SCHOOL OF MATERIALS AND MINERAL RESOURCES ENGINEERING

ENGINEERING CAMPUS

UNIVERSITI SAINS MALAYSIA

VALIDATION OF ESTABLISHED METHODS FOR DETERMINATION OF FINE PARTICLE BREAKAGE

By

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Dissertation submitted in partial fulfillment

of the requirements for the degree of Bachelor of Engineering with Honours

(Mineral Resources Engineering)

Universiti Sains Malaysia

June 2017

DECLARATION

I hereby declare that I have conducted, completed the research work and written the dissertation entitled "Validation of Established Methods for Determination of Fine Particle Breakage". I also declare that it has not been previously submitted for the award of any degree or diploma or other similar title of this for any other examining body or University.

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Date : 1st JUNE 2017

ACKNOWLEDGEMENTS

First of all, thanks to The Almighty Allah for giving me the strength to endure all the challenges during completing my Final Year Project. There are countless of people that I would like to express the deepest appreciation for lending me a hand throughout this project. Besides, I am able to gain some precious knowledge in term of size reduction process. I take this opportunity to record my sincere thanks to Assoc. Prof Ir Dr Syed Fuad Sayid Hashim for his guidance and advice throughout this project. I am highly indebted to Dr Syed Fuad for his tremendous support and valuable assistance during the process of completing this final year project. Without his continuous encouragement, I won't be able to achieve for this level.

A special thanks to Ms. Norazirah Ahmad, a master student under the Dr. Syed Fuad supervision for her endless support and guidance. I place on record, my sincere gratitude to my university, Univeristi Sains Malaysia for providing necessary facilities for my research. Last but not least, I would like to compliment and give credit to my family and colleagues for continuous support and encouragement during my ups and downs.

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LIST OF ABBREVIATIONS & SYMBOLS

JKMRC	Julius- Kruttschnitt Mineral Research Centre
ECS	Specific Communition Energy
Eis	Specific Input Energy
mm	millimeter
%	Percentage

ABSTRAK

Kajian ini dijalankan dengan tujuan untuk mengesahkan dua kaedah yang telah dicipta untuk mengkaji ciri - ciri pemecahan bahan dan kesan saiz partikel terhadap pemecahan, Dalam konteks ini, kajian adalah bertumpukan partikel halus. Oleh kerana mana-mana proses pemecahan batu menggunakan tenaga yang tinggi, JKMRC telah memulakan usaha untuk mengetahui ciri pemecahan. Ujian pencirian batu telah dihasilkan untuk tujuan ini iaitu; pemecahan berkumpulan dan pemecahan satu batu. Hasil daripad ujikaji ini akan menghasilkan data untuk menganalisa kesan pemecahan batu. Kemudian, nilai t10 yang menunjukkan darjah kehalusan digunakan untuk mendapatkan nilai parameter a dan b. Akhir sekali, nilai graf pemecahan akan diperolehi. Hasilnya, pemecahan berkumpulan tidak dipengaruhi oleh size kerana grafnya adalah sama bagi semua saiz. Walaubagaimanapun, pemecahan satu batu menunjukkan keputusan yang agak berbeza kerana nilai graf adalah berbeza bagi setiap size. Namun begitu, perbezaan itu ada sangat kecil dan boleh dilupuskan. Oleh itu, kesimpulannya, kedua- dua kaedah ini sesuai digunakan dan saiz tidak mempengaruhi pemecahan batu untuk mana mana kaedah.

ABSTRACT

The objective of the study is to validate two methods which have already been establish to study the breakage behaviour of materials and study the effect of particle size on the breakage of particles. In this case, it focuses on fine particle breakage. As any size reduction process consumes much energy, JKMRC initiated the study of breakage behaviour of material. Laboratory ore characterization tests are derived for this purposes; bed breakage and single particle breakage. Result of these tests would produce the date that is needed for the particle size analysis. From this analysis, t10 values- fineness index will be created and used to compute the a, b parameters. These parameters are then finally being used to get the breakage function. Result of breakage function displays the same breakage function value for bed breakage method. Hence, size doesn't affect the breakage in bed breakage. However, result of single particle breakage shows a slight difference of breakage function value for the different size. The difference is so small that it is considered as not significant. This leads to a conclusion that, both methods are suitable to determine the breakage behavior and size does not affect the breakage of particles for both methods.

CHAPTER 1

Introduction

1.1 Introduction

Commonly, valuable minerals are interconnected and associated closely with the gangue minerals. In order to achieve the separation, they must be “unlocked” or “liberated”. This can be achieved by *comminution*, a process in which the size of the ore is gradually reduced until the liberation state is reached. *Comminution* of ores is performed in the mineral processing plant by crushing or grinding process. Crushing is accomplished by several mechanisms; compression, impaction, abrasion and shearing of the ore against rigid surfaces. Grinding is in the other hand performed by impaction and abrasion of the ore, by the free moving media such as balls, pebbles or rods.

Comminution is always associated with the energy-size relationship as the energy input will determine and contribute to the size reduction of ores. Nevertheless, most of the energy input to a crushing/ grinding machine is lost by the machine itself; hence a small balance is available for breaking the ores. Consumption of energy will be governed not only by the duty but also the ‘hardness’ of the material to be broken. In any comminution related work, the focus has always been to develop reliable ways to evaluate how a particular material breaks.

Speaking of hardness, it is a complex physical characteristic, hard to be defined and not necessarily straightforward. Common rock mechanics strength tests like uniaxial or biaxial compressive test is not really accurate for comminution studies since it provides information on stress required to cause failure.

Meanwhile, in comminution, it concentrates on product size distribution resulting from a particular breakage mechanism which involves given feed size, energy needed to produce product size.

In order to know how material breaks, breakage characterisation tests with respect to comminution energy and size reduction are derived. Breakage behaviour of material is vital for comminution machines and it is defined by the breakage distribution function. Tests are made to predict the performance of these comminution machines by simulation. In addition, it is also aiding the comminution equipment specification, circuit design and optimisation. The tests are including Bond test, batch grinding, bed breakage test and single particle impact test.

These tests are developed at the JKMRC for assessing impact breakage properties of ores. They are classified under drop weight technique which is the convenient and practical methods for determination of breakage distribution of different particle sizes at various energies. They provide information on energy utilization during size reduction. These tests will yield the product particle size analysis that will be utilised to get t_n values which later would give the A, b parameters and finally appearance function/breakage probability function is created. These results will aid to understand how breakage of particle in comminution machines behaves.

1.2 Objectives

I. To determine the effect of size of particle on breakage of limestone.

I. To validate the methods used in determining fine particles breakage.

II. To compare the fine particle breakage in different methods.

1.3 Problem Statement

Comminution is not an energy friendly process as the energy is mostly used by the machines itself and not being utilised to do the breakage effectively. Most of the energy supplied would be released as heat, leaving a few percents left for the real breakage to take place. Energy wastage is a common issue in comminution which would cost a lot due to the high energy usage. In addition, these machineries would cost more on maintenance because they tend to face damages in short period.

The problems get tougher when it involves a variation of sizes of particle, shapes and properties of rocks as it is very complicated to regulate the optimum rate for maximum breakage to happen. These complications have already taken into the consideration of the professionals to scrutinize the finest way to simulate the comminution, on fine particle breakage especially, with variety of sizes in order to come up with several better understandings.

Breakage behaviour of material is significant for modelling of size reduction equipment as every material has different breakage characteristics. Determination of fine particle breakage is even more essential to make models reliable. The breakage behaviour of coarse particles has already been identified, but the understanding of fine particle breakage is still blurry and uncertain. An effort for evaluating fine particle breakage behaviour is developed and modelled to reflect the effect results. Hence, this study would focus totally on fine particle breakage.

In order to curb this problem, laboratory tests are carried out to observe the breakage behaviour/ breakage characteristics of the fine materials. Tests included are bed breakage test & single particle impact test. Since there are 2 tests available to simulate the breakage, this study aims to validate these tests, compare the results in terms of the breakage probability, appearance function and breakage function, and finally to conclude the effect of sizes of particles on breakage for both methods.

1.4 Scope

This study focuses on fine particles of limestone that will be tested by the different type of tests; bed breakage & single particle impact test.

Table 1; Scope of study in bed breakage

Size fraction (mm)	Specific comminution energy (kWh/t)		
-5+4.75mm	2	3	5
-4.75+3.35mm	X	X	X
-3.35+2.36mm	X	x	X
-2.36+1.18mm	X	x	X
-1.18+0.850mm	X	X	x

Table 1.2; Scope of study in single particle breakage

Size fraction (mm)	Specific comminution energy (kWh/t)		
-5+4.75mm	2	3	5
-4.75+3.35mm	X	X	X
-3.35+2.36mm	X	x	X

CHAPTER 2

Literature Review

2.1 Introduction

Comminution means disintegration, the breaking down of mineral to smaller sizes, reducing the size of ores from coarse to finer in order to separate the valuable minerals from the gangue. Gangue is the unwanted or less valuable mineral that is uneconomical to be processed. Blasting can be considered as the first stage in comminution as explosives are used to remove the ores from their original natural bed. Minerals from run-of-mine come in all ranges of sizes; from lumps to small chips and dust. Crushing and grinding are later performed in plant for further size reduction. It is performed in several stages; primary, secondary, tertiary and quaternary with small reduction ratio ranging from 3-6.

Crushing is the first mechanical stage in comminution which is usually a dry operation, performed in 2-3 stages. First crushing process performed on the sample is primary stage followed by secondary stage which reclaims all the primary crushing products and finally tertiary stage. Note that in every crushing process, it comes with vibrating screen to separate undersize and oversize particles. Crushing may be in open/closed circuit depending on the product size. Examples of crushers are jaw crusher, gyratory crusher and cone crusher.

Grinding is the last stage in comminution where particles are reduced in size by impaction and abrasion either in dry or wet process. This step takes place in rotating cylinder steel vessel which contains grinding medium that moves freely inside mill to break the particles.

Grinding mills are classified in two types which depend on the motion of the medium; tumbling & stirred mill. Examples of mills are ball mill, AG mill and roller mill.

Grinding mechanisms include impact/ compression, due to the force applied almost normally to the particle surface; chipping due to oblique forces; and abrasion due to forces acting parallel to the surfaces. These mechanisms distort the particles, change their shape beyond limits and cause breakage.

Nevertheless, comminution since the beginning is an energy-intensive process as much expensive energy is wasted. It is extremely wasteful in terms of energy expended, since the ore is mostly broken in repetition and random impacts. The energy supplied is used in the production of heat which means by the machine itself and only a little amount of energy is used for the breakage. In a ball mill, for instance, it has been shown that less than 1% of the total energy input is available for actual size reduction in ball mill (Wills et al ., 1979).

Material characterization is vital to determine the machine suitability and overall circuit performance. The properties of materials can be listed as grindability, breakage, crushability and mineralogy which can be easily determined. Materials breakage behaviour is one of the significant properties that are taken into consideration in comminution machines as it illustrates how materials break; the breakage distribution function (Eksi et al., 2010) Some laboratory breakage characterisation tests have been developed to assist in comminution equipment specifications, circuit design and optimisation. In particular, it focuses on the energy-size reduction relationship. For example, bond test, bed breakage test and singe particle testing. These tests are essential as they predict the performance of industrial comminution machines by simulation.

The significant parameters on breakage characteristics of most materials may include particle size, shape and ore type. In order to model the effect of particle size on breakage, determination of breakage behaviour of fine particles becomes crucial.

Bed breakage test and single particle impact test are carried out to determine the fine particles breakage.

2.2 History of Comminution Research

In the mineral processing circuit operation, comminution phase is crucial to obtain the valueable mineral as it needs to be separated and liberated. Rock breakage process has always been an energy intensive compared to other mining processes. (Ballantyne et al ., 2014) stated that, comminution equipment consumed 36% of mining energy. The comminution energy per unit metal product has been presented in a graphical form similar to a cost curve (Figure 2.1)

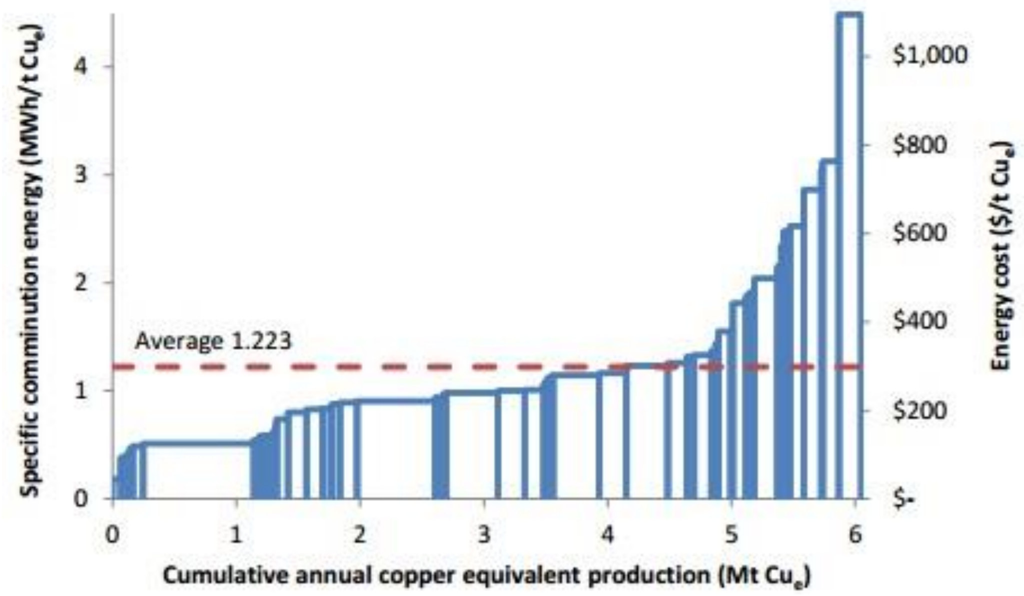

Figure 2.1; The comminution energy per unit metal (Ballantyne et al., 2004)

Intensive comminution energy is required due to the incompetence of the comminution machine such as crusher, mill and grinding roll.

For instance; primary crushers are commonly designed to operate 75% of the available time, however interruption has caused by insufficient crusher feed and by mechanical delays in crusher (Lewis et al., 1976)

Therefore, it is a must to reduce or optimizing the energy requirement in this stage. The drive in comminution research has mainly been to understand the causatives and breakage (Austin et al., 2002, Schonert et al., 1991, Austin et al., 1971). Over the years, studies have been conducted concerning the breakage in comminution machine to understand the breakage mechanism in comminution machine. The profound founding reached is that the particle size reduction occurs via three basic mechanisms (Napier-Mun et al., 1999) ;

- Impact breakage: A high force/ shock introduced to a surface over a short period of time when two or more bodies collide. The effects depend on the velocity of one bodies and another.
- Abrasion: Mechanical scraping of a rock surface by friction between rocks or friction between rocks and wall of comminution machines. The intensity of abrasion is based on the hardness, concentration, velocity or mass of the moving particles.
- Attrition: A small pebbles from previous larger rocks grind into finer size. It typically occurs at faster rate than abrasion mechanism.

2.3 Theories of comminution

Communition theory concerns the relationship on energy input- product size distribution. As mentioned, comminution contains problem that lesser its efficiency; energy wastage. There is a relationship between energy needed to break material and the new surface produced in the process, but this is legit if the energy consumed in creating new surface can be measured separately. Another factor is plastic materials will consume more energy to change its shape which it will retain without producing any significant surface. Hence, all comminution theories assume that the material is brittle so that no energy is adsorbed in the processes. (Wills et al., 1979)

Various theories have been suggested, none of them is entirely satisfactory (Wills et al., 1993). (Kolsky et al., 1949) and (Fuerstenau et al., 1995) state that these theories have been modified to suit the modern circuit. The most important aspects to be considered are (Maurice et al., 2003);

- Breakage of ore particles needs forces and energy that significantly depend on size and composition.
- Breakage of small particles requires extremely large forces.
- Accurate prediction of the size distribution of broken fragments for a given energy input has required the development of detailed models.
- Increase classification efficiency contributes significantly to improved energy economy in comminution technology.

In 1867, Rittinger proposed that the energy consumed in the size reduction is directly proportional to the new surface formed. The surface area of a known weight of particles with uniform diameter is inversely proportional to the diameter, hence;

$E = K (1/D_2 - 1/D_1)$ where;

E= energy input, D_1 = initial particle size, D_2 = final particle size, K= constant

"Rittinger law shows that energy required to break a particle from 10µm to 1µm is 100 times greater than energy required to break a 1000µm particle to 100µm."

Second theory is that of Kick (1885) who stated that the work required is proportional to the reduction in volume of the particles concerned. Reduction ratio, *R*, if *f/p* where *f* is the diameter of feed particles and *p* is the diameter of product particles (Wills et al., 1979) Kick suggested that the energy required for producing a specified reduction ratio is proportional to the log of reduction ratio. (Jain et al., 1987)

$E = K_2 \ln (X_f / X_p)$ where;

E = net specific energy, X_f and X_p are the feed and product indices, K_2 = constant

Third theory was proposed by Bond (1952) that the work input is directly correlates to the new crack tip length formed in particle breakage and equals the work done by the product minus that represented by the feed. For similar shape particles, the surface area of unit volume of material is inversely proportional to the diameter. The crack length in unit volume is considered proportional to one side of that area and so inversely proportional to the diameter square root.

Bond's 3rd theory; $W= \frac{10Wi}{\sqrt{P}} - \frac{10Wi}{\sqrt{F}}$ where; W is work input in kWh/t, Wi= work index, P= diameter in microns which 80% of the product pass, F = size which 80% of feed pass.

Hukki (1975) suggests that the energy-particle size relationship is a composite form of three laws. The breakage probability is high for large particles, and goes lower for finer sizes. Kick's law is reasonably accurate for crushing range above about 1cm diameter; Bond's theory can be applied in the range of conventional rod and ball mill grinding and Rittinger's law applies well in fine grinding range of 10 – 1000 µm (B.A Wills ,. 1979)

2.4 Breakage & fine ore characterisation

The main objective of this paper is to get the breakage distribution function which would explain the breakage characteristics. There are many approaches to calculate this function and represent it mathematically. Yet, breakage distribution function can also be formed by using batch grinding test in laboratory mills, back calculation method and single particle breakage under controlled condition. In this dissertation, it focuses on single particle & bed breakage characterization.

Few types of tests can be conducted to characterize this breakage for comminution modelling. Three methods are available for the single particle and bed breakage under controlled conditions; impact test, slow compression test & abrasion test. Impact test method includes single impact test & double impact test. Meanwhile, double impact test comprises of twin pendulum test, drop weight test, Hopkinson pressure bar and ultra-fast load cell test.

The twin pendulum test was first used in JKMRC which consists of two sizes pendulum that is used to cover the particle size range from 31.5-4.75mm in standard test (Narayan et al., 1985). JK drop weight tester replaced the twin pendulum test which is suitable for particles of 63-11.2mm that can be tested by different drop weights and heights.

The Julius Kruttschnitt Mineral Research Centre (JKMRC) has initiated the development of ore characterisation test for fine particles; JKFBC (JK fine particle breakage characteriser) to produce an index which signifies the ore hardness of the stirred mill feed.

As mentioned earlier, the index is Stirred Mill index (SM_i) which measures the particles hardness and create a generic tn-family curve, which is used to establish energy base breakage function. Breakage in JKFBC is characterized by the t_{10} function which includes the size effect.

JKRMC has developed the drop weight test (JKDWT) to investigate the ore characteristics for comminution machines. Its goal is to separate ore characteristics from those of the processing machine which can be done by simulation the model of grinding and crushing. This is achieved by using separate ore and machine parameters. Single particle impact test which goals to demonstrate rock in the perspective of comminution is used to develop ore parameters.

Essentially, ore characterisation test measures the ore specific energy/ size reduction behaviour, which can be conveyed as degree of breakage at specific comminution energy, Ecs (kWh/t), also known as breakage/ appearance functions. Particle size distribution of the product for a given amount of energy at selected feed size can be obtained by particle breakage characterisation via specific breakage mechanism. Size distribution is crucial for defining the t_{10} cumulative percentage passing $1/10^{th}$ of the initial stage. For characterisation and modelling, the t10 acts as the breakage index (S. Palaniady et al,. 2016)

2.5 Device used for Impact Breakage Tests

Single impact represents the most elementary process in comminution (Schonert et al., 1991). Impact breakage experiments have been widely used as efforts to recognize the useful trends in comminution breakage and provide data to be employed in design and optimization of circuits. There are a few devices that can be used to conduct impact breakage test. Of the single particle breakage experiments include:

- Pendulum test
- Drop weight test
- Split Hopkinson bar test
- Ultrafast load cell experiments
- Rotary breakage test
- Batch grinding test

2.5.1 Pendulum Test

Twin pendulum device is first being used to study the effect of velocity on single particle breakage and to emphasise the need for such a device for conducting breakage studies under controlled conditions (Fahernwald et al., 1938). Fahernwald found that an increase in impact velocity will raise the fines production resulting from the breakage of particle.

Bond (1946) developed a twin pendulum apparatus to determine the impact crushing strength of 76 × 50mm rock particles under controlled crushing conditions. This is the crushability test. Gaudin & Hukki (1946) used a pendulum device to perform single particle crushing test in order to determine the size distribution and new surface of the comminuted products.

Correlating the specific fracture energy with the new surface created is of the feature that has been studied by using pendulum test. This relationship exhibits a fineness limit to account for the fact that material infinite fineness cannot be made by infinitely increasing the specific fracture energy (Yashima et al., 1981, 1982). It was also shown that crushing efficiency of irregular specimens was better than that of spherical particles for a wide range of input energy.

Awachie (1983) conducted some single particle breakage test to determine the breakage function for crusher modelling. The products of slow compression, drop weight and pendulum test were compared and happen to be same. Awachie chose the compression test as it was considered that this breakage mechanism is most closely resembled the breakage mode in an operating crusher.

A study on energy losses during the breakage of regular shaped materials using twin pendulum and a small calorimeter has shown that most of the input energy is dissipated as heat (Zeleny and Piret et al.,1972)

The twin pendulum test as shown in (Figure 2.2) consists of an input and rebound pendulum from a rigid frame. The rebound pendulum swings between a laser supply and a sensor which are attached on an optical bench at right angles to the plane of swing of the pendulum. The motion of the rebound pendulum is monitored by a computer that records the time taken for a multiple fin arrangement to pass through the laser beam. 25 swings of the rebound pendulum are checked to determine the period. The particle selected for testing is fixed to the rebound pendulum by a piece of tape, or a similar arrangement, and the input pendulum is released from a known height to swing down and collide with the particle.

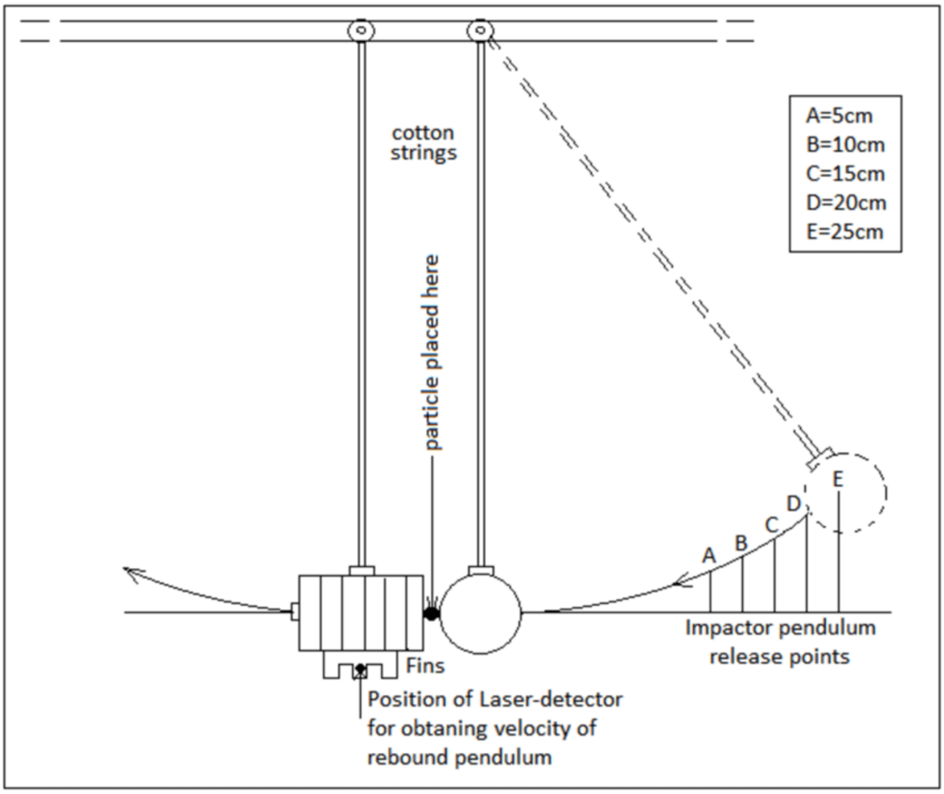

Figure 2.2; Schematic of a twin pendulum device (Rahul et al., 2010)

The energy transferred to the rebound pendulum, Et is determined from the computer-logged timing signals (Narayan & Whiten 1988). This is calculated from

Et = Mr (L-L cos ǿ), where ǿ is the angle of the displacement of the rebound pendulum from its equilibrium position, Mr is the mass of the rebound pendulum and L is the length of the pendulum. The angle of displacement is computed from the corrected period P, and the calibration constants, a and b, using the expression

$$P = a + b\theta^2$$

a and b are determined by regression on a set of measured p and θ values.

The principles of conservation of momentum permit the velocity of the input pendulum after impact and thus its residual energy, Er to be figured. The energy balance during a collision of the input pendulum with a particle attached to the rebound pendulum can be written as:

$$Ei = Er + Et + Ec$$

Where Ei = input energy, Ec = total energy loss. The energy loss may signify the energy expended by the sample to break and to other losses such as acoustic, thermal, etc.

The specific comminution energy, Ecs is defined as the variance in the input pendulum energy before impact and the rebound energies and input pendulum after impact (Narayanan 1985). It thus concludes the comminution energy for size reduction plus any acoustic and heat energy dissipated during the breakage process.

In addition, the specific comminution energy, Ecs also defined as the comminution energy per unit mass, which can be defined from result using equation;

$$Ecs = \frac{Mr}{Mi+Mr}(1-e^2)\ Eis$$, where;

Mr = mass of the rebound pendulum

Mi = mass of input pendulum

e = coefficient of restitution

Eis = specific input energy

M= mass of particle

2.5.2 The Hopkinson Pressure Bar

This device is also been constructed to study the breakage properties of rock. It is a collaboration of JKMRC and Centre for Mining Technology and Equipment. In term of fracture principles, HBP has strong resemblances to the Brazilian Test.

As shown in (Figure 2.3), it consists of a horizontally suspended steel bar of 6.4m long. The rock sample is then impacted and compressed by the collision of an impact bar. The impact bar is attached on linear bearings and is mounted to a linear spring at the opposite bar end. It is compressed to a known distance so that impact velocity can be controlled. By using an optical sensor to measure the speed of impact bar at the point of impaction, the input energy is computed.

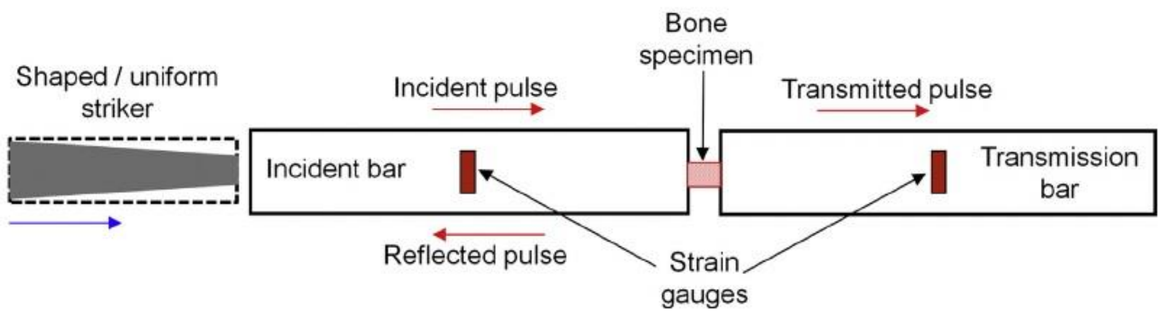

Figure 2.3; The layout of the Split-Hopkinson Pressure Bar for dynamic compression testing (Bekker et al., 2015)

The rock experiences force as equivalent to the forces exerted by the ends of the two bars during the collision. The force propagates as a longitudinal strain wave down the impact and Hopkinson bar. A strain gauge bridge is utilised to measure the force.

The force of the rock is resolvable and the force at which failure happens is known as a sudden release of force in the strain signals.

The HPB can investigation the strength of individual rocks which can contribute to fracture probability in comminution (Briggs & Bearman 1995). In order to study the destruction in a pre-failure regime, discs of granite were impacted at growing level of energy until failure takes place. The energy was stepped down in phases, and the number of consecutive hits necessary to cause failure was recorded and used as a amount of the damage tempted in a material prior to breakage.

2.6 Drop Weight Test

Drop weight test was later introduced and replaced the twin pendulum test. This test is used to evaluate the breakage characteristics of finer materials. The principle of this test; a suitable weight is dropped on the particle where the height is adequate to reach the necessary energies. Gross (1938) used this device to establish relationship between surface area produced and input energy. Then, Piret (1953) has modified this Gross' to crush brittle particles, to create a relationship between energy input and product size distribution.

Later in 1954, Fairs used the drop weight apparatus established by Gross and improvised by Piret as he led a particle bed breakage test and established a relationship between the net input energy and the new surface area produced. Hoffler & Herbst (1990) used this apparatus to conduct single particle and particle bed breakage tests for application of ball mill modelling.

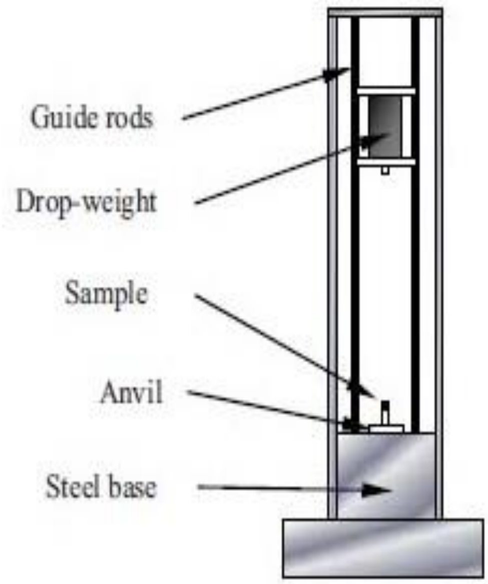

Figure 2.4; Schematic diagram of drop weight tester (Sensor Product Inc)

The drop weight tester was introduced to replace the twin pendulum apparatus for assessing impact breakage characteristics of ores (Brown 1992). This device as seen in (Figure 2.4) consists of;

1) Steel drop weight mounted on two guide trails.
2) Manual winch to raise or lower weight to a known height.
3) Rock steel anvil as platform for impaction
4) Steel base as base that holds the device.

Weight is released manually and falls under gravity to crush the particles placed on the anvil. To achieve wide range of energies, the weight is released at different heights. The drop weight load is fitted with 3.445kg mass. The mean mass of each seat of particles to be tested is calculated. From the necessary specific input energy, the height of weight released is calculated by this relationship;

$$hi = \frac{mEis}{0.0272Md}$$

hi; the initial height (cm) from which the drop weight is released

m; mean mass of each set of particles to be broken

Eis; specific input energy (kWh/t)

Md; mass of drop weight (kg)

Drop weight tester provides exactly similar data to twin pendulum plus several advantages;

- Variety input energy range
- Shorter test duration
- Extended particle size range
- Greater precision
- Possibility to conduct particle bed breakage studies

It is suitable for impact breakage assessment required for crusher models, also to detect the effects of particle size/ rock damage on comminution strength.

2.7 Single Particle & Bed Breakage Tests

Single particle breakage tests have been conducted to study numerous significant features of the complex communition process. It is to determine breakage behaviour of materials which assumes that breakage is size independent (Eksi 2010). Bed breakage method was established for determination of fine particle breakage. Both breakage tests utilise impaction as their breakage mechanisms. The particles are crushed between two hard surfaces; a particle resting on a hard surface is struck by a falling weight (single particle test).

Basically, single particle &bed breakage run the same operations but bed breakage involves more than a particle on the surface, arranged as in a layer covering the whole platform hence it is called as bed. It just differs by the arrangement and number of particles on the platform. Though the differences seem meaningless, it is actually affect significantly on the product in term of the fineness.

These tests count in the initial particle size and impact energy which will create a quantitative description of breakage probability of different sizes in a mastercurve. It also can be applied for qualitative description of breakage function. As impaction has been performed on the particles, here comes the initial and important part. Product size distribution is a process to determine the quality of grinding and the degree of mineral liberation by using different mesh sizes to measure. Screen with decreasing sizes are sorted from top to bottom and sieved in a vibrator shaker for few minutes to get accurate result.

Product particle size distribution data obtained from the tests is used to acquire t_2, t_4, t_{10}, t_{25}, t_{50} and t_{75} values. T_{10} is the fineness index, percent passing of one tenth of the original mean particle size. In other words, it is the degree of impact breakage. t_2, t_4, t_{10}, t_{25}, t_{50} and t_{75} is the percent passing ½, ¼, 1/25, 1/50, 1/75 of the original mean particle size. tn values vary with particle size and specific comminution energy. tn is calculated by the relationship;

$t_n = (A \times (1\text{-}e^{-b\times Ecs\ -X}))$, where Ecs = specific comminution energy(kWh/t), X= geometric mean of the size interval (mm), A, b are the breakage parameters, n = 2,4,10,25,50,75.

A is the limiting value of t10 for high energy impacts. The product of A. b is the slope of the relation at zero input energy which can also be indicator of ore hardness, the resistance of ore to impact breakage.

t_n values are then used to compute the values for A and b parameters through computerisation system. As A and b values are obtained, then the breakage functions can be achieved. t_n values can be plotted against corresponding energy to give curves that smooth the size distribution and allow the computation of breakage distribution function (Figure 2.5)

Breakage function describes the size distribution of the fragments, not taking account the amount of undestroyed particles. Breakage probability explains the fraction of particles which is destroyed in an experiment. As for regular shapes, breakage can be evaluated by fragments missing from the original shape. This is not applicable for a large number of irregular shaped particles.

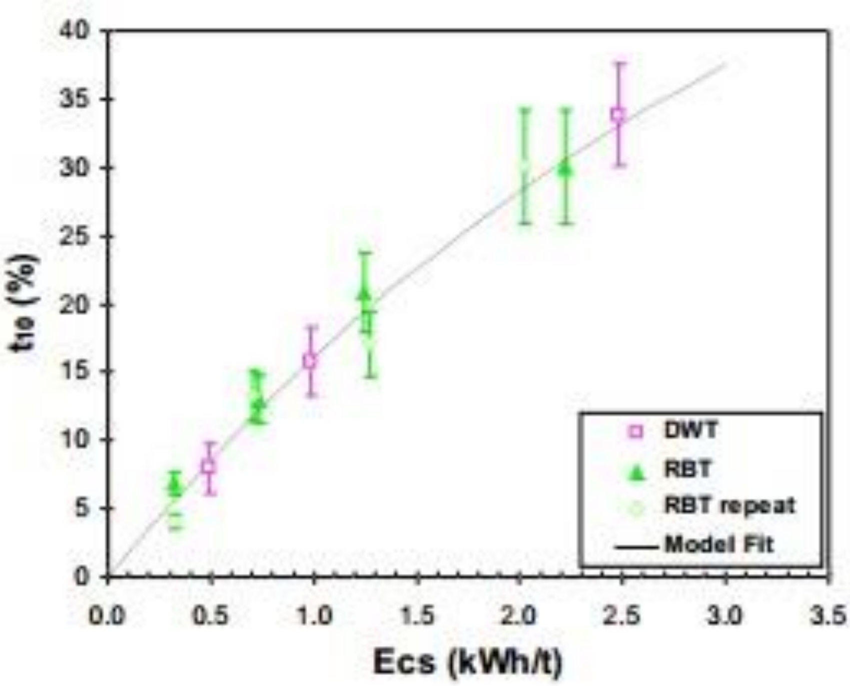

Figure 2.5; Example of graph of t10 values against Ecs (Kojovic et al., 1996)