SCHOOL OF MATERIALS AND MINERAL RESOURCES ENGINEERING

UNIVERSITI SAINS MALAYSIA

A STUDY ON THE RELATIONSHIP OF ROCK STRENGHT AND GRINDABILITY OF LIMESTONE, GRANITE AND METALLIC ORE

By

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DECLARATION

I hereby declare that I have conducted, completed the research work and written the dissertation entitled “A Study on The Relationship of Rock Strength and Grindability of Limestone, Granite and Metallic Ore”. I also declare that it has not been previously submitted for the award of any degree or diploma or other similar title for any other examining body or university.

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TABLE OF CONTENTS

APPENDIX A

APPENDIX B

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS AND SYMBOLS

PLI	Point Load Index Test
UCS	Uniaxial Compressive Strength (MPa)
Is	Uncorrected Point Load Strength Index (MPa)
$Is_{(50)}$	Corrected Point Load Strength Index (MPa)
BWi	Bond Grindbility Work Index (kWh/t)

KAJIAN KE ATAS HUBUNGAN DIANTARA KEKUATAN BATUAN DAN KEBOLEHKISARAN SAMPEL BATU KAPUR, GRANIT DAN BIJIH BERLOGAM

ABSTRAK

Kebolehkisaran sampel batuan bergantung kepada sifat mekanikal bahan dan mekanisma pengisaran. Kekuatan batuan merupakan salah satu sifat mekanikal batuan, dan ia ditakrifkan sebagai nilai tekanan maksima kegagalan batuan. Kajian ini telah dijalankan dengan tujuan untuk mengkaji kesan kekuatan batuan keatas indeks kerja Bond sampel batuan yang berbeza. Ujian Beban Titik (PLI) telah dijalankan untuk menentukan indeks kekuatan beban titik dan untuk menganggarkan Abstrak Kuat Tekan (UCS) sampel batuan. Sementara itu, ujian kebolehkisaran Bond dilakukan untuk menentukan indeks kerja kebolehkisaran Bond sampel batuan. Hubungan antara kekuatan batuan dan kebolehkisaran sampel batuan yang berbeza ditentukan berdasarkan korelasi kekuatan mampatan dan indeks kerja kebolehkisaran Bond. Terdapat korelasi yang kuat antara kekuatan mampatan batuan yang diuji dan indeks kerja Bond mengikut persamaan $Wi = 36.95\ln(x) - 62.31$ dan $Wi = 36.95\ln(x) - 179.76$ dengan koefisien korelasi 92%. Kajian ini telah berjaya menunjukkan bahawa terdapat hubungan yang kukuh antara kekuatan batuan dan kebolehkisaran sampel batuan batu kapur, granit dan bijih berlogam.

A STUDY ON THE RELATIONSHIP OF ROCK STRENGTH AND GRINDABILITY OF LIMESTONE, GRANITE AND METALLIC ORE

ABSTRACT

The grindability of rock samples depends on both the mechanical properties of the materials being ground and the mechanism of grinding. Rock strength is one of the mechanical properties of rock, and it is defined as the maximum value of stress at which the rock fails. This study has been carried out with the aim to study the effect of rock strength on the Bond work index of different rock sample. Point load test was carried out to determine the point load strength index and to estimate the uniaxial compressive strength of the rock sample. While, Bond ball mill grindability test was performed to determine the Bond grindability work index of the rock sample. The relationship between rock strength and grindability of different rock sample was determined based on the correlation of compressive strength and Bond grindability work index. There is a strong correlation found between the compressive strength of tested rock and the Bond work index according to the equation $Wi = 36.95\ln(x) - 62.31$ and $Wi = 36.95\ln(x) - 179.76$ with the correlation coefficient 92%. From this study, it is found that there are a strong relationship between rock strength and grindability of limestone, granite and metallic ore.

CHAPTER 1

INTRODUCTION

1.1 Research Background

In general, rock strength is referred to the maximum value of stress at which the rock fails. The rock strength at failure in unconfined compression or tension is the values which are limited to the samples of any particular rocks alone. The rock in its natural state is always being constraint (West, 2010). So, the strength will depend on the size of the sample, the rate of force applied, the fabric and texture of the rock, uniformity of the rock formed, the size of the mineral grain and a few other factors. The geological condition of the rock also gives influenced to the strength of the rock. Study on the rock strength is important in engineering field such as in civil engineering, mining engineering, mineral processing and petroleum engineering.

In the context of comminution, the rock strength can be defined as resistance of materials to breakage. In this case, the rock strength can be measures based on destructive tests such as point load index (PLI) test and uniaxial compressive strength (UCS) test. It has been a common practice in the mineral industry to relate such tests to comminution attributes (Bearman, Briggs and Kojovic, 1997).

PLI test is an easy and common method that used for determining the compressive strength of rock. The procedure is simple and the sample preparation is also easy compared to the other test. This test is carried out by subjecting a rock specimen to an increasingly intense load until failure occurs on the rock specimen by splitting the rock specimen. The intense load is applied through a pair of truncated conical platens. In PLI test, the point load strength index is determined using the failure load at the rock specimen fails. PLI test also used to estimate the UCS value of the tested rock (ASTM, 1985a).

In mineral processing, there is a process called comminution. Grinding is the last stage in the comminution processes. In grinding stage, the particles of rocks, ores or other materials are liberated and reduced in size by a combination of impact and abrasion. Grinding process is performed in a rotating cylindrical steel vessel that contain a charge of loose crushed rocks, ores or other materials and the grinding medium. The grinding charge is free to move inside the grinding mill, thus liberating and reduced the size of the rocks, ores or other materials particles (Wills and Napier-Munn, 2005c). The most commonly used of grinding media is steel balls and steel rods.

Grindability is defined as the ease with which rocks or materials can be reduced in size and liberated. Data from the grindability tests are used in the evaluation of grinding efficiency. The most widely used parameter to measure ore grindability is the Bond work index (Wills and Napier-Munn, 2005b).

In this study, the rock samples that has been used are limestone, granite and metallic ore. The PLI test is performed to determine the point load strength index (I_s) of the rock samples while the Bond grindability test is carried out to determine the Bond grindability work index (BW_i) of the rock samples. The relationship between the rock strength and grindability of the rock samples then determined by correlate the I_s values with the BW_i. The graph of BW_i against I_s is plotted and the Pearson correlation coefficient, r of the BWi and Is is determined in order to study the relationship of the rock strength and grindability of the rock samples.

1.2 Problem Statements

The objective of mineral processing is to extract valuable minerals from ores. Comminution (crushing and grinding) is the process of size reduction to give sufficient liberation of the valuable mineral to optimal economic recovery. Grinding stage in any processing plant consume large amounts of energy (more than 50% of plant's energy) in comparison to other stages. The grindability of rocks, ores or other materials depends on both the mechanical properties of the materials being ground and the mechanism of grinding. Comprehensive data on the strength of rocks and Bond grindability work index of different types of rocks or materials are available but their relationship is not well established. So, it is interesting to study the effect of rock strength on the Bond grindability work index of different type of rock sample. The work conducted in this study hopefully can be used to correlate the important information between the rock strength and Bond grindability work index of the tested rock. The outcome from this study hopefully can provide more information and benefit to related industries especially in mining, quarrying and mineral processing industries.

1.3 Objectives

The objectives of this research are:

i. To characterize the behaviour and physical properties of different rock samples.
ii. To determine the point load strength index and rock strength classification of different rock samples.
iii. To determine the Bond grindability work index of different rock samples.
iv. To study the relationship of rock strength and grindability of the rock samples.

1.4 Study Area

The rock samples that have been provided are taken from different location of mine and quarry site in Peninsular Malaysia. The sample of limestones are taken from three different quarry sites located in Kinta Valley, Perak. The sample of granite is taken from a quarry located in Bukit Mertajam, Pulau Pinang. Lastly, the sample of metallic ores are taken from Rahman Hydraulic Tin Mine located in Klian Intan, Perak.

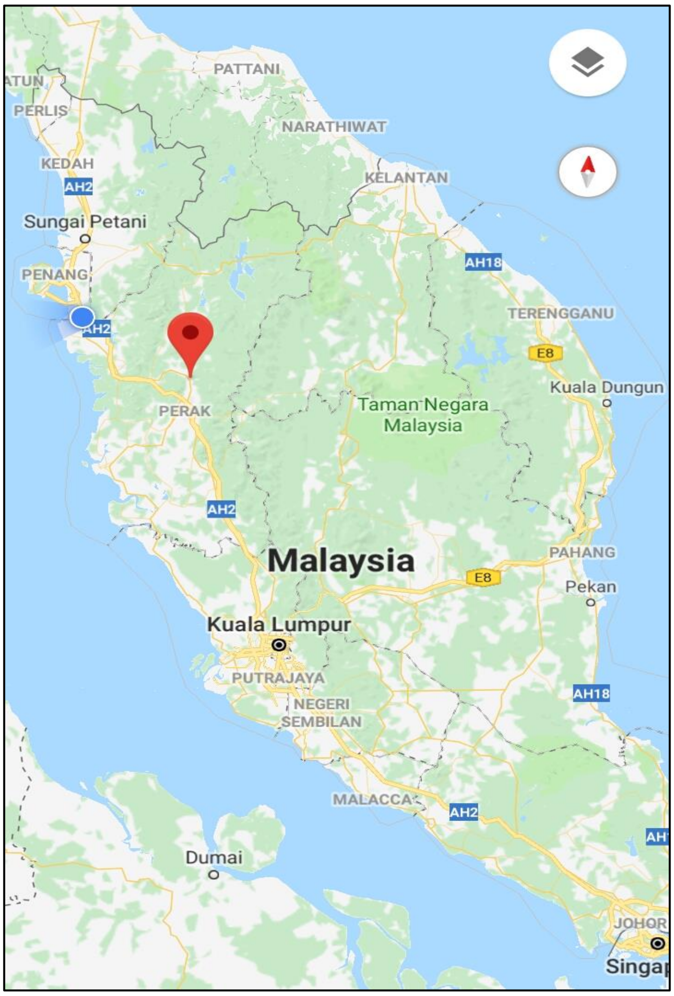


Figure 1.1: Map of Peninsular Malaysia showing state boundaries and the position of Kinta Valley, Perak.

Figure 1.1 shows the location of Kinta Valley, Perak where the sample of limestone are collected. Limestone 1, Limestone 2 and Limestone 3 are taken from Imerys Minerals Malaysia Sdn. Bhd., Tasek Quarries Sdn. Bhd., and Pulai Rock Industries Sdn. Bhd. respectively. Kinta Valley is one of the major limestone deposition areas in Peninsular Malaysia. It is surrounded by jagged terrain of limestone hills name as the Kinta Limestone Formation. It comes in all shape and size, generally formed as a single outcrop with the limestone bedrock is mostly covered by alluvium.

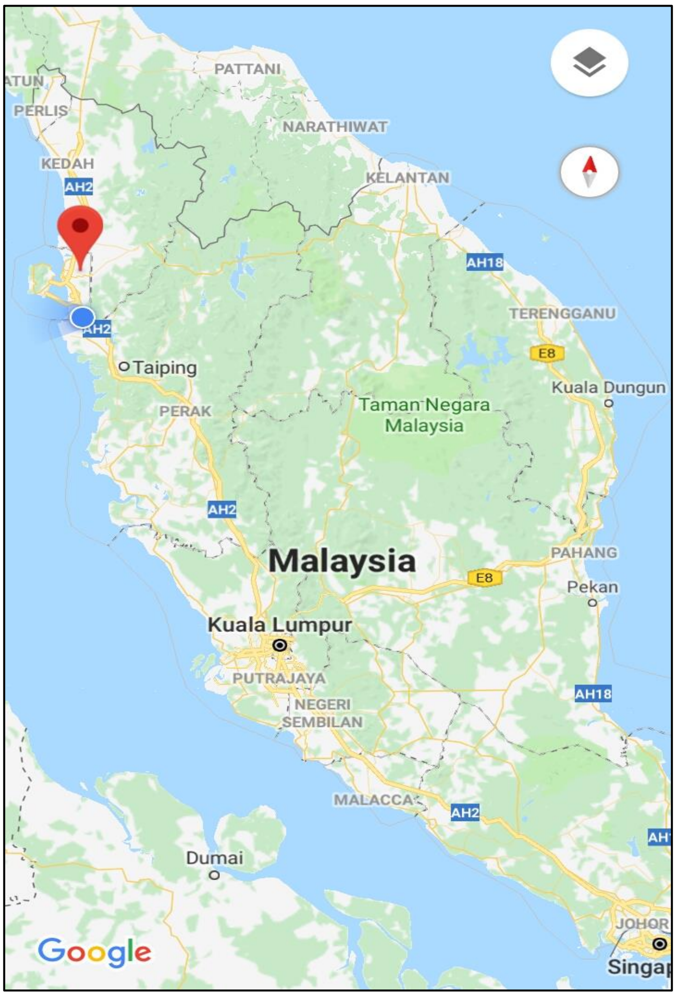


Figure 1.2: Map of Peninsular Malaysia showing state boundaries and the position of Bukit Mertajam, Pulau Pinang.

Figure 1.2 shows the location of Bukit Mertajam, Pulau Pinang where the sample of granite is collected. Granite is taken from Kuad Quarries Sdn. Bhd. Basically, the area of Pulau Pinang is underlain by granite intrusive and sedimentary rocks of the Sungai Petani and Mahang Formations. Bukit Mertajam and other numerous isolated outlying hills to the west are generally made up of medium to coarse-grained porphyritic granite. The quarry site is located near Bukit Penanti, Bukit Mertajam, Pulau Pinang.

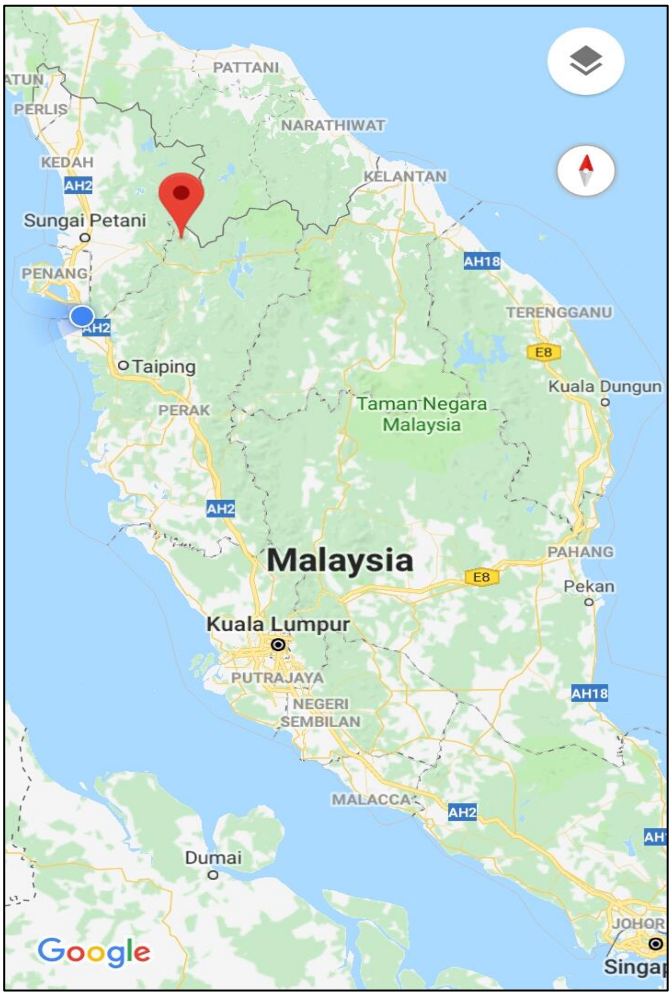


Figure 1.3: Map of Peninsular Malaysia showing state boundaries and the position of Klian Intan, Perak.

Figure 1.3 shows the location of Klian Intan, Perak where the sample of metallic ore are collected. Both Metallic Ore 1 and Metallic Ore 2 are taken from Rahman Hydraulic Tin Mine Sdn. Bhd. Rahman Hydraulic Tin Mine has been in operation in Klian Intan since 1907. Gunung Paku which is located within the western Tin belt of Peninsular Malaysia near Klian Intan is a primary tin deposit in Malaysia. The mining company carried out the largest mining activities of hard rock tin ore in Malaysia. The use of hydraulic pumps to extract tin ore into the hearth distinguishes Rahman Hydraulic from other mines.

1.5 Research Approach

The research was carrying out at the lab of the School of Materials and Mineral Resources Engineering, Engineering Campus, Universiti Sains Malaysia. The samples that were provided are collected from different mine and quarry sites in Peninsular Malaysia.

This project studies on the relationship of rock strength and grindability of different rock samples. The samples that have been used are limestone, granite and metallic ore. Point load index test is performed to determine the point load strength index while Bond grindability test is performed to determine the Bond grindability work index for the grinding process of different rock samples. The behaviour and physical properties of the rock sample also characterized based on the colour, the grain size, degree of weathering and the ease of the rock to break.

1.6 Outline of Thesis

This thesis is divided into five chapters. The first chapter is briefly discussed about the general idea of this research and its purposes. The second chapter is the literature review which is the information that is extracted from the reading of journals and books. The third chapter is methodology which will be discussing about the way to conduct the research. Besides, it also discussed the apparatus and the materials used for the research. In the chapter four, this thesis discusses about the result and discussion of the point load index test and Bond grindability test. The relationship of rock strength and grindability of different rock samples also will be discussed in this chapter four. In chapter five, it is respectively stated the conclusions and the recommendations for future works.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Rock strength is one of the mechanical properties of rock. The strength of rock will affect the grinding process and energy consumed in the mineral processing plant. Therefore, study on the relationship of rock strength and grindability of rock material have been done by many researchers. There is a strong correlation between rock strength and grindability of rock sample. There is a direct proportionality between the BW_i and compressive strength where the BW_i increases with increasing the compressive strength.

2.2 Physical Properties of Rocks

The physical properties of rocks and minerals are commonly used by geologists and mineralogists to help in the identification of a rock and mineral specimen. Some of the properties can be observed easily in the field, but some of them need specific laboratory tests and equipment. The properties are as follow:

a) Colour

Colour is sometimes an extremely diagnostic property of a rock and mineral. Most rocks and minerals have a different and distinctive colour that can be used for identification. Therefore, colour alone is not reliable as a single identifying characteristic of rock and mineral. The colour of rock will depends on the minerals contains on the rock and the occurrence of the rock itself. In opaque minerals, the colour tends to be more consistent, so learning the colours associated with these minerals can be very helpful in identification (Frederick H. Pough, 1996).

b) Cleavage and Fracture

Minerals tend to break along lines or smooth surfaces when hit sharply. Different minerals break in different ways showing different types of cleavage. Cleavage is defined using two sets of criteria. The first set of criteria describes how easily the cleavage is obtained. Cleavage is considered perfect if it is easily obtained and the cleavage planes are easily distinguished. It is considered good if the cleavage is produced with some difficulty but has obvious cleavage planes. Finally, it is considered imperfect if cleavage is obtained with difficulty and some of the planes are difficult to distinguish. Fracture describes the quality of the cleavage surface. Most minerals display either uneven or grainy fracture, conchoidal (curved, shell-like lines) fracture, or hackly (rough, jagged) fracture (Frederick H. Pough, 1996).

c) Texture

The characteristics related to grain size are known as a rock's texture, coarse-grained, fine-grained, and glassy are all descriptions of a rock's texture. The texture of igneous rocks can be analysed to understand how the rock became solid or crystallized from liquid, melted rock (Frederick H. Pough, 1996).

d) Degree of weathering

Rocks can be classified on the basis of its degree of weathering. These types of rock classification give the engineer qualitative idea of rock mass. This type of classification is generally done on site and only by a through visual inspection rocks can be classified. While making classification as per degree of weathering rocks are classified as grade I, II, III etc. Table 2.1 shows the classification of rock based on degree of weathering of the rock mass as suggested by Geological Society of London.

Table 2.1: Weathering grade of rock masses (Brand, 1990).

Grade	Term	Description
I	Fresh rock	No visible sign of material weathering.
II	Slightly weathered rock	Discoloration indicates weathering of rock material and discontinuity of surfaces. All the rock material may be discoloured by weathering and may be somewhat weaker than its fresh condition.
III	Moderately weathered rock	Less than half the rock material is decomposed and/or disintegrates to soil. Fresh or discoloured rock is present either as a continuous frame work of as core stones.
IV	Highly weathered rock	More than half the rock material is decomposed and/or disintegrated to soil. Fresh or discoloured rock is present either as a discontinuous frame work or as core stones.
V	Completely weathered rock	All rock material is decomposed and/or disintegrated to soil. The original mass structure is largely intact.
VI	Residual and colluvial soils	All rock material is converted to soil. The mass structure and material fabric are destroyed. There is a large change in volume, but the soil has not been significantly transported.

2.3 Mechanical Properties of Rock

2.3.1 Strength of Rock

Rock strength is defined as the maximum value of stress at which the rock fails. Generally, there are three primary types of stresses, which are compressive, shear and tensile. West (2010) was stated that the compressive stress tends to decrease the volume of the rock by forces that act inward and directly opposite to each other. While, shear stress is caused by two equal forces acting in opposite directions, and tensile forces tend to pull a substance apart by outward acting, equally opposing forces (West, 2010). The compressive, tensile and shear stresses are illustrated as in Figure 2.1:

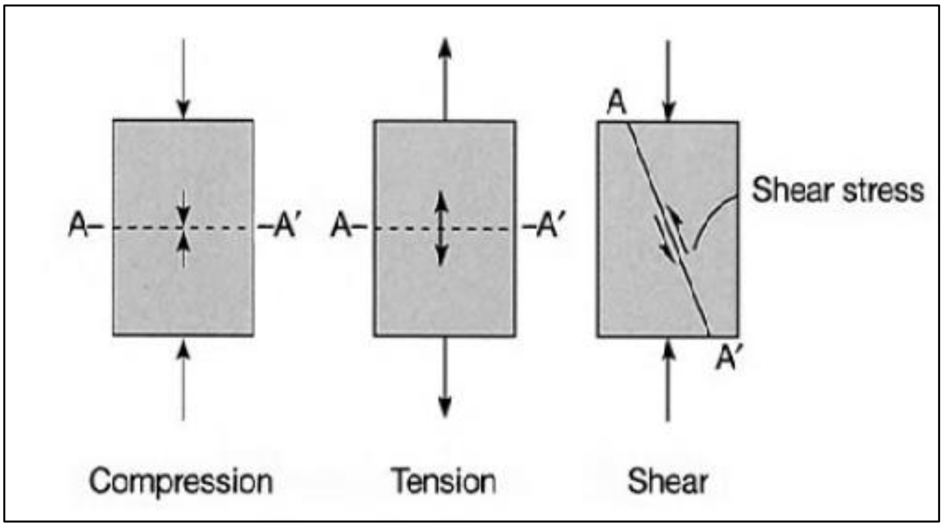


Figure 2.1: Primary type of stresses acting on the rock (West,2010).

The compressive strength of a rock is referred to the compressive stress required to break the specimen. It is measured in the unit of N/m^2 or Pa. The unconfined compressive strength (also known as uniaxial compressive strength) related to rocks unconfined at their sides while the load and pressure is applied vertically until failure occurs. The uniaxial compressive strength is determined by the formula:

$$\sigma = P/A \qquad \text{(Equation 2.1)}$$

where σ is the compressive strength in N/m2. P is the failure load in newtons and A is the cross-sectional area of the sample in m^2. The unconfined compressive strength of rocks normally ranges from a 1 MPa for weak shales to more than 250 MPa for some basalts and quartzites. The rock strength classification was made by referring to the table field estimates of intact rock based on uniaxial compressive strength and point load index (Marinos and Hoek, 2000).

Table 2.2: Field estimates of intact rock (Marinos and Hoek, 2000).

Grade[a]	**Term**	**Uniaxial compressive strength (MPa)**	**Point load index (MPa)**	**Field estimate of strength**	**Examples**
R6	Extremely strong	>250	>10	Specimen can be chipped with a geological hammer	Fresh basalt, chert, diabase, gneiss, granite, quartzite
R5	Very strong	100 – 250	4 – 10	Specimen requires many blows of a geological hammer to fracture it	Amphibolite, sandstone, basalt, gabbro, gneiss, granodiorite, limestone, marble, rhyolite, tuff
R4	Strong	50 – 100	2 – 4	Specimen requires more than one blow of a geological hammer to fracture it	Limestone, marble, phyllite, sandstone, schist, shale
R3	Medium strong	25 – 50	1 – 2	Cannot be scraped or peeled with a pocket knife, specimen can be fractured with a single blow from a geological hammer	Claystone, coal, concrete, schist, shale, siltstone
R2	Weak	5 – 25	[b]	Can be peeled with a pocket knife with difficulty, shallow indentation made by firm blow with point of a geological hammer	Chalk, rocksalt, potash
R1	Very weak	1 – 5	[b]	Crumbles under firm blows with point of a geological hammer, can be peeled by a pocket knife	Highly weathered or altered rock
R0	Extremely weak	0.25 – 1	[b]	Indented by thumbnail	Stiff fault gouge

[a] Grade according to Brown (1981)

[b] Point load tests on rocks with a uniaxial compressive strength below 25 MPa are likely to yield ambiguous results

2.3.2 Laboratory Rock Strength Tests

There are many laboratory tests to study the rock strength of a rock sample whether using triaxial compression, point load test, uniaxial compressive test, direct shear stress and Brazilian test. The most common used method to determine the rock strength is PLI test. This is because, the operating procedure of the test is simple and low cost.

2.3.2.1 Point Load Index Test

The UCS test is used to indicate the compressive strength of the rock specimens, but it is a time-consuming and expensive test that requires specimen preparation. When extensive testing is required for preliminary and reconnaissance information, an alternative test such as point load test can be performed in the field to reduce the time and cost of compressive strength test.

The PLI test is used as an index test for the strength classification of rock materials. The test results should not be used for design or analytical purposes. Rock specimens is in the form of either core (diametral and axial tests), cut blocks (block tests), or irregular-lumps (irregular lump tests) are tested by application of concentrated load through a pair truncated, conical platens. Little or no specimen preparation is required.

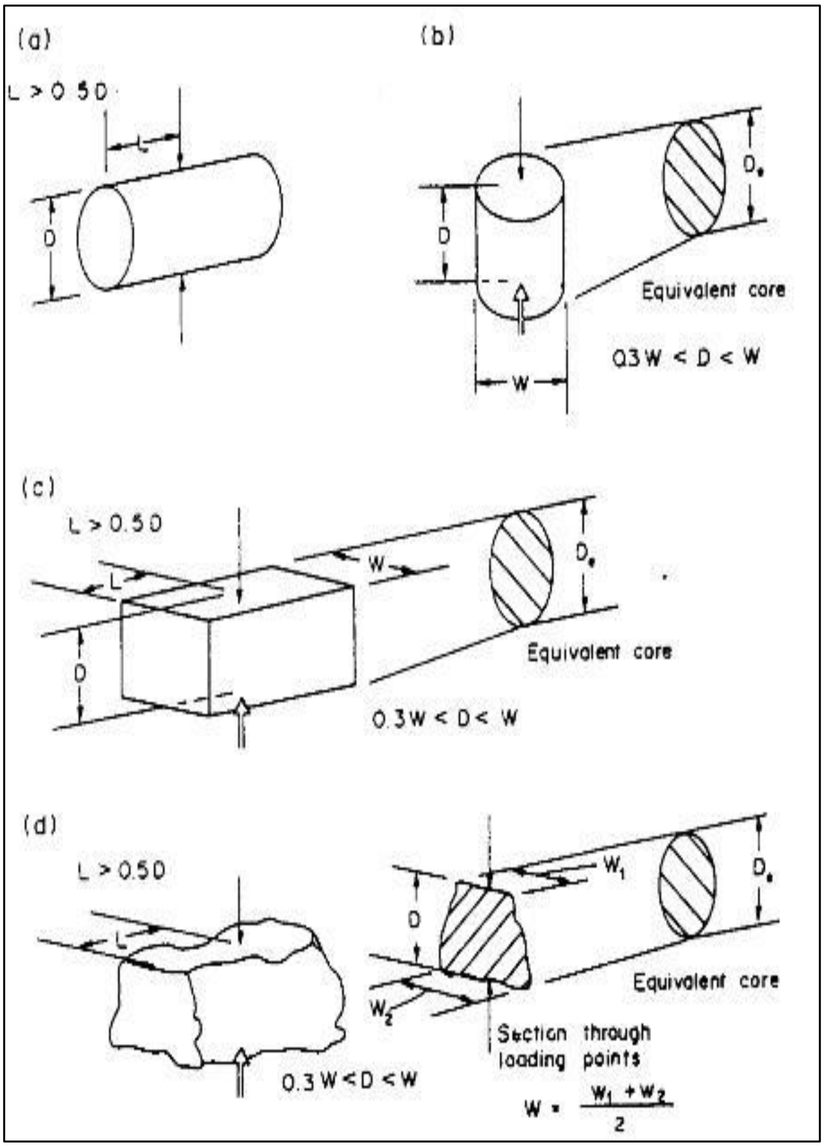
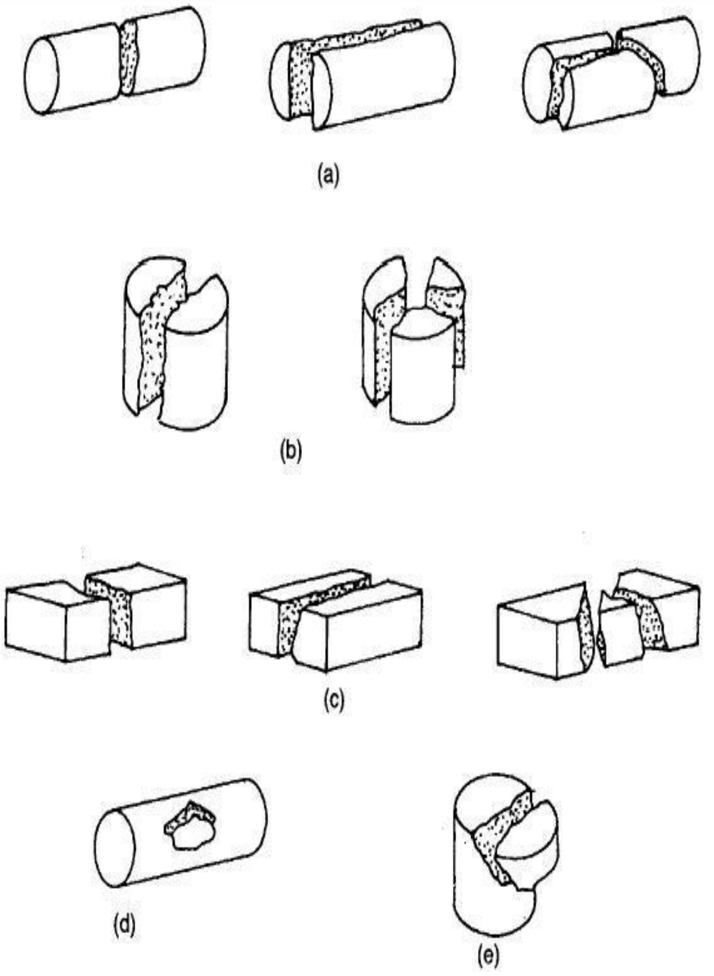


Figure 2.2:Load configuration and specimen shape require for diametral test, axial test, block test and irregular lump test (ASTM D5371).

Rock samples are grouped on the basis of both rock type and estimated strength. When testing core block specimens, at least ten specimens are required. When testing irregular-shaped specimens obtained by other means, at least twenty specimens are required. Specimens in the form of core are preferred for more precise classification. The specimen's external dimensions shall not be less than 30 mm and not more than 85 mm with the preferred dimensions about 50 mm (ASTM, 1985a).



TYPICAL MODES OF FAILURE FOR VALID AND INVALID TESTS (a) VALID DIAMETRAL TESTS, (b) VALID AXIAL TESTS, (c) VALID BLOCK TESTS, (d) INVALID CORE TEST, (e) INVALID AXIAL TEST

Figure 2.3: Typical modes of failure for valid and invalid tests (ASTM D5371).

2.3.3 Effects of Physical Properties of Rock on Rock Strength

2.3.3.1 Effect of Grain Size on Rock Strength

The grain size of rock-forming minerals is the main cause of strength variation (Přikryl *et al.*, 2003). The term of grain size is applied for the average grain size of the major rock-forming minerals. Tensile strength of low porosity rock is higher for the larger grain size and it is corresponds to a very good correlation. It is also observed that weak mineral percentage becomes smaller for larger grain size. It is realized that due to loading, the coarser composition such as quartz becomes the main stress-bearing skeleton and is able to accumulate large quantities of elastic strain energy because of their higher strength and brittleness. In many studies on crystalline rocks, the strength of rock material decreases for larger grain size. Most of the researcher refers to the relationship between grain size and strength which was first linked to Griffith's theory by Brace. In stating the correlation between the grain size and rock strength there are some important factors should be considered. Different rock type has different mineral composition and they also have different micro-scale fracture process. The grain size range of studied rock material is another factor should be considered. Porosity parameter will play a role when the effect of grain size is looked at relatively wide range.

2.3.3.2 Effect of Hardness on Rock Strength

Shalabi, Cording and Al-Hattamleh (2007) stated that there are several studies that have been performed to study the relationship between rock strength and rock hardness. The unconfined compressive strength and modulus of elasticity of rock can be estimated based on simple linear relations between these engineering properties and the hardness of the rock. Poisson's ratio of rock can be predicted based on the results of unconfined compressive strength and hardness. The results will decrease with increase in rock strength and hardness.

2.3.3.3 Effect of Mineral Composition on Rock Strength

Mineralogical composition is one of the main properties controlling the rock strength. Quartz considered as a strong element in rock material. In many studies, there is a strong positive correlation between quartz content and compressive strength where there is the increasing in the strength of rock. Normally, mix of mica and carbonate minerals is the weak mineral's contents. If there is large quartz content then the tensile strength is high, however, if there is higher percentage of a mix of mica and carbonate, then the tensile strength is low. Besides, the limited amount of flaky minerals or easy cleavable also can decrease the tensile strength (Li *et al.*, 2018).

2.4 Grindability Test

Grinding, or also known as milling is the process of size reduction and liberation of the rocks, ores or other materials in the mineral processing industries. It is the last stage in the process of comminution. In this stage, the particles of rocks, ores or other materials are reduced in size by a combination of impact and abrasion. Grinding process is performed in rotating cylindrical steel vessels that loaded with a charge of loose crushing bodies and the grinding medium. The grinding charge is free to move inside the grinding mill, thus liberating the rocks, ores or other materials particles (Wills and Napier-Munn, 2005c). Grindability is defined as the ease with which materials can be liberated, and data from grindability tests are used in the evaluation of grinding efficiency. The common widely used parameter to indicate ore grindability is the Bond work index. If the breakage characteristics of a material remain constant for all size ranges, then the calculated work index would be expected to remain constant since it expresses the resistance of material to breakage (Wills and Napier-Munn, 2005b). However, the breakage characteristics for most naturally occurring raw materials are depending on particle size, which can result in variations in the work index. Besides Bond work index, there is another parameter to measure ore grindability which is Hardgrove grindability index (HGI). Normally, HGI and BW_i is a measure for the grindability of coal (Williams *et al.,* 2015).

2.4.1 Bond Ball Mill Grindability Test

A Bond ball mill grindability test is a standard test to determine the ball mill work index of a sample of ore. This test was developed in 1952 and modified in 1961 by Fred Bond (JKRMC CO., 2006). The test is run in a laboratory ball mill until a 250% of circulating load is developed and will achieved after 7-10 times of grinding cycles, which shows that the procedure is a lengthy and complex one and is therefore susceptible to errors (Ahmadi and Shahsavari, 2009). The alternatives to the standard method have been developed by many researchers because of the difficulty in determination of this index (Deniz and Ekincioğlu, 2006) . In the determination of ball mill work index 15 kg of representative ore at 100% + 3.35mm is crushed to 100% - 3.35mm (Am- tech, 2006). The first grinding test is started with an arbitrarily chosen number of mill revolutions. At the end of each grinding cycle, the entire product is discharged from the mill and is screened on a test sieve. Fresh feed material is added to the oversize to bring the total weight back to that of the original charge. This charge is then re- turned to the mill. The number of revolutions in the second grinding cycle is calculated so as to gradually produce the 250% circulating load. After the second cycle, the same procedure of screening and grinding is continued until the test-sieve under size produced per mill revolution becomes constant for the last three grinding cycles. This will give the 250% circulating load (Bond, 1961).

The purpose of the grinding section is to exercise the product size and for this reason, correct grinding is often said to be the key to good minimal processing.

Undergrinding of the ore will result in the product which is too coarse, with a degree of liberation too low for economic separation, poor recovery and enrichment ratio will be achieved in the concentration stage. Over grinding needlessly reduces the particle size of the subsequently liberated major constituent (usually the gangue) and may reduce the particle size of the minor constituent (usually the mineral value) below the size required for most efficient separation. High energy is wasted in the processes. It is important to realize that grinding is the most energy-intensive operation in mineral processing. It has been estimated that 50% of the energy consumed in a US mills is used in comminution. On a survey of the energy consumed in a number of Canadian copper concentrators it was shown that the average energy consumption in kWh/t was 2.2 for crushing, 11.6 for grinding and 2.6 for floatation (Joe, 1979). Since grinding is the greatest single operating cost, the ore should not be ground any finer than is justified economically. Finer grinding should not be carried out beyond the point where the NSR for the increased recovery become less than the added operating cost (Steane, 1976). It can be shown, using Bon's equation that 19% extra energy must be consumed in grinding one screen size finer on a screen series.

Even though tumbling mills have been developed to a high degree of mechanical efficiency and reliability, they are extremely wasteful in terms of energy expanded, since the ore is mostly broken as a result of repeated, random impacts, which break liberated as well as unreliable particles. There is no practical way at present that these impacts can be directed at the interfaces between the mineral graims, which would produce optimum liberation, although vatious ideas have been postulated (Wills and Atkinson, 1993). Although the correct liberation is the principle purpose of grinding in the mineral processing, this treatment is sometimes used to increase the surface area of the valuable minerals even they may essentially liberated from the gangue.

Grinding within the tumbling mill is influenced by the size, quality, the type of motion and the spaces between the individual pieces of the medium in the mill. As compared to crushing, which takes place between the relatively rigid surface, grinding is a more random process, and is subjected to the laws of probability. The degree of grinding of an ore particle depends on the probability of the ore entering the zone between the medium shapes and the probability of some occurrence taking place after entry.

2.4.2 Bond Work Index

The term grindability work index is mainly used to provide a measure of the difficulty or the energy required to comminute a certain material from an initial coarse size to a finer one. The indices proposed by Hardgrove (1932), and Bond (1961) are related to the equipment used and according used to Fuerstenau and Kapur (1994) to not satisfy the requirement for an ideal measure of the inherent grindability of a solid that must be independent of feed size, product fineness, quantum of energy dissipation and the nature of the comminution equipment employed. Using the experimental methodology of Kerber and Schoenert, describe by Kerber (1984), consisting of an instrumented roll mill that can crish single [articles under compression, Fuerstenau and Kapur (1994) have proposed a new grindability index that still is dependent on feed size. One should note that the dimensions of these indices are energy per unit mass (kWh/t). (Elias Th. Stamboliadis, 2006).

The Bond equation (Bond, 1952) is the most widely used in the mineral processing for designing size reduction unit operation. The Bond work index is used to estimates the required energy to grind the rocks or ore sample using a specific lab-scale ball mill (Bond, 1960). The Bond equation is given by:

$$\mathrm{W} = 10\mathrm{Wi}\left(\frac{1}{\sqrt{\mathrm{P}}} - \frac{1}{\sqrt{\mathrm{F}}}\right) \qquad \text{(Equation 2.2)}$$

where W is the required energy of breakage in kWh/t and Wi is the Bond work index in kWh/t. P and F are the sizes aperture of the screens in microns through which 80% of the product and feed pass respectively. Numerical Wi is the energy in kilowatt hours per tonne required to reduce the material from notational infinite feed size to 80% passing 100µm. In practice Wi has to be determined from plant data or by conducting laboratory grinding tests in which W, P and F are measured. Theoretically, the standard Bond work index can be calculated by using this formula:

$$W_i = \frac{44.5}{\mathrm{P_i}^{0.23} \times \mathrm{Gb}^{0.82}\left(\frac{10}{\sqrt{\mathrm{P}_{80}}} - \frac{10}{\sqrt{\mathrm{F}_{80}}}\right)} \qquad \text{(Equation 2.3)}$$

where Pi is the sieve opening at which the test is made in micron, Gb is Bond standard ball mill grindability, net grams of ball mill product passing sieve size Pi produced per mill revolution (g/rev), P_{80} is the sieve opening which 80% of the product passes in micron and F_{80} is the sieve opening which 80% of the feed passes in micron.

The BWi is a measure of ore grindability. A typical classification of BWi for ore grinding behaviour is documented by Napier-Munn et al. (1996). Based on their classification, an ore with BWi value of less than 9kWh/t is regarded as soft for grinding and a BWi value of more than 14kWh/t is hard. The BWi values between 9 and 14 kWh/t are considered as medium for grinding. Measurement of Bond ball mill work index requires a large amount of material (~30Kg) for sample preparation.

Grindability is based upon performance in carefully defined piece of equipment according to a strict procedure. The Bond standard grindability test has been described in detail by Deister (1978), and Levin (1989) has proposed a method for determining the grindability of the materials. Table below lists standard Bond work indices for a selection of materials (Wills and Napier-Munn, 2005b)

Table 2.3: Selection of Bond work indices.

Material	**Work index (Wi)**
Barite	4.73
Bauxite	8.78
Coal	13.00
Dolomite	11.27
Emery	56.70
Ferro-silicon	10.01
Fluorspar	8.91
Granite	15.13
Graphite	43.56
Limestone	12.74
Quartzite	9.58
Quartz	13.57

The Bond Wi can be used not only for determining the grinding power but also can used to estimate the difference in power consumption while handling material of difference hardness. Every material has a characteristic bonding strength at molecular and grain level. The power required to break the bonds is higher for harder materials. The effect of circulating load and test sieve size on the Bond grindability index and Bond work index has been investigated.

Bond (1952) proposed the Third Law of grinding. The law states that the net energy required in comminution is proportional to the total length of the new cracks formed. The equation is:

$$E = K3\left(\frac{1}{\sqrt{xp}} - \frac{1}{\sqrt{xf}}\right) \qquad \text{(Equation 2.4)}$$

where E is the net specific energy, xf and xp are the feed and product size indices respectively, and K3 is constant. Bond (1962) evaluated these energy-size relationships stating that each of Rittinger, Kick and Bond theories might be applicable for different narrow size ranges. Kick's equation is applicable in the conventional milling range.

Application of Kick's and Rittinger's theories has been met with varied success and realistic for desingning size reduction circuits (Charles,1957). However, Bond's Third Law empirical basis of Bond's theory, it is the most widely used method for the sizing of grinding mills and has become more likely a standard.

Deniz and Umucu (2013) was studied the interrelationships between the Bond Grindability with Physicomechanical and Chemical Properties of Coal. In the research, different techniques for the estimation of Bond grindability (Gbg) values of coals are studied. Data from ten sub-bituminous coals from Turkey are used by featuring physicomechanical (ISI, Is, and FD) and eight chemical coal parameters, which include proximate analysis (moisture, ash, volatile matter, fixed carbon, and calorie). Linear and multivariable linear regression techniques are used for predicting the Gbg values for the specified coal parameters. Results indicate that a multivariable linear regression gave the most accurate Gbg prediction than simple regression in the estimation process (Deniz and Umucu, 2013).