanding the properties of the raw material was possible via a controlled laboratory investigation studied on fewer selected rocks. Furthermore, while at the site triangulation plotting was marked out to represent positions of sample collection such that the distance between every point was approximately about 5 m apart and for every collection point

an average mass not exceeding 17 kg was collected by grabbing. The total canvas sheet mass collection was 51 kg, all this activity took place at the mining pit where the blasting and excavation of the diorite material generally occur. A shovel was used to collect another 50kg mass from the -15 mm to +12 mm screen size which comprised the finished concrete material for construction purposes. All this was done in order to strengthen the probability of our sampling for a stronger comparison in the diorite rock properties. The finished concrete diorite aggregates were necessary because they are readily handled by the laboratory crusher when conducting further studies on the material especially material in the range -4.75 mm and +3.35 mm for the road construction engineering activities.

Consequently, few select samples were then broken down and grounded to smaller sizes and measured following particle size distribution and sieve analysis. Regarding this work, diorite obtained was prepared through measuring less than 2300g of the material weighed using a laboratory scale and crushing with a Jaw crusher and gyratory crusher before it was grind to powder form with the assistance of a milling device, therefore converting the mass to a powdered phase via laboratory ball milling operation with revolution speed, 250 rpm and for a duration not exceeding 20 minutes (Sutherland , 2007). The final sample was then subjected to an x-ray diffraction scan for identifying various geochemical mineral components within each specimen thus differentiating their lithological units.

3.2.3 Sample characterization

The physical and chemical compositions of diorite play a significant role in determination of processing techniques and providing vital data for prediction of behavior during processing. Hence, visual inspection was initially carried out on diorite samples acquired from the two locations. Following this, an *In-situ* X – ray powder diffraction scan was performed at room temperature and pressure conditions on the powdered samples of diorite (a) and (b). Various components were identified which revealed that phase composition is significant in determining the strength of material and processing parameters.

Powder diffraction technology offer reliable estimations ont material property and composition with x-ray diffraction scan measurements that are expeditious, information evaluation

simultaneously displaying on a computer monitor for straightforward analysis as well as identification and classification. In-situ x-ray diffraction considers the crystal structure of polycrystalline materials identifying crystalline phase components together their relative amount and phase magnitude relative to the whole matrix (James , 2007).

3.2.4 XRD analysis

In-situ x-ray diffraction (XRD) technique was employed to qualitatively identify phase presence in the pulverized samples of diorite rocks. Peak deflection patterns were obtained using a PAN-analytical X'Pert PRO x-ray diffractometer equipped with a sealed proportional detector device with a $\text{CuK}\alpha$ radiation, operating at a voltage of 45KV and current 40mA. A vertically adjustable multi-purpose sample stage was prepared and the pulverized rock specimen placed symmetrically on an aluminum x-ray sample holder which constantly was aligned to bisect the x-ray beam-(Cullity, 1978).

Phase analysis of the material was carried out at normal temperature and pressure (20 – 30 °C) with the $\text{Cu K}\alpha$ radiation such that, each rock specimen were held under radiation for a period not exceeding 1200s prior a general scan for peak deflection zone identification that was done for 120s in order to guarantee accuracy and stability of the scan to represent the whole rock area under study. XRD was employed in order to distinguish the order of atom arrangement with respect to each other together with significant trace elements at interstitial site of the crystal lattice and or other minor unknown compounds hidden in the structure (Cullity, 1978). In order to accurately measure the peak position within the powdered rock sample and their intensity, the scan results were automatically quantified by matching the theoretical diffraction diagrams to the measured data on match3 software which revealed the respective mineralogy of the rocks and this was carried out with the aid of an expert.

3.2.5 Comminution experimental procedure

A unified crushing chamber was assembled and calibration for the reduction ratio and power required by the equipment employed for primary crushing unit and secondary crushers as well as tertiary crushing system were properly identified such that a series combination was achieved and so, mathematical equations at each size miniaturization stage were thus stated regarding any

calculations of dimensional reduction. The aim was to the understanding of Particle size distribution (PSD) behavior for diorite rocks complex which were samples taken at Serowe central district within the country and also Panda rocks of Francistown in the North-East District. After sifting the mass, statistical analysis on particle behavior was carried out, an investigation on particulate systems that attempts to address the problems faced by the manufacturing industry which to some extent could be agglomeration of aggregates because of developed properties for smaller particles. Information on rock types, availability and methodology for treatment was clearly examined, therefore concluding that the ROM (run-off-mine) material at Panda quarries require only less breakage before being subjected to various applications. Methodology employed when processing or handling is important since it preserve rocks with large phase composition or large grain size (coarse-grained structure) for applications which render additional strength on the rock usable such as in the road industry. Material stability can be easily understood from varying controllable parameters during treatment such as choke feeding percentages, chamber alignment, milling time and also energy supply on the device. Data acquired was statistically revealed in graphical interpolations and illustrated central points on different distributions with their standard deviation for simpler interpretation of the powdered material (Rustan , et al., 2010). Common and modern methodologies for handling crushing operations were also scrutinized for easy comparisons on behavior of these rocks thus giving them best results. Operations were interchanged after switching to a particular parameters and circuiting i.e. milling speed, milling time, sieve stack aperture variations, close-circuiting and open-circuiting the material because of resistance to breakage.

3.3 Main objectives for carrying out comminution tests

- To understand the behavior of powdered particle of igneous diorite rock.
- To develop an accurate prediction on the behavior of fragmented diorite rock after the grinding activity having different mineral contents.
- To study and determine size reduction of diorite in terms of reduction ratio and power required for the device therefore alternatively understanding the influence of sifting crushed material.

- To determine the quantitative distribution of the particles after milling in order to criticize the impact of milling time and the milling speed on quarry mine products.

CHAPTER 4

4.0 Results and Discussions

4.1 Petrographic analysis of the diorite rocks

The petrographic characteristics for the two diorite samples from Master quarry and Panda quarry were determined with an aim of clearly separating inherent properties for both rocks that were developed during formation or as consequence of rock provenance. X-ray diffraction was used to reveal the composition in terms of percentage and average grain size of the major mineral crystal constituents thus for Master quarry diorite rock comprised mainly plagioclase, berlinite, bazzite, quartz and traces of sericite and clay compounds along some of the grain boundaries as also depicted in figure 4.1. The diorite from Serowe region or central district of Botswana (Master quarry), revealed an average grain size with an aphanitic texture or rather porphyritic texture due to fewer grain distribution appearance within a fine-grained matrix. However Panda diorite of Francistown the north-east district, were mainly incorporate with large mineral crystal grain on average identifying as dark amphibole, plagioclase, clinopyroxene minerals and reporting with a grain size slightly above 1 mm (Anthony, et al., 2014) and (Sutherland , 2007). This phaneritic texture of the rock suggested formation to have occurred at greater depth beneath the surface and rather at slower cooling rates to allow formation of large crystal grains with less clay deposit incorporated within the structure.

The data acquired by the diffractogram for each rock material, clarity was estimated between the two rock samples and rooted on the mineralogical background for each rock, the Master quarry diorite contained large quantities of plagioclase crystal units which account about 40 % of the rock according to table 4.3 and from the pie-chart which is occupied by the blue sector on figure 4.4. Large amounts of quartz crystal grains suggested the rock crystallized at high temperatures but at rather rapid rates considering the almost equigranularity or the homeoblastic nature of the

microstructural morphology of figure 4.1 (Schmeide, et al., 2014). According to Table 4.2 the panda diorite rock samples were manifested mainly with dark amphibole mineral within its structure as the major constituent and having the clinocllore complex as minor inclusion as it occupied slightly 12% of the matrix from the phyllosilicate family of minerals characterized by their perfect cleavage on their phase orientation (figure 4.2 and 4.3). However, more peak-deflection for these Panda rock source suggested perfect crystallization hence it exposed valuable mineral crystals within its matrix such as clinopyroxene, dolomite and also traces of mica, the rock crystalized at rather greater depths around high temperatures but at slower cooling rates in comparison (HUGHES, 1982) and (Wen, et al., 1997).

4.2 Surface Texture and Grain Distribution

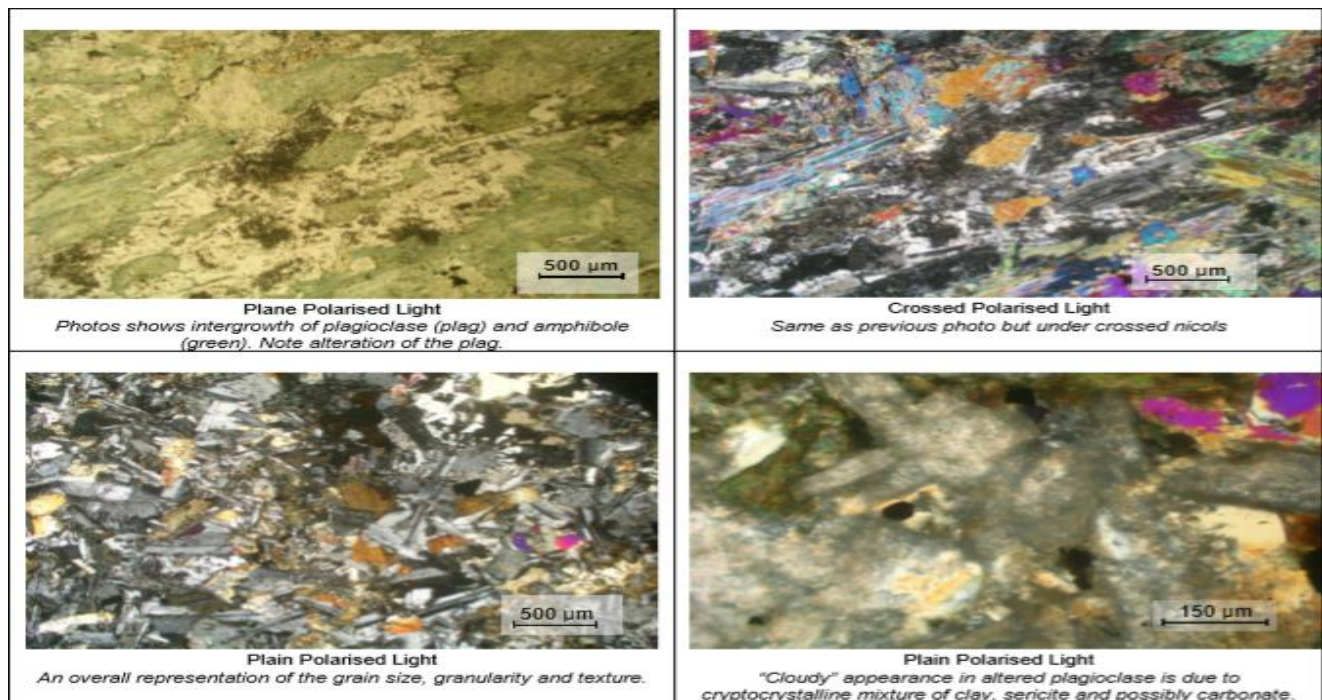


Figure 4.1 Microscopic images for the master quarry diorite as viewed under light microscope with varying polarity and magnification. A light microscopy (plain and crossed polarized light) reveals the surface grain-structure for master quarry diorite complex, (a) ingrowth of plagioclase inside amphibole matrix (light green), (b) crossed polarized light with various grain size, granularity and texture, (c) fragments of featured clay, sericite and carbonate inclusions.

Also as can be seen on figure 4.1 the grain size, granularity and texture for the Master diorite rock sample as observed under light microscopy can easily address some of its physical properties that are inherently adopted due to structural patterns. The sample is mostly fine – grained with an average mineral crystal grain diameter not exceeding < 1 mm, and generally with an interlocking granular texture appearance (Jiki, et al., 2019) and (Hughes, 1982). The relative size of the crystalline components are equi-granular and consequently having an approximate size, a factor that could have developed because of rapid cooling of the magma being nearest to the surface. Some micrographic phase intergrowths were also observed between mineral crystals manifesting as twinning within some of their grain components. Observable grain size relates to the number of crystals seen in a given field view in the microscope which were taken under the same magnification.

The Master quarry diorite rock specimen under investigation presented a ground mass that contained altered plagioclase, berlinite and also bazzite mineral crystal constituents, while occurring in minor trace amount were relatively lazurite and sericity mineral crystals as illustrated by Table 4.2-(Joseph , 1913). Plagioclase however occurs as a fresh mineral phase deposit, and some slightly altered traces of the complex into a clay phase composition, also majority of plagioclase appeared to have been largely transformed into the amphibole phase structure. The “cloudy” impression depicted within the figure 4.1 is due to cryptocrystalline mixture of clay, sericite and possibly carbonates that are opaque in nature. Quartz however occurs ubiquitously such that it was identified as insignificant on the visible surface grains or probably as trace component of the material. The opaque minerals are made up of the finely dispersed minerals that are disseminated up to ± 16 μm , and highly constitute of titanium-iron oxide, manaccanite complex which is sporadically distributed throughout the rock (Floyd, et al., 1993).

Photographic image of the Panda quarry diorite rocks sample and its surface microstructural



Figure 4.2 Panda quarry diorite rock sample imagery taken with a camera during lab preparation for microstructural imaging

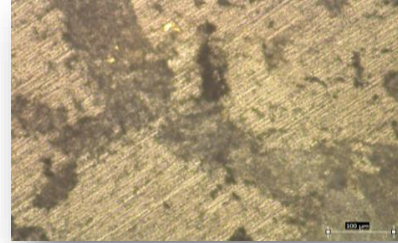


Figure 4.3 Panda rock microstructure image with 100 μm magnification viewed under an optical light microscope

Table 4.1 Master quarry diorite rock mineralogical analysis and relative percentage abundance.

Mineral	Crystal System	Approximate Formulae	Approximate Abundance %
Plagioclase	Triclinic	$(\text{Ca,Na})_{2-3}(\text{Mg,Fe,Al})_5(\text{Al,Si})_8\text{O}_{22}(\text{OH,F})_2$	39.8
Berlinite	Trigonal	$\text{Al}(\text{PO}_4)$	23.2
Bazzite	Hexagonal	$\text{Be}_3\text{Sc}_2\text{Si}_6\text{O}_{18}$	16.1
Quartz	Trigonal – hexagonal	SiO_2	12.4
Lazurite	Cubic	$(\text{Na,Ca})_8[(\text{S,Cl,SO}_4,\text{OH})_2(\text{Al}_6\text{Si}_6\text{O}_{24})]$	5.8
Chlorite	Monoclinic-primitive	$(\text{Mg,Fe})_6(\text{Si,Al})_4\text{O}_{10}(\text{OH})_8$	2.4
Sericite	Monoclinic	$\text{KAl}_2(\text{AlSi}_3\text{O}_{10})(\text{OH})_2$	1.2
Total			100

Table 4.2 showing the prospected panda quarry diorite mineralogical constituents and their relative percentage abundance, %

Mineral	Crystal System	Repeating Unit	Approximate Abundance %
Dark amphibole	Monoclinic	$\text{Mg}_7\text{Si}_8\text{O}_{22}(\text{OH})_2 - \text{Fe}_7\text{Si}_8\text{O}_{22}(\text{OH})_2 - \text{Ca}_7\text{Si}_8\text{O}_{22}(\text{OH})_2$	39.20
Plagioclase	Triclinic	$\text{NaAlSi}_3\text{O}_8 - \text{CaAl}_2\text{Si}_2\text{O}_8$	31.74
<u>Clinochlore</u>	Monoclinic/ Triclinic	$(\text{Mg, Fe, Al})_6(\text{Si, Al})_4\text{O}_{10}(\text{OH})_8$	12.26
Quartz	Trigonal	SiO_2	6.92
<u>Clinopyroxene</u>	Monoclinic	$(\text{CaNa.Mg.Fe.Al.Ti})_2\text{Si}_2\text{O}_6$	5.70
<u>Dolomite</u>	Trigonal	$\text{CaMg}(\text{CO}_3)_2$	2.78
Micas	Monoclinic	$\text{KAl}_2(\text{Si}_3\text{Al})\text{O}_{10}(\text{OH,F})_2$	1.40
Total			100.00

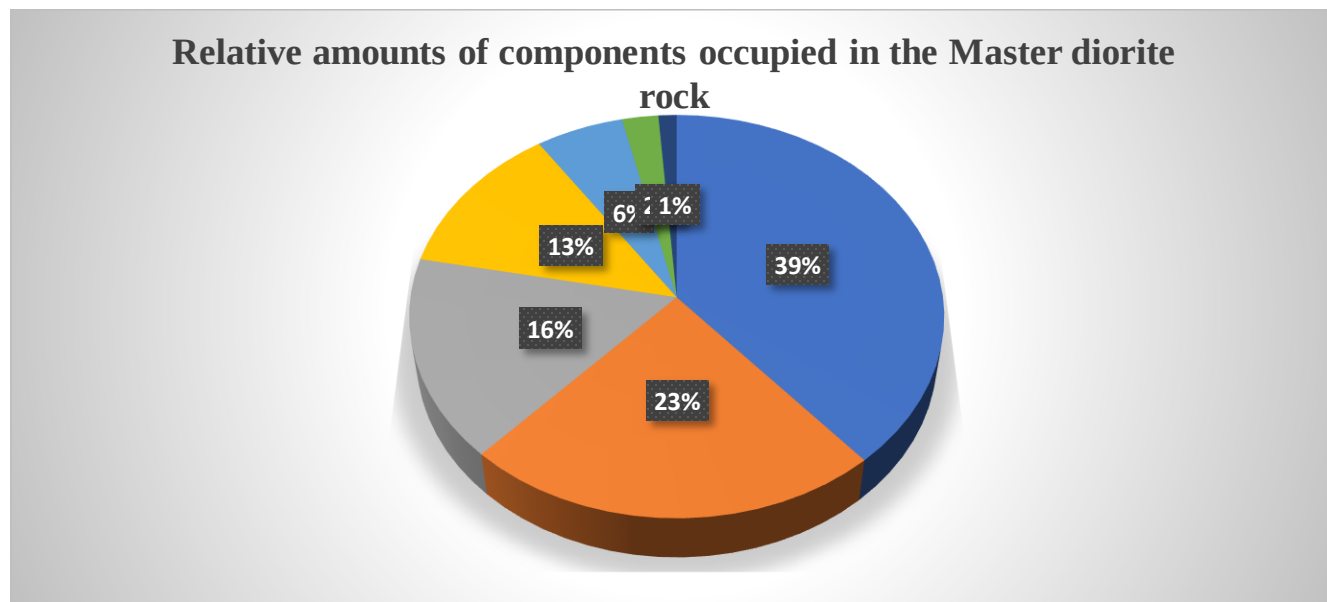


Figure 4.4 pie-chart presentations for the identified crystalline phase components of the master quarry rock showing the largest mineral composition to be dominating 39% of the entire mineral phase present.

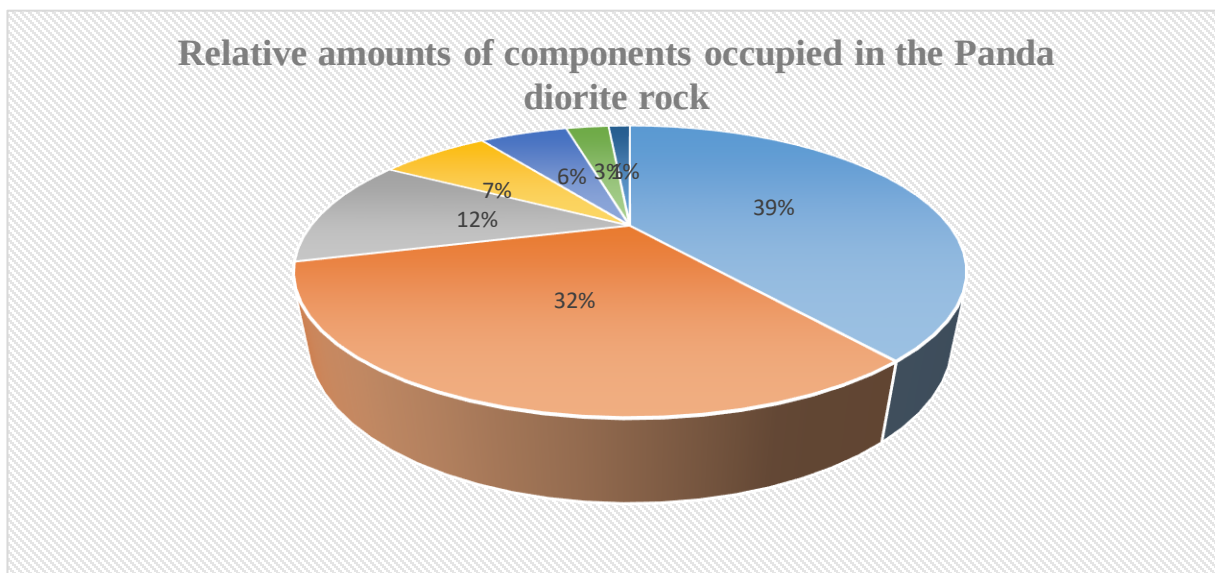


Figure 4.5 pie-chart presentations for the crystalline phase components identified in the panda diorite rock samples acquired at the north-eastern part of Botswana.

Table 4.3 show the relative percentage of crystalline phase present within the master diorite complex with quartz being 13% and lazurite at 6% within the matrix.

Color	Mineral Code	Percentage %
Pale Blue	Plagioclase	39
Brown	Berlinite	23
Grey	Bazzite	16
Yellow	Quartz	13
Light Blue	Lazurite	6
Green	Chlorite	2
Dark Blue	Sericite	1

Table 4.4 show the relative percentage amounts of components that are occupying the panda diorite sample from dark amphibole with 39% to micas with 1% of the overall components.

Color	Mineral Code	Percentage %
Pale Blue	Dark amphibole	39
Brown	Plagioclase	32
Grey	Clinochlore	12
Yellow	Quartz	7
Dark Blue	Clinopyroxene	6
Green	Dolomite	3
Light Blue	Micas	1

The x-ray crystallography was performed on the master quarry diorite samples obtaining the powder diffraction results as illustrated on figure 4.7. Majority of crystalline phase components were identified with the most prevalent being the plagioclase phase constituent followed by berlinite complex with a trigonal crystal structure. Both samples were highly pulverized into an extreme powder form at a revolution speed 300 (revolutions per minutes) rpm for a duration not exceeding 30 minutes and from the peak-to-peak deflections only few reported peaks were identified thus presenting a large amount of the rock sample to be occupied by an amorphous phase constituents such as clay and other trace inclusions. The panda diorite material when subjected to the same analytical test however presented much better results in contrast showing a large amount of the crystalline phase constituents as illustrated by figure 4.6 therefore majority of the heterogeneous dioritic mineral was largely comprised of dark amphibole 39%, clinochlore 12%, quartz 7% and traces of micas 1% .

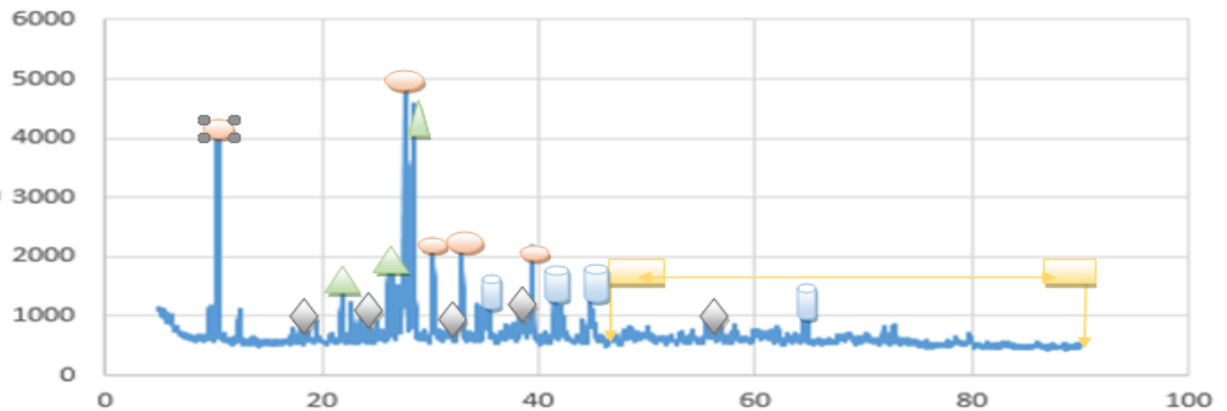


Figure 4.7 x-ray diffractogram of the diorite rock sample obtained in Serowe Central Botswana having crystal minerals identified for Master quarry are mainly plagioclase, berlinite, bazzite, quartz, lazurite and other trace elements.

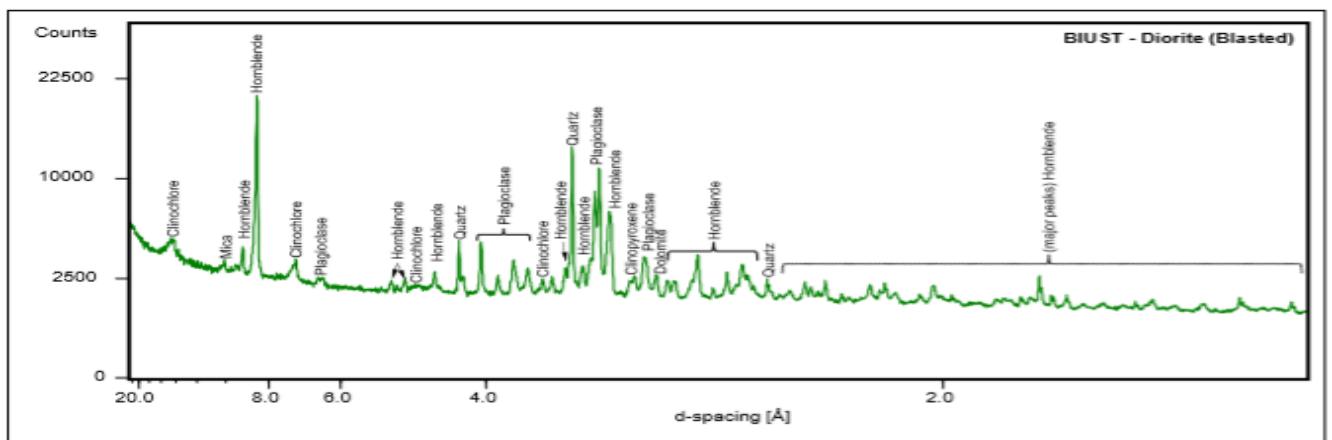
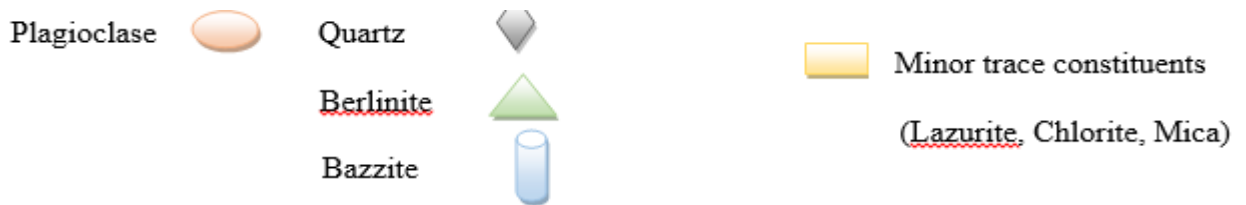


Figure 4.6 x-ray diffractogram of the diorite rock obtained in Panda-north Botswana with crystal mineral phases identified presented the Panda quarry diorite sample to comprise dark amphibole, plagioclase, clinocllore, quartz, clinopyroxene and some minor traces of dolomite and micas.

4.3 Particle distribution of diorite after breakage (results)

Table 4.5 shows simplified statistical information for the particle size distribution during the comminution experiments. Typical data was arranged from a sieving test and its results were used to estimate patterns of behavioral changes during breakage and also how the particle size range varied when going down the stack pile from largest sieve size to the smallest. From the table, the first column (1) represent the sieve range of arranged together with the spacing between adjacent sieve plates. Sieve mass fraction (2) including the percentage weight of material by mass (g) retained at each sieve plate such that 4.23g of the material passed through the +180 μ m sieve plate but was retained on the +125 μ m sieve. Therefore, with these logical adjustments, the weight percentage by masses are then transformed into weight percentages (3) to find the relative amount of each mass retained comparatively towards the initial total mass that was initially used in the crushing device. The nominal aperture size (4) of the sieve must be also inclusive within the data for proper discrimination and rather to specify the sieve plate of interest. After these calibrations it is vital to calculate also the cumulative percentages (5) for the material passing through the average or nominal aperture size, for example; 66.3% of the mass is less than 90 μ m in size while 33.3% of the sifted mass weight was retained in the sieve. The data presentation format is helpful since interpolation is necessary for graphical illustrations which can be easily used to predict the behavior when dealing with larger quantities of the material (Golwalkar, 2015).

Table 4.5 show the particle size distribution amongst the sieve range and the basic calculations associated with fragmentation behavior of crystalline mineral ores.

(1) Sieve Size Range (μm)	(2)	(3)	(4) Nominal Aperture size (μm)	(5)	(6)
	Sieve fraction			Cumulative %	
	wt (g)	wt (%)		Undersize	Oversize
+250	0.02	0.1	250	99.9	0.1
-250 to +180	1.32	2.9	180	97.0	3.0
-180 to +125	4.23	9.5	125	87.5	12.5
-125 to +90	9.44	21.2	90	66.3	33.7
-90 to +63	13.10	29.4	63	36.9	63.1
-63 to +45	11.56	26.0	45	10.9	89.1
-45	4.87	10.9			

“The results of a sieving test should always be plotted graphically to assess their full significance (Napier-Munn et al., 1996)”

Table 4.6 shows the initial stage for the jaw crusher feed material estimations. Diorite rock samples acquired at Master quarry mine were weighed using an electric laboratory balance and obtaining three (3) set of mass recording of **480.1g**, **507.3g** and **447.2g**. The procedure was carefully followed because the laboratory crusher is a small type with an approximate jaw size of **100 x 150 mm** thus Choke feeding was avoided since diorite is an igneous rock type that is highly dominated by ferromagnesian minerals with high breakage strength therefore pressure on the crusher belt was significantly reduced. From the table calculations the equivalent volume diameter (vmd) of the crusher together with the fed rock equivalent diameter (**d**) of a sphere having the same volume was measured out as in the example above hence revealing a vmd value of **68.53**. The reduction ratio for any crusher is directly proportional to the production of crushed material fines in the products even when all other controllable crushing parameters are kept constant. When choosing the right crusher for fragmentation of any material the reduction ratio (R/R) is of great importance because it reveals the comparison of two vmd values for the fed material and product for any crushing operation. Information of how the crusher will be affected by the type of feed material in terms hardness, partial attrition forces between the particles, direction of applied crushing mechanism and the crushing efficiency for that particular crusher. Therefore, the above table information is significant when only a second type of data set calculations are made available by further sifting the total acquired mass and thus setting an upper limit and lower limit for our sieve stack range. Sieve Stack was arranged after careful consideration of our laboratory Jaw crusher size and how the majority of the igneous material was fragmented, therefore with the largest sieve aperture diameter of +11.2 mm and the smallest sieve of aperture size +0.10 mm an arrangement was made according to table 4.7 with Approximately **36.5g** of the diorite material was lost from the single piece feeding of the material to the jaw crusher a factor that could have occurred due to experimental errors. Table 4.7 also shows an extension of the data analysis obtained after sifting the material products of the Jaw crusher with the sieve stack arrangement as shown, it is clear that most of the material did not break since the largest sieve of aperture approximate size +11.2 mm retained the largest mass record of **993.6g** thus dominating **71.1%** of the total mass processed while sieve plate +6.3 mm retained 204.7g (14.6%) and gradually the retained mass decreased steadily with reduction in the aperture size of the screen so that the smallest sieve plate retained only 0.894%

as the amount of crusher dust. With such valuable information of both tables 4.6 and 4.7 the Jaw crusher device reduction ratio was estimated to be 6.233 a dimensionless number.

For the Master Quarry Diorite Rock Feed samples of the Jaw Crusher device:
Density = **2.85 g/cm³**; Vmd(F) = **68.530** & Reduction ratio = **6.233**.

Table 4.6 show the feed material information of the master quarry dioritic rocks that were fed to the Jaw crusher device.

Material	Mass of feed (g)	Mass Fraction (n)	Equivalent diameter (d)	n.d³	n.d⁴
1	480.1	0.33465774 4	68.52	107659.6 4	7376839
2	507.3	0.35361773 3	69.79	120202.5 4	8388935
3	447.2	0.31172452 3	66.92	93419.76 4	6251651
Total	1434.6	1		321281.9 4	2201742 4

Sample calculations

$$\text{Mass} = \frac{4}{3}\pi r^3 \rho, \rho = 2.85 \text{g/cm}^3 [\text{Finding diameter of a sphere}] \quad \text{Eq. (4.1)}$$

$$507.3 \text{g} = \frac{4}{3}\pi r^3 \left(\frac{2.85 \text{g}}{\text{cm}^3}\right) \Rightarrow \pi r^3 \approx \frac{3}{4(2.85)} (507.3) \equiv \frac{1521.9}{11.4} \cong 133.5$$

$$\pi r^3 = 133.5 \text{ cm}^3 \neq r^3 = \frac{133.5 \text{ cm}^3}{\pi} = 42.49 \text{ cm}^3 \neq r = \sqrt[3]{42.4943698055} \text{ cm} \equiv 3.49 \text{ cm}$$

$$d = 2r = 2(3.49) = 6.98 \text{ cm} \approx 69.79 \text{ mm}$$

Master quarry rock diorite products of the Jaw Crushing device

$$[V_{md}(P) = 10.995]$$

Table 4.7 show the sifted mass of the master diorite samples after crushing with Jaw crusher equipment in a closed circuiting environment for computation of volume mean diameter of the sample.

Sieve Size, mm (d)	Mass Retained (g)	Mass fraction (n)	n. d ³	n. d ⁴
+11.2	993.6	0.710678778	998.4525147	11182.668
+6.3	204.7	0.146412989	36.61012867	230.64381
+4.75	46.9	0.033545526	3.595136927	17.0769
+3.35	40.8	0.029182462	1.097125599	3.6753708
+2.0	38.9	0.027823475	0.222587798	0.4451756
+1.0	31.9	0.02281668	0.02281668	0.0228167
+0.71	13	0.009298333	0.003327976	0.0023629
+0.3	15.8	0.011301051	0.000305128	9.154E-05
+0.1	12.5	0.008940705	8.94071E-06	8.941E-07
Total	1398.1	1	1040.003952	11434.535

The above information was further analyzed to extract data regarding the sieve fractions together with their retained cumulative percentages % for both undersize and oversize particle size analysis PSD. From data obtained in table 4.8, the average aperture size on the sieve stack was then plotted against the cumulative undersize percentage % to make clear distinction on how the material was distributed amongst the sieve plates. A graphical presentation was obtained in figure 4.8 revealing that for a laboratory jaw crusher only about 8 results were recorded mass dominating 14.3 % of the cumulative undersize material while 85.7 % was retained mainly as oversize particles that partially fragmented to make the statistic. From the graph, majority of the material did not break a factor that might be due to presence of clay inclusions within the master quarry diorite structure as well as monoclinic compounds of sericite, chlorite and quartz that occurred in smaller traces within the structure made it harder for dislocation movements thus presenting the whole rock difficult to break.

Table 4.8 show the sifted mass results of the master diorite rock samples with estimated values of their sieve fractions and the cumulative mass percentages.

<i>Sieve Aperture Size (mm)</i>	<i>Sieve Fraction</i>		<i>Nominal Aperture size (µm)</i>	<i>Cumulative Percentage %</i>	
	<i>Mass retained(g)</i>	<i>Weight Percent %</i>		<i>Undersize</i>	<i>Oversize</i>
+11.2	993.6	71.1	11.2	28.9	71.1
+6.30	204.7	14.6	6.30	14.3	85.7
+4.75	46.9	3.35	4.75	10.95	89.05
+3.35	40.8	2.92	3.35	8.03	91.97
+2.0	38.9	2.78	2.0	5.25	94.75
+1.0	31.9	2.28	1.0	2.97	97.03
- +0.71	13.0	0.93	0.71	2.04	97.96
+0.3	15.8	1.13	0.3	0.91	99.09
+0.1	12.5	0.89	0.1	0.02	99.98
TOTAL	1398.1	100			

Graphical presentations for semi-logarithmic plot for the Master diorite rock following primary crusher equipment.

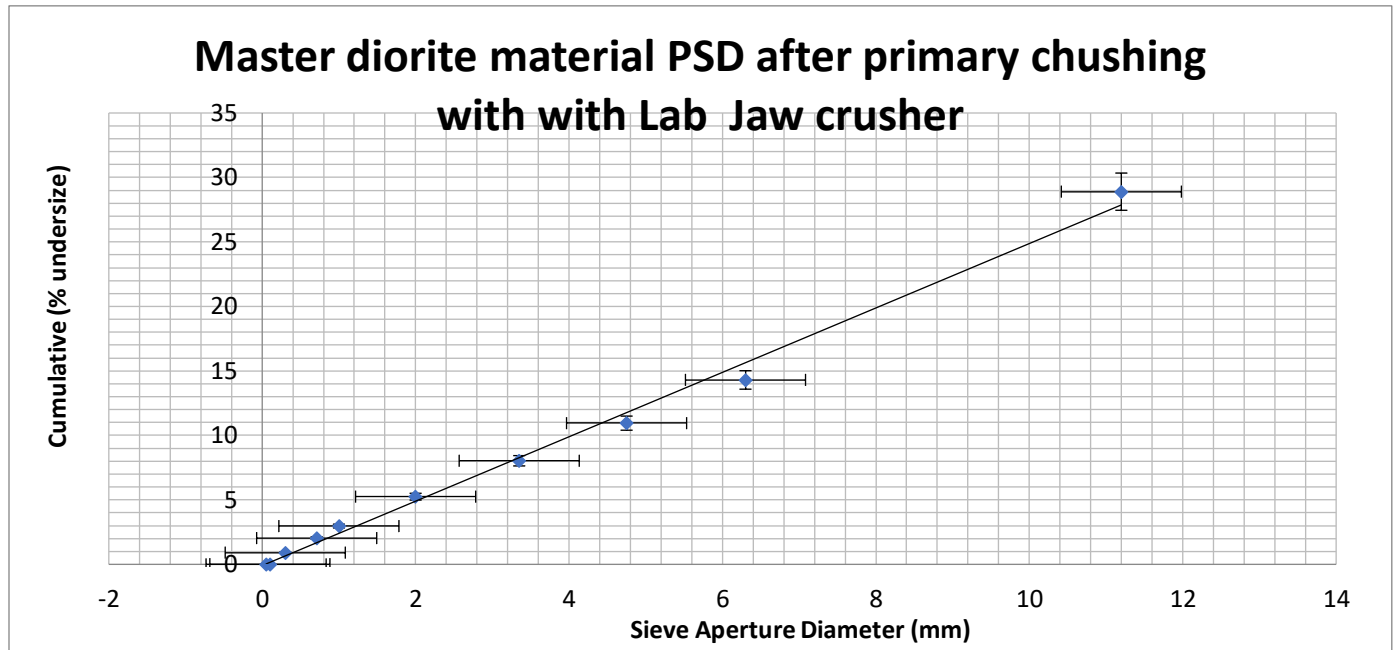


Figure 4.8 graphic presentations for the cumulative undersize percentage weight against particle size of master diorite rocks sample distribution amongst sieve arrangement.

The Master quarry rock samples received as jaw crusher products were further subjected to a cone crusher or gyratory crusher. Afterwards, the rock samples were collectively measured out using an electric balance and fed directly therefore containing data mainly comprised of products with an average sieve aperture size strictly lower than +13.2 mm as can be seen according to table 4.8 but following further discrimination on the results sieve stack range with an upper limit of +6.3 mm was selected because approximately 70 % of the Master quarry mine rock, did not fragment. The steps were carefully repeated for the calculations of the reduction ratio and the volume mean diameter for the gyratory crusher while keeping the sieve class range of +4.75 mm and +3.35 mm of interest since the focus of the experiment was on energy required for the breakage of the rock and the rock strength. Majority of road construction companies and civil construction works, consume quarry products with a rock aggregate size between these

sieve range classes, it is thus easy to predict the rock strength and also, factors affecting its breakage mechanism. For easy investigation of the rock fragmentation characteristic parameters here, it can be observed that the sieve stack selection was kept constant throughout the experiment and after plotting the particle size distribution curve it was clear that majority of the material contained within the sieve class was 10.95 % and 8.03 % progressively.

Master quarry diorite for product of the gyratory crusher

$$[Vmd(P) = 6.0722]$$

With the information presented on table 4.9 the volume mean diameter of the Master rocks were calculated to be **6.0722**. The pattern of rock fracture was mainly uniform from the sieve plate +4.75 mm to lower sieve plates while the upper sieve plate retained 55.09 % of the fractured material therefore suggesting that Master rocks possess extensive rock hardness and would be recommend for infrastructural work where larger particles of the rock find utilization. The reduction ratio of the gyratory crusher was computed to be **1.811**, thus presenting inconsistent value due to crusher dust production when comparing to the reduction ratio of the Jaw crusher device (**6.233**) having a smaller crushing chamber. From the table 4.9 and figure 4.9 it is clear that majority of the material was collected in the sieve range -3.35 mm to +2.00 mm due to this material defects and instability in its breakage behavior, a factor that arose because of smaller grain size and domination of microstructural defects like inhomogeneous grain orientation of the Master quarry diorite rocks.

Table 4.9 show the results obtained from sifting the master diorite sample mass products of the Gyratory crusher device with calculated values of their mass fractions and volume mean diameter of the material.

<i>Sieve Aperture Size (mm)</i>	<i>Mass Retained (g)</i>	<i>Mass fraction (n)</i>	<i>n.d³</i>	<i>n.d⁴</i>
+6.3	728.6	0.550926276	137.75746	867.872014
+4.75	164.2	0.12415879	13.30633	63.20506912
+3.35	136.8	0.103440454	3.8888826	13.02775687
+2	115.2	0.08710775	0.696862	1.393724008
+1.0	86	0.065028355	0.0650284	0.065028355
+0.71	22.8	0.017240076	0.0061704	0.004380993
+0.3	39.9	0.030170132	0.0008146	0.000244378
+0.1	29	0.021928166	2.193E-05	2.19282E-06
<i>Total</i>	1322.5		155.72157	945.5682199

Table 4.10 shows the sieve analysis results for a Gyratory crusher device with calculations of cumulative mass percentages and weight fractions for the fragmented mass of master quarry material.

Sieve Aperture Size (mm)	Sieve Fraction		Nominal Aperture size (μm)	Cumulative Percentage %	
	Mass retain ed(g)	Weight Percent %		Undersize	Oversize
+6.30	728.6	55.09	6.30	28.9	71.1
+4.75	164.2	12.42	4.75	14.3	85.7
+3.35	136.8	10.34	3.35	10.95	89.05
+2.0	115.2	8.71	2.0	8.03	91.97
+1.0	86	6.50	1.0	5.25	94.75
+0.71	22.8	1.72	0.71	2.97	97.03
+0.3	39.9	3.02	0.30	2.04	97.96
+0.1	29	2.19	0.10	0.91	99.09
TOTAL	1322.5	100			

When considering figure 4.9 there is high predictability of the breakage pattern below the sieve range -4.75 mm to +0.10 mm because a linear regression or plot was obtained which exposes the behavior, thus 10.95 % of the material fed to the gyratory crusher behaved linearly while majority of the material did not disseminate to be consider with higher confidence since it occupied the oversize material these results was perhaps obtained because of poor force distribution within the Master quarry rock due to material defects like voids and porosity factors.

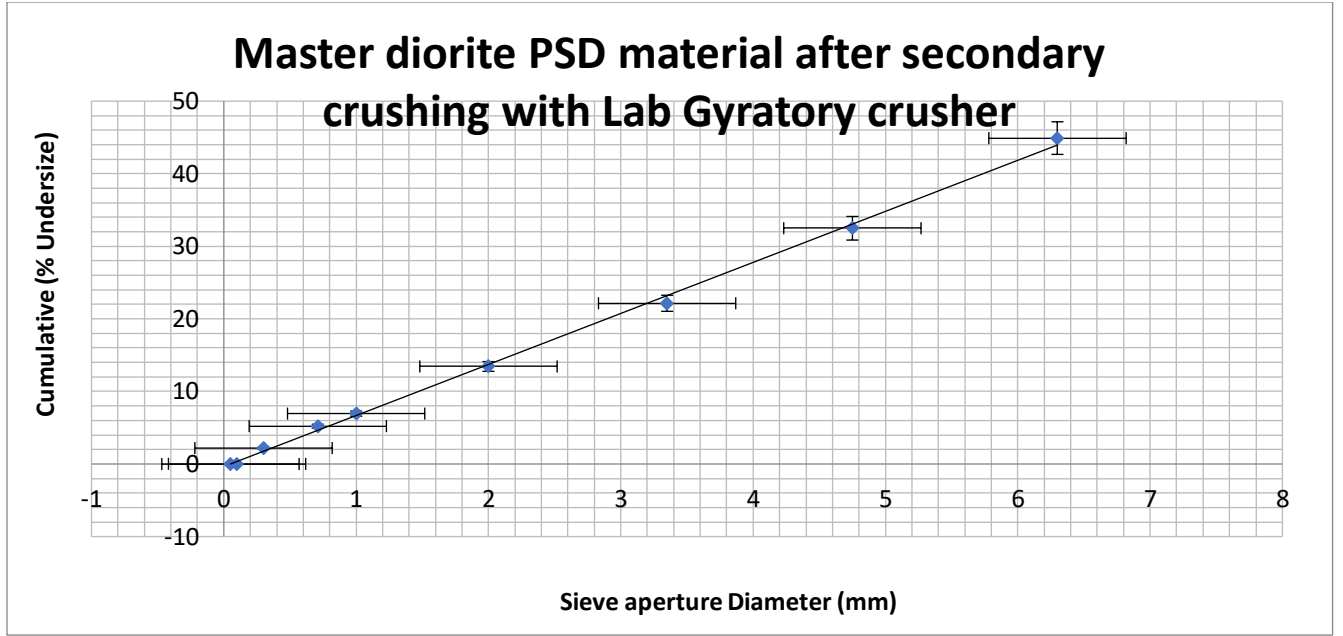


Figure 4.9 showing particle distribution of the sifted mass of master diorite samples following crushing via a Gyratory crusher device and here the cumulative percentage undersize was plotted against the nominal sieve aperture size/ particle size.

Power required by the Jaw crusher to fragment Master Quarry diorite rocks

$$PR = W_i \times 10 \left[\left\{ \frac{1}{\sqrt{vmd(P)}} \right\} - \left\{ \frac{1}{\sqrt{vmd(F)}} \right\} \right]; W_i = 23.0 \text{ KWh } t^{-1} \quad \text{Eq. (4.4)}$$

$$PR = \frac{230 \text{ KWh}}{1000000 g} \left[\left\{ \frac{1}{\sqrt{10.99470311}} \right\} - \left\{ \frac{1}{\sqrt{68.52991527}} \right\} \right]$$

$$\cong (0.00023 \text{ } g^{-1}) \left[\left(\frac{1}{3.316} \right) - \left(\frac{1}{8.278} \right) \right]$$

$$0.00023(0.18078592088)g^{-1} \approx 0.00004158076 \cong \mathbf{41.58 \text{ KWh } t^{-1}}$$

The equivalent sphere theory was used to compute the equivalent diameter for the feed rock samples initially fed to the jaw crusher and the result assisted in estimation for the volume mean diameter for the feed and products of the Jaw crushing device. (Wills, et al., 2013).

$$vmd = \frac{\sum n.d^4}{\sum n.d^3} \text{ [Volume mean diameter]} \quad \text{Eq. (4.2)}$$

$$\text{Reduction Ratio, RR} = \frac{vmd (\text{feed})}{vmd (\text{products})} \quad \text{Eq. (4.3)}$$

A comparison for both the reduction ratio and power required must be established between the two rock samples using the Jaw crusher equipment. For easier comparison, sieve analysis was used to determine the aggregate size distribution for the coarse fragmentation of the crusher products, thus information was derived for important factors that determine design, material selections and hence performance of the breakage procedure and only dry sifting of particles in the powder state was investigated. Extreme caution needs be adhered especially, since erroneous results can lead to improper particle-size analyses which can result in poor product quality and high rejection rates and therefore, numerous economic losses (Wills, et al., 2013). Graphical plot for the data is very vital as it assist to illustrate the visible behavior of the particles and therefore openly make recommended decisions which are significant towards product improvement or otherwise suggestion to processing routes that would otherwise minimize cost of production in order to reduce expenditure load on the mine or processing factory. As can be seen from the above table of information showing the sieve test results, analysis was made simple through focusing on important factors such as sieve fraction and the cumulative weight percentage for the retained mass in the sieve plates. After chronologically arranging the sieve range and making sure their range was well isolated with a difference not more than, $2\sqrt{2}$, the sieve fraction column was calculated thus representing information on the mass retained for every level together with relative percentages. Such that, 115.2g of mass passed through the 3.35 μ m sieve but was retained on the +2.0 μ m sieve. Therefore these consecutive weight masses can be expressed to percentage of the total for simplicity. The nominal aperture size column was for sieve retaining the material at every conjunction while the column 5 and 6, are for cumulative mass and weight percentage for the sifted material; for example 10.95 % would represent the actual percentage of the material that passed via the sieve +4.75 mm whereas 89.05 % would be for the mass that the sieve retain and will be classified as oversized material. The purpose for this simplified illustration is to provide easy statistical information on the particle size distribution behavior during sifting and so, arithmetic plots are made to represent undersize weight percent against particle size as can be seen above (Mehrotra, et al., 1995).

Table 4.11 below is a presentation of the Panda quarry diorite. Pieces (3) of the rock were obtained and fed to the Jaw crusher in order to acquire values for the equivalent diameter (**d**) of the rock. The main objective of the procedure is to measure and record the volume mean diameter (vmd) after it has been crushed as a primary crusher feed.

For the Panda Quarry Diorite Rock Feed samples of the Jaw Crusher device:

Density = **2.85 g/cm³**; Vmd = **80.81** and Reduction Ratio **6.24**

Table 4.11 shows the feed material information of the panda rocks that were fed to the Jaw crusher device with also the mass fraction calibrations.

<i>Material</i>	<i>Mass of feed (g)</i>	<i>Mass Fraction (n)</i>	<i>Equivalent diameter (d)</i>	<i>n.d³</i>	<i>n.d⁴</i>
1	752.98	0.320554792	79.61	161735.4216	12875756.91
2	749.37	0.319017961	79.48	160172.7788	12730532.46
3	846.64	0.360427247	82.79	204527.2895	16932814.3
Total	2348.99	1		526435.4899	42539103.67

Sample calculations

$$\text{Mass} = \frac{4}{3}\pi r^3 \rho, \rho = 2.85\text{g/cm}^3 \text{ [Diameter of a sphere]} \quad \text{Eq. (4.5)}$$

$$752.98 = \frac{4}{3}\pi r^3 \left(\frac{2.85\text{g}}{\text{cm}^3}\right) \neq \pi r^3 \approx \frac{3}{4(2.85)}(752.98) \equiv \frac{2258.94}{11.4} \cong 198.15$$

$$\pi r^3 = 198.15 \text{ cm}^3 \neq r^3 = \frac{198.15\text{cm}^3}{\pi} = 63.08\text{cm}^3 \neq r = \sqrt[3]{63.0739416049} \text{ cm} \equiv$$

$$3.981\text{cm}$$

$$d = 2r = 2(3.981) = 7.961\text{cm} \approx \mathbf{79.61\text{ mm}}$$

Table 4.12 showing the volume mean diameter of the panda rock was easily calibrated and with this value the power required by the Jaw crusher equipment in breaking and handling the rock was estimated. From the presented data the value was calculated to be **12.95** (vmd), therefore showing the device to have a slightly higher reduction ratio of 6.24 when handling the Panda diorite rock samples. Therefore, having only a slight insignificant value difference of **0.01**. It required approximately the same amount of power to break the material since a variable amount of feed mass were crusher and the average sieve stack ranges were employed. Therefore, factors of attrition and chemical bonding energy embedded within each material must have been the main contributory aspect of the fracture pattern observed for both rocks and also, suggesting that choke feeding the material into the device plays a major role especially when crushing the diorite igneous rock material using a small laboratory crusher.

Table 4.12 shows information of the sieve range with mass distribution of the panda diorite samples to aid in calculations of the volume mean diameter following fragmentation with a Jaw crusher. The vmd value was found to be **12.954**.

<i>Sieve Size (d)</i>	<i>Mass Retained (g)</i>	<i>Mass fraction (n)</i>	<i>n.d³</i>	<i>n.d⁴</i>
13.2	1510.22	0.667969977	1536.309571	20279.28634
11.2	117.49	0.051965801	73.0082094	817.6919453
6.3	291.8	0.129063076	32.27183506	203.3125609
4.75	56.04	0.02478648	2.656413513	12.61796419
3.35	64.09	0.028346993	1.065715833	3.57014804
2	62.54	0.027661428	0.221291427	0.442582854
1	55.05	0.024348603	0.024348603	0.024348603
0.71	18.25	0.008071971	0.002889047	0.002051224
0.3	52.29	0.023127856	0.000624452	0.000187336
0.1	33.14	0.014657815	1.46578E-05	1.46578E-06
Total	2260.91	1	1645.560913	21316.94813

For easy comparison on the diorite rock breaking dynamics as well as the processing equipment, it was necessary to also calculate the vmd of the material with results obtained from the Cone crusher. Choke feeding was recommended since majoring of the rock had already been subjected to a primary crushing activity and thus might have incurred material internal strain energy within the grain matrix structure which would otherwise promote dislocation growth which promotes material fracture and other structural instabilities. The reduction ratio for the gyratory crusher was calculated to be **2.045** when processing the Panda diorite material a value that was high than when crushing the Master quarry diorite, hence showing comparatively that lower force was required to further break the material and no other material was rejected because the gyratory crusher used was able to accommodate all the feed material. The reduction ratio was lower therefore the rock was more stable and intact within these selected sieve range, this was also revealed when the material did not produce a lot of crusher dust and hence undersize material which dominated the rejects.

Table 4.13 shows results obtained from the sieve range and particle distribution values after subjecting the panda diorite samples to a Gyratory crusher the information was vital for volume mean diameter estimation which was found to be **6.334**.

<i>Sieve Size (d)</i>	<i>Mass Retained (g)</i>	<i>Mass fraction (n)</i>	<i>n.d³</i>	<i>n.d⁴</i>
11.2	15.31	0.008320924	11.69029842	130.9313423
6.3	477.35	0.259437808	64.87164552	408.6913667
4.75	283.91	0.154303945	16.53704307	78.5509546
3.35	377.59	0.205218648	7.715272045	25.84616135
2	261.61	0.142183984	1.137471874	2.274943748
1	162.22	0.088165918	0.088165918	0.088165918
0.71	50.93	0.02768025	0.009907066	0.007034017
0.3	152.5	0.082883137	0.002237845	0.000671353
0.1	58.52	0.031805385	3.18054E-05	3.18054E-06
Total	1839.94	1	102.0520736	646.3906432

Further discrimination of the results obtained was necessary in order to investigate the rock particle distribution for both the Jaw crusher and the gyratory crusher, therefore the percentage mass retained at every particular sieve range was calculated and for the jaw crusher device a closer focus was given to sieve diameter of +13.2 mm, +11.2 mm, +6.30 mm to +0.30 mm sieve average diameter. It was done in order to select the particle size aggregate of interest with reasonably strong properties of impact strength and fewer material defects. From the information obtained values for the cumulative percentage undersize and oversize were acquired with an aim of plotting the average sieve diameter (mm) against cumulative undersize % and considering the sieve size ranges of +4.75 mm and +3.35 mm of higher interest because majority of the construction work and civil engineering task such as road construction and maintenance consume materials of particularly these sieve range classes.

The figure 4.10 reveals that there was a great inconsistency distribution of particulates because from the data it can be seen that the sieve range class +13.2 mm, +11.2 mm and +6.3 mm retained the majority of the material that was broken down which accounted 84.90 %. Therefore only a small amount of the material was fragmented to lower sieve range and it occupied 12.62 % of the total material being handled, thus for primary crushing of the Panda diorite rock the

undersize or crusher dust obtained in the rejected material only contributed a smaller percentage it could due to the intact rock strength inherent within the rock structure because the homogeneity of the crystalline phases embedded within its structure therefore this type of rock would find greater recommendations for applications and/ or activities such as civil construction and infrastructural work.

Table 4.14 shows the nominal sieve diameter (d) together with the cumulative undersize percentage passing at every range of the panda diorite rocks that were crushed using Jaw crusher equipment with mass retained at each level.

Sieve Aperture Size (mm)	Mass Retained (g)	Mass fraction (n)	Percentage Retained %	Undersize %	Oversize %
11.2	117.49	0.156509	15.65093	84.34906553	15.65093
6.3	291.8	0.388709	38.87091	45.47816009	54.52184
4.75	56.04	0.074651	7.465132	38.01302801	61.98697
3.35	64.09	0.085375	8.537479	29.47554916	70.52445
2	62.54	0.08331	8.331002	21.14454702	78.85545
1	55.05	0.073333	7.333253	13.81129361	86.18871
0.71	18.25	0.024311	2.431097	11.38019689	88.6198
0.3	52.29	0.069656	6.965592	4.41460523	95.58539
0.1	33.14	0.044146	4.414605	0	100
Total	750.69	1	100		100

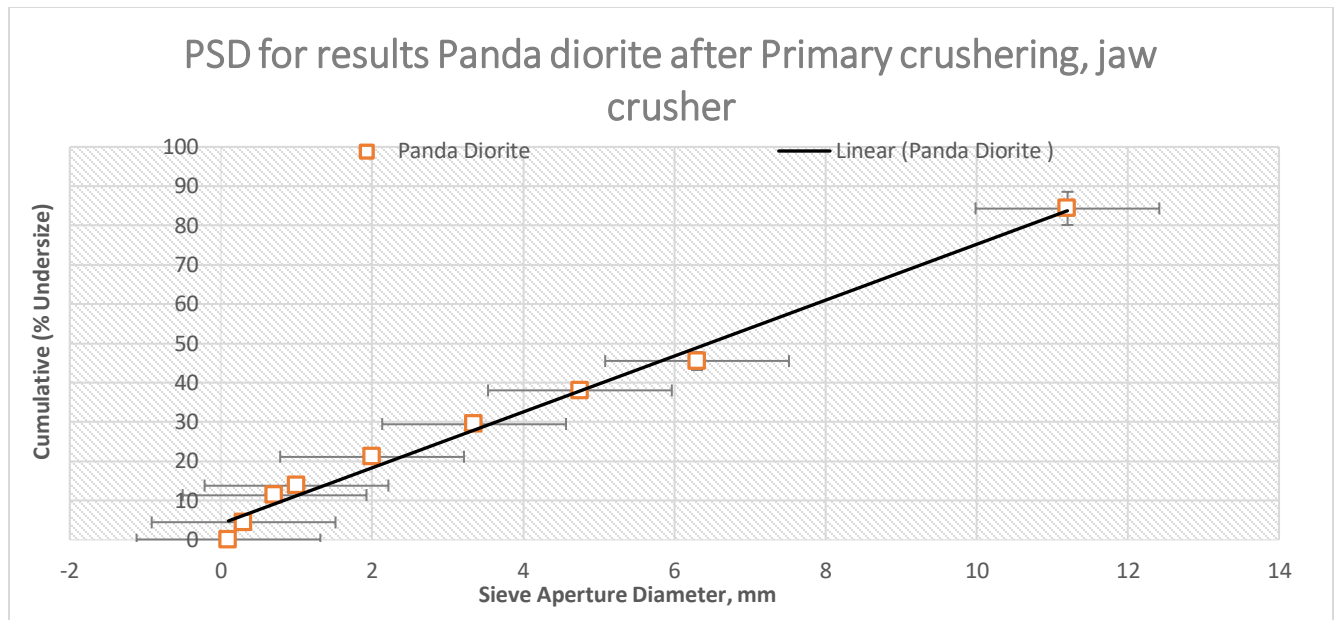


Figure 4.10 graphical presentation for sifted panda diorite mass after subsection to crushing with a Jaw crusher device and the percentage undersize mass was plotted against the nominal aperture size of the sieve distribution.

Table 4.15 presents the information of crushed products of the Gyratory crusher after breaking the diorite material for panda quarries. The Sieve range selection was only from +11.2 mm, +6.3 mm, +4.75 mm down to +0.10 mm and it was largely because the device was used as a secondary crusher hence the focus was on lower sieve plates particularly sieve plates +4.75 mm and +3.35 mm range. Major selection of aggregates is mainly selected in this particular sieve range for construction and civil work therefore sieve range with +13.2 mm average diameter was rejected because the products dominates primary crusher material for infrastructural duties. From the fragmentation of the rock, results show more stability of recorded values thus revealing consistency within the rock structure as can be seen from figure 4.11, all the size range classes are well represented and breakage predictability is made easy. This is significantly revealed by the figure below because when operating between the sieve range diameter of +0.1 mm to +6.3 mm there is positive correlation and much more reliance on the fragmented rock results thus better approximation below the 80 % cumulative percentage.

Table 4.15 shows information from the sieve range with panda diorite rocks that were fragmented using Gyratory crusher and the mass fraction for each section was carefully calculated together with cumulative percentage oversize that were retained.

Sieve Aperture Size (mm)	Mass Retained (g)	Mass fraction (n)	Percentage Retained %	Undersize %	Oversize %
6.3	477.35	0.261615	26.16147	73.83853165	26.16147
4.75	283.91	0.155599	15.55987	58.27866472	41.72134
3.35	377.59	0.206941	20.69406	37.58460619	62.41539
2	261.61	0.143377	14.3377	23.24690485	76.7531
1	162.22	0.088906	8.89057	14.35633526	85.64366
0.71	50.93	0.027913	2.791251	11.56508443	88.43492
0.3	152.5	0.083579	8.357859	3.207225575	96.79277
0.1	58.52	0.032072	3.207226	0	100
Total	1824.63	1	100		100

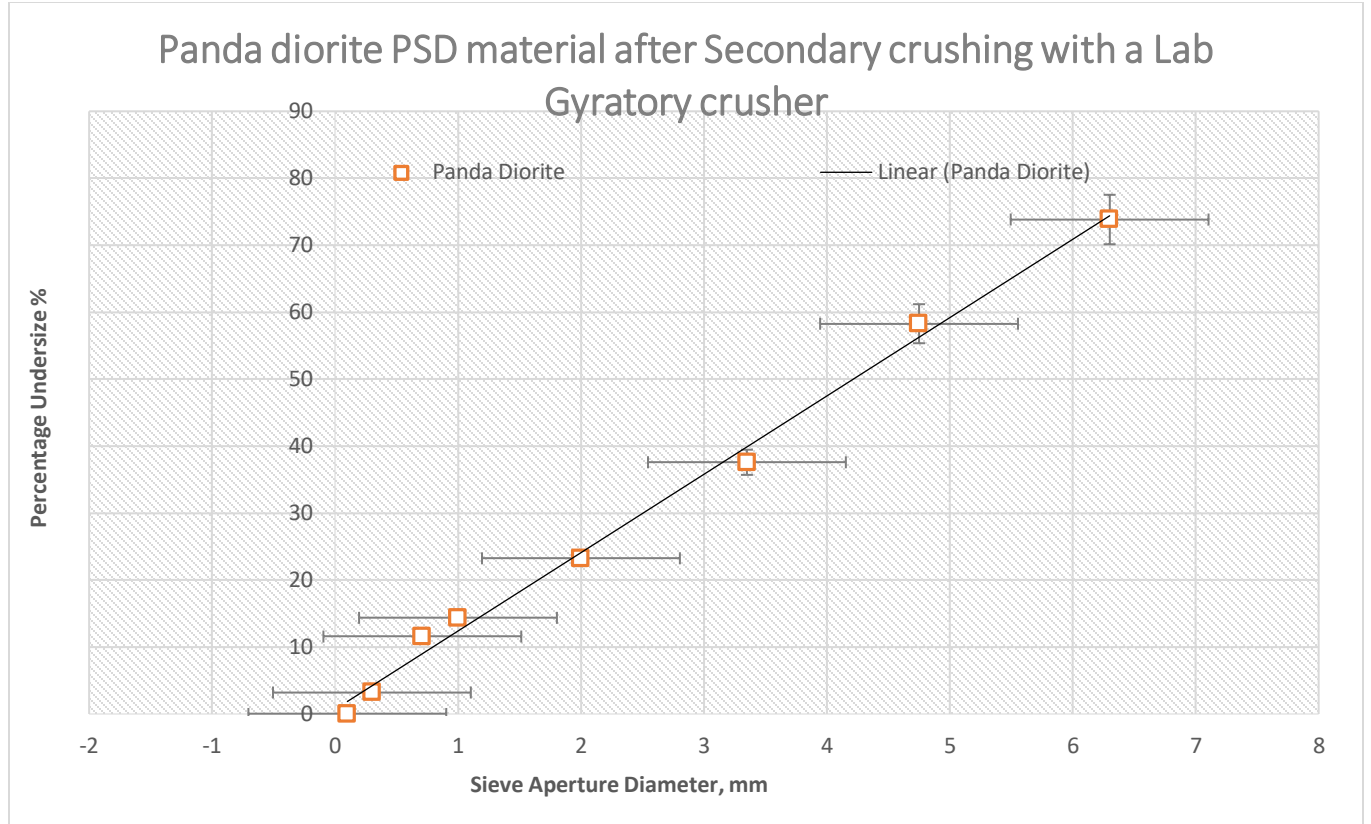


Figure 4.11 Particle size distribution of panda diorite rock samples subjected to breakage via a Gyratory crushing device and the cumulative percentage of undersize material was plotted against the average aperture size of the sieve stack array.

Power required by the Jaw crusher to break panda diorite rock samples.

$$PR = W_i \times 10 \left[\left\{ \frac{1}{\sqrt{vmd(P)}} \right\} - \left\{ \frac{1}{\sqrt{vmd(F)}} \right\} \right]; W_i = 23.0 \text{ KWh } t^{-1} \quad \text{Eq. (4.6)}$$

$$PR = \frac{230 \text{ KWh}}{1000000g} \left[\left\{ \frac{1}{\sqrt{12.95}} \right\} - \left\{ \frac{1}{\sqrt{80.81}} \right\} \right] \cong (0.00023 \text{ } g^{-1}) [(0.277885007) - (0.111241656)]$$

$$0.00023(0.16664335)g^{-1} \approx 0.000038327 \cong \mathbf{38.33 \text{ KWh } t^{-1}}$$

Using the equivalent sphere theory, the diameter of the feed material fed to the jaw crusher was calibrated and the result was used to compute the estimation for the volume mean diameter for

the feed as well as the material crushed using the gyratory crusher device therefore for both crushing equipment. The power required when crushing the Panda diorite rock samples was found to be slightly lower than the power required to fragment diorite rock samples of the Master quarry mine by a factor of approximately 10 units according to sample calculation of equation 4.6.

Master quarry diorite rock samples required **41.58 KWh t⁻¹** while Panda quarry diorite rocks required only **38.33KWh t⁻¹** while using the same crushing laboratory devices and under similar conditions. Therefore since the power required by the crushing device is a factor that is directly proportional to the volume mean diameter (vmd) and the mass retained per sieve plate, the sieve range was kept constant for accurate discrimination on the breakage pattern of both diorite rock samples. It was found that consistence and reliability was found when working with Panda Diorite than Master quarry diorite, a contribution that might have been due to environmental impact since location of the diorite rock mineral largely affects material structure and characteristic inclusions that are naturally found within the rock specimen and also the crystallization temperature during formation.

$$vmd = \frac{\sum n.d^4}{\sum n.d^3} \text{ [Volume mean diameter]} \quad \text{Eq. (4.7)}$$

$$\text{Reduction Ratio, RR} = \frac{vmd \text{ (feed)}}{vmd \text{ (products)}} \quad \text{Eq. (4.8)}$$

A general comparison for both rock species was carried out on the breakage mechanization and of the particle size distribution (PSD) while the sieve range aperture diameter was kept constant for most part of the investigation; therefore the reduction ratio of the rocks and power required by the equipment established a solid contrast between the two rock species.

Table 4.16 show results obtained for four milling cylinders of the Master quarry diorite rock. Samples of the feed material were acquired from the secondary crusher unit after calibration regarding the reduction ratio and powers required were investigated. The focus of the experiment was basically targeting the behavior of the sieve range of +4.75 mm and +3.35 mm of the

primary and secondary crushing units. An approximate mass was varied for every cylinder, the number of milling balls kept constant together with the milling speed (300 rpm, revolutions per minute). This was done to further discriminate the rocks and how milling time affected production of crusher dust thus for every quarry activity factors of attrition and particle-particle interaction play an important role/ impact in the fragmentation processes. An attempt to study effects of choke feeding the diorite rock material was implemented thus regulating production of unwanted material as undersize particles that would otherwise find low market. Milling grind coarse materials using various forms and type of grinding method and for this experiment ball milling was engaged in the method of pulverization. Milling can quickly produce fine powders from a rough and coarse aggregated state. The grinding equipment that was employed in this experimental setup used grinding balls which utilizes attrition method to break down particle into smaller sizes hence the number of balls used in the milling cylinder are of great importance because through impact with the material fragmentation is achieved. The particle size used in the grinding media, number of balls, material hardness, grinding time, material density and the milling speed must all be taken into consideration when pulverizing any material. Thus materials that are normally adopted in the grind procedure for the ball material are usually ceramic balls, pebbles, stainless steel balls basically because of their inherent hardness properties that do not allow them to chip or break while in operation.

Table 4.16 shows the sieve range information that was acquired after successively grinding the master quarry material using a planetary ball mills at four different time intervals of 10 minutes, 15 minutes, 20 minutes and 25 minutes.

<i>Sieve size (μm)</i>	<i>Mass (g)</i> <i>[10 mins]</i>	<i>Mass (g)</i> <i>[15 mins]</i>	<i>Mass (g)</i> <i>[20 mins]</i>	<i>Mass (g)</i> <i>[25 mins]</i>
300	98.3	93.5	63.8	50.5
212	9.20	1.60	0.70	0.00
150	21.9	13.6	7.70	16.8
106	5.50	10.9	42.3	9.20
75	36.6	39.4	0.70	46.4
53	2.20	1.30	0.10	1.70
37.5	1.0	0.10	0.00	0.10
Total	174.7	160.4	115.3	124.7

A contrast was also established with by selecting material between the sieve range of +4.75 mm and +3.35 mm with the scope of varying the milling times while all other controllable parameters are kept constant thus the milling speed was set at 300 revolutions per minutes (rpm) and the sieve stack arrangement kept the same. Table 4.17 is the presentation of all the milling cylinders set at 5 minutes intervals, the breakage mechanism on the rocks was thus investigated to study the effects of loading and fracture toughness on the rock samples and how internal stresses are distributed during loading hence establishing further similarity of the rock structural deformities. Cyclic loading on the rock can have major influence on the accumulation of rejected products or crusher dust which is hard to control and usually lead to crushing equipment choking which to a greater extent results to damage.

From the objective of the research we are to find out factors affecting the fragmentation behavior of diorite rocks acquired at various localities during the three main crushing stages being primary, secondary and the tertiary crushing of the mining circle, 10 minutes milling on the sample provided an accurate point of study on the grinded rock results because according to our

study and the obtained results of tables 4.16 and 4.17 it was clear that after the rocks were grinded for 10 minutes the behavior was almost uniform and their remain insignificant difference between the two rock types.

Table 4.17 shows the sieve range information that was acquired after successively grinding the panda quarry diorite material using a planetary ball mills at four different time intervals of 5 minutes, 10 minutes, 15 minutes and 20 minutes.

<i>Sieve Size, μm (d)</i>	<i>Mass(g) 5 minutes</i>	<i>Mass(g) 10 minutes</i>	<i>Mass (g) 15 minutes</i>	<i>Mass (g) 20 minutes</i>
300	59.19	50.87	42.64	32.34
212	2.38	0.41	0.14	0.1
150	1.03	0.2	0.01	0.06
106	5.4	15.8	22.25	32.12
75	9.75	10.18	9.94	15.17
53	14.18	14.98	17.79	12.61
37.5	0.99	0.79	1.22	0.81
Total	92.92	93.23	93.99	93.21

Figure 4.12 portrays the information presented by the Table 4.18 and therefore a logarithmic regression was extrapolated in order to investigate any existence of relationship or the reproducibility of results on the cumulative undersize percentage when the sieve aperture range is maintained constant. Because only dry sieving was done, there was a problem of aperture blockage in the lower sieve range classes hence making it hard to record the retained weight percentage for each sieve plate. The larger sieve with aperture size +300 μm passes approximately 43.75% of the mass sifted and progressively the sieve plate +150 μm passed 25.94 % of the total mass. From the graph, it can be predicted that the Master quarry diorite averagely had an aggregate particle size of approximately 0.30 μm after the material had been sifter for 10 minutes because when considering the oversize percentage at that sieve range about 77.20 % of the cumulative material were oversize thus presenting a greater level of confidence on the assumption. Also, from the graph it is clear that below the sieve level +106 μm there is

insignificant difference in the values retained for each sieve plate, proving that majority of the mass was lost through aperture blockage.

Table 4.18 shows the results of particle distribution for master diorite samples that were grinded for 10 minutes with data for the mill presenting data for the mass retained in the factions and the cumulative percentage passing of undersize.

<i>Sieve Size (d) (mm)</i>	<i>Mass (g) 10 mins</i>	<i>Mass fraction n (n)</i>	<i>Percentage Retained %</i>	<i>Undersize %</i>	<i>Oversize %</i>
<i>300</i>	<i>98.2</i>	<i>0.562</i>	<i>56.24</i>	<i>43.75</i>	<i>56.24</i>
<i>212</i>	<i>9.2</i>	<i>0.0526</i>	<i>5.269</i>	<i>38.48</i>	<i>61.51</i>
<i>150</i>	<i>21.9</i>	<i>0.125</i>	<i>12.54</i>	<i>25.94</i>	<i>74.05</i>
<i>106</i>	<i>5.5</i>	<i>0.0315</i>	<i>3.150</i>	<i>22.79</i>	<i>77.20</i>
<i>75</i>	<i>36.6</i>	<i>0.209</i>	<i>20.9</i>	<i>1.832</i>	<i>98.16</i>
<i>53</i>	<i>2.2</i>	<i>0.0126</i>	<i>1.260</i>	<i>0.572</i>	<i>99.42</i>
<i>37.5</i>	<i>1</i>	<i>0.0057</i>	<i>0.572</i>	<i>0</i>	<i>100</i>
<i>Total</i>	<i>174.6</i>	<i>1</i>	<i>100</i>		

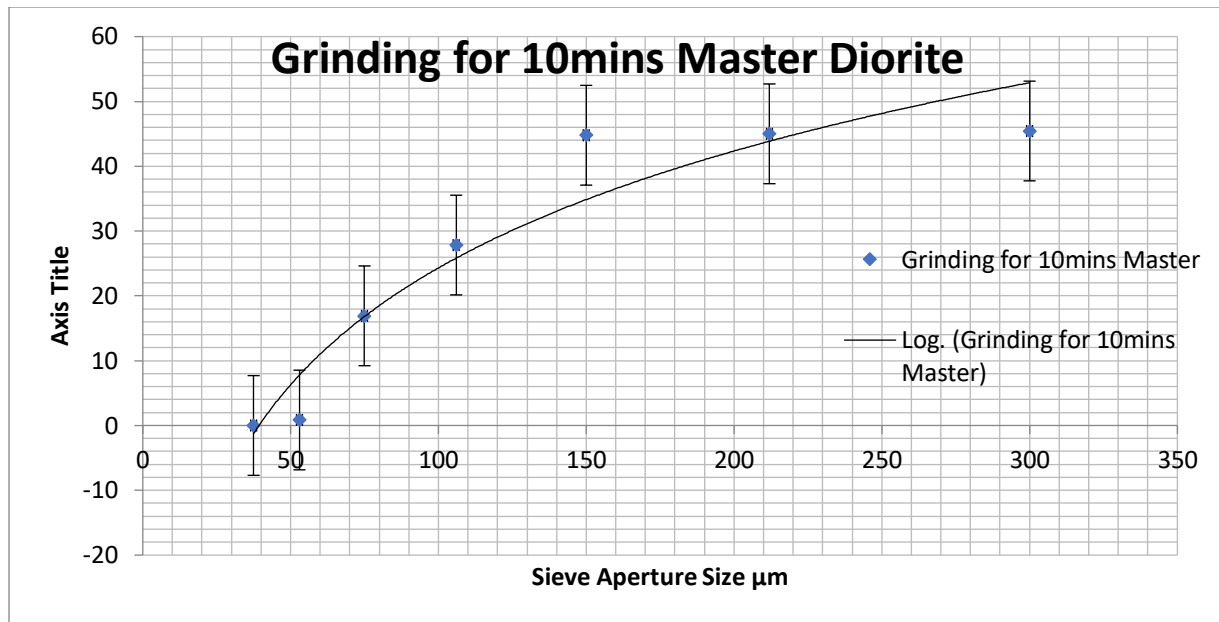


Figure 4.12 showing the results of aggregate size distribution among sieve stack after a milling activity of the master diorite rock samples for 10 minutes and here a semi-logarithmic plot was attained after plotting the cumulative percentage undersize against the nominal aperture size of sieve array.

From Table 4.18 and the experimental data of Appendix B, Table B19 which was acquired after the Panda diorite material was grinded for 10 minutes following also the logarithmic plot of figure 4.13 providing further justification of the information and how the Panda rock particulates were distributed amongst the sieve arrangement stack. It was observed that majority of the material was collected in the upper sieve plate hence 54.6 % was retained while 45.4 % was recorded at undersize material to justify the six recorded mass in the lower progressive sieve classes. Therefore, the sieve class of +212 μm did not retain a large quantity of material because of the insignificant recorded value of 0.44 % mass material retained that only dominated the 0.41g of the total material mass and so, the Panda rock material was to a greater extent well grinded and distributed since majority of the material rock mass was occupied but the lower sieve class ranges. When considering the sieve class of +106 μm about 27.8 % of the material was passed as the undersize material while the other 72 % was retained in sieve plate and have an average particle diameter greater than 106 μm . It can also be seen that panda diorite

was easily manageable and controlled below the sieve plate with nominal aperture diameter of +75 mm and +53 mm because steady reading where recorded on the sieve plates for better approximation. The figure 4.13, presents the information in a graphical format that shows rapid increase in the production of crusher dust material because of a very high gradient in the curve below the 106 μm aperture mark which decreases slowly but steadily above 212 μm diameter region. The Panda diorite has generally well defined grain structure patterns and lower amounts of embedded impurities within the rock structure therefore force distribution is improved during crushing and grinding.

Table 4.19 shows the results of particle distribution for panda diorite samples that were grinded for 10 minutes with data for the mill presenting data for the mass retained in the factions and the cumulative percentage passing of undersize.

Sieve Size (d)	Mass(g) 10 minutes	Mass fraction (n)	Percentage Retained %	Undersize %	Oversize %
300	50.87	0.545639816	54.56398155	45.43601845	54.56398155
212	0.41	0.004397726	0.439772605	44.99624584	55.00375416
150	0.2	0.002145232	0.214523222	44.78172262	55.21827738
106	15.8	0.169473345	16.94733455	27.83438807	72.16561193
75	10.18	0.10919232	10.91923201	16.91515607	83.08484393
53	14.98	0.160677893	16.06778934	0.847366727	99.15263327
37.5	0.79	0.008473667	0.847366727	2.84217E-14	100
Total	93.23	1	100		

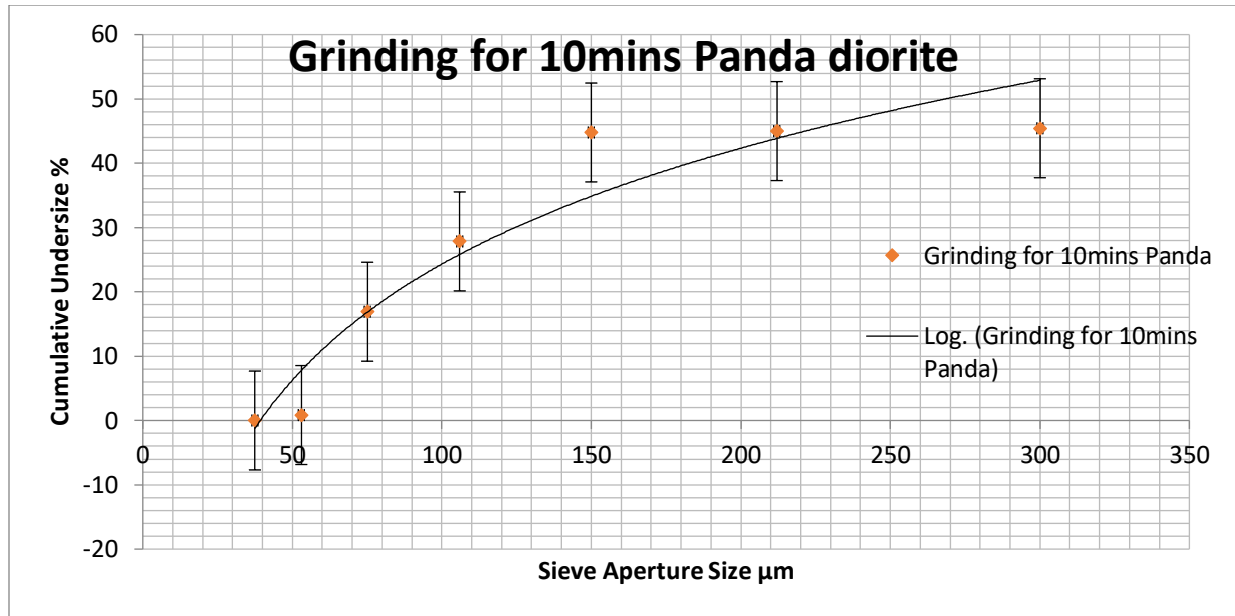


Figure 4.13 showing results of a semi-logarithmic plot obtained from plotting the cumulative percentage undersize of the panda diorite rock samples against the average sieve diameter. The milling operation was continued for a duration not exceeding r milling 10 minutes.

4.4 Recommendations

During the experimental procedure three (3) important separation stages were carefully conducted following each size reduction process therefore for the primary crushing stage material with an aggregate particle size not exceeding +13.2 mm was subjected to a sieve stack of 9 sieve plates with the largest sieve aperture diameter of 11.2 mm and the bottom sieve having an aperture diameter of 0.1 μm . The sieve selection criterion was carried out while considering the particle diameter size associated with primary crushers because at this stage material with feed size range between 1 m – 1.5 m in diameter is fed to the device and reduced to a product size range between 10 cm to 15 cm (Hayden, 1998). The results

obtained from the jaw crusher after processing the diorite material is somewhat questionable and not consistent with the expected outcome when considering the XRD results from both rock samples. Master diorite from the central district was mostly resilient to breakage and showed a high fracture toughness characteristics in comparison to the panda rocks because according to the figure 4.14 and the experimental results of Appendix B, Tables B1 – B4, the material shows partial fragmentation between sieve range 11.2 mm, 6.3 mm and 4.75 mm. From simple observation on the graph 14.7% of the master diorite material that fragmented revealed almost consistent mass distribution within the recorded sieve fractions and this was largely because of high Quartz inclusion of about 12.4% embedded within the material and Chlorites with a monoclinic-primitive crystal structure dominating 2.4% of the matrix composition (Callister , 2007). Based on the outcome of the results for panda diorite mass it can be seen that the sieve range class +13.2 mm, +11.2 mm and +6.3 mm retained the majority of the material that was broken down which accounted 84.90%. Therefore only a small amount of the material was fragmented to lower sieve range and it occupied 12.62 % of the total material being handled mainly due to structural intactness perhaps results due to high percentage of crystalline phases within the panda rock material in comparison. It is therefore recommended that more sieve numbers be used to accommodate the size class range between -20 mm and +13.2 mm for better approximation because breakage mechanism is largely due to attrition and shear rather than compression and impact since the particle are averagely small in diameter.

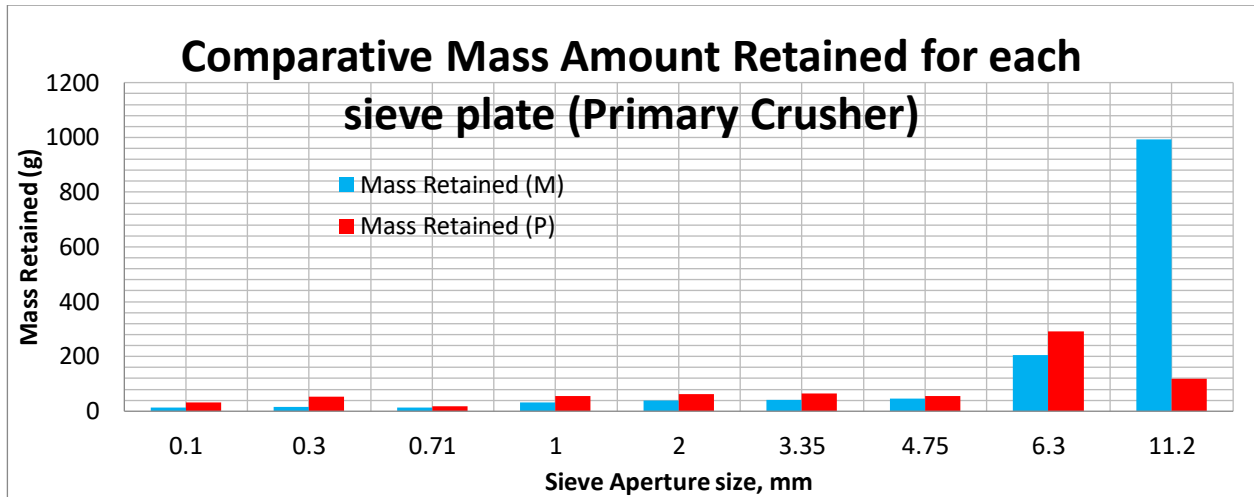


Figure 4.14 showing relative amounts of diorite mass material retained at each sieve interval after primary crushing activity.

According to the graph of figure 4.15 it is clear that from the size class of interest where the road construction aggregate size are commonly harvested being sieve class +4.75 mm and +3.35 mm large quantities of the material were collecting during separation for both master and panda diorite. However the master diorite material is to a greater deal recommended for civil engineering works and infrastructural construction such as steel reinforcement because of high percentage of crusher dust material that is mainly useful to assist the bulk structure in strengthening hence presence of Sericite and Chlorite which are monoclinic in nature and clay can help delay decomposition when exposed to extreme environmental temperature variations and also inclusion within the cement complex for easy mixing can significantly improve the building properties of the material to rendering it more stable and with improved structural hardness.

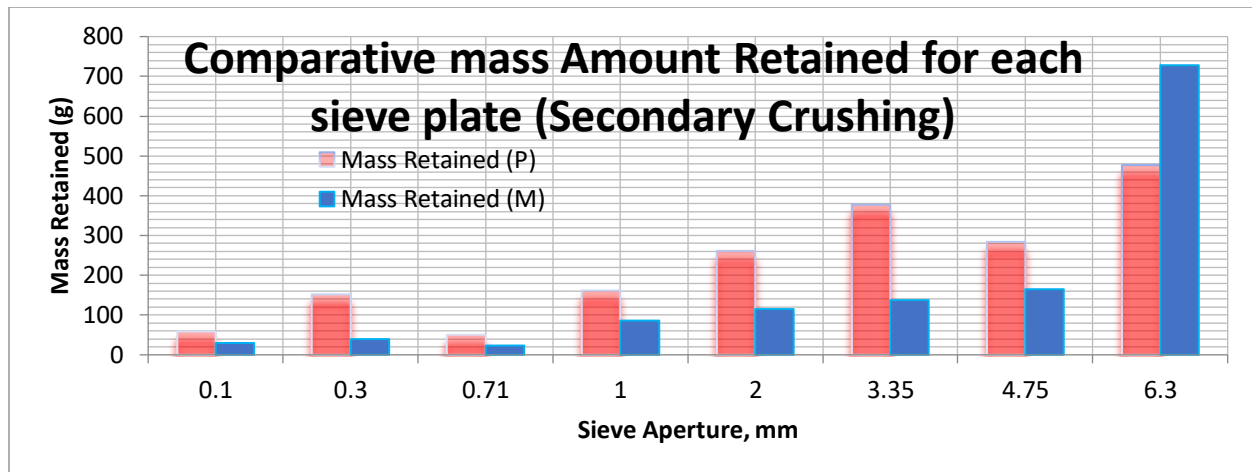


Figure 4.15 shows the mass distribution of the Gyratory crusher equipment after processing master diorite and panda diorite mineral rocks.

Diorite material extensively finds application in various activities and thus studying and understanding the behavior of the material at various particle size is of great significance to the research. Tertiary stage was also performed on the samples within the sieve range that collected majority of the mass after secondary crushing and because of structural intactness for the size class milling was necessary in order to test how the sample would perform especially after grinding for a significant amount of time and 10 minutes was chosen as the best grinding time because there was less or no observable difference in the particle behavior when grinding for more than 10 minutes. The figure 4.16 illustrate the material distribution pattern of the samples and the from the graph there is high confidence on breakage resistance revealed by the panda diorite rock in since there were no recorded values for the size class 0.71 μm and 0.60 μm while for master diorite the majority of the material fragmented to occupied lower sieve size class a factor that could have resulted due to numerous material defects such as voids, high crack density and large amorphous phase presence. It is therefore recommended that when pulverizing panda diorite more grinding time would be required to downsize the particle diameter in comparison to the master diorite material (Wills, et al., 2006).

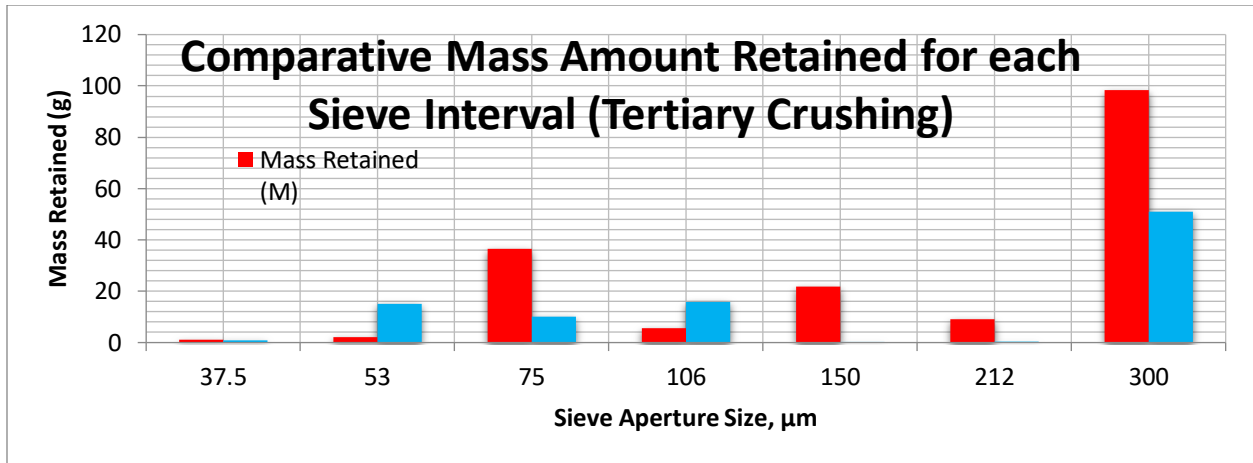


Figure 4.16 show the mass distribution characteristics of master quarry diorite and panda quarry diorite a behavior that was observed after a milling activity that lasted for 10 minutes.

CHAPTER 5

5.0 Conclusions

The main objective of the research was to characterize heterogeneous dioritic ore materials obtained at various quarry mines with an aim of identifying the geochemical composition giving the material its intrinsic properties within each rock sample therefore initially the grain size, granularity, texture and grain distribution of these igneous diorite samples from Serowe (Central region) and Francistown (Northern region) were analyzed using an optical microscopy. Based on the data in appendix A, Table A 1 the bonding characteristics of igneous material are of the ionic type and are generally brittle in nature especially when subjected to diverse loading mechanisms therefore natural residual stress are retained within the material following crystallization, forming, extraction and processing (Callister , 2007), result to disputed grain growth within the whole complex thus leading to development of a heterogeneous crystalline structure with an appearance of a poly crystalline material. It was hence concluded that Master diorite is mostly fine-grained with an average mineral grain size diameter not exceeding < 1 mm and having an interlocking granular texture appearance, while Panda diorite incorporated large grain size mineral particles identified to comprise about 40% of dark amphibole which extensively contribute towards material strength and also 32% plagioclase as can be seen from the information of Appendix B, Tables B1 – B4. The Panda diorite, was also reported to contain particle aggregated size that was slightly above 1 mm due to the magnitude of the identified components. The Master diorite of Serowe central revealed an average grain size with an aphanitic texture as rather porphyritic texture because of fewer grain distributions within a fine-grained matrix and having numerous material defects in contrast to the panda diorite. Particle size analysis (PSD) was employed in assessing quality on the fragmentation products by calibrating the power required (PR), Volume mean diameter (VMD) and the Reduction Ratio (RR) for both the Jaw crusher and Gyratory crusher and master diorite required 41.58 KWh t^{-1} while panda diorite rocks required only 38.33 KWh t^{-1} to fragment using the same crushing laboratory devices.

The laboratory experimental tests of the comminution characteristics on both diorite rock samples suggested that both were suitable for road construction engineering and civil engineering activities because of their high densities and resistant to crushing or fracture

toughness of the material mainly resulting from inclusion of plagioclase and dark amphibole complex. Both materials generally consisted of approximately large grain size constituents and a well-defined composition that would promote the hardness of the material (Gupta, et al., 2016). Studying and understanding the crystallography for the material was the objective of the research and data analysis for master diorite rock displayed random and a homeoblastic grain size distribution with less crystallinity of components because the peak-deflection ration was less compared to panda diorite therefore showing an amorphous phase embedded within its matrix which contributed to inherently fine – grained crystal structure consisting of clay and minor trace constituents of lazurite, and other silicates. Polycrystalline material are generally characterized by poor elasticity which render them poor absorbers of strain energy when subjected to loading mechanisms and from the experimental test of both rocks it was clear that plastic deformation of the material was directly proportional to the number of vacancies within the material as well as material defects which extensively weaken the material fracture properties. According to (Floyd, et al., 1993) structural deformities concentrates the applied strain energy during loading at unique points within the crystal thus promoting asymemetric fracture of the whole rock, trans-granular fracture was dominantly observed in the master diorite because of its inherent defects that lead to poor force transmission within the structure. The components that were identified for both dioritic rock sample contributed significantly toward the inherent mechanical properties and resulted to intrinsic properties such as hardness, toughness, friction resistance etc. Under an optical microscopy random orientation of the grain structure were generally observed that were near homogeneous in panda samples thus making the rock suitable for energy absorption and so, compressive stress and tensile stress during crushing were equally distributed during loading throughout the material.

REFERENCES

- Allen Terence** Powder Sampling and Particle size determination [Book]. - The Netherlands : Elsevier B.V, 2003.
- Angela Raffle E and Gray Muir J** Screening Evidence and Practice [Book]. - Oxford : Oxford University Press, 2007.
- Anthony chukwu and Smart Obiora Chika** whole-rock geochemistry of basic and intermediate intrusive rocks in the ishiagu area: further evidence of anarogenic setting of the lower benue rift, south eastern Nigeria [Journal] // earth science. - 2014. - pp. 427-443.
- Balasubramanian A** SIZE REDUCTION BY GRINDING METHODS [Report]. - Mysore : University of Mysore, 2017.
- Ballantyne Grant R, Hilden Marko and Van der Meer frank peter** improving characterisation of ball milling energy requirements for HPGR products [Journal] // Minerals Engineering . - 2018. - pp. 72-81.
- Barry Wills A and James Finch A** Mineral processing technology [Book Section] // Mineral Processing Technology:- An introduction to the practical aspects of ore treatment and mineral recovery / book auth. Barry wills a. - amsterdam : elsevier, 2016.
- Bogoch Ron, Avigad Dov and Weissbrod Tuvia** Geochemistry of the quartz diorite - granite association, roded area, southern Israel [Journal] // Journal od African Earth science . - 2002. - pp. 51-60.
- Callister william D** Material Science and Engineering: An Introduction [Book]. - united States of America : John Wiley and Sons Inc, 2007. - Vol. 7th.
- Chimwani N, Mulenga F K and Hildebrandt D** Ball size distribution for the maximum production of a narrowly-sized mill product [Journal] // Powder Technology. - 2015. - pp. 12-18.
- Cloos U** Cylpebs: An altenative to balls as grinding media. [Journal] // world mining. - 1983. - pp. 36-59.
- Cullity B D** Elements of x-ray diffraction [Book]. - Reading : Addison-Wesley Publishing Company Inc, 1978.
- Danha G [et al.]** application of basic process modeling in investigating the breakage behavior of UG2 ore in wet milling [Journal] // Powder Technology. - 2015. - pp. 42-48.
- Danha Gwiranai [et al.]** A fundamental investigation on the breakage of a bed of silica sand particles: An attainable region approach. Powder Technology 301 (2016) 1208-1212 [Journal] // Powder Technology . - 2016. - pp. 1208-1212.
- Danha Gwiranai** Identifying opportunities for Increasing the milling efficiency of a Bushveld Igneous Complex (BIC) upper Group (UG) 2 [Report]. - Johannesburg : University of Johannesburg, 2013.
- David Sutherland** Estimation of mineral grain size using automated mineralogy [Journal] // Minerals Engineering. - 2007. - pp. 452-460.
- David Day A, Neal B and Benjamin H** Construction Equipement Guide: Second Edition [Book]. - New York : John Wiley And Sons, Inc, 1991.
- David Williams B and Carter Barry C** Transmission electron microscopy:- A textbook for material science [Book]. - New York : springer-science+business media, LLC, 2009.
- Deniz V** Effects of Two Important Parameters on Capacity of a Laboratory Jaw crusher of different coals: Choke feed levels and effective reduction ration [Journal] // International Journal of Coal Preparation and Utilization. - 2011. - pp. 335-345.
- Deniz V** Effects of two important Parameters on Capicity of a Laboratory Jaw crusher of different coal: choke feed level and effective reduction ration [Journal] // International Journal of Coal Preparation and Utility . - 2011. - pp. 335-345.
- Dhingra Onkar D and Sinclair James B** Basic Plant Pathology Method- Second Edition [Book]. - Boca Raton : Lewis Publishers , 1995.
- Dunne Robert C, Kowatra Komar S and Young Courtney A** SME Mineral Processing and Extractive Metallurgy Handbook:Volume one and two [Book]. - United States of America : Society of for mining, metallurgy and extraction, 2019.
- Floyd P A, Exley C S and Styles M T** Igneous Rocks of South-west England [Book]. - London : CHAPMAN AND HALL, 1993.

Fuerstenau Maurice C and Han Keneth N Principles of Mineral Processing [Book]. - United States of America : Society for mining, metallurgy and exploration, Inc, 2003.

Gavhane K A Unit Operation-I: Fluid flow and Mechanical Operations SI Units [Book]. - Pragati : Arihant Printers, 2009.

Golwalkar Kiran Process Equipment Procurement in the chemical and related industries [Book]. - Switzerland : Springer, 2015.

Gupta A and Yan D S Mineral Processing Design and Operations [Book]. - Amsterdam : Elsevier B.V, 2006.

Gupta Ashok and Yan Denis Mineral Processing Design and Operations [Book]. - Australia : Elsevier B.V, 2016.

Gwiranai Dahna Identifying Opportunities for increasing the milling efficiency of a Bushveld Igneous complex (BIC) upper Group (UG) 2 ore [Book]. - Johannesburg : University of South Africa, 2013.

Hayden Julian D The Sierra Pinacate [Book]. - Canada : The University of Arizona Press, 1998.

Herbst J A and Lo Y C Grinding efficiency with balls or cones as media, [Journal] // International Journal of Mineral Processing . - 1989. - pp. 141-151.

Hlabangana N [et al.] Application of the attainable region method to determine optimal conditions for milling and leaching [Journal] // Powder Technology. - 2017. - pp. 400-407.

Hlabangana N [et al.] A fundamental investigation on the breakage of a bed PGM ore particles: An attainable region approach, part 2. [Journal] // Powder Technology . - 2019. - p. xxx.

Howat D D and Vermeulen L A Fitness of grind and the consumption and wear rates of metallic grinding media in tumbling mills, [Journal] // Powder Technology . - 1988. - pp. 231-240.

HUGHES CHARLES J IGNEOUS PETROLOGY [Book]. - AMSTERDAM : ELSEVIER, 1982.

Ipek H The effects of grinding media shape on breakage rate, [Journal] // Minerals Engineering . - 2006. - pp. 91-93.

James Connolly R Introduction to x-ray diffraction [Report]. - New Mexico : University of New Mexico, 2007.

Jennings B R Particle Size Measurement: the equivalent spherical diameter [Article] // Proceedings of the Royal Society of London. - September 8, 1988. - pp. 137-149.

Jiki Kozlik and Petr Harauba Microstructural and texture formation in commercially pure titanium prepared by cryogenic milling and spark plasma sintering [Journal] // Material Characterization. - 2019. - pp. 1-5.

Joseph Iddings Paxson igneous rocks: composition, texture and classification, description and occurrence [Book]. - New York : John Wiley and Sons, Inc, 1913.

Kapadia Sunny and Weber Alfred Comminution in mineral processing [Report]. - Clausthal : Clausthal University of Technology, 2019.

kawatra Komar S Advantages in comminution [Book]. - Colorado : Society of Mining, Metallurgy and Exploration, Inc, 2006.

Kelsall D F, Stewart P B and Weller K R Continuous grinding in a small wet ball mill Part 5. A study of the influence of media shape [Journal] // Powder Technology . - 1983. - pp. 10-59.

Khumalo N and Glasser D An experimental validation of a specified energy based approach for comminution [Journal] // Chemical Engineering . - 2007. - pp. 2765-2776.

Khumalo N and Hausberger B The application of the attainable region analysis to comminution [Journal] // Chemical Engineering. - 2006. - pp. 5969-5980.

Legendre Daniel and Zevenhoven Ron Assessing the energy efficiency of a Jaw crusher [Journal] // Energy. - 2014. - pp. 119-130.

Lindqvist J E, Akesson U and Malaga K Microstructure and functional properties of rock materials [Journal] // Material Characterization . - 2007. - pp. 1183-1188.

Marcus Johansson, Magnus Bengtson and Magnus Evertsson A Fundamental Model of an Industrial-scale Jaw Crusher [Journal] // Mineral Engineering 105. - 2017. - pp. 69-78.

Mehrotra S P and Shekhar Rajiv Mineral Processing Recent Advantage and Future trends [Book]. - New Delhi Bombay : Allied Publishers limited , 1995.

Michaud L D 911 Metallurgist [Online] // Open and Closed Circuit Crushing . - February 29, 2016. - <https://www.911metallurgist.com/blog/open-or-closed-circuit-crushing>.

Musa Fiesal and Morrison Rob A more sustainable approach to assessing comminution efficiency [Journal] // Minerals Engineering. - 2009. - pp. 593-601.

Pasi Airikka Automatic Feed rate control with feed-forward for crushing and screening process [Journal] // IFAC-PaperOnline. - 2015. - pp. 149-154.

Patil Kiran D Mechanical Operations: fundamental Principles and applications Enlarged and Revised second Edition [Book]. - Pragati : Nirali Prakashan, 2009.

- Peterson M S** Experimental Rock Deformation. The brittle field [Book]. - Australia : Springer-verlag Berlin Heidelberg Gmbll, 1978.
- Qian H Y, Kong Q G and Zhang B L** The effects of grinding media shapes on the grinding kinetics of cement clinder in ball mill. [Journal] // Powder Technology. - 2013. - pp. 422-425.
- Raymond Bayer G** Mechanical Wear fundamental and Testing: Second Edition [Book]. - New York : MARCEL DEKKER, INC, 2004.
- Rhodes Gale** Crystallography made crystal clear [Book]. - Amsterdam : Elsevier, 2006.
- Rustan Agne, Cunningham Claude and Fournery William** Mining and Rock Construction Technology Desk Reference rock mechanics [Book]. - London : Taylor and Francis Group, 2010.
- Sabba Rao D V** Textbook of Mineral Processing [Book]. - Andhra Pradesh : Scientific Publisher (India), 2017.
- Sands Donald E** Introduction to crystallography [Book]. - America : W. A Benjamin, inc, 1969.
- Schmeide K [et al.]** Interaction of U(VI) with Aspo diorite: A batch and In Situ ATR FT-IR sorption study [Journal] // Applied Geochemistry. - 2014. - pp. 116-125.
- Sen G** Introduction to igneous rocks [Book]. - Berlin : springer-verlag berlin heidelberg, 2014.
- Sijing Wang and Marinos P** Proceeding of the 30th International Geological Congress Engineering Geology [Book]. - Netherlands : VSP BV 1997, 1996.
- Simba K P and Moys M H** Effects of mixtures of grinding media of different shapes on milling kinetics, [Journal] // Minerals Engineering . - 2014. - pp. 40-46.
- Stanlvey-wood N G and lines R W** Particle Size Analysis [Book]. - Cambridge : Royal society of chemistry, 1992.
- Sutherland David** estimation of mineral grain size using automated mineralogy [Journal] // Minerals Engineering . - 2007. - pp. 452-460.
- Sutherland David** Estimation of Mineral grain Size using automated Mineralogy [Journal] // Minerals Engineering . - 2007. - pp. 452-460.
- Sutherland David** Estimation of Mineral grain Size Using Automated Mineralogy [Journal] // Minerals Engineering . - 2007. - pp. 452-460.
- Swain Anup K, Patra Hemlata and Roy G K** Mechanical Operation [Book]. - New Delhi : Tafa Mc Graw-Hill, 2011.
- Thorpe Edgar and Thorpe showick** The pearson CSAT Manual [Book]. - India : Dorling Kindersley Pvt. Ltd., 2011.
- vitalij pecharsky k and peter zavalij y** Fundamentals of powder diffraction and structural characterization of materials [Book]. - new york : Springer science + business media, inc , 2003.
- Washington Clive** Particle Size Analysis in Pharmaceutics and other industries, theory and practice [Book]. - new York : Elsevier, 1992.
- Wen S B, Yang C S and Hsieh C S** The abnormal size distribution of comminuted heterogeneous ores due to detachment of grain boundaries fracturing [Journal] // Mineral Processing. - 1997. - pp. 183-200.
- Wills B A and Napier-Munn T J** Will's Mineral Procesing Technology: An Introduction to the Practical Aspects of Ore Treatment and Mineral Recovery [Book]. - Amsterdam : Elsevier , 2006.
- Wills Barry A and Hopkins D W** Mineral Processing Technology: An Introduction to the Practical Aspects of Ore Treatment and mineral recovery (In SI/Metric Units) International series on materials science and technology [Book]. - Amsterdam : Elsevier, 2013.

APPENDIX A: CLASSIFICATION OF MATERIALS BY THEIR INHERENT BONDING TYPE WITHIN THEIR CRYSTAL UNIT STRUCTURE

Table A 1: material classification according to the atomic bonding pattern of the crustal unit (Callister , 2007).

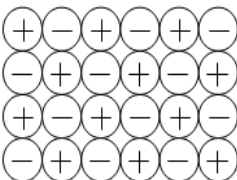
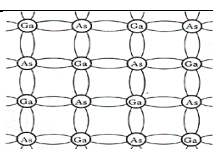
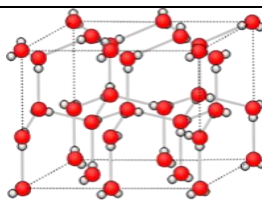
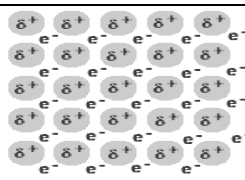
Bond Type and Structure	Bond	Properties	Example
 Ionic bond	Electron/ ionic attraction	▪ Hard ▪ High Melting point ▪ Soluble in polar liquids ▪ Electrical insulators	▪ Alkali Halides ▪ Oxides (Na₂O)
 Covalent bond	Shared Electrons	▪ Very hard ▪ High melting point ▪ Insoluble in nearly all liquids ▪ semiconductors [9]	▪ Diamond, C.
 Molecular bond	Van der Waals Forces	▪ Soft ▪ Low melting and boiling points ▪ Soluble in covalent liquids ▪ Electrical Insulators	Methane (CH₄)
 Metallic bond	Electron Sea	▪ Ductile ▪ Metallic luster ▪ High electric and thermal conductivity	Sodium (Na)

Table A 2: types of Jaw crusher model designs commonly adopted for engineering applications (Wills, et al., 2013)

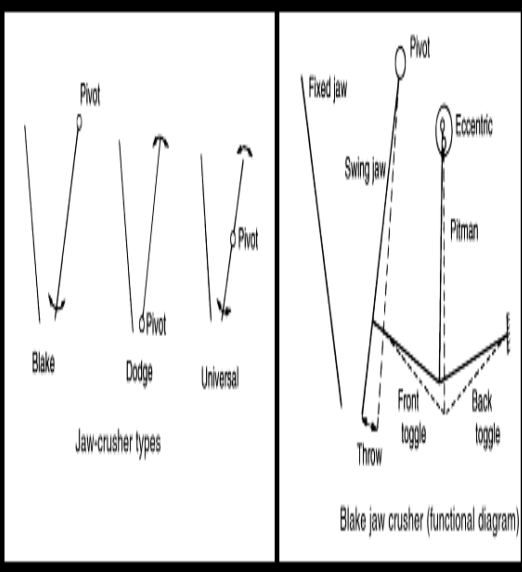
Name	Equipment Classifications	Specifications	Uses
4. Blake	 Jaw-crusher types Blake jaw crusher (functional diagram)	Variable discharge opening and fixed feeding area. Pivot position at the top.	Industrial usage and laboratory.
5. Dodge		Pivot located at bottom with fixed discharge opening and variable feeder area	Laboratory use only.
6. Universal		Receiving and delivery areas are variable as pivot is at the middle.	Industrial usage and laboratory.

Table A 3: Design Long shaft primary gyratory crusher (Barry , et al., 2016)

Characteristics	Small	Large
Size	63.5 – 711 mm	1829 – 2294 mm
Set range	25.4 – 44.5 mm	228 – 305 m
Rev/min	700	175
Power (kW)	2.2	298

Table A 4: Design Long shaft primary gyratory crusher (Barry , et al., 2016)

Characteristics	Small	Large
Size	762 – 1524 mm	2133-2794 mm
Set range	50.8 – 152 mm	178-305 mm
Rev/min	425	275
Motor rating (kW)	149	750

Table A 5: Design Long shaft primary gyratory crusher (Barry , et al., 2016)

Characteristics	Small	Large
Size	203.2-813 mm	635-5538 mm
Set range	31.7 mm	-
Rev/min	750	480
Motor rating (kW)	16.8	83.9

APPENDIX B: COMPARISON OF HETEROGENEOUS AND HOMOGENEOUSITY FOR TWO DIORITE ROCK COMPLEX OF BOTSWANA QUARRIES.

Table B 1: Master diorite rock crystalline phase composition in percentages relative to other constituents.

Mineral	Crystal System	Approximate Formulae	Approximate Abundance %
Plagioclase	Triclinic	$(\text{Ca,Na})_{2-3}(\text{Mg,Fe,Al})_5(\text{Al,Si})_8\text{O}_{22}(\text{OH,F})_2$	39.8
Berlinite	Trigonal	$\text{Al}(\text{PO}_4)$	23.2
Bazzite	Hexagonal	$\text{Be}_3\text{Sc}_2\text{Si}_6\text{O}_{18}$	16.1
Quartz	Trigonal – hexagonal	SiO_2	12.4
Lazurite	Cubic	$(\text{Na,Ca})_8(\text{S,Cl,SO}_4,\text{OH})_2(\text{Al}_6\text{Si}_6\text{O}_{24})$	5.8
Chlorite	Monoclinic-primitive	$(\text{Mg,Fe})_6(\text{Si,Al})_4\text{O}_{10}(\text{OH})_8$	2.4
Sericite	Monoclinic	$\text{KAl}_2(\text{AlSi}_3\text{O}_{10})(\text{OH})_2$	1.2
Total			100

Table B 2: Panda diorite rock crystalline phase composition in percentages relative to other constituents.

Mineral	Crystal System	Repeating Unit	Approximate Abundance %
Dark amphibole	Monoclinic	$\text{Mg}_7\text{Si}_8\text{O}_{22}(\text{OH})_2 - \text{Fe}_7\text{Si}_8\text{O}_{22}(\text{OH})_2 - \text{Ca}_7\text{Si}_8\text{O}_{22}(\text{OH})_2$	39.20
Plagioclase	Triclinic	$\text{NaAlSi}_3\text{O}_8 - \text{CaAl}_2\text{Si}_2\text{O}_8$	31.74
<u>Clinochlore</u>	Monoclinic/ Triclinic	$(\text{Mg, Fe, Al})_6(\text{Si, Al})_4\text{O}_{10}(\text{OH})_8$	12.26
Quartz	Trigonal	SiO_2	6.92
<u>Clinopyroxene</u>	Monoclinic	$(\text{CaNa,Mg,Fe,Al,Ti})_2\text{Si}_2\text{O}_6$	5.70
<u>Dolomite</u>	Trigonal	$\text{CaMg}(\text{CO}_3)_2$	2.78
Micas	Monoclinic	$\text{KAl}_2(\text{Si}_3\text{Al})\text{O}_{10}(\text{OH,F})_2$	1.40
Total			100.00

Table B 3: constituents nomenclature of naturally occurring homogeneous crystalline phase for the Master diorite rock complex and relative abundance in percentages.

Color	Mineral Code	Percentage %
Pale Blue	Plagioclase	39
Brown	Berlinite	23
Grey	Bazzite	16
Yellow	Quartz	13
Light Blue	Lazurite	6
Green	Chlorite	2
Dark Blue	Sericite	1

Table B 4: constituents nomenclature of naturally occurring homogeneous crystalline phase for the Panda diorite rock complex and relative abundance in percentages.

Color	Mineral Code	Percentage %
Pale Blue	Dark amphibole	39
Brown	Plagioclase	32
Grey	Clinochlore	12
Yellow	Quartz	7
Dark Blue	Clinopyroxene	6
Green	Dolomite	3
Light Blue	Micas	1

Table B 5: particle size distribution estimation using sieve stack range for small laboratory experiments regarding size reduction activities together with important statistical mass calculations associated with the fragmentation behavior.

(1) Sieve Size Range (μm)	(2)	(3)	(4) Nominal Aperture size (μm)	(5)	(6)
	Sieve fraction			Cumulative %	
	wt (g)	wt (%)		Undersize	Oversize
+250	0.02	0.1	250	99.9	0.1
-250 to +180	1.32	2.9	180	97.0	3.0
-180 to +125	4.23	9.5	125	87.5	12.5
-125 to +90	9.44	21.2	90	66.3	33.7
-90 to +63	13.10	29.4	63	36.9	63.1
-63 to +45	11.56	26.0	45	10.9	89.1
-45	4.87	10.9			

Table B 6: show the feed material information of the master quarry dioritic rocks that were fed to the Jaw crusher device.

Material	Mass of feed (g)	Mass Fraction (n)	Equivalent diameter (d)	n.d³	n.d⁴
1	480.1	0.33465774 4	68.52	107659.6 4	7376839
2	507.3	0.35361773 3	69.79	120202.5 4	8388935
3	447.2	0.31172452 3	66.92	93419.76 4	6251651
Total	1434.6	1		321281.9 4	2201742 4

Table B 7: show the sifted mass of the master diorite samples after crushing with Jaw crusher equipment in a closed circuiting environment for computation of volume mean diameter of the sample.

Sieve Size, mm (d)	Mass Retained (g)	Mass fraction (n)	n. d³	n. d⁴
+11.2	993.6	0.710678778	998.4525147	11182.668
+6.3	204.7	0.146412989	36.61012867	230.64381
+4.75	46.9	0.033545526	3.595136927	17.0769
+3.35	40.8	0.029182462	1.097125599	3.6753708
+2.0	38.9	0.027823475	0.222587798	0.4451756
+1.0	31.9	0.02281668	0.02281668	0.0228167

+0.71	13	0.009298333	0.003327976	0.0023629
+0.3	15.8	0.011301051	0.000305128	9.154E-05
+0.1	12.5	0.008940705	8.94071E-06	8.941E-07
Total	1398.1	1	1040.003952	11434.535

Table B 8: show the sifted mass results of the master diorite rock samples with estimated values of their sieve fractions and the cumulative mass percentages.

Sieve Size Range (mm)	Sieve Fraction		Nominal Aperture size (µm)	Cumulative Percentage %	
	Mass retained(g)	Weight Percent %		Undersize	Oversize
+11.2	993.6	71.1	11.2	28.9	71.1
+6.30	204.7	14.6	6.30	14.3	85.7
+4.75	46.9	3.35	4.75	10.95	89.05
+3.35	40.8	2.92	3.35	8.03	91.97
+2.0	38.9	2.78	2.0	5.25	94.75
+1.0	31.9	2.28	1.0	2.97	97.03
- +0.71	13.0	0.93	0.71	2.04	97.96
+0.3	15.8	1.13	0.3	0.91	99.09
+0.1	12.5	0.89	0.1	0.02	99.98
TOTAL	1398.1	100			

Table B 9: show the results obtained from sifting the master diorite sample mass products of the Gyrotory crusher device with calculated values of their mass fractions and volume mean diameter of the material.

Sieve Size (d)	Mass Retained (g)	Mass fraction (n)	n.d³	n.d⁴
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+6.3	728.6	0.550926276	137.75746	867.872014
-6.3 to +4.75	164.2	0.12415879	13.30633	63.20506912
-4.75 to +3.35	136.8	0.103440454	3.8888826	13.02775687
-3.35 to +2	115.2	0.08710775	0.696862	1.393724008
-2 to +1.0	86	0.065028355	0.0650284	0.065028355
-1.0 to +0.71	22.8	0.017240076	0.0061704	0.004380993
-0.71 to +0.3	39.9	0.030170132	0.0008146	0.000244378
-0.3 to +0.1	29	0.021928166	2.193E-05	2.19282E-06
Total	1322.5		155.72157	945.5682199

Table B 10: shows the sieve analysis results for a Gyratory crusher device with calculations of cumulative mass percentages and weight fractions for the fragmented mass of master quarry material.

Sieve Size Range (mm)	Sieve Fraction		Nominal Aperture size (µm)	Cumulative Percentage %	
	Mass retain ed(g)	Weight Percent %		Undersize	Oversize
+6.30	728.6	55.09	6.30	28.9	71.1
-6.30 to +4.75	164.2	12.42	4.75	14.3	85.7
-4.75 to +3.35	136.8	10.34	3.35	10.95	89.05
-3.35 to +2.0	115.2	8.71	2.0	8.03	91.97
-2.0 to +1.0	86	6.50	1.0	5.25	94.75
-1.0 to +0.71	22.8	1.72	0.71	2.97	97.03
-0.71 to +0.3	39.9	3.02	0.30	2.04	97.96
-0.3 to +0.1	29	2.19	0.10	0.91	99.09

TOTAL	1322.5	100			
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Table B 11: shows the feed material information of the panda rocks that were fed to the Jaw crusher device with also the mass fraction calibrations.

Material	Mass of feed (g)	Mass Fraction (n)	Equivalent diameter (d)	$n.d^3$	$n.d^4$
1	752.98	0.320554792	79.61	161735.4216	12875756.91
2	749.37	0.319017961	79.48	160172.7788	12730532.46
3	846.64	0.360427247	82.79	204527.2895	16932814.3
Total	2348.99	1		526435.4899	42539103.67

Table B 12: shows information of the sieve range with mass distribution of the panda diorite samples to aid in calculations of the volume mean diameter following fragmentation with a Jaw crusher. The vmd value was found to be **12.954**.

Sieve Size (d)	Mass Retained (g)	Mass fraction (n)	$n.d^3$	$n.d^4$
13.2	1510.22	0.667969977	1536.309571	20279.28634
11.2	117.49	0.051965801	73.0082094	817.6919453
6.3	291.8	0.129063076	32.27183506	203.3125609
4.75	56.04	0.02478648	2.656413513	12.61796419
3.35	64.09	0.028346993	1.065715833	3.57014804
2	62.54	0.027661428	0.221291427	0.442582854
1	55.05	0.024348603	0.024348603	0.024348603
0.71	18.25	0.008071971	0.002889047	0.002051224
0.3	52.29	0.023127856	0.000624452	0.000187336
0.1	33.14	0.014657815	1.46578E-05	1.46578E-06
Total	2260.91	1	1645.560913	21316.94813

Table B 13: shows results obtained from the sieve range and particle distribution values after subjecting the panda diorite samples to a Gyratory crusher the information was vital for volume mean diameter estimation which was found to be **6.334**.

<i>Sieve Size (d)</i>	<i>Mass Retained (g)</i>	<i>Mass fraction (n)</i>	<i>n.d³</i>	<i>n.d⁴</i>
11.2	15.31	0.008320924	11.69029842	130.9313423
6.3	477.35	0.259437808	64.87164552	408.6913667
4.75	283.91	0.154303945	16.53704307	78.5509546
3.35	377.59	0.205218648	7.715272045	25.84616135
2	261.61	0.142183984	1.137471874	2.274943748
1	162.22	0.088165918	0.088165918	0.088165918
0.71	50.93	0.02768025	0.009907066	0.007034017
0.3	152.5	0.082883137	0.002237845	0.000671353
0.1	58.52	0.031805385	3.18054E-05	3.18054E-06
Total	1839.94	1	102.0520736	646.3906432

Table B 14: shows the nominal sieve diameter (d) together with the cumulative undersize percentage passing at every range of the panda diorite rocks that were crushed using Jaw crusher equipment with mass retained at each level.

<i>Sieve size (d)</i>	<i>Mass Retained (g)</i>	<i>Mass fraction (n)</i>	<i>Percentage Retained %</i>	<i>Undersize %</i>	<i>Oversize %</i>
13.2	1510.22	0.667969977	66.79699767	33.20300233	66.79699767
11.2	117.49	0.051965801	5.196580138	28.00642219	71.99357781
6.3	291.8	0.129063076	12.90630764	15.10011456	84.89988544
4.75	56.04	0.02478648	2.478647978	12.62146658	87.37853342
3.35	64.09	0.028346993	2.834699302	9.786767275	90.21323272
2	62.54	0.027661428	2.766142836	7.020624439	92.97937556
1	55.05	0.024348603	2.4348603	4.585764139	95.41423586
0.71	18.25	0.008071971	0.807197102	3.778567037	96.22143296

<i>0.3</i>	<i>52.29</i>	<i>0.023127856</i>	<i>2.31278556</i>	<i>1.465781477</i>	<i>98.53421852</i>
<i>0.1</i>	<i>33.14</i>	<i>0.014657815</i>	<i>1.465781477</i>	<i>0</i>	<i>100</i>
Total	2260.91	1	100		

Table B 15: shows information from the sieve range with panda diorite rocks that were fragmented using Gyrotory crusher and the mass fraction for each section was carefully calculated together with cumulative percentage oversize that were retained.

<i>Sieve Size (d)</i>	<i>Mass Retained (g)</i>	<i>Mass fraction (n)</i>	<i>Percentage Retained %</i>	<i>Undersize %</i>	<i>Oversize %</i>
<i>11.2</i>	<i>15.31</i>	<i>0.008320924</i>	<i>0.832092351</i>	<i>99.16790765</i>	<i>0.832092351</i>
<i>6.3</i>	<i>477.35</i>	<i>0.259437808</i>	<i>25.94378078</i>	<i>73.22412687</i>	<i>26.77587313</i>
<i>4.75</i>	<i>283.91</i>	<i>0.154303945</i>	<i>15.43039447</i>	<i>57.7937324</i>	<i>42.2062676</i>
<i>3.35</i>	<i>377.59</i>	<i>0.205218648</i>	<i>20.52186484</i>	<i>37.27186756</i>	<i>62.72813244</i>
<i>2</i>	<i>261.61</i>	<i>0.142183984</i>	<i>14.21839843</i>	<i>23.05346913</i>	<i>76.94653087</i>
<i>1</i>	<i>162.22</i>	<i>0.088165918</i>	<i>8.816591845</i>	<i>14.23687729</i>	<i>85.76312271</i>
<i>0.71</i>	<i>50.93</i>	<i>0.02768025</i>	<i>2.768025044</i>	<i>11.46885225</i>	<i>88.53114775</i>
<i>0.3</i>	<i>152.5</i>	<i>0.082883137</i>	<i>8.288313749</i>	<i>3.180538496</i>	<i>96.8194615</i>
<i>0.1</i>	<i>58.52</i>	<i>0.031805385</i>	<i>3.180538496</i>	<i>0</i>	<i>100</i>
Total	1839.94	1	100		100

Table B 16: shows the sieve range information that was acquired after successively grinding the master quarry material using a planetary ball mills at four different time intervals of 10 minutes, 15 minutes, 20 minutes and 25 minutes.

<i>Sieve size (mm)</i>	<i>Mass (g) [10 mins]</i>	<i>Mass (g) [15 mins]</i>	<i>Mass (g) [20 mins]</i>	<i>Mass (g) [25 mins]</i>
1000	98.3	93.5	63.8	50.5
710	9.20	1.60	0.70	0.00
600	21.9	13.6	7.70	16.8
300	5.50	10.9	42.3	9.20
200	36.6	39.4	0.70	46.4
100	2.20	1.30	0.10	1.70
75	1.0	0.10	0.00	0.10
Total	174.7	160.4	115.3	124.7

Table B 17: shows the sieve range information that was acquired after successively grinding the panda quarry diorite material using a planetary ball mills at four different time intervals of 5 minutes, 10 minutes, 15 minutes and 20 minutes.

<i>Sieve Size, mm (d)</i>	<i>Mass(g) 5 minutes</i>	<i>Mass(g) 10 minutes</i>	<i>Mass (g) 15 minutes</i>	<i>Mass (g) 20 minutes</i>
1000	59.19	50.87	42.64	32.34
710	2.38	0.41	0.14	0.1
600	1.03	0.2	0.01	0.06
300	5.4	15.8	22.25	32.12
200	9.75	10.18	9.94	15.17

100	14.18	14.98	17.79	12.61
75	0.99	0.79	1.22	0.81
Total	92.92	93.23	93.99	93.21

Table B 18: shows the results of particle distribution for master diorite samples that were grinded for 10 minutes with data for the mill presenting data for the mass retained in the factions and the cumulative percentage passing of undersize.

Sieve Size (d) (mm)	Mass (g) 10 mins	Mass fraction (n)	Percentage Retained %	Undersize %	Oversize %
1000	98.2	0.562	56.24	43.75	56.24
710	9.2	0.0526	5.269	38.48	61.51
600	21.9	0.125	12.54	25.94	74.05
300	5.5	0.0315	3.150	22.79	77.20
200	36.6	0.209	20.9	1.832	98.16
100	2.2	0.0126	1.260	0.572	99.42
75	1	0.0057	0.572	0	100
Total	174.6	1	100		

Table B 19: shows the results of particle distribution for panda diorite samples that were grinded for 10 minutes with data for the mill presenting data for the mass retained in the factions and the cumulative percentage passing of undersize.

Sieve Size (d)	Mass(g) 10 minutes	Mass fraction (n)	Percentage Retained %	Undersize %	Oversize %
1000	50.87	0.545639816	54.56398155	45.43601845	54.56398155
710	0.41	0.004397726	0.439772605	44.99624584	55.00375416

<i>600</i>	<i>0.2</i>	<i>0.002145232</i>	<i>0.214523222</i>	<i>44.78172262</i>	<i>55.21827738</i>
<i>300</i>	<i>15.8</i>	<i>0.169473345</i>	<i>16.94733455</i>	<i>27.83438807</i>	<i>72.16561193</i>
<i>200</i>	<i>10.18</i>	<i>0.10919232</i>	<i>10.91923201</i>	<i>16.91515607</i>	<i>83.08484393</i>
<i>100</i>	<i>14.98</i>	<i>0.160677893</i>	<i>16.06778934</i>	<i>0.847366727</i>	<i>99.15263327</i>
<i>75</i>	<i>0.79</i>	<i>0.008473667</i>	<i>0.847366727</i>	<i>2.84217E-14</i>	<i>100</i>
<i>Total</i>	<i>93.23</i>	<i>1</i>	<i>100</i>		