Developing an abrasion characterisation test for measuring superficial breakage in comminution

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A thesis submitted for the degree of Master of Philosophy at
The University of Queensland in 2015
Sustainable Minerals Institute
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Abstract

Three motivations were presented for conducting this research. Firstly, comminution is primarily concerned with breaking of rocks therefore it is imperative to fully understand the breakage mechanisms involved in size reduction processes to be able to develop reliable and predictive models and consequently facilitate process optimisation. Impact breakage has been investigated extensively in literature as well as at the Julius Kruttschnitt Mineral Research Centre (JKMRC). However, surface breakage is poorly understood despite the fact it contributes significantly to new surface area generation in grinding.

Another motivation for conducting this research was a contribution to the Unified Comminution Model (UCM). The UCM is a mechanistic model framework, and thus requires, as fundamental inputs, the response of a rock particle to the common modes of breakage found in comminution, independent of each other. Hence, this research aimed to isolate the abrasion mechanism with an appropriate device and to develop an abrasion characterisation test for measuring superficial breakage in comminution. This was because most of the prior comminution experiments investigating abrasion were conducted in tumbling mills which neither isolated the mechanism nor eliminated secondary breakage.

Lastly, Leung (1987) reported that low specific energy impact events can produce similar product size distributions to that of abrasion. But, the abrasion experiments were conducted in a tumbling mill. Hence, the possibility of substituting low energy impact breakage for shear abrasion breakage was investigated as well. Abrasion tests and impact tests were conducted over a range of energies with the same ore type and the results were compared.

Surface breakage experiments were conducted with single ore particles and particle beds. The single particle tests included a novel use of the Steel Wheel Abrasion Tester (SWAT) device as well as single impact tests with the JK Rotary Breakage Tester (JKRBT). Batch (bed) experiments were conducted on the bench scale with a planetary mill and the results compared with the single particle outcomes. A novel methodology was followed to produce the results which included the application of an insert to minimise secondary breakage.

The results showed that despite the fact that energy directly contributed to the production of product mass during abrasion, the primary driver of mass loss in ore particles was the applied load. It was found that the mass loss rate (g/kJ) was directly proportional to the applied load during the steady state phase of the rock’s response to the abrasion mechanism. This introduced the possibility of establishing an abrasion index for rock particles.
The findings also revealed that, at face value, neither low nor high energy, single point, single impact breakage produced appearance functions similar to that of abrasion. Therefore, single impact breakage mechanisms cannot be used as a proxy for abrasion breakage mechanism, at least not for the energy range in which the experiments were conducted (0.005 – 3 kWh/t).

The primary outcome of this thesis was the IMLAT (Incremental Mass Loss Abrasion Test). The IMLAT provides the methodology and outputs necessary to characterise a rock’s response to the steady state abrasion mechanism in comminution. However, it was never the aim of this project to develop the models or generate the abrasion index of all ores, but merely to demonstrate how one would go about achieving it. In other words, this thesis paves the road to an abrasion index of ores and a mechanistic abrasion model. Both of which could be meaningful in the comminution context.

Results from the planetary mill experiments revealed that a bed of particles can produce appearance functions similar to the IMLAT (single particles). The IMLAT was laborious and produced significant noise pollution. Moreover, the statistical significance of the results was questionable due to the small number of samples in each test. Therefore, it was recommended that future research investigate the possibility of conducting batch tests in a planetary mill as a proxy for the IMLAT. These tests would be fast and simple and therefore easily repeated to improve the statistical significance of the results. Moreover, it would be the first truly batch abrasion characterisation test.
Declaration by author

This thesis is composed of my original work, and contains no material previously published or written by another person except where due reference has been made in the text. I have clearly stated the contribution by others to jointly-authored works that I have included in my thesis.

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Publications during candidature

No publications

Publications included in this thesis

No publications included

Contributions by others to the thesis

Dr. N. Weerasekara supplied the energy data for the planetary mill results from his DEM work on the mill.

Statement of parts of the thesis submitted to qualify for the award of another degree

None
Acknowledgements

This author would like to thank the following persons or companies for their generous support, for without it this thesis would not have become what it is now:

- Anglo American and the JKMRC for the financial support.
- Dr. M. Yahyaei, my primary advisor.
- Dr. N. Weerasekara, my co-advisor.
- Prof. M. Powell, my co-advisor.
- JKMRC pilot plant staff, especially Mr. J. Worth and Mr. J Parkes.
Keywords

Abrasion test methodology, comminution, abrasion index, surface breakage, ore characterisation

Australian and New Zealand Standard Research Classifications (ANZSRC)

091404 Mineral Processing/Beneficiation, 100%

Fields of Research (FoR) Classification

0914 Resource Engineering and Extractive Metallurgy, 100%
To my loving parents,
who always encouraged me
to follow my dreams.

The Road not taken
BY ROBERT FROST

Two roads diverged in a yellow wood,
And sorry I could not travel both
And be one traveller, long I stood
And looked down one as far as I could
To where it bent in the undergrowth;

Then took the other, as just as fair,
And having perhaps the better claim
Because it was grassy and wanted wear,
Though as for that the passing there
Had worn them really about the same,

And both that morning equally lay
In leaves no step had trodden black.
Oh, I kept the first for another day!
Yet knowing how way leads on to way
I doubted if I should ever come back.

I shall be telling this with a sigh
Somewhere ages and ages hence:
Two roads diverged in a wood, and I,
I took the one less travelled by,
And that has made all the difference.
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List of Abbreviations

JKMRC | Julius Kruttschnitt Mineral Research Centre | IMLAT | Incremental Mass Loss Abrasion Test
UCM | Unified Comminution Model | AG | Autogenous Grinding
DEM | Discrete Element Modelling | SAG | Semi-autogenous Grinding
SWAT | Steel Wheel Abrasion Tester | DWT | Drop Weigh Tester
JKRBT | Julius Kruttschnitt Rotary Breakage Tester | RWAT | Rubber Wheel Abrasion Tester
PSD | Particle Size Distribution | RPM | Revolutions Per Minute
SOP | Standard Operating Procedure | DAQ | Data Acquisition
MLR | Mass Loss Rate | CoV | Coefficient of Variation
MLPD | Mass Loss Probability Distribution
CHAPTER 1

Introduction

Arguably the mining industry’s main challenge in recent years is to treat larger volumes of low grade ore while energy and operating costs increase constantly. It has been well documented that comminution is the most energy intensive operation of most mineral processing circuits. Moreover, it makes up a significantly large fraction of a mineral processing plant’s capital and operating costs. The biggest consumers of energy in comminution (as much as 90%) are undoubtedly the grinding equipment, especially grinding mills (Alvarado et al., 1998).

Moreover, grinding mills are notoriously energy inefficient, converting a few percent (at most) of the total input energy into rock breakage (Alvarado et al., 1998). To improve the efficiency of the comminution process it is essential to understand the underpinning mechanisms of size reduction. In the light of this understanding it is possible to identify potentials for refining the breakage process as well as enhancing predictability of process models.

1.1 Modes of breakage

To optimise comminution circuits and to model novel circuits successfully, it has become essential to understand the mechanics of size reduction processes. In a typical AG and SAG mill two modes of breakage are present: body breakage (impact and attrition) and surface breakage (abrasion and chipping). It is therefore vital that the appearance functions of these modes of breakage be reliable and accurate. Impact tests developed at the JKMRC (Drop Weight Tester (DWT) and Rotary Breakage Tester (RBT)) are already well established in measuring the appearance functions for impact breakage.

However, there is no such a robust methodology available for characterising the abrasion breakage of rock particles. Moreover, impact testing devices are not appropriate for testing abrasion breakage. There is an “Abrasion Test” available at the JKMRC (Napier-Munn et al., 1996) used to determine the $t_a$, an abrasion parameter, for the AG/SAG mill model. But, since the experiment is conducted in a sealed tumbling mill, secondary breakage and repetitive impact events are a concern. Hence, there is a need for a new or modified device that imparts only surface damage to ore particles. The steel wheel abrasion tester (SWAT) device is potentially an ideal candidate. The
SWAT is an upgrade of the rubber wheel abrasion tester (RWAT) (Misra and Finnie, 1980). The basic operation of the SWAT involves a steel specimen or ore particle forced at a specific load against a rotating steel wheel while an abrasive or water is fed into the contact zone (Radziszewski et al., 2005, Chenje, 2007).

1.2 Surface breakage

Surface breakage results in the production of large amounts of fines, although taking place at low energies, has a high frequency of occurrence and therefore contributes significantly to create new surface area within mills. The importance of abrasion and chipping has been confirmed as the dominant comminution mechanism of coarse particles in AG milling through numerical modelling (Yahyaei et al., 2013, Powell et al., 2008, Morrison and Cleary, 2004). Results showed that the majority of the collisions occurred at low energies sufficient to cause surface breakage but not body breakage (Figure 1).

![Figure 1 - Frequency of collisions vs. normal energy in an AG pilot mill (Yahyaei et al., 2013)](image)

1.3 Mechanistic models

Recent research effort has been into decoupling material and machine factors in the modelling of comminution process so that predictability of existing and new processes can be enhanced. The aim is to develop a robust mechanistic framework that unites all comminution models. To that end, the unified comminution model (UCM) has been proposed (Powell, 2006). Existing empirical scale up
models consist of parameters which carry effects of both ore and equipment and they cannot be extrapolated to conditions beyond what they are calibrated for. Therefore, they are only valid for that specific equipment within its tested operating range. In contrast, mechanistic models have the ability to model the breakage process over a wide range of operation which is common in mineral processing. This is due to the fact that they are based on understanding the underlying physical mechanisms of size reduction.

This novel approach to modelling comminution processes aims to separate the mechanical environment parameters (e.g. energy, share of modes of breakage, etc.) from the ore breakage characteristic and incorporate them in one grand model that accurately predicts the breakage events and appearance function for any given device. However, developing such a model requires a novel approach in ore characterisation. One of the components is abrasion characterisation of ore particles (Morrison and Cleary, 2004). Understanding the underpinning mechanisms and variables involved in abrasion breakage form the foundation of this thesis.

1.4 Investigations into superficial breakage

Extensive research has been conducted into the abrasive wear of materials other than ore particles (metals, glass, ceramics, etc.) in a variety of devices. Researchers in the field of tribology investigate friction, wear and lubrication of engineering materials. These types of investigations are concerned with the condition of the metal or ceramic material used as grinding media or the state of the metal device in which the grinding process is taking place (e.g. ball, AG and SAG mills) (Moore, 1974, Spero et al., 1991, Radziszewski et al., 2005). Since the grinding media (steel balls) and steel liners contribute significantly to a mineral processing plant’s operating costs, it seems prudent that much research is done to study the abrasive behaviour of the rock particles and how to minimise the impact of it.

However, these studies have very little reach into this project which is not concerned with the state of the grinding media or liner lifespan. On the contrary, this project will investigate the effect the steel media has on the ore particles.

Some work has been done in geology to study the effect of abrasion on the rock properties (e.g. shape and size) (Krumbein, 1941) incorporating tumbling barrels. Though relevant, the emphasis of this project is the converse - addressing what effect ore properties have on the abrasion product.

Considerable research has been conducted to quantify the abrasion behaviour of ore particles. This includes work done by implementing the DWT, RBT, tumbling mills, the planetary mill and Discrete Element Modelling (DEM) simulations to name a few (Goldman and Barbery, 1988,
Loveday and Naidoo, 1997, Banini, 2000, Loveday, 2004, Khanal and Morrison, 2008, Larbi-Bram, 2009). The JKMRC also has a standard “Abrasion Test” that is followed to generate the abrasion appearance function \(t_a\). This test has become the accepted standard at the JKMRC for the SAG mill model.

The validity of this test as an abrasion test is questionable because the mode of breakage present is not exclusively abrasion and secondary breakage is also possible. As noted, one shortcoming of previous published work is the possibility of secondary breakage. If the product is not removed after a certain period of time, the freshly formed product can experience re-breakage and form secondary products. This is especially relevant to the mills. Attempts have been made to solve this issue including creating holes along the periphery of the tumbling device and running for shorter periods (Loveday et. al., 2006, Yahyaei et al., 2013).

Another disadvantage to this type of testing (batch grinding) is the challenge of separating machine-specific properties (breakage rates) and material-specific properties in a meaningful way that is still relevant to the UCM. After all, the UCM requires the breakage mechanisms to be investigated independent of the tumbling environment. Hence, studying abrasion in a tumbling device is counterproductive as it does not separate device and breakage mechanism ultimately.

Another complication regarding abrasion is the contribution of low energy impact events. They are not mutually exclusive events, at least not in a milling environment. Hence, another shortcoming of previous work done in this field is the uncertainty of modes of breakage present during the experiments. This raises questions such as: is abrasion the only or the dominant mode of breakage or low energy impact breakage contributes too? And if so, to what degree does it contribute? In other words, is grinding really a reliable abrasion test? Or would it be more realistic to consider it a superficial breakage test (due to the contributions of both low energy impacts and abrasion)?

Although the application of DEM to the comminution process has been rewarding, it is not limitation free. Simulating particles as spheres, though reducing the computational time, drastically effects the contribution asperities have on abrasion breakage. Even with asperities, the results will be estimates at best, because the simulation does not include breakage. Therefore, since DEM does not predict breakage or the transfer of energies during collisions or breakage events, its contribution is limited.
1.5 Hypotheses and Objectives

This research aims to develop an abrasion characterisation test for measuring abrasion breakage in comminution.

This thesis aims to test the following hypotheses:

(i) Rock response to abrasion can be isolated from other breakage mechanisms and quantified with an appropriate testing methodology.

(ii) The normal load (and not total input energy) is the key driving mechanism of abrasion of ore particles.

(iii) Low energy impact breakage mechanism does not produce an appearance function similar to abrasion breakage mechanism.

(iv) Particle bed (batch) experiments in a planetary mill can produce similar appearance functions compared to single particle abrasion tests, such as the IMLAT (Incremental Mass Loss Abrasion Test).

To achieve the aim and address the hypotheses, the following objectives are to be met:

- Isolate the abrasion mechanism and investigate different compression loads and input energies to identify key drivers of abrasion.
- Propose a generic methodology to test the abrasion characteristic of ores.
- Quantify the abrasion characteristic of ore particles.
- Quantify differences and similarities between low energy impact breakage and abrasion.
- Quantify differences and similarities between single particle (IMLAT) and surface breakage in a bed of particles (e.g. planetary mill).
1.6 Thesis structure

This thesis comprises 6 chapters, including the introduction as Chapter 1.

Chapter 2 reviews the breakage theory found in comminution literature, common industry tests conducted for ore characterisation, and abrasion studies found in four different fields of research. The author also exposes the shortcomings of aforementioned research as motivation for this project.

Chapter 3 outlines the experimental approach taken to meet the objectives. It includes the experimental design framework which is structured according to the key aims of this thesis resulting from the gaps and shortcomings in the literature highlighted in Chapter 2. Then a detailed description is provided of the equipment used to conduct (single particle and particle beds) abrasion and impact experiments and the methodologies followed to produce and analyse the results. The description of the experimental device will include details on the basic design of the devices, the physical principles on which the equipment operate, and the scope of the investigations. The methodologies will include the standard test program and raw data analysis procedures.

Chapter 4 presents the relevant results from all the experiments conducted. The results are structured according to the objectives under investigation and will provide evidence for the acceptance or rejection of the hypotheses. All results include a discussion of the trends observed and inferences drawn from them.

Chapter 5 summarises the entire IMLAT methodology from sample preparation to data analysis.

Chapter 6 summarises the key outcomes of this thesis along with commenting on the validity of the proposed hypotheses. The chapter concludes with recommendations for future work.
CHAPTER 2

Literature review

This chapter presents a summary of comminution breakage theory, a comprehensive review of abrasion breakage studies found in literature and identifies their shortcomings as motivation for this research. Terminology that frequent literature on breakage processes is defined from the outset along with a summary of fundamental comminution theory. A summary of tests common in industry for ore characterisation then follows. Abrasion of rock and other materials is investigated in four major research fields in literature: geology, tribology, materials handling and comminution. A brief overview of the progress on abrasion research within each discipline is presented in chronological order. After which a case for the unified comminution model is made. The chapter concludes with highlighting weaknesses in the literature, models and laboratory tests as motivation for this thesis.

2.1 Definitions

In this section a description of the breakage mechanisms assumed to operate in autogenous grinding (AG) and semi-autogenous grinding (SAG) mills, as adopted by the JKMRC, will be presented. It then concludes with a discussion on inconsistencies that exist in literature over definitions of common terminology found in abrasion processes.

At the JKMRC it is commonly accepted that three breakage mechanisms are present in AG/SAG milling (Napier-Munn et al., 1996). Breakage in these mills is the result of either:

(i) Impact,

(ii) Attrition, or

(iii) Surface breakage (abrasion and chipping).

Definitions for these terms vary in literature, therefore is it judicious to provide a specific definition of each mechanism adopted throughout this thesis (Larbi-Bram, 2009: 16; Banini, 2000: 88; Napier-Munn et al., 1996: 165):
“Abrasion is considered as a surface breakage phenomenon which occurs when two particles move parallel to their plane of contact. In this case small pieces of particles are removed from one or both particles leaving the parent particle largely intact.”

“During chipping lateral cracks propagate approximately parallel to and underneath the free surface of the particle. The intersection of the lateral cracks with the free surface leads to the removal of relatively small quantities of the parent rock, which remains largely intact.”

“Attrition breakage results when a relatively small particle is trapped and rubbed between two much larger particles or between the mill shell and a particle. The small particle is subsequently broken [due to compression and shear] in preference to the larger ones.”

“In impact breakage, the impacting particle moves perpendicular to the plane of contact.” The result could be the particle breaks into two or more pieces; cracks form and propagate radially through the main body of the rock (leaving the particle intact but weaker); surface breakage occurs; or nothing happens.

Body breakage due to impact and attrition are high energy breakage events and produce a normal product size distribution. Chipping and abrasion are considered low energy breakage mechanisms resulting in a characteristic bimodal product size distribution since the parent particle remains largely intact. The three main mechanisms are illustrated in Figure 2 below along with their typical progeny size distribution.

Figure 2 - Breakage mechanisms found in AG/SAG milling (de Paiva Bueno, 2013)
Interestingly, chipping is considered the limiting case of fracture and abrasion. As such, both mechanisms can produce a chipping-like product depending on the energy environment. It is commonly assumed that chipping is the first phase of abrasion and is a dynamic process which leads to the steady state abrasion phase once the parent particle’s surface had been worn smooth and more rounded as a whole. Figure 3 represents a mechanistic view of the breakage product produced by the mechanisms mentioned above.

<table>
<thead>
<tr>
<th>Body breakage</th>
<th>Surface breakage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impact/Attrition</td>
<td>Chipping</td>
</tr>
</tbody>
</table>

![Figure 3 - Mechanistic view of products produced by common breakage mechanisms (Kelly and Spottiswood, 1982)](image)

It is common practice in comminution to classify a mass loss of 10% or more of the original particle as the product of body breakage (Tavares and King, 1998) and anything less as surface breakage. As a result, impact and attrition are deemed body breakage mechanisms whereas chipping and abrasion are surface breakage mechanisms. However, low energy impact events can also produce surface breakage. Therefore, abrasion and surface breakage cannot be considered synonyms. Surface damage on the other hand has no related mass loss but is associated with surface cracks and micro tears caused by a stressing event.
Many other definitions of the same mechanisms defined above can be found in the literature spanning different research fields. Naturally there is no right or wrong definition, but it is unfortunate that there is not more consistency among disciplines.

A reason for this is most likely due to researchers following the traditions of their respective disciplines and the independent nature of their investigations (silo effect). Hopefully in the future as more collaborative inter-disciplinary research is conducted, the metallurgist and the materials engineer will have the same understanding of the term attrition for example. Some examples found in the literature of the same terminology but defined differently follow:

D. Crabtree et al. (1964: 201) defined impact grinding and attrition as two distinctly separate mechanisms in comminution: “Attrition, on the other hand, is that form of grinding which cannot be called impact grinding, and comprises both abrasion and chipping grinding.”

Neil and Bridgwater tested various materials in an annular attrition cell. The authors defined attrition to mean “accidental damage to particles”. “The term attrition will be used to embrace both particle abrasion and fracture.” (Neil and Bridgwater, 1994: 207)

Yavuz et al. (2008: 260) reported on the abrasion resistance of carbonate rocks. They defined abrasion as “a result of the wearing and tearing away of particles from the dimension stone surface by friction or impact, or both.”

L.M. Tavares (2009: 327) reported on the analysis of particle fracture, repeated stressing as damage accumulation. He defined attrition as “the gradual breakage of a particle that merely polishes its surface, leaving the size of particle relatively unchanged and a more rounded shape along with fine progeny,…”.

It was evident that similar terms found in literature for common breakage mechanisms had different meanings depending on the discipline. Fortunately the authors defined the terms clearly from the start to avoid any confusion. To that end, the breakage mechanisms frequently referred to in this thesis were defined on page 8. However, this inconsistency in the definitions of common terms associated with breakage can make the review of the literature frustrating for a researcher. In some cases the definitions were similar, but the mechanisms occurring in the testing devices did not correspond to the definitions. As a result, a researcher who might be investigating ‘abrasion’ by their definition was actually investigating the effect of low energy impact breakage. This disparity is addressed in the section 2.5.
2.2 Ore characterisation

This section summarises popular laboratory breakage characterisation tests used to model the performance of conventional industrial comminution machines by relating the input comminution energy and size reduction. This includes standard tests such as the Bond work index tests and single particle breakage tests developed at the JKMRC. These tests determine material-specific parameters that characterises the rock particle’s breakage behaviour since these parameters are required for the process models.

The breakage systems applied can be grouped into four broad categories:

- Batch grinding (abrasion and Bond tests)
- Impact (twin pendulum test, drop weight test, rotary breakage tester)
- Slow compression, and
- Shear

Slow compression tests typically do not involve abrasion breakage but rather attrition and therefore are not discussed here. Shear tests frequent literature in the fields of tribology and materials handling and will be discussed in section 2.3. Batch grindability and impact tests make up the bulk of ore characterisation tests typically found in comminution literature, but also in other disciplines like geology. Hence, only the latter breakage systems will be discussed in this section.

2.2.1 The Bond work index tests

To size comminution devices, a reliable method for predicting the energy input for size reduction is required. Bond (1952) proposed a relationship correlating the work input to the new crack tip length produced during particle breakage in rod and ball milling. This relationship is often referred to as the “Third Law” of comminution (Bond, 1952) and is still used to the present day (often erroneously) as a design and optimisation tool of crushing and grinding circuits. Equation 2.1 relates the Bond work index to power required for comminuting rock for a given $F_{80}$ to a required $P_{80}$:

\[ P = T \times W = T \times 10 \cdot WI \left( \frac{1}{\sqrt{P_{80}}} - \frac{1}{\sqrt{F_{80}}} \right) \]  (2.1)
The ball mill work index is defined as the specific energy required reducing the feed size from a theoretically infinite size to 80% passing 100 micron. The model parameter expresses the amenability of the rock particles to crushing and grinding. Bond derived equations for calculating the work indexes of three comminution devices (crushers, rod mill and ball mill) by following a standardised grindability laboratory test for each device. Equation 2.1 can also be used to calculate the ‘operating work index’ (WI₀) of existing comminution circuits to assess the performance and grinding efficiency of the circuit under different operating conditions.

2.2.2 Twin Pendulum Test

The twin pendulum device was used on single particles to generate ore-specific breakage functions due to impact breakage (Narayanan, 1985; Narayanan and Whiten, 1988). Each device consists of two pendulums (impact and rebound) of different sizes suspended from a rigid frame (Figure 4). The impact pendulum is released from different known heights depending on the required input energy and collides with the rock particle affixed to the rebound pendulum. The rebound pendulum swings on impact and its motion is monitored by laser and computer. The specific comminution energy can then be determined by Equation 2.2:

\[ E_{cs} = \frac{M_r}{M_i + M_r} (1 - e^2).E_{is} \]  

(2.2)

where

- \( M_r \) = mass of rebound pendulum (kg)
- \( M_i \) = mass of impact pendulum (kg)
- \( e \) = coefficient of restitution
- \( E_{is} \) = specific input energy (kWh/t)
- \( m \) = mass of sample particle (kg)
The advantage of the twin pendulum is that it is a simple device for estimating the specific energy consumed in impact breakage. However, its operation and the results obtained have weaknesses. Its design restricts the range of input energies and particle sizes that can be tested. Moreover, it is time consuming in its operation while large numbers of particles need to be tested for the results to be statistically significant. Often the calculated breakage energy is imprecise due to the secondary motion of the rebound pendulum (Napier-Munn et al., 1996).

2.2.3 Drop Weight Tester (DWT)

Due to the limitations of the twin pendulum device, the drop weight tester was designed as an alternative single particle impact tester. It consists of a steel drop weight confined in perspex mounted on two guide rails as shown in Figure 5 (Napier-Munn et al., 1996).

A single rock particle placed on a steel anvil gets crushed as the weight drops and fall under gravity after it is released by a pneumatic switch. The device is built on a rigid steel frame which is bolted to a concrete base.

A larger range of input energies (0.05 – 50 kWh/t) is achievable with this device by changing the release height and mass of the drop weight (based on 10 to 50 mm particles). A typical ore characterisation assessment requires 500 - 1300 particles in all to be tested (50-100 kg of material).

The mean mass ($\bar{m}$) of each set of particles to be broken must be calculated. The specific comminution energy is then given by Equation 2.3 provided the drop weight does not rebound on impact.


\[ E_{cs} = \frac{0.0272 M_d (h_i - h_f)}{\bar{m}} \]  \hspace{1cm} (2.3)

where

\[ h_i = \text{initial drop height (cm)} \]
\[ h_f = \text{average offset (cm)} \]
\[ \bar{m} = \text{mean mass (kg)} \]
\[ M_d = \text{mass of the drop weight (kg)} \]

The drop weight tester has several advantages over the twin pendulum including larger input energy and particle size ranges as well as greater precision. However, like the twin pendulum, a large number of particles need to be tested for statistical significance and completing a test regime is slow and laborious.
2.2.4 *Ore abrasion test*

The JKMRC has a standard ore abrasion test which is performed to generate the ore-specific abrasion parameter ($t_a$) used in the SAG/AG mill model (see section 2.4). The test consists of tumbling a 3 kg sample of -55+38 mm ore for 10 minutes in a 300 mm x 300 mm mill at 70% critical speed. The mill has four 10 mm lifter bars installed. The product is dry sieved down to -38 micron on a $\sqrt{Z}$ series of sieves. The results are imported into a software program which calculates the $t_{10}$ value (mass % of progeny passing $1/10^{th}$ of the initial mean particle size) using cubic spline regression techniques. The $t_a$ parameter is then arbitrarily taken as $1/10^{th}$ of the calculated $t_{10}$ estimate. The $t_a$ value can be as low as 0.2 for very hard ores, to values above 2 for very soft ores. This test assumes that the abrasion mechanism is particles size and input energy independent. Both assumptions will be proven to be invalid from the literature review. Furthermore, a fixed amount of material with different densities will surely result in a different number of rock particles. The number of particles directly affects the product mass and size distribution.

2.2.5 *Ore parameters in modelling*

The results from the impact breakage tests (twin pendulum, drop weight or JKRBT) are used to relate the energy input to the size distribution of the product. The method employed by the JKMRC is the characteristic $t_{10}$ marker. $t_n$ is defined as the cumulative mass % of product passing an aperture of $1/n$ of the original mean particle size. Therefore, $t_2$ is the mass percentage of product passing half of the original particle size, $t_4$ the percentage passing 25% of the original particle size and $t_{10}$ is the percentage passing one tenth of the parent particle size (Whiten, 1972).

An ore-specific family of $t$-curves can be generated by plotting the $t_{10}$ value against $t_2$, $t_4$, $t_{25}$, $t_{50}$ and $t_{75}$ at different input energies (see Figure 6). This graph is useful as it generates the complete product size distribution, expressed as cumulative mass percent passing, for any $t_{10}$ value. After extensive experiments it was found that the same family of $t$-curves describes the breakage behaviour of a wide range of ore types.

This relationship can be represented by Equation 2.4:

$$t_{10} = A[1 - e^{-bE_{cs}}]$$

where $E_{cs}$ is the specific comminution energy (kWh/t) and $A$ and $b$ are ore-specific impact breakage parameters characterising the ore’s breakage behaviour.
$t_{10}$ can be interpreted as a ‘fineness index’ implying that ore types with larger $t_{10}$ values are more amenable to breakage resulting in a finer product size distribution. $A$ is a limiting value, usually around 50 for hard ores, indicating at higher energies less additional breakage occurs as the size reduction process becomes less efficient. The product $A\times b$ has commonly been used as an index for rating the ore’s resistance to breakage (Shi et al., 2013). It is equal to the gradient of the curve in Figure 7 at “zero” energy. A larger ‘$A\times b$’ value implies a ‘softer’ ore more amenable to breakage.

The aforementioned data reduction procedure adopted by the JKMRC has a weakness: it does not take particle size into account. It was found (Shi and Kojovic, 2007, Banini, 2000) that larger particles exhibit a larger crack density than smaller particles – larger particles tend to be weaker and therefore easier to break than smaller particles.

Since the prior art procedure only uses one set of average $A$ and $b$ parameters, it is assumed that all rocks will behave the same when subjected to identical specific energies. This simplification leads to questionable model outputs. Shi and Kojovic (2007) proposed a modified $t_{10}$-energy relationship, taking account of particle size, specific impact energy as well as the number of collisions applied (Equation 2.5):

$$t_{10} = M\{1 - \exp[-f_{mat} \times k (E_{cs} - E_{min})]\}$$  (2.5)
where $M$ (%) is the maximum $t_{10}$, $f_{\text{mat}}$ (kg.J$^{-1}$.m$^{-1}$) is a material breakage parameter, $x$ (m) the initial particle size, $k$ the number of impacts, $E_{cs}$ (J.kg$^{-1}$) is the specific impact energy, and $E_{\text{min}}$ (J.kg$^{-1}$) the threshold energy.

Figure 7 illustrates the improved output of this new model. But, Larbi-Bram (2009) proved that both models over-predict the breakage in low energy tumbling. To that end, Larbi-Bram proposed a modified version of Equation 2.5. Each breakage mode (body and surface breakage) was modelled with its own characteristic $t_{10}$-energy relationship with corresponding parameters. Model predictions were in good agreement with experimental results.

Figure 8 illustrates the improved output of this new model. But, Larbi-Bram (2009) proved that both models over-predict the breakage in low energy tumbling. To that end, Larbi-Bram proposed a modified version of Equation 2.5. Each breakage mode (body and surface breakage) was modelled with its own characteristic $t_{10}$-energy relationship with corresponding parameters. Model predictions were in good agreement with experimental results.
2.2.6 Julius Kruttschnitt Rotary Breakage Tester (JKRBT)

Shi et al. (2009) reported on a new novel rapid particle breakage characterisation device - JKRBT. Since all the impact breakage characterisation tests developed by the JKMRC are conducted on single rock specimens, they are both slow and hence impractical. Moreover, the statistical validity of the derived ore characteristics from single particle characterisation tests is moot. Clearly there was a need, if not demand, for a rapid consistent particle breakage characterisation device.

To that end the JKRBT was developed. The device uses kinetic energy to break rocks and so is considered a practical alternative for rapid breakage characterisation, since it no longer requires the manual positioning of rock specimens on an anvil. Moreover, according to the authors it provides outstanding consistent results. (Shi et al., 2009).

The device consists of a rotor-stator impacting component with drive system, a rotary feeder, and a control unit. The particles are fed via the feeder randomly into one of three radial channels in the rotor. Once accelerated in the channel, the particle is ejected along the circumference of the rotor.

The particles then collide with the stator at a predetermined velocity. The particle breaks at impact and the product of breakage is collected from a vessel underneath the rotor (Figure 9).

![Figure 9 - First industrialised JKRBT (Shi et al., 2009)](image)

Despite all the advantages the JKRBT has over its predecessor, it still suffers from uncertainties in the impact energy and the possibility of secondary breakage. Since the JKRBT only causes impact breakage, its suitability as an abrasion breakage testing device is questionable. However, one of the hypotheses will be investigated with this device and therefore its inclusion in this thesis.
2.3 Previous work on surface breakage

This section summarises previous work found in literature on the superficial breakage of rock and other materials. It covers a time span from as early as 1879 up to 2013. Surface breakage of (rock) particles has not been investigated exclusively in the mineral processing field, but also exhaustively in other industrial disciplines like tribology, materials handling and geology. A synopsis of the investigations into abrasion in each research field will be presented separately and in chronological order. The aim was to consolidate as much knowledge and insights of superficial breakage studies from different disciplines to better investigate abrasion of ore particles specific to comminution. Table 1 (pp. 38-39) summarises the key experiments and equations (2.6–2.20).

2.3.1 Geology

Rock abrasion is important to geologist since it is a result of natural transportation of sediments, e.g. pebbles in a stream or glacier movement. Abrasion studies can offer answers to the distance of transport, the agent and conditions of transport.

Marshall published a series of papers from 1927 to 1929 of his studies on the abrasion of natural beach sediments. He conducted his studies in a Deval machine consisting of iron drums inclined 30° to the horizontal. His results showed that under certain conditions of abrasion there can be negligible changes in size of the sediment (Krumbein, 1941). His results could be explained by his using of natural beach gravel which probably had been rounded by natural means before his experiments. In Krumbein’s opinion, Marshall’s biggest contribution to this field was defining the terminology used in particle wear like “abrasion”, “impact” and “grinding”. Marshall also confirmed earlier findings that the main product of abrasion was mud rather than sand. The conclusions drawn regarding the abrasion of rocks were expressed qualitatively as summarised below.

Krumbein (1941: 486) summarised some of Marshall’s findings as follows:

- “The wear of particles may be divided into three separate processes: abrasion, impact, and grinding.”
- “During abrasion a mixture of various-sized particles tends to approach equilibrium proportions among the several sizes present.”
• “After equilibrium is approached, prolonged abrasion on a frequency distribution of particles may not significantly change the parameters of mean size, degree of spread, or skewness.”

• “If a sample of gravel contains an appreciable amount of fine material (under 4 mm diameter), the smaller particles are crushed to silt and finer material, and the mean size of the remaining gravel may actually increase with abrasion.”

Schoklitsch investigated pebble abrasion in tumbling barrels and natural wear along streams. In 1933 he confirmed Sternberg’s law of size reduction using a 0.7 meter diameter tumbling barrel which rotated on a central shaft. In 1875 Sternberg proved that the weight of a pebble decreases exponentially during abrasion (Equation 2.6 in Table 1)

Listed below are results of Schoklitsch’s studies relevant to this project (Krumbein, 1941: 488):

• “Sternberg’s law is valid during abrasion and may be expressed not only in terms of weight but also approximately in terms of volume or length for given pebbles.”

• “The coefficient $a$ of Sternberg’s law is constant for a particular kind of rock under given conditions, but it varies as the fourth root of the velocity of movement of the tumbling barrel.”

• “The abrasion of a particle is controlled in part by the size distribution of the material with which it is associated. An increase in the mean size of the associated material causes a linear increase in the coefficient $a$.”

• “Wear by impact (breakage) is more rapid than wear by abrasion; in some instances more than ten times as great.”

To investigate geological applications of abrasion, Krumbein (1941) investigated what effect abrasion has on the size, sphericity, and roundness of limestone fragments. The equipment used consisted of a metal oil drum, 18 inches in diameter and 21 inches long mounted on two horizontal shafts which rotated the barrel at 21 RPM (Figure 10). The charge had a mass of 5kg and consisted of water and limestone pebbles ranging from 45 to 54 mm.
He derived mathematical models (using Schoklitsch’s results as a starting point) to predict the change in size, sphericity and roundness with distance. His predictions correlated well with the experimental data. The application of his theory to field situations of interest to geologists was limited since it is only valid for the particular equipment and special conditions of the experiment.

Abrasion also causes breakwater degradation. Progressive disintegrating of the armour rock due to abrasion causes weight loss of the blocks and poor interlocking between individual blocks. The abrasion resistance of materials used to construct breakwaters and coastal protection works are therefore important to the engineer concerned with armour layer performance.

Latham and Poole (1987) investigated the abrasion resistance of breakwater armourstone in an attempt to design an aggregate autogenous abrasion test to predict the long-term performance of the material. They tumbled limestone rocks in a 176 mm diameter mill at 20 RPM while constantly washing the fines and product from the mill. The authors fitted the results to a wear model, initially proposed by Austin et al. (1984), but made some modifications to it (Equation 2.7).

They proposed that $k_s$ most likely represents a material property of the sample since it was the least variable of the two $k$ coefficients.

They conducted similar experiments one year later to confirm the reproducibility of the test and the abrasion index value ($k_s$). They also proposed an abrasion theory to predict the change in shape of the rock particles. They defined $k_f$ the *smoothing resistance index*, a parameter that quantifies the roughness of the original particle due to irregularities and asperities of the particle surface. Once the surface has been worn smooth the mass loss is governed by a material property, $k_s$ called the *abrasion resistance index*. The results for carboniferous limestone supported the model well.
2.3.2 Tribology

Extensive research has been conducted into the abrasive wear of materials other than rock particles in a variety of devices. Researchers in the field of tribology investigate friction, wear and lubrication of engineering materials. Tribology is defined as “the science and technology of interacting surfaces in relative motion and embraces the study of friction, wear and lubrication” (Hutchings, 1992: 1). Tribology focuses heavily on the wear of metals and how to minimise this by lubrication. Since the grinding media (steel and ceramic balls) and steel (and rubber) liners contribute significantly to a mineral processing plant’s operating costs, it justifies the abundant research conducted into the abrasive wear characteristic of steel and ceramic media and how to improve its performance.

In 1962, Mulhearn and Samuels investigated the mass loss of non-work hardening metal specimens at various loads against silicon carbide abrasive papers that were cemented to a rotating table. A theoretical model, based on results of the microscopic examinations of the abrasive papers, was proposed to predict the mass loss of metal (Equation 2.8). A typical result of the mass removed from a cold steel specimen is given in Figure 11.

![Figure 11 - Total mass loss of a steel specimen on 220-grade silicon carbide paper (Mulhearn & Samuels, 1962)](image)

It was found that the experimental results were in good agreement with the theoretical model.
The authors also investigated the effect of surface area on the metal removal. Surface area did not appear explicitly in the mass removal equation, but was adopted into the model indirectly. The number of contact points (asperities) increased proportionately with an increase in surface area. Subsequently the load per contacting point decreased in the same ratio. Therefore, more scratches were witnessed with an increase in specimen surface area, but each scratch had a smaller cross-sectional area. Results showed that the all mass removal curves were coincidental regardless of the specimen area (0.27 to 2.7 cm\(^2\)) having kept all other variables constant.

Queener et al. (Bond, 1964) proposed a similar but improved model in 1964 with the addition of a linear wear contribution (Equation 2.9). They developed a model that assumed the total metal wear was the sum of two separate, independent contributions: a transient component and a linear component (Figure 12). The transient component accounted for the “breaking in” of the surface by the removal of surface asperities which was dependent on the surface roughness. Once the surface was worn smooth, the linear component dominated the removal rate at a steady state.

![Figure 12 - Metal wear as a function of two independent contributions (Queener et al, 1965)](image)

The authors used a Caterpillar gear-roller test machine in which two metal specimens (3.6 and 2.4 inch in diameter) were mounted on parallel shafts and rotated against each other at specific angular velocities and applied loads. The initial surface roughness of each specimen was prepared by lapping with different grades of silicon carbide grit paper. It was found that the theoretical model fit the experimental results well (Figure 13). The authors assumed a simplified model for the surface roughness \( R_s \) such that

\[
\beta = 2\rho AR_s
\]  

(2.10)

where \( \rho \) is the density of the metal specimen and \( A \) the area of the wear scar.
To test the model $\beta$ was determined empirically from the wear plots (Figure 13) and compared with the Equation 2.10 which predicts a linear relationship between $\beta/\rho A$ and $R_s$. The comparison is shown in Figure 14. The authors were pleased with the comparison considering the underlying grossly simplified model of surface roughness as a regular array of triangular asperities.

![Figure 13 - Wear plots of 4340 steel specimens with different surface roughnesses (Queener et al., 1965)](image1)

![Figure 14 - Comparison between experimental and theoretical results (Queener et al., 1965)](image2)

In 1964, Bond reported on an abrasion-impact testing procedure which also measured metal wear (also known as the Allis-Chalmers abrasion test) (Hawk et al., 1999). The device was an impeller-tumbler with a single paddle rotating rapidly within a 1.6 kg ore sample of -19+13.2 mm. The paddle was made of a standard grade of steel. The drum rotated in the same direction but at a slower speed than the impeller. During operation the paddle collided with the abrasive ore causing wear on the broad face due to impact and abrasion. After the test, the wear of the paddle was determined by simply weighing on an analytical balance.

The author ranked the abrasion characteristic of different ores by introducing an Abrasion Index (AI) representing the relative wear of the paddle. Typical results for lead zinc ore, gold ore and bauxite were of 0.21g, 0.48g and 0.02g respectively (Bond, 1964). The Bond abrasion index was used in empirical equations derived for different types of crushing and grinding devices to predict the metal wear.

Spero et al. (1991) conducted a comprehensive review of test methods for assessing abrasive wear in ore grinding applications. The standard abrasive wear laboratory tests can be divided into two general groups: those that employ a pin-shaped specimen sliding against a fixed abrasive (two-body), or those that use a rotating wheel sliding against a plane specimen while loose abrasive
particles are continuously introduced between the two (three-body). Figure 15 illustrates both modes.

![Figure 15 - Illustration of two-body and three-body abrasive wear (Harsha and Tewari, 2003)](image)

The authors limited their investigation to three-body laboratory test methods common in industry. In open three-body abrasion wear, the abrasive particles (grit, sand or rock particle) are free and loose to interact with the wearing surface. This form of media wear is common in size reduction processes.

The widely accepted quantitative abrasive wear model used, and which Archard (1953) derived from physical analysis of sliding wear, is presented as Equation (2.11).

Several laboratory apparatus have been used over the years to measure abrasive charge media wear. However, the rubber wheel abrasion tester, RWAT easily adapts to suit grinding media wear tests and therefore is the most commonly used. The RWAT set-up is illustrated in Figure 16.

The metal specimen, either a plate or block, is forced under a constant load against the rim of a rotating rubber wheel of defined hardness. The abrasive particles (typically silica) of a narrow size distribution are fed into the contact region at a constant rate via a feed hopper. Wear is measured by weighing the sample before and after a prescribed grinding time and having changed other test variables.

![Figure 16 - General RWAT machine set-up (Misra and Finnie, 1980)](image)
The theoretical relationship between abrasive wear and applied force can be described by Equation (2.12) originally proposed by Rabinowicz and Mutis (1965). In essence this model predicts the mass loss of metal caused by an abrasive grain cutting into the surface and sliding a distance \( x \) (Figure 17). This model was adopted by Radziszewski (2001) while conducting research with the RWAT, but modified it to include the effect of load on the abrasive grain angle (Equation 2.13).

The RWAT has one major limitation; it was used as a low stress abrasion tester. These stresses were not comparable to stress levels experienced by the grinding media in industrial size reduction processes. To this end a new modified tester was developed and verified. The major modification was the substitution of the rubber test wheel with that of mild steel. Preliminary test results using the steel wheel abrasion tester, SWAT, showed that not only is the machine robust, it also gives results which are reproducible. The SWAT device (Chenje, 2007) is illustrated in Figure 18.

Results from the test work conducted with the SWAT device (Radziszewski et al., 2005) suggested a modification to Equation (2.13) with the introduction of the friction coefficient, \( \mu \) (Equation 2.14). The friction coefficient was determined using the results of the torque meter with Equation (2.21):

\[
\mu = \frac{T}{F \times r}
\]

where \( F \) is the normal applied force (N), \( T \) the torque (Nm), and \( r \) (m) the radius of the abrasion wheel.

The SWAT device is considered an ideal test device for abrasion breakage studies since it only applies shear stress to the rock particle causing surface breakage. The following figure of hypothetical particle force diagrams demonstrates the difference between impact breakage (random and repetitive) versus shear stress breakage (Figure 19).
Figure 18 - Steel wheel abrasion tester (SWAT)
The JKRBT and DWT mimic diagram (a), a particle being impacted randomly with the same magnitude of specific energy. These devices break the particle in a similar manner as observed in a real AG/SAG milling environment (Larbi-Bram, 2009). The SWAT device applies a constant shear friction force (diagram (b)) to the surface of the rock particle due to a constant normal load dependent on the selected weights and constant rotational speed of the steel wheel.

Yavuz et al. (2008) reported on the abrasion resistance of carbonate rocks and correlations between abrasion and rock properties. The equipment used to investigate the abrasion behaviour was the Bohme abrasion testing device (Figure 20). It employed three-body abrasion; the abrasive particles were free to move between a rotating steel disc and the sample surface under a constant load.

The abrasive material used was Al₂O₃ particles with average grain size of 125 μm. The authors noted that abrasion was the result of “wearing and tearing away of particles from the dimension stone surface by friction or impact, or both.” (Yavuz et al., 2008: 208)
Conclusions drawn from results included a linear increase in abrasion rates with distance (as predicted by Archard (1953)), more abrasion-resistant rocks are likely to exhibit high bulk density, hardness, tensile strength, compressive strength and low porosity, and good correlations exist between abrasion rate and the rock properties tested.

Radziszewski (2009) widened the scope of his research by using the SWAT device to investigate abrasive ore breakage and media wear simultaneously. Ore breakage was quantified by the $t_{10}$ (or $Axb$) methodology commonly employed to characterise the breakage behaviour of ore tested for the AG/SAG mill model parameters at the JKMRC (Napier-Munn et al., 1996). Tests were performed dry with Ottawa foundry sand abrasive of three distinct size fractions at three different constant applied loads with a SAE 1018 steel wheel sample. The test results provided a $t_{10}$-curve which matched that of a typical ore characterisation impact breakage test conducted at the JKMRC. Hence, not only is the SWAT device a reliable and robust grinding media wear tester, its versatility allows it to be used for abrasive breakage characterisation of ore particles too.
2.3.3 **Materials handling**

Attrition (here, undesired breakage) of particulate materials is inevitable in any manufacturing process where use or movement of the particles is a necessary component. Particle attrition is widespread and industries like the chemical and automotive industries (use of catalysts), gas-liquid chromatography (generation of fines in packed columns) and the food and pharmaceutical industries suffer from the effects of attrition to name a few.

Attrition is not limited to a specific industrial process but rather to an environment where bulk material moves through or in a vessel. Hence attrition is prevalent in cyclones, fluidised beds, stirred vessels and pneumatic and hydraulic transport systems too. The unwanted breakage occurs when the particulates move and experience mechanical forces exerted by either the wall of the vessel or by another particulate.

In 1987, Bemrose and Bridgwater conducted an extensive review of attrition and attrition test methods. The tests were grouped in either single particle tests or multi-particle tests. Modelling of particle breakage was quantified by one of three techniques: using selection and breakage functions which were common in grinding applications (adopted by Epstein in 1948) or kinetic formulations such as first order breakage or Gwyn’s relationship. Breakage due to abrasion was absorbed into these models despite other breakage mechanisms being dominant.

Fluidised bed tests frequented the literature as the preferred multi-particle attrition test, largely because it simulated hydraulic or pneumatic transport through pipes. Forsythe and Hertwig (1949) were the first to implement a high-velocity air-jet for investigating attrition of catalysts and much subsequent work was based on their apparatus. Kono (1981) studied relatively coarse (1-4 mm) spherical particles under a range of process variables in three different types of fluidised beds. The researcher proposed correlations between attrition rates and the various parameters, where attrition rate $R$ was defined by

$$ R = - \frac{1}{M} \frac{dM}{dt} \times 100 $$

(2.15)

Using tumbling drums (with or without lifter bars) to quantify attrition has also been reported on. An American standard, ASTM D4058 (1981), prescribed tumbling 100 g of catalysts and catalyst carrier particles for 1800 revolutions at 60 rev/min in a drum of prescribed dimensions and internal surface roughness. Mass loss due to attrition was defined as the percentage product passing a 850 μm sieve. Similar industrial tumbling tests such as the Hardgrove grindability test (1932) for coal and the Bond grindability test (1961) are commonly accepted industrial attrition tests.
Both tests used a ball mill containing steel balls to assist and encourage breakage. Naturally, impact breakage was the primary breakage mechanism observed.

Bemrose and Bridgwater (1987) found that the available standardised tests they reported on, though ample, had limited use or applicability since each test focused on a specific discipline exclusively. The more fundamental the test became, the more arbitrary were its results making it difficult to relate to real-life applications.

Paramanathan and Bridgwater (1983) investigated the attrition behaviour of particulate solids in an annular shear cell. The materials tested included granular salt, laboratory salt and soda ash having regular cubic, spherical and hexagonal shapes. The authors formulated a surface abrasion model to explain their results. The rate of abrasion was assumed to be proportional to the change in radius of the particle to some arbitrary power (Equation 2.16). After mathematical manipulation the equation reduced to Gwyn’s attrition relationship first proposed in 1969 (Equation 2.17).

It was found that particle attrition occurred via fracture and surface abrasion, abrasion contributing more as strain increased. Surface abrasion attrited mainly the edges and corners of the soda ash and laboratory salt samples making it more rounded. The results fit Gwyn’s relationship well since the theoretical surface abrasion model proposed reduced effectively to the same relationship.

Neil and Bridgwater (1994) used a modified annular attrition cell to study eleven different granular materials. The authors established that the particles degraded by both surface abrasion and body breakage. Moreover, it was found that the attrition rate was governed by the particle size and internal structure. The authors concluded that none of the traditional “laws” of comminution or first order kinetics could adequately model the breakage behaviour witnessed. Gwyn’s empirical relationship proved to be most effective.

In the same year Wang and Scholz reported on a study of wear processes during frictional sliding of granite rock in a modified shear cell device (Wang and Scholz, 1994). A theoretical model was developed to understand the mechanisms of wear and verified by experimental results. The model, based on two rough surfaces in elastic contact, predicts that wear occurs in two distinct stages: a transient stage and a steady state stage.

During the transient stage, the wear mechanism was interpreted as shearing off of interlocking asperities (chipping). During the second stage the wear rate was much lower and is linear with displacement (shear abrasion). The amount of wear was governed by the normal load and the initial roughness of the two surfaces. The model predictions were found to be in good agreement with the experimental results.
2.3.4 Comminution

Comminution is concerned with size reduction of rock particles in the most efficient way possible. This has been achieved by a constantly growing variety of comminution technologies and devices including crushers, tumbling mills and stirred mills. Since surface breakage is prevalent in AG/SAG mills and to a lesser extent in ball mills (Yahyaei et al., 2013, Powell et al., 2008, Morrison and Cleary, 2004), it seems prudent to investigate the development of AG/SAG mill principles and its corresponding breakage mechanisms. The majority of research on abrasion (within comminution) has been for the sake of improving model performance. However, the model developments will be discussed in more detail in section 2.4.

As early as 1974, Stanley emphasised the differences between autogenous (AG) milling and non-autogenous (ball and rod) milling:

- Two main modes of breakage are present in autogenous milling: abrasion and crushing. These modes of breakage overlap on the size scale. Ball and rod mills are often considered as purely impact (body breakage) devices.

- The AG mill load grinding parameters are not independent of the mill feed. Rod mills and to a lesser extent ball mills are relatively insensitive to changes in mill feed.

Experiments were conducted in a 1.6 m diameter by 0.3 m long Hardinge ‘Cascade’ mill running at 70% critical speed. The author developed a satisfactory steady state model that included the special characteristic of AG/SAG mills (simultaneous occurrence of abrasion and crushing breakage) based on the perfect mixing hypothesis.

It was assumed that particles in each size fraction lost 1.0% of their mass due to surface breakage. Of the 1.0% progeny, 35.4% \( \left( \frac{1}{11.9} \right)^3 \) reported to the next smaller size fraction while the remainder (64.6%) was arbitrarily given a Rosin-Rammler distribution six size fractions below the original particle size. The author admits that “in the work reported here, abrasion breakage was described by a largely intuitive function based on a consideration of the nature of abrasion breakage” (Stanley, 1974: 79).

Austin et al. (1986) investigated chipping fracture and abrasion in autogenous grinding. The authors proposed that autogenous grinding, in general, should be modelled as a combination of fast and slow fracture each with an associated abrasion component. A theoretical solution to unsteady state batch abrasion revealed that abrasion did not lead to first-order breakage kinetics (Austin et al., 1986).
However, the solution for a combined first-order fracture plus abrasion lead to apparent first-order breakage kinetics, only if the abrasion breakage rate ($S_A$) was relatively small compared to the fracture breakage rate ($S_C$), i.e. the ratio of $\frac{(S_C+S_A)}{S_A} > 4$.

The authors emphasised the prevalence of fracture breakage over abrasion breakage in autogenous grinding. Their predictions and the experimental results were in agreement within the desired accuracy. The presence of fines complicated their studies since the breakage rates decreased with an increase in fine material due to the cushioning effect. To avoid varying parameters caused by the cushioning, tests were performed dry for short grinding periods, after which the fines were removed and replaced with fresh material to preserve the desired mill filling.

In 1986, Menacho emphasised that three modes of breakage were present in autogenous milling: “three basic mechanisms of size reduction [contribute]. The first one is the complete fracture of the small particles by impact or nipping between the large lumps or between large lumps and the mill liners. On the other hand there is abrasion size reduction resulting from rubbing of lumps against other particles or against the mill liners. Many rocks are reduced in size by losing small pieces which have a size distribution different from the normal primary progeny fragments. This partial fracture or chipping is the third controlling size reduction mechanism…” (Menacho, 1986: 87).

This is in accordance with the approach adopted by the JKMRC as discussed in section 2.1.

Goldman and Barbery (1988) studied the surface breakage mechanisms of coarse particles in wet autogenous grinding to model the load size distribution of a 1.75 m diameter mill. The effects of percentage fines, load volume, particle roughness and mill diameter on breakage rates were investigated. Autogenous batch tests were conducted at 70% critical speed and 93% solids with pre-rounded particles. After the test, broken particles were discarded and not considered for analysis.

Results showed that chipping was the predominant wear mechanism observed even for well-rounded particles. Hence, a single straight line (Equation 2.18) was adequate to model wear rates as a function of particle weight in the size range studied (25.4 – 152 mm).

Also observed by Austin et al. (1986) was that an increase in the level of fines in the load resulted in a decrease in breakage rates due to a cushioning effect. Wear rates for a fresh particle decreased with grinding time. It was found that after losing 4% of its mass a fresh particle starts to behave like a rounded one. Wear rates increased with percentage filling, but decreased significantly after 22% such that 33% and 11% fillings produced similar breakage rates and at 50% filling the breakage rates were at its lowest.
In 1997, Loveday and Naidoo experimented on waste rock from South-Africa in a 600 mm diameter autogenous mill. The authors investigated the effect of different mill operating conditions on the rate of abrasion of the rock. Preliminary tests were conducted on fresh quartzite rock ranging from 50 mm to 170 mm and then on gold mine waste rock of similar size distribution. The rounded pebbles from this test were then used in the abrasion study. Sand was added to the mill in some runs to determine the effect of fines on the rate of abrasion of the rocks. The mill was 500 mm long, fully rubber-lined, operated at 70% critical speed and 45% filling, and had no lifters installed. Water was constantly added to the mill to flush out products through holes along the end-plate, thereby minimising secondary breakage.

It was found that the size distribution of the abrasion product of rounded pebbles was independent of operating conditions, but seemed to be controlled by the grain structure of the rock. The initial chipping phase was complete after the particles lost about 7% of their mass whereupon a remarkably constant size distribution was observed. With smooth liners, the rate of abrasion wear increased linearly with mill speed. Furthermore, a reduction in the overall rate of wear resulted when sand in the form of limestone was added to the mill (Loveday and Naidoo, 1997). Scatter in the data was significantly reduced by normalising to surface hardness as determined by a Schmidt hammer.

Loveday and Dong (2000) conducted similar experiments with pilot plant mills in their optimisation studies of primary and secondary autogenous grinding performance. They found the 1.8 m diameter mill performed much better than anticipated: the specific wear rate of rock abrasion was seven times higher in the 1.8 m mill than in the 0.6 m mill. Empirical equations predicted the specific grinding rate to increase by only a factor of 1.7. This dramatic increase was credited to possible impact breakage occurring in the large mill and insufficient specific energy available in the small mill. It was concluded that data obtained from the 0.6 m mill will be conservative when used for scaling up. Pre-rounded rocks were used in the experiments.

A batch test procedure was developed by Loveday in 2004 for determining the rate of abrasion and breakage of rounded rocks in a 1.2 m diameter mill. Grinding rates were increased by the presence of steel balls (75 mm) and fines escaped the mill through 20mm peripheral ports due to constant water flushing. The authors emphasised that predicting the rate of abrasion and body breakage was a complex task. The authors explained why: “The rate of abrasion and breakage of full-size rocks is influenced by the natural shape of rocks produced by primary crushing and the inherent flaws and natural inhomogeneity of the rocks.” (Loveday, 2004: 1093)
Since no two rocks are identical (in shape or internal structure), determining a relationship to predict the ‘general’ behaviour of rocks (like rate of breakage) remains a challenge. The ‘specific rate’ ($R_S$) of rounded rocks was used for modelling purposes (Equation 2.19). It was defined as the rate of loss of rock mass per unit mass (Loveday, 2004).

This definition should not be confused with the breakage rate parameter used in population balance modelling (more on this in section 2.4). Results showed that the specific rate remained fairly constant over the tested range of sizes (20–180 mm), justifying the implementation of an average rate for calculating mill performance. The authors concluded that the semi-batch test on rounded rocks provided a convenient and realistic platform for determining specific rates similar to those of a full-scale mill.

In 2006, Loveday et al. reported on similar batch tests performed in a 1.2 m diameter mill to investigate the effect of operating conditions on the rate of abrasion and breakage of rocks. It was found that the rate of abrasion and breakage improved significantly by the addition of steel balls. The authors emphasised the difficulty commonly experienced in classifying breakage in batch grinding: “However, it was not possible to distinguish between breakage and abrasion from the steady state data which was expressed in terms of size only.” (Loveday et al., 2006: III-382) Results showed that rate of abrasion at 69% critical speed was significantly lower than at 75%. A combination of chipping and abrasion were the mechanisms causing breakage at 75%.

In 2009, Stephen Larbi-Bram reported on his studies of ore breakage characterisation for AG/SAG mill modelling. He developed and validated a novel methodology for ore breakage characterisation implementing the JKRBT device under high energy single impact and low energy repetitive impact conditions.

He proved that both the prior-art and the Shi and Kojovic models over-predicted the breakage in a low energy tumbling environment. Low energy incremental breakage was found to be “one of the significant modes of breakage found in AG/SAG mills” (Larbi-Bram, 2009: 126). Other breakage mechanisms like attrition and abrasion were not considered and excluded from the scope of the test work.

More than 1,400 experiments were conducted with the JKRBT device, gravity drop tests, and two pilot plant mills of 0.6 m and 1.1 m diameter respectively. The author defined a parent rock subjected to an impact event to be ‘broken’ only if the product was smaller than the next root 2 series sieve below the size range of the parent particle.
Breakage product was classified as body breakage, surface breakage or a combination of the two depending on the input energy. Losses less than 10% were assumed to characterize surface breakage, while losses 10% or higher represented body breakage.

The author proposed two similar but modified forms of the Shi and Kojovic (2007) breakage models: one for body breakage and the other for surface breakage with corresponding breakage parameters (see equation (2.5)). The new proposed methodology for AG/SAG mill modelling was successfully validated with two independent ore samples.

Recently, Devasahayam (2013) reported on abrasion characteristics of ores. The author tumbled five different ores types of size range 25 to 50 mm for different lengths of time in a 300 x 300 mm tumbling mill. The objective was to develop a calibration equation for predicting the JKMRC standard $t_{10}$ abrasion parameter from a small diameter core material.

Since shape was an important parameter, the author defined the Shape Factor (SF) as the ratio of the number of particles (if they were all spheres) to the real number of particles for a given 3 kg batch of ore.

The data fitted the proposed model reasonably well within a 95% confidence interval – scatter was explained by the 11.9% coefficient of variation observed in repeatability tests, implying large differences in ore variation existed between samples (which was a common problem). Results showed that chipping occurred at a faster rate and depended on the ore and SF of the particle. Moreover, it was found that chipping occurred mostly with particles larger than 20 mm and was size dependent, but this was not the case for the abrasion or attrition processes.

Yahyaei et al. (2013) proposed a methodology of characterising surface breakage of ore rocks using multi-size pilot mills. The mills (with diameters 0.8 m, 1.2 m and 1.8 m) were rotated at 40% of critical speed to create an environment of rock sliding over one another, promoting abrasion as the principal breakage mechanism. Fine products (<20 mm) are washed out of the mill by spray water and left through 20 mm ports along the periphery of the mills - minimising secondary breakage.

Since surface breakage causes new surface area generation, abrasion rates (rate of mass loss) were normalised to the net energy input, initial charge mass as well as the surface area (Equation 2.20). This unit made the results comparable between different mill sizes. Results showed that after 6 minutes the specific mass loss rates levelled off, implying that the dominant breakage mechanism changed from chipping to abrasion at that point. For the same ore type, higher chipping rates were found in the smallest mill. However, identical grinding rates were found (after 6 minutes) - independent of the mill size (Figure 21).
DEM results supported the findings. DEM simulations indicated that the ratio of normal to tangential energy (impact to abrasion) was largest in the 0.8 m mill and smallest in the 1.8 m mill (Figure 22). The author proposed that this result could explain why a higher chipping rate and larger surface areas were observed in the 0.8 m and 1.8 m mills respectively.

Figure 21 – Superficial breakage rates for three different mill sizes (Yahyaei et al., 2013)

Figure 22 - Energy spectra for different mill sizes (Yahyaei et al., 2013)
<table>
<thead>
<tr>
<th>Field</th>
<th>#</th>
<th>Researcher(s)</th>
<th>Model</th>
<th>Parameters</th>
<th>Material</th>
<th>Type</th>
<th>Device</th>
<th>Mechanism(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GEOLOGY</td>
<td>(2.6)</td>
<td>Sternberg (1875)</td>
<td>$m = m_0 e^{-ax}$</td>
<td>$m$ is mass at any distance $x$, $m_0$ is initial mass of pebble, and $a$ is coefficient of size reduction</td>
<td>Limestone rocks</td>
<td>Bed</td>
<td>Tumbling barrel</td>
<td>Surface breakage</td>
</tr>
<tr>
<td>GEOLOGY</td>
<td>(2.7)</td>
<td>Latham &amp; Poole (1987)</td>
<td>$w(t) = (1 - b) e^{-k_f t} + be^{-k_s t}$</td>
<td>$w(t)/w_0$ is mass fraction of original material after time $t$, $k_f$ is specific rate for fast breakage, $k_s$ is equivalent slow breakage parameter, and $b$ is proportionality parameter</td>
<td>Limestone rocks</td>
<td>Bed</td>
<td>Tumbling barrel</td>
<td>Surface breakage</td>
</tr>
<tr>
<td>TRIBOLOGY</td>
<td>(2.8)</td>
<td>Mulhearn &amp; Samuels (1962)</td>
<td>$M_n = M_\infty (1 - e^{-\beta n})$</td>
<td>$M_n$ is total mass loss up to $n$th traverse, $M_\infty$ is ultimate mass loss, and $\beta$ is deterioration constant of abrasive paper</td>
<td>Metal</td>
<td>Single samples</td>
<td>Rotating table</td>
<td>Two-body shear abrasion</td>
</tr>
<tr>
<td>TRIBOLOGY</td>
<td>(2.9)</td>
<td>Queener et al. (1965)</td>
<td>$W = \beta (1 - e^{-nK}) + KL$</td>
<td>$W$ is total mass loss, $n$ a dimensional constant, $\beta$ is maximum mass loss possible during transient stage, $K$ is steady state wear rate, and $L$ is total sliding distance</td>
<td>Metal</td>
<td>Single samples</td>
<td>Caterpillar gear rollers</td>
<td>Two-body shear abrasion</td>
</tr>
<tr>
<td>TRIBOLOGY</td>
<td>(2.10)</td>
<td>Queener et al. (1965)</td>
<td>$\beta = 2\rho AR_s$</td>
<td>$\rho$ is the density of the metal specimen, $A$ the area of the wear scar, and $R_s$ is surface roughness</td>
<td>Metal</td>
<td>Single samples</td>
<td>Caterpillar gear rollers</td>
<td>Two-body shear abrasion</td>
</tr>
<tr>
<td>TRIBOLOGY</td>
<td>(2.11)</td>
<td>Archard (1953)</td>
<td>$dV/dl = k.L/3p$</td>
<td>$V$ is volume of worn material, $k$ is dimensionless wear coefficient, $L$ is fixed load, $l$ is sliding distance and $p$ is yield pressure of hardness of wear surface</td>
<td>Theoretical particle</td>
<td>Single particle</td>
<td>-</td>
<td>Shear abrasion</td>
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<tr>
<td>Field</td>
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<td>Model</td>
<td>Parameters</td>
<td>Material</td>
<td>Type</td>
<td>Device</td>
<td>Mechanism(s)</td>
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<tr>
<td>TRIBOLOGY</td>
<td>(2.12)</td>
<td>Rabinowicz &amp; Mutis</td>
<td>( \frac{dV}{dl} = \frac{L \cdot \tan \theta}{\pi \cdot p} )</td>
<td>( V ) is volume of worn material, ( \tan \theta ) is weighted average angle of abrasive particles, ( L ) is fixed load, ( l ) is sliding distance and ( p ) is yield pressure of hardness of wear surface</td>
<td>Theoretical</td>
<td>Single particle</td>
<td>-</td>
<td>Shear abrasion (abrasive)</td>
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<td></td>
<td>(2.13)</td>
<td>Radziszewski</td>
<td>( m_{abr} = \frac{\rho \cdot \tan(\theta(F))}{\pi \cdot H_r} \cdot F \cdot x )</td>
<td>( m_{abr} ) is total metal loss due to abrasion, ( F ) is fixed load, ( H_r ) is specimen hardness, ( x ) is sliding distance, ( \rho ) is specimen density, and ( \theta ) is abrasive grain angle</td>
<td>Metal</td>
<td>Single samples</td>
<td>RWAT</td>
<td>Three-body shear abrasion</td>
</tr>
<tr>
<td></td>
<td>(2.14)</td>
<td>Chenje &amp; Radziszewski</td>
<td>( m_{abr} = \frac{\rho \cdot \tan(\theta(F))}{\pi \cdot H_r} \cdot \mu \cdot F \cdot x )</td>
<td>Similar to above, ( \mu ) is coefficient of friction</td>
<td>Metal</td>
<td>Single samples</td>
<td>SWAT</td>
<td>Three-body shear abrasion</td>
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<td></td>
<td>(2.15)</td>
<td>Kono</td>
<td>( R = -\frac{1}{M} \frac{dM}{dt} \times 100 )</td>
<td>( R ) is the attrition rate and ( M ) is the initial catalyst mass</td>
<td>Alumina-silica</td>
<td>Bed</td>
<td>Fluidised beds</td>
<td>Attrition</td>
</tr>
<tr>
<td></td>
<td>(2.16)</td>
<td>Paramanathan &amp; Bridgwater</td>
<td>( \frac{dr}{dy} = -K(r_0 - r)^{-b} )</td>
<td>( r_0 ) is initial particle radius, ( r ) is radius after applying shear strain ( \gamma ), ( K ) and ( b ) are experimental parameters</td>
<td>Salts</td>
<td>Bed</td>
<td>Annular shear (attrition) cell</td>
<td>Bulk shear</td>
</tr>
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<td></td>
<td>(2.17)</td>
<td>Gwyn</td>
<td>( W = k \gamma^m )</td>
<td>( W ) is fraction progeny mass passing coarsest sieve, ( \gamma ) is shear strain (equivalent to time), ( k ) and ( m ) are dimensional parameters</td>
<td>Catalyst particles (silica-alumina)</td>
<td>Fluidised bed</td>
<td>Attrition apparatus</td>
<td>Attrition (bulk breakage)</td>
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<td>Parameters</td>
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<tr>
<td>COMMINUTION</td>
<td>(2.18)</td>
<td>Goldman &amp; Barbery (1988)</td>
<td>$\frac{dM}{dt} = -KM^\beta$</td>
<td>$M$ is original mass, $K$ is breakage rate (hr$^{-1}$), and $\beta = 1$ for chipping, or $2/3$ for abrasion</td>
<td>Rock</td>
<td>Bed</td>
<td>Tumbling mill</td>
<td>Surface breakage</td>
</tr>
<tr>
<td></td>
<td>(2.19)</td>
<td>Loveday (2004)</td>
<td>$R_s = \frac{3k}{D} = \frac{3}{D} \frac{dD}{dt}$</td>
<td>$R_s$ is ‘specific rate’ and $D$ is rock diameter</td>
<td>Rock</td>
<td>Bed</td>
<td>Tumbling mill</td>
<td>Surface breakage</td>
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<tr>
<td></td>
<td>(2.20)</td>
<td>Yahyaei et al. (2013)</td>
<td>$R(t) = \frac{m(t_2) - m(t_1)}{m_o} \frac{m_o}{E_{ss}(t_2)}$</td>
<td>$m(t)$ is mill holdup mass at time $t$, $m_o$ is initial mill load, and $E_{ss}$ is surface specific comminution energy (kWh/m$^2$)</td>
<td>Rock</td>
<td>Bed</td>
<td>Tumbling mill</td>
<td>Surface breakage</td>
</tr>
</tbody>
</table>
2.4 Empirical scale up models versus Mechanistic models

A brief overview of the structure of common empirical comminution models is presented. This includes the development of the AG/SAG mill model used at the JKMRC. After which, a case for the unified comminution model (UCM), mechanistic in nature, is made.

2.4.1 Empirical AG/SAG models

The population balance matrix model developed by A. Whiten (1974) and applied to autogenous milling by Stanley also in 1974 is presented below. It is based on a mass balance around a single size fraction (Figure 23).

\[
\frac{d\tilde{s}}{dt} = (AR - R)\tilde{s} + \tilde{f} - \tilde{p}
\]  \hspace{1cm} (2.21)

where \(\tilde{s}\) is a vector of mass contents in the mill per size fraction,

\(\tilde{f}\) is a vector of mass flowrates of feed of every size fraction,

\(\tilde{p}\) is a vector of the discharge mass flowrates from every size fraction,

\(R\) is a diagonal matrix containing the breakage rate of each element of \(\tilde{s}\),

\(A\) is a lower triangular matrix (appearance function) containing the breakage function for every size fraction of \(\tilde{s}\), and

\[
\tilde{p}_i = D_{ij}\tilde{s}_j
\]  \hspace{1cm} (2.22)

where \(D\) (the discharge function) is a diagonal matrix containing the discharge rates of each element of \(\tilde{s}\). At steady-state the accumulation term \(\frac{ds}{dt} = 0\), thus

\[(AR - R - D).\tilde{s} + \tilde{f} = 0\]  \hspace{1cm} (2.23)
If the mill contents, $\tilde{s}$, is not known (which is almost always the case), then $R$ and $D$ cannot be separated and a combined parameter, $DR^{-1}$, can be determined if $\tilde{f}$ and $\tilde{p}$ are known. This model is often called the ‘first order rate model’ because it assumes that the breakage per size fraction is only dependent on the mass of that size fraction within the mill load contents.

It was assumed arbitrarily that the mill contents will lose 1.0% of its mass due to abrasion breakage per size fraction. 35.4% (i.e. $(\frac{1}{2})^3$) of the 1.0% will report to the size fraction directly below the original particle size fraction, while the remaining 64.6% reports to the 8‒18 size fractions in a Rosin-Rammler distribution (arbitrarily chosen). The original parent particle is in the first size fraction and thus retains 99% of its mass.

To define the crushing breakage, the author used the Rosin-Rammler distribution first modified by Whiten (1974):

$$B(x,y) = \frac{1-e^{-(x/y)p}}{1-e^{-1}} \quad (2.24)$$

where $B(x,y)$ is the proportion of particles originally of size $y$ that are smaller than size $x$ after breakage. Stanley decided $p = 2$ for his work.

The author set the lower (abrasion) limit and the upper (crushing) limit by visual examination of the load. It was found that the abrasion-crushing transition zone covered six consecutive $\sqrt{2}$ size fractions in general. The breakage function for the transition zone was defined as a linearly weighted function of the pure abrasion and crushing functions dependent on the size position in the transition zone:

$$B = aB_1 + (1 - a)B_2 \quad (2.25)$$

where $B_1$ and $B_2$ are the abrasion and crushing breakage functions respectively, and $a$ is the proportion of the distance (in size-interval terms) across the transition zone.

After studies of pebble wear rates, it was postulated that two types of pebble abrasion can occur, namely mass dependent abrasion (chipping) and surface-dependent abrasion (shear friction). He assumed that the progeny size distribution from surface-dependent abrasion remained constant regardless of the parent pebble size. The appearance matrix was hereafter updated to include both abrasion modes and thus consisted of four parts. Breakage and discharge rates were calculated by a suite of empirical relationships covering all four breakage ‘zones’.
2.4.2 JKMRC AG/SAG mill model

The breakage processes occurring inside an AG/SAG mill can be represented in a simplified form as shown in Figure 24. Fresh feed enters the mill and is subject to breakage events due to other particles and/or the mill shell. The products either exit via the grate or are recycled to undergo further breakage. Essentially the process consists of three interactive components:

- Collision frequency (breakage rate),
- Product size distribution after breakage (appearance function), and
- Particle transport out of the mill (discharge rate).

At steady state, the perfect mixing model mass balance equations (Whiten, 1974) are expressed as follows (a special case of the population balance model):

\[ 0 = f_i - p_i + \sum_{j=1}^{i} r_j s_j a_{ij} - r_i s_i \]  \hspace{1cm} (2.26)

and

\[ p_i = d_i s_i \]  \hspace{1cm} (2.27)

where

- \( f_i \) = feed rate of particles of size \( i \)
- \( p_i \) = product rate of particles of size \( i \)
- \( r_i \) = breakage rate of particles of size \( i \)
- \( s_i \) = mill contents of particles of size \( i \)
- \( d_i \) = discharge rate of particles of size \( i \)
- \( a_{ij} \) = appearance or breakage distribution function

The appearance function (or breakage distribution function) is the product size distribution of ore particles resulting from breakage events. Characterisation tests have to replicate the breakage modes and conditions that occur within the mill. Since it is believed that both impact (high energy) and surface breakage (low energy) occur in AG/SAG milling, appearance functions for both modes of breakage have to be accounted for.
This is determined using laboratory ore characterisation tests as outlined in section 2.2. The outcome of the testing is a characteristic $t_{10}$-E curve from which the $t_{10}$, $t_a$ and A×b values, and full product size distributions for both high and low energy can be determined. The combined appearance function is simply a weighted average of both modes’ appearance functions:

$$a = \frac{t_a a_{le} + t_{he} a_{he}}{t_a + t_{he}}$$

(2.28)

where $t_a$ is one tenth of the $t_{10}$ as determined by the abrasion (low energy) test and $t_{he}$ is equal to the $t_{10}$ value derived from the impact (high energy) tests.

Loveday and Whiten (2002) derived a theoretical model of rock abrasion and applied it to steady state pilot plant data for fully and semi-autogenous grinding. A model to predict the steady state size distribution of the load and to determine the feed rate required for maintaining an optimum level in the mill was envisioned. Only rocks coarser than the grate size were modelled. Simplifying assumptions included that a certain mass fraction of all rocks (10%) was rapidly transferred to “fines” (<13mm) during the initial rounding which resulted in a transfer of 20% of the mass to the next size fraction.

Model outputs for AG showed that the abrasion rates (mm/h) remained relatively constant for sizes 13 to 75 mm, but increased dramatically for larger sizes. On the other hand, specific rates decreased initially but levelled off and remained relatively constant for larger pebbles. Both rates were higher for low charge level compared to a high filling. Similar trends were observed from (larger) industrial mill data, but at enhanced rates. The authors concluded with an important observation: the model was purely empirical at that stage and was, therefore, no better than the population-balance model.
2.4.3 Unified comminution model (UCM)

Powell and Morrison discussed the future of comminution modelling in 2007. Quoting King (1993) the authors emphasised the need for better understanding fundamental processes in comminution: “A fundamental understanding of the basic micro-processes associated with the dynamics of particulate systems – their transport and fracture – is still lacking … the really significant advances in comminution technology in the forthcoming decade will only come from the exploitation of basic fundamental understanding of the fracture process to improve industrial comminution processes.” (Powell and Morrison, 2007: 228)

Limitations of current semi-empirical scale-up models include (Powell et al., 2008):

- Models are only valid over the range of operation for which they were developed,
- Only applies to existing types of equipment for which they were developed,
- Cannot handle multiple ore components
- Power/energy is independently calculated, not used as inputs for breakage determination,
- Finer design details (like liner design) are not easily incorporated

Clearly there is a need for understanding and modelling the fundamental mechanisms involved in size reduction processes independent of the tumbling environment. This lies at the heart of mechanistic modelling and the UCM. This would preclude fitting rates to mature empirical relationships which are ore and machine dependent. With this philosophy, the UCM has been proposed as the ideal platform for unifying all comminution models. The model definition as proposed by Powell et al. (2008: 745) states:

“The unified comminution model (UCM) traces the mechanical collision environment experienced by particles in a comminution device and calculates the resultant damage to the particle in order to predict the progeny of the device.”

The model (Figure 25) relies on mechanical environment predicted by computational techniques. Using the collision environment predicted by simulation, the degree of damage or breakage can then be calculated dependent on the breakage mechanisms present. The total damage is summed over time to provide the breakage product of the device. A transport function is required to track the progress of the particles into, through and out of the device.

Conservation of mass is ensured by a population balance framework similar to the AG/SAG mill model. For the sake of brevity the population balance structure will not be shown here, but is explained fully in Powell et al. (2008).
Currently DEM is used to simulate the mechanical environment created by the device. The result is collision frequency spectra across all energies for all each size class and every mode (related to the mode of breakage). Energy dissipation is assumed to occur according to the contact model; therefore each particle class has an associated normal (impact) and tangential (abrasion) energy loss spectrum. The normal energies will be classified into three zones: single hit breakage, multiple impact breakage and no bulk damage. The tangential energies are commonly assumed to cause surface abrasion wear. The contribution of DEM is limited since it does not predict breakage or the transfer of energies during collision and breakage events.

![UCM - Unified Commination Model](image)

*Figure 25 - UCM model structure (Powell and Weerasekara, 2010)*
Outputs from the DEM will guide the breakage testing techniques. These breakage characterisation tests must represent the exact conditions over the range of energies that occur in the comminution device. Mineralogical liberation of the ore should be measured from the test product. This will be a major advantage over current breakage tests. According to the authors, this area of the model requires substantial development, and is considered the major obstacle to successful implementation of the UCM.

Characteristic breakage tests include incremental and single impact tests, abrasion and chipping, and compression and shear tests (like compressed bed breakage).

Currently mechanistic flow relationships are used to predict transport and discharge of the contents of the device. However, this is equipment specific and will generally not be valid for new devices. An improved transport and discharge function is critical to model real industrial mills. Applying smoothed particle hydrodynamics (SPH) has been considered and is the subject of continuous investigation (Cleary et al., 2006).

It is the vision of the authors (Powell et al., 2008: 744) that the UCM will eventually provide an integrated framework to:

- “unify all comminution models,
- improve the predictive power of current models,
- incorporate liberation,
- link to up-stream and down-stream processes,
- provide the information for prediction of liner and media wear, and
- be able to model current and novel comminution devices.”
2.5 Shortcomings

Presented below is a brief overview of the shortcomings found in the literature presented in the previous sections. This author will argue that batch grinding (by far the most frequently implemented to study abrasion) is not an appropriate abrasion test and will explain why. A short note on the validity of impact tests and numerical simulations follows. A critique on some of the abrasion tests found in literature is briefly presented then after which the limitations of the empirical models are identified. This section then concludes with a summary of the knowledge gaps as motivation for this thesis.

2.5.1 Batch grinding

Much of the research done into investigating abrasion has been conducted in tumbling barrels or mills. As mentioned before, two modes of breakage are commonly accepted to be present in a milling environment: body and surface breakage. Even if the researcher conducts the test at low filling and low speed, there is no certainty that abrasion and chipping (surface breakage) are the only breakage mechanisms present. Abrasion and chipping might be the dominant breakage mechanisms, but low energy impact events contribute too.

It could be argued that the results found by previous researchers who conducted experiments in tumbling mills were actually measuring the effects of impact and/or attrition, as well as abrasion. Ultimately, no one knows. It therefore begs the question: to what degree do each of these breakage modes contribute? Maybe abrasion breakage dominated? Is there any realistic answer that will satisfy a researcher wanting to investigate abrasion only? Hence, the first shortcoming with using batch grinding as an abrasion test is the uncertainty in the modes of breakage (and their frequency and intensity) occurring in the mill.

The second shortcoming is the possibility of secondary breakage. Since the product is not free to escape the mill at first breakage, it can experience re-breakage by any of the aforementioned modes of breakage. Analysing the final product and assuming it is the result of abrasion only, is questionable. Installing peripheral ports has minimised the possibility of secondary breakage, but has not eliminated it.
Another shortcoming of batch milling is the impossibility of measuring intra-particle or particle-shell forces. Since a product size-energy relationship is an objective of the project (similar to those presented in this document), being able to measure the forces applied to the particles during breakage is vital. The only solution is to use the mechanical torque reading experienced by the shaft as an average input energy into the mill.

Lastly, modelling results from batch grinding ultimately defeats the objective of the UCM. The UCM aims to model fundamental mechanisms occurring in the grinding device independent of the tumbling environment. Hence, studying abrasion in a tumbling device is counterproductive as it does not separate device and breakage process ultimately.

However, the tumbling mill can yet offer valuable insights into surface breakage studies. When considering a bed of particles for surfaces breakage tests, the tumbling mill offers unique loading mechanisms. Changing the speed, mill diameter and filling will create a number of different energy environments with corresponding breakage mechanisms. Isolating the process variables that maximises surface breakage events will remain a challenge. Conducting tests in large mills is also appealing since it can replicate industrial conditions which small mills often lack.

2.5.2 Shear testing

Traditionally the annular shear cell has been used to investigate the source of attrition of particulate material (e.g. powders). This device compresses the sample by applying a defined normal load and then rotates the bottom half of the cell at a selected speed to create shear strain. The size of the particulates typically ranges from 200 to 2000 µm, but can be larger. Investigating superficial breakage with particles of this size can be problematic, even unrealistic from a comminution point of view. This size range also falls outside the scope of this project which is concentrating on an AG/SAG mill feed size range (10 – 150 mm).

Furthermore, the aforementioned weaknesses are also applicable in these tests since a bed of particles was studied. Compression can also lead to the fracturing of the particulate into several pieces frequently referred to as body breakage. This type of breakage is unwanted and is not investigated in this project. The theoretical model proposed by Paramanathan and Bridgwater (1983), though conceived for surface abrasion, was found to model fracture better than abrasion (Bridgwater, 2007). Essentially, this was because most of the breakage that occurred was body breakage. Since attrition is one of the three modes of breakage occurring in AG/SAG milling, a student investigating attrition would be wise to consider test work in the annular shear cell.
2.5.3 Impact tests

The definition of abrasion clearly defines the mechanisms involved in abrasion and it does not include impact events, even at low energy. Therefore, impact tests are not suitable for testing ore response to abrasion breakage; yet. However, one of the hypotheses of this project is to investigate the possibility of substituting low energy impact breakage for abrasion breakage. Clearly both mechanisms must be isolated and tested independently on the exact same ore type and size. To that end, tumbling ore in a mill to test its abrasion characteristic for comparison with low energy impact tests (conducted with the JKRBT) is unwise. Largely because it is not certain if the latter is absent from the mill.

2.5.3 DEM simulations

The application of DEM to comminution processes has been rewarding. It was numerical modelling that confirmed the importance of abrasion and rounding as the dominant comminution mechanism of coarse particles in SAG milling (Yahyaei et al., 2013, Powell et al., 2008, Morrison and Cleary, 2004). Results showed that the majority of the collisions occurred at low energies sufficient to cause surface breakage but not body breakage. But DEM is not limitation free. Simulating particles as spheres, though reducing the computational time, drastically effects the contribution asperities have on abrasion breakage. Even with asperities, the results will be inaccurate because the simulation does not predict breakage or the associated absorbed energies. Therefore, since DEM does not predict breakage or the transfer of energies during collisions or breakage events, its contribution is limited.

2.5.4 Model Limitations

Since AG/SAG milling explicitly assumes surface breakage is present in the mill, the appearance function has to include the progeny generated by superficial breakage events. To that end, the ore abrasion test (p. 15) was developed. Since this test is conducted in a sealed tumbling mill, all the shortcomings of batch grinding mentioned previously are also applicable here. Furthermore, the appearance function of the AG/SAG mill model is defined such that the t_{10}-value generated by the abrasion test is arbitrarily divided by 10 to produce the t_a parameter used in the appearance function. Moreover, there is no justification why the appearance function was defined as a weighted average (Banini, 2000). This could lead to model predictions that underestimate the contribution of superficial breakage to the mill product.
2.5.5 Abrasion tests

It could be argued that the abrasion experiments conducted (Mulhearn and Samuels, 1962, Yavuz et al., 2008) with an abrasive between the specimen and a horizontal rotating disc run the risk of trapping the abraded product. The trapped product in turn can contribute to the mass loss of the specimen during subsequent revolutions of the disc or experience secondary breakage. A solution adopted by some researchers was to only abrade the specimen for one full revolution before adjusting its position radially. This approach should minimise the contributions of a trapped product, but does not eliminate it. This applies to both two-body (cemented abrasive) and three-body (free flowing abrasive) abrasion experiments. The planned abrasion experiments to be conducted for this project will not include an abrasive (to minimise the amount of variables) and will incorporate water to flush the primary product from the abrasion zone.

2.5.6 The SWAT device

It should be evident that the tumbling mill is not the ideal testing device for superficial breakage studies for a myriad of reasons. The two main reasons are that the researcher does not know with certainty that abrasion is the only breakage mechanism present in the mill at any one time and that the milling environment ultimately defeats the objective of the UCM. The UCM aims to isolate the breakage mechanisms present in the tumbling environment and investigate their individual contributions to the overall product. This has to be conducted independent of the milling environment. The concerns regarding the annular shear cell have also been highlighted, mainly its use as an attrition testing device.

To that end, the SWAT device was considered a potential candidate for surface breakage investigations. This device only applies shear friction at different normal loads. Hence the abrasion mechanism is isolated making it possible to investigate superficial breakage due to abrasion and chipping only. This would not be possible in a milling environment since low energy impact events also contribute to superficial breakage. The SWAT device also complies with the requirements of the UCM and therefore its inclusion in this thesis. This will be a novel use of this device.

However, the device had a few limitations which had to be addressed during this project. Firstly, a data acquisition device (DAQ) had to be installed to record the load cell readings. Secondly, fine steel filings from the wheel had to be removed before measuring the product particle size distributions. Lastly, literature showed that sliding speed affected mass loss rates. Unfortunately, the gearbox motor rotated at a fixed speed only which made it impossible to investigate the effect of sliding speed on the rock mass loss rates.
CHAPTER 3

Experimental Approach

In this chapter the experimental strategy followed to meet the research outcomes is presented. The experimental design framework is structured according to the key objectives resulting from gaps and shortcomings in the literature identified in the previous chapter. Each objective is addressed individually. The design framework includes a brief summary of which equipment was used, why it was chosen and the experimental plan followed to conduct the experiments. After the conceptual design section, the detailed experimental methodologies followed to produce the results are presented.

3.1 Conceptual design framework

3.1.1 Single particle vs batch tests

This thesis aims to understand the mechanisms of superficial breakage of ore particles for the development of an abrasion characterisation test. This aim arose from the shortcomings found in the literature on surface breakage studies discussed in Chapter 2. Two options were considered to address this aim: single particle tests and batch (bed) tests.

Many batch tests already exist in literature and industry to quantify a rock’s response to abrasion. However, the concerns raised in the previous chapter regarding batch abrasion tests (secondary breakage and impact breakage contributions) validated the necessity for a single particle abrasion test. Most of the single specimen tests found in the literature were of materials other than ore particles, e.g. metals, ceramics and salts. To that end, both options were investigated in this thesis, but significant modifications were made to the test procedures to overcome the weaknesses of previous research.
3.1.2 Single particle tests

The following objectives were investigated with single ore particle tests:

- Isolate the abrasion mechanism and investigate different compression loads and input energies to identify key drivers of abrasion.
- Propose a generic methodology to test the abrasion characteristic of ores.
- Quantify the abrasion characteristic of ore particles.
- Quantify differences and similarities between low energy impact breakage and abrasion.

3.1.2.1 Key drivers of abrasion

As discussed in chapter 2, the SWAT device was an ideal candidate for abrasion studies of single rock particles. This device isolates the shearing mechanism and is capable of applying different normal loads to the test specimens. Moreover, this complied with the objective of the UCM too. Hence, after having modified the device, the first objective can be addressed with this equipment.

Rock particles were subjected to four different normal loads (310, 510, 710, and 910 N), while keeping the total input energy and other variables constant. The results will validate whether applied energy or shear stress was the primary driver of abrasion breakage.

3.1.2.2 Generic methodology

The procedure followed to conduct the single particle SWAT tests will be generalised into a standard reproducible methodology called IMLAT. The generic methodology will include the sample preparation, SOP, product processing, and data analysis protocols. The full IMLAT methodology is available in chapter 5.

3.1.2.3 Abrasion index

The third objective of single particle tests was to quantify the abrasion characteristic of different ore types, i.e. introducing an abrasion index. The applied load, energy and mass loss results from the data analysis formed the basis of the proposed abrasion index. It is argued that ore particles from different ore bodies will have different degrees of hardness (due to their mineralogy and texture) and should therefore respond differently to the abrasion mechanism. The response was quantified by the average mass loss observed for every constant normal load applied. Two ore types were investigated with the SWAT device: Beaudesert ore (a homogeneous quarry rock) and Cadia East ore (a copper porphyry ore).
3.1.2.4 Low energy impact breakage proxy

The fourth objective of the single particle tests was to investigate, and subsequently to quantify, any differences or similarities between abrasion tests and low energy impact tests. This objective was motivated by the third hypothesis of this thesis of whether low energy impact breakage appearance functions could be used as a proxy for abrasion breakage. To answer this objective, tests were conducted with the SWAT device and the JKRBT, the latter subjecting the particles to an impact breakage mechanism.

Twelve samples (50 particles each) of Beaudesert ore were tested in the JKRBT with specific energies ranging from 0.005 kWh/t (the lowest possible with this device) to 0.4 kWh/t. Particle size distributions (PSDs) from IMLAT tests and JKRBT were then compared. Since the breakage mechanisms of the two devices were completely different, it was argued that any frame of reference defined as a basis for comparison would be physically meaningless. Hence, the appearance functions were compared on face value. Any differences or similarities were then quantified.

It was also suggested to test the highest specific energy possible with the JKRBT since it is well documented that a higher impact specific energy produces a finer product. As a result, two samples (50 particles each) were subjected to a 3 kWh/t specific energy in the JKRBT and their resulting product PSDs compared to that of the IMLAT tests.

3.1.3 Batch tests

The following objective was investigated with a bed of ore particles:

- Quantify differences and similarities between single particle surface breakage (IMLAT) and particle bed surface breakage test devices (planetary mill).

As mentioned previously, this author had reservations regarding conducting abrasion experiments in a tumbling device. However, these devices can accommodate a wide range of loading mechanisms and size ranges that other equipment cannot.

Also, experimenting with a bed of particles supports the statistical significance of the results compared to single particle outcomes which often contain significant scattering due to the natural variability of the ore.
But, it was hypothesised that an abrasion breakage mechanism would prevail due to the dynamics of the device. The mill rotated at relatively high rotational speeds which exceeded the critical speed. The estimated critical speed of the mill was 156 RPM. It was understood that the mill operated much like a washing machine during the ‘spin’ cycle. The rocks would shear against the mill shell and against each other due to the centrifugal forces, but do not repetitively impact each other or the mill shell (Walters and Weerasekara, 2012).

The planetary mill was used to study beds of ore on a small scale (-22.4 mm). A special steel basket insert (Figure 26) had been designed and manufactured for this device. The insert had a large amount of holes in it (along the side and base) to allow the progeny to escape the basket and therefore minimise secondary breakage. This was a novel use of this device which has not been reported on in the literature to this date. Tumbling tests were conducted at low energies (200 RPM to 500 RPM) and different mill fillings (25% to 100%), and the results compared to single particle outcomes.

The possibility of using the planetary mill to conduct abrasion tests as a substitute for the IMLAT has been investigated. The energy readings from the planetary mill were not available, and therefore had to be determined from DEM simulations. The DEM simulations needed to support this project was kindly provided by JKMRC staff (Weerasekara, 2015) as part of a wider study.

A summary of the project design framework is presented in Table 2.
### Table 2 - Experimental design framework

<table>
<thead>
<tr>
<th>Aim</th>
<th>Developing an abrasion characterisation test for measuring superficial breakage in comminution</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Category</strong></td>
<td>Single particle tests</td>
</tr>
<tr>
<td><strong>Objectives</strong></td>
<td>Isolate the abrasion mechanism and investigate different compression loads and input energies to identify key drivers of abrasion</td>
</tr>
<tr>
<td></td>
<td>Propose a generic methodology to test the abrasion characteristic of ores</td>
</tr>
<tr>
<td></td>
<td>Quantify the abrasion characteristic of ore particles</td>
</tr>
<tr>
<td><strong>Equipment</strong></td>
<td>SWAT device</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Parameters</strong></td>
<td>Four different loads (310, 510, 710 and 910 N)</td>
</tr>
<tr>
<td></td>
<td>Constant energy</td>
</tr>
<tr>
<td></td>
<td>Two ore types (Beaudesert and Cadia East) Flat surfaces</td>
</tr>
</tbody>
</table>
3.2 Single Particle Tests

In the following sections, a detailed description of the equipment used to conduct single particle abrasion and impact experiments and the methodologies followed to produce and analyse the results will be reported. The description of the experimental device will include details on the basic design of the devices, the physical principles on which the equipment operates, and the scope of the investigations. The methodologies will include the sample preparation, calibration, test program and raw data analysis. All simplifying assumptions will be stated.

3.2.1 Abrasion response of rocks: SWAT device

Experiments were conducted with the SWAT device to investigate three of the four hypotheses (given below) and their subsequent objectives as identified in chapter 1.

(i) Rock response to abrasion can be isolated from other breakage mechanisms and quantified with an appropriate testing methodology.

(ii) The normal load (and not total input energy) is the key driving mechanism of abrasion of ore particles.

(iii) Low energy impact breakage mechanism does not produce an appearance function similar to abrasion breakage mechanism.

3.2.2 The basic setup of the SWAT device

The steel wheel abrasion tester, developed by Radzisewski (2002), was an upgrade (V2) from the rubber wheel abrasion tester (RWAT), and was first investigated by Gore and Gates (1995) for three-body media wear studies. The RWAT was considered version 1 (V1). The rubber wheel was substituted for a steel wheel because the rubber wheel could not produce the forces needed to simulate the levels of high stress abrasion found in real industrial applications. Another advantage of version 2 was the addition of a strain gauge on the gear box shaft which then made it possible to measure the torque experienced by the wheel and also to calculate the friction coefficient. Further modifications were made to version 2 giving birth to version 3 (V3). Version 3 had the following additional advantages (Chenje, 2007):
• can operate under both wet and dry conditions.
• device is smaller and more compact than V2.
• abrasive ore breakage sampling now possible.
• can be operated by a single person.
• can adapt to accommodate larger samples.
• robust, yet portable.

The basic setup of the device consists of a mild steel wheel connected to a gear box and motor. Hanging vertically from a pivot point was the sample holder which fastens to a lever. A horizontal bar (attached at the pivot point) was connected to the weight stack at one end and an adjustable counterweight at the other end. Directly below the sample holder was a chute to direct the flow of abrasive or water with fine product into collection buckets.

The setup of the SWAT (V3) device is illustrated below:

![Diagram of SWAT device](image)

**Figure 27 - Basic design of the SWAT device (not drawn to scale)**

The design of the SWAT (V3) was similar to the prescribed setup detailed in the American standard, ASTM G65. The standard prescribed a 9” chlorobutyl rubber-coated steel wheel, but the SWAT uses a solid 9” mild steel wheel. The gearbox was connected to a fixed speed drive motor and hence rotated at a constant rotational speed. The normal load applied to the sample was determined by the amount of standard weights chosen in the weight stack.
Two load cells had been attached to the device: one directly behind the sample holder, measuring the force applied to the sample holder, and the other underneath the gearbox, measuring the force applied to the gearbox. Below is a force diagram of the wheel forces acting on the rock sample:

![Force diagram](image)

**Figure 28** - Force diagram of forces acting on the rock sample

Listed below are some of the physical parameters of the SWAT device and the steel wheel. The R-values are the wheel’s roughness parameters and is explained in section 3.2.6:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d_1$ [m]</td>
<td>0.400</td>
<td>Motor power [kW]</td>
<td>4.0</td>
</tr>
<tr>
<td>$d_2$ [m]</td>
<td>0.200</td>
<td>Steel grade (SAE)</td>
<td>1018</td>
</tr>
<tr>
<td>Wheel radius [m]</td>
<td>0.1131</td>
<td>$R_a$ [μm]</td>
<td>3.5</td>
</tr>
<tr>
<td>Wheel width [mm]</td>
<td>13.65</td>
<td>$R_q$ [μm]</td>
<td>11.5</td>
</tr>
<tr>
<td>Rotational speed [RPM]</td>
<td>163.6</td>
<td>$R_{max}$ [μm]</td>
<td>36</td>
</tr>
</tbody>
</table>

### 3.2.3 The sample holder

The sample holder is made of mild steel of fixed dimensions. The rock sample was placed inside the holder and secured in place by fastening three pins with an Allen key. The sample holder is illustrated alongside:

![Sample holder](image)

**Figure 29** - The sample holder of the SWAT device illustrating the pins and dimensions
3.2.4 Scope

The SWAT device can apply normal forces of up to 91 kg or 910 N to the sample. Abrasion experiments were conducted with loads ranging from 310 N to 910 N. The sample holder can accommodate rock samples smaller than 50 mm. Therefore, samples were prepared for abrasion tests in the size range -54+45 mm. Initial trial runs were conducted to determine the degree of mass loss of the rocks. It was found that the Beaudesert rock samples, a homogeneous finely disseminated quarry rock, was a competent ore and produced mass losses of 0.12 g per 30 seconds on average when a maximum load of 910 N was applied.

It was observed that the rock broke easily when it had an irregular shape making it hard to secure in place inside the sample holder. The product from this body breakage was also captured in the same buckets as the surface damage product and as such influenced the product size distribution results. Since body breakage was undesired during the experiments, it was decided to cut the rocks with a saw to facilitate confining the rocks in place inside the sample holder along flat planes and to eliminate all breakage other than that created by the steel wheel.

For all tests conducted with the SWAT device it was assumed that the rock sample as a whole was competent enough to withstand the normal load applied, therefore the only breakage accounted for in the results were due to abrasion. If the particle lost mass due to some edges having broken off, its contribution was excluded from the average mass lost.

The fine product was sent through a Davis tube to remove all traces of the steel (product of the steel wheel abrading during the test) before the particle size analysis was conducted. This device removes metallic contaminants from a solution with the aid of a strong electromagnet.

Typically experiments conducted with the SWAT device (media wear tests) fed an abrasive between the sample and the wheel to aid with abrasion. However, all the experiments conducted with the SWAT device for this project did not incorporate an abrasive. Hence, there was one less variable to account for which in turn made the experiments simpler and provided better control over the independent variables under investigation. The roughness of the rocks was another variable excluded from the scope of this project. It would have been a logistical challenge and a time-consuming endeavour to measure the roughness of hundreds of rocks. Therefore, the effect of roughness was not investigated for the sake of simplicity and strict time constraints, but will be recommended for future investigation.
3.2.5 Calibration

As mentioned before, the SWAT device is equipped with two PT100LC compression load cells: one directly behind the sample holder and the other underneath the gearbox. This is illustrated in the following figure:

Figure 30 - Photographs of SWAT device (V3) and normal load cell (a), enlarged in (b); electromotor and gearbox (c), gearbox support applying a force on torque load cell (d)
The load cells measure the forces exerted on the rock sample and gearbox (or wheel) respectively. The signals from the load cells were transmitted to a data acquisitioning device (DAQ) which converts the electronic signals from volts to kilograms. The DAQ device (NI USB-6008 DAQ) in turn connected to a laptop via a USB port. Installed on the laptop was a signal collection software programme (*Labview SignalExpress™*) that collected the responses in real-time during each experiment. These responses made it possible to determine the applied normal load and torque experienced by wheel, which was used subsequently to calculate the amount of energy supplied to the rock sample.

The responses had to be calibrated to produce reliable results. The normal load cell (behind the sample holder) was calibrated by applying known weights, selected from the weight stack, to the sample holder and recording the electronic output from the software program. This was conducted by increasing the weights up to the maximum (45.5 kg) and also recording the responses as the weights were reduced. It should be noted that due to the design of the device, the ratio of \( \frac{d_1}{d_2} = 2 \), the force experienced by the sample holder was effectively double the weight selected in the weight stack. The physics principle of torque (around the pivot point) will validate this claim. Below are the recorded results of the calibration as well as the calibration curve for the normal load cell:

![Table 4 - Calibration data of normal load cell](image)

<table>
<thead>
<tr>
<th>Total weight from weight stack [kg]</th>
<th>Force applied to sample holder [kg]</th>
<th>Response when increasing weight [kg]</th>
<th>Response when reducing weight [kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>1.250</td>
<td>1.253</td>
</tr>
<tr>
<td>2.6</td>
<td>5.2</td>
<td>6.62</td>
<td>6.60</td>
</tr>
<tr>
<td>13</td>
<td>26</td>
<td>26.92</td>
<td>26.98</td>
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<tr>
<td>25.5</td>
<td>51</td>
<td>53.10</td>
<td>53.20</td>
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<tr>
<td>35.5</td>
<td>71</td>
<td>70.80</td>
<td>70.81</td>
</tr>
<tr>
<td>45.5</td>
<td>91</td>
<td>90.30</td>
<td>90.30</td>
</tr>
</tbody>
</table>
Below are the results for the calibration of the torque load cell. In this case the load cell was removed and arranged such that known weights were hung from a hook attached directly to the load cell.

**Figure 31** - Calibration curve of normal load cell

**Figure 32** - Calibration curve of torque load cell
The electromotor had a fixed drive which rotated the wheel at a fixed rotational speed. The speed was calculated with the aid of a high speed camera. Three samples were recorded having a 310 N, 620 N and 910 N load applied respectively. The videos were analysed and it was found that the rotational speed remained constant even when the maximum normal load was applied. This can be attributed to the motor having sufficient power to ensure constant rotational speed. The fixed rotational speed of the wheel and the power of the motor were reported in Table 3.

3.2.6 Material properties of wheel

The wheel was manufactured from SAE 1018 steel as reported by the supplier. Bringas (2007) explains the grading systems of steel and interantional steel standards in his work.

“Roughness constitutes a surface microrelief and it is defined as a population of irregularities with relatively small sampling as measured, for example, using the assessment length (Figure 33). (Myshkin et al., 1997: 4) The roughnesses of the wheel and the rock sample both contribute to the mass loss observed in abrasion. However, neither variables were investigated in this project primarily due to the labourious nature of the measurements and time constraints.

The surface profile parameters reported in Table 3 are defined below (Whitehouse, 2012):

Arithmetic average of absolute value of deviations

\[ R_a = \frac{1}{n} \sum_{i=1}^{n} |y_i| \]  

(3.1)

Room mean square of deviations

\[ R_q = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (y_i)^2} \]  

(3.2)

Maximum height of profile

\[ R_{max} = \text{maximumpeak height} - \text{maximumvalleydepth} \]  

(3.3)

Figure 33 - Typical rough surface with associated parameters (Myshkin et al., 1997)
Figure 34 illustrates the roughness measurements taken of the steel wheel. The R-values (roughness parameters) reported in Table 3 were derived from these measurements.

![Roughness measurements of steel wheel](image1)

However, it was assumed that the roughness of the steel wheel was constant throughout the entire project and therefore need not be considered. This proposition was motivated by Myshkin et al. (1997: 5): “The original roughness of working surfaces becomes significantly modified by friction and wear reaching the so-called stationary roughness which is apparently reproducible under normal friction conditions.” (Figure 35) Also, the wheel had been in use for three years prior to the commencement of this project. The roughness of the ore particle contributes largely to the initial chipping phase (stage I), but has little bearing on the steady state phase (stage II). Since the latter was the primary objective of this work, it was decided to recommend investigating the effect of roughness on the abrasion product for future work.

![Wear profile of working surface](image2)

Figure 35 – Wear profile of working surface (Myshkin et al., 1997)
3.2.7 Test methodology

Each test regime conducted followed the same methodology: sample preparation, abrasion test, parent particle processing, product fines processing, and data analysis.

3.2.7.1 Sample preparation

The rock samples were crushed and screened to the required size (-54+45 mm) after which they were cut with a saw to fit easily and securely inside the sample holder. Samples were washed, then dried, marked and weighed to track their mass. 60 rock samples per load were prepared (20 rocks per third time increment). Once all the samples were ready, the physical abrasion tests were conducted with the SWAT device.

3.2.7.2 Abrasion test methodology

The standard operating procedure (SOP) was followed for every test. The SOP is available in chapter 5 of this thesis. The only differences between the tests were the load applied to every sample and the total abrasion times. The grinding times for each test are shown in Table 5. These times provided reasonably constant total input energies (in kJ) to the rock samples being mindful of the contribution of the surface roughness of the rocks as well.

<table>
<thead>
<tr>
<th>Load [N]</th>
<th>Time [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>310</td>
<td>270</td>
</tr>
<tr>
<td>510</td>
<td>162</td>
</tr>
<tr>
<td>710</td>
<td>114</td>
</tr>
<tr>
<td>910</td>
<td>90</td>
</tr>
</tbody>
</table>

3.2.7.3 Parent particle processing

After the abrasion tests, the parent rock particle was cleaned and dried before being weighed to determine the amount of mass lost during the abrasion experiment.

3.2.7.4 Product processing

The fine product sheared off the surface of the parent particle was collected in buckets placed underneath the end of the chute at regular predetermined intervals. Water was fed via the hopper located above the wheel to a point just above the rock sample and flushed the product from the shearing zone into the collection buckets via the chute.
The product contained small amounts of steel fines which had to be removed. Since steel is magnetic, the simplest solution was to run the product suspension through a magnet which would attract the magnetic contaminants and hence facilitate separation.

The Davis tube consisted of a glass tube with an electromagnet around the outside of the tube. The tube was also connected to a motor which rotated the tube at a selected speed. It was installed to wash the magnetic suspension liberating any non-magnetics possibly caught in between the steel fines. Once the product fines were steel free, it was pressure filtered, dried and weighed. Thereafter it was sent for particle size analysis using a laser diffraction particle size analyser, 1190 CILAS, device. Often the samples were too large and had to be split down into smaller samples (typically 0.1 g) using a micro-splitter.

3.2.7.5 Data analysis

Both load cells took 10 readings every second (10 Hz). Results collected from SignalExpress™ were exported into Excel for further analysis. Both load cell readings remained reasonably constant over the period of the experiment therefore a simple average was taken for calculation purposes. Once the real response was determined it was then scaled according to the calibration equation to determine the ‘corrected’ value. This corrected value was used to determine the input energy.

Initially, the mass of each particle was only measured before and after each test during the scoping trials. Therefore it was unknown how much mass the particle lost incrementally. It was hypothesized that the particle should lose more mass initially due to the rough outer surface of the rock and chipping, and this would decrease as the wheel sheared into the rock’s interior. The incremental mass loss was inferred from the mass of fines collected in the buckets at regular time intervals. However, these buckets also collected pieces of rock that broke off along the edges of the sample which could bias the results. This was an undesirable outcome and needed to be addressed.

To that end the fourth trial (910 N load) and all subsequent tests were conducted to investigate incremental mass loss directly instead of by inference. But for the first three scoping tests conducted, the incremental mass loss was estimated from the total mass loss. The mass of the products collected in regular intervals were weighed and the ratio of each interval’s contribution to the total was taken as the percentage mass loss incrementally. This process was unnecessary for the subsequent IMLAT tests, because the average mass loss of the 20 rocks was equal to the incremental mass loss for that time interval.
3.2.8 Continuous vs incremental breakage: scoping trials

Initially scoping trials were conducted to validate the proof of concept. 50 Beaudesert rock samples per load were prepared and abraded in the SWAT device at 910 N and 310 N. These two tests were conducted by abrading the particles continuously for the entire grinding period. However, the products were collected incrementally during three equal time intervals, for example every 30 seconds for the 910 N experiments which ran for 90 seconds in total. After the grinding period the samples were dried and weighed to determine their total mass lost.

But the problem with this approach was that only total mass loss for the entire period could be determined and not the incremental mass loss throughout the experiment. A solution to this obstacle was to weigh the dried products collected incrementally. Naturally the mass of the products must equal to the mass lost by the parent particles. This approach was adopted initially before a complication presented itself. Often small pieces of rock would break off around the edges of the parent particle, especially at high loads. These unwanted contaminants would end up in the fines buckets biasing the results. When this occurred, the parent particle’s mass loss was excluded from the results, but unfortunately the same was not possible for the size analysis results.

Because the contaminants were generally larger (typically +1 mm) compared to the products (P80 of 20 micron), it was suggested to pass the products through a 1 mm screen before processing the undersize in the Davis tube. This solution was not ideal because the real products could be larger than 1 mm or the contaminants could be smaller than 1 mm. The alternative was not to determine the incremental mass loss from the products, but rather the parent particles. Also, modifying the sample preparation procedure so that the samples had less edges and micro flaws that could break off easily. Consequently, the IMLAT tests were created.

During the IMLAT tests the incremental mass loss was determined solely from the parent particles and the product PSD from the fines buckets. Therefore, if an edge broke off from a sample, the sample would be excluded from the incremental mass loss results. It would have no effect on the subsequent results which was not the case in the continuous abrasion tests. Also, fewer particles broke along their corners during the IMLATs due to a modification to the sample preparation procedure. The corners were sawn off with a blunt saw to ensure a tight grip in the sample holder and to eliminate weak edges that could easily break off. The products were still passed over a 1 mm screen to remove the few pieces that did break off.
3.3 Low energy surface breakage studies: JKRBT

Experiments were conducted with the JKRBT to address the following hypothesis:

(iii) Low-energy impact breakage mechanism does not produce similar appearance functions as abrasion breakage mechanism.

3.3.1 Basic design of the JKRBT

The Rotary Breakage Tester (RBT) was developed by the comminution research team of the JKMRC for rapid particle impact breakage characterisation. The researches were of the opinion that the prior art testing devices (Twin pendulum, DWT, SILC, etc.) were both time-consuming and expensive. This lead to a limited amount of rock samples that could be tested (10-30 samples per size fraction) for the test to remain useful and practical. Subsequent results however now lacked the statistical support of large sample sets and inevitably brought the validity of the ore characteristics into question.

Hence, the JKRBT was designed based on the kinetic energy concept with the support of a body of evidence from literature. This was considered a viable alternative to the laborious pre-existing technologies which required the manual placing of the samples on an anvil. Moreover, the specific input energies can be accurately controlled and the JKRBT provides exceptionally consistent results (Shi et al., 2009).

The JKRBT essentially consists of a rotary feeder, rotor-stator device with its own drive system and an operation control unit. The rotor consists of three guiding radial channels and a distribution cone which randomly distributes the particles into one of the three channels after entry. Once in a channel, the particle is accelerated to a predetermined speed and ejected from the circumference of the rotor. The particles collide with the surrounding anvils and subsequently break. After impact, the products slide along the base of the device due to its inclined design (30° to the horizontal) and fall into a collection box underneath the rotor. The first industrial unit was designed and manufactured by Russell Mineral Equipment (RME) and commissioned at Anglo Research Pilot Plant in Johannesburg, South Africa. A photograph of an industrial unit was presented in section 2.2.6.
Below is a schematic of the rotor device with velocity vectors of the particle:

![Schematic of the rotor and motion of a particle](image)

**Figure 36 - Schematic of the rotor and motion of a particle (Shi et al., 2009)**

An efficiency factor, $C$, was introduced to account for the frictional losses along the guide channels. The velocity constant was defined as the ratio of the actual velocity of the particles to the theoretical velocity predicted by literature, and quantified the efficiency of the design in transferring the kinetic energy from the rotor to the particle. The value of the constant was determined by using a high speed camera to measure the actual velocity of the particle. Results showed it varied from approximately 0.85 to 0.95. The specific energy transferred to the particle was determined by:

$$E_{cs} = 3.046 \times 10^{-6} C^2 N^2 r^2$$

(3.1)

where $E_{cs}$ is the specific energy (kWh/t), $r$ the rotor radius (m), $N$ the rotor speed (RPM), and $C$ a machine design constant.

The high speed video camera data also demonstrated that larger particles exhibited higher velocity constants $C$ than smaller ones. After fine scrutiny of the recordings, it was deduced that the particle remained in contact with the guide channel until its complete ejection from the channel. Effectively the particle was in longer contact with the channel than first predicted, explaining the higher $C$ values calculated from the results. To account for this observation, the effective rotor radius was increased by at least half of the particle diameter. Breakage characterisation results seemed to support the effective rotor radius concept. Equation (3.1) was therefore modified to include this improvement:

$$E_{cs} = 3.046 \times 10^{-6} C^2 N^2 \left( r + \frac{x}{2} \right)^2$$

(3.2)

where $x$ is the geometric mean particle size (m).
The physical parameters of the JKRBT are listed below:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotor diameter [mm]</td>
<td>450</td>
</tr>
<tr>
<td>Motor power [kW]</td>
<td>7.5</td>
</tr>
<tr>
<td>Maximum rotor speed [RPM]</td>
<td>5000</td>
</tr>
<tr>
<td>Maximum particle size [mm]</td>
<td>45</td>
</tr>
<tr>
<td>Energy range [kWh/t]</td>
<td>0.001–3.8</td>
</tr>
</tbody>
</table>

3.3.2 Scope

Surface breakage requires a small amount of input energy typically less than 0.5 kWh/t. Fortunately the JKRBT can operate at these small specific energies and still produce consistent results. It was therefore decided to conduct a suite of low energy single impact experiments with the Beaudesert ore. The aim was to investigate if abrasion breakage could be substituted for low energy impact breakage. Ultimately, the results will be compared with that of the SWAT device to find an answer to the hypothesis. It was recommended by previous users not to operate below 0.005 kWh/t as it was not certain if the particle would reach the stator at such low energies. Consequently, twelve samples of 50 particles of Beaudesert ore each were tested under the following conditions:

<table>
<thead>
<tr>
<th>Particle size: -11.2+9.5 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific energies [kWh/t]</td>
</tr>
<tr>
<td>0.005</td>
</tr>
<tr>
<td>0.01</td>
</tr>
<tr>
<td>0.025</td>
</tr>
<tr>
<td>0.04</td>
</tr>
<tr>
<td>0.05</td>
</tr>
<tr>
<td>0.075</td>
</tr>
<tr>
<td>0.1</td>
</tr>
<tr>
<td>0.15</td>
</tr>
<tr>
<td>0.2</td>
</tr>
<tr>
<td>0.25</td>
</tr>
<tr>
<td>0.3</td>
</tr>
<tr>
<td>0.4</td>
</tr>
<tr>
<td>Rotational speed [RPM]</td>
</tr>
<tr>
<td>263</td>
</tr>
<tr>
<td>358</td>
</tr>
<tr>
<td>537</td>
</tr>
<tr>
<td>662</td>
</tr>
<tr>
<td>730</td>
</tr>
<tr>
<td>874</td>
</tr>
<tr>
<td>994</td>
</tr>
<tr>
<td>1189</td>
</tr>
<tr>
<td>1351</td>
</tr>
<tr>
<td>1492</td>
</tr>
<tr>
<td>1618</td>
</tr>
<tr>
<td>1838</td>
</tr>
</tbody>
</table>

The products were analysed with the *Camsizer* (+1.0 mm) and the *CILAS* optical analyser (−1.0 mm). The only challenge was that the SWAT and JKRBT did not operate on the same energy basis making it difficult to compare the results. Results from the SWAT are energy based (g/kJ), while those of the JKRBT are specific energy based (g/(kWh/t)). Converting the SWAT results to specific energy would be meaningless since the mass of the parent particle was not motivating the breakage. With the SWAT experiments the energy was transferred to a specific area of the particle (and not the entire particle) provided the particle was competent enough to remain intact during the experiment.
It is also possible that there is no common basis for comparison since the breakage mechanisms were completely different. The device at the JKMRC has been calibrated (Shi et al., 2009) and therefore does not require any further pre-test assessments.

3.3.3 Test procedure

The standard operating procedure, provided by pilot plant staff, was followed when conducting the tests. The samples of a specific size range were washed and weighed on a four decimal Mettler Toledo laboratory scale before the experiment. The 50 particles per sample were then fed individually to the JKRBT at the predetermined rotor speed. The rotor speed was determined by the following calibration curve:

![Calibration curve for determining the required rotor speed (particle size: -11.2+9.5 mm)](image)

The products of all 50 particles were collected as a whole from the base of the device and from the collection bin at the end of every experiment. By collecting all the products, it was impossible to differentiate between surface breakage and body breakage products. This process was repeated until all 600 particles had been impacted once with low energy in the JKRBT at the corresponding impact energy. The products were then sent for optical analysis to determine their particle size distribution. Due to the scope limitations of the analysers, the products had to be separated at 1.0 mm. The undersize was sent to the CILAS device for particle size analysis and the oversize was sent to the Camsizer. Both devices operated on optics principles to determine the size distribution of the sample.
The *Camsizer* takes photos of the particles and determines the size of the particle from image analysis software. The *CILAS* device incorporates laser diffraction to determine the particle size. It is assumed that similar sized particles reflect the lasers identically; hence the detectors will collect responses of similar sized particles at the same positions. All samples for both devices were tested in triplicate and the averages used for reporting purposes.

### 3.3.4 Data analysis

The mass loss of each individual particle was recorded. It was assumed that if a particle lost less than 10% of its original mass, the particle suffered only surface breakage. Any mass loss greater than 10% was assumed to be due to body breakage. Once all the masses were recorded a mass loss distribution was created. The distribution revealed the amount of particles (as a percentage of the total) that experienced surface breakage and body breakage independent of each other versus the specific energy. The average surface breakage mass losses were also determined and compared with the SWAT results. Lastly, the PSDs of the -1 mm products were compared with the results from the abrasion experiments to determine if they were similar or not.
3.4 Surface breakage of particle beds: Planetary mill

Autogenous batch surface breakage tests were conducted in a RETSCH PM100 planetary mill to investigate the last hypothesis:

(iv) Particle bed (batch) experiments in a planetary mill can produce similar appearance functions compared to the IMLAT.

The planetary mill was chosen as an ideal test device due to its convenient size (500 ml) and rapid DEM simulation potential. A different number of Beaudesert ore particles were tumbled at various speeds to measure the material’s response to autogenous shear grinding. The energy readings from the planetary mill were not available, and therefore had to be determined from DEM simulations. The DEM simulations needed to support this project was kindly provided by JKMRC staff as part of a wider study (Weerasekara, 2015).

Table 8 summarises the experimental conditions:

<table>
<thead>
<tr>
<th>Test</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
<th>16</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>-11.2+9.5 mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Speed [RPM]</td>
<td>200</td>
<td>300</td>
<td>400</td>
<td>500</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Filling [%]</td>
<td>25</td>
<td>50</td>
<td>75</td>
<td>100</td>
<td>25</td>
<td>50</td>
<td>75</td>
<td>100</td>
<td>25</td>
<td>50</td>
<td>75</td>
<td>100</td>
<td>25</td>
<td>50</td>
<td>75</td>
<td>100</td>
</tr>
<tr>
<td>Particles</td>
<td>40</td>
<td>80</td>
<td>120</td>
<td>160</td>
<td>40</td>
<td>80</td>
<td>120</td>
<td>160</td>
<td>40</td>
<td>80</td>
<td>120</td>
<td>160</td>
<td>40</td>
<td>80</td>
<td>120</td>
<td>160</td>
</tr>
<tr>
<td>Mass [g]</td>
<td>78.2</td>
<td>176</td>
<td>20</td>
<td>293</td>
<td>84.9</td>
<td>160</td>
<td>219</td>
<td>301</td>
<td>77.8</td>
<td>153</td>
<td>222</td>
<td>302</td>
<td>86.7</td>
<td>164</td>
<td>213</td>
<td>323</td>
</tr>
</tbody>
</table>

3.4.1 Planetary mill setup

This device was designed for sample preparation (pulverisation), but can be used to investigate autogenous grinding behaviour if the steel media is replaced with a coarse material sample. The planetary mill essentially consisted of four main components (Figure 38). The sample holder (500 ml) was conventionally charged with the load (and grinding media), and locked into place with the locking mechanism. A counter balance is then adjusted to compensate for combined holder and charge weight to ensure the sun wheel rotated safely. The speed and grinding times were adjusted on the control panel on the right hand side of the device.

A common concern regarding grinding processes is the contributions of secondary breakage to the final product. To eliminate, or at least minimise, the contributions of secondary breakage it was
suggested to have a steel basket (Figure 39) manufactured. The insert has multiple 4 mm holes along the side and bottom of the basket to facilitate the escape of the primary breakage product. The basket was placed inside the planetary mill sample holder and secured to it with the aid of a rubber ring and the locking mechanism mentioned before. That was to ensure that the basket did not rotate inside the sample holder, but rather rotate with the container.

Figure 39 – Retsch planetary mill and major components

Figure 38 – Steel basket with multiple peripheral exit points
3.4.2 Scope

Due to the sizes of the mill and steel basket only relatively small particles could be accommodated. Also, since an investigation into the comparability between bench scale batch and single particle test devices was the objective, the same ore types had to be used in both devices. As a result, Beaudesert ore particles of the size -11.2+9.5 mm were chosen for the planetary mill experiments. The results of prior tests conducted (Walters and Weerasekara, 2012) with this device on a similar ore type showed that this particle size produced realistic amounts of product in a reasonable grinding time. Results also showed that 12 minutes grinding time was sufficient to record the chipping and steady state phases of the abrasion mechanism. However, two scoping trials were conducted on Beaudesert ore to validate these assumptions.

The device can operate at a maximum speed of 600 RPM. But, it was suggested not to conduct tests at the maximum speed because the device vibrated violently. Also, at 100 RPM the mill produced too little product to collect and weigh accurately. As a result, four speeds were chosen spaced evenly apart: 200, 300, 400 and 500 RPM. To investigate the effect of filling, four different percentage fillings were chosen also: 25%, 50%, 75% and 100%. This was equivalent to 40, 80, 120 and 160 particles respectively. The aim was to cover a wide range of fillings as well as speeds within one test regime.

3.4.3 Test methodology

Each test followed the same protocol: sample preparation, abrasion test, holdup processing, product processing, and data analysis.

3.4.3.1 Sample preparation

Large Beaudesert rocks were crushed down to 11mm with the aid of jaw crushers. Afterwards, the products were sized on Gilson screens until sufficient -11.2+9.5 mm particles were collected. The particles were subsequently washed and dried. After which individual particles were randomly selected and counted to form four groups of 40, 80, 120 and 160 particles each, placed in bags and labelled.
3.4.3.2  ***Grinding test procedure***

After cleaning the device, the sample was placed inside the steel basket. The basket and its contents were then weighed and the initial mass was recorded. The basket was then placed inside the sample holder ensuring a tight and secure fit. Then the sample holder was locked into place on the sun wheel with the locking mechanism. After which the counter balance was adjusted to compensate for the mass of the sample holder, steel basket and its contents.

Once everything was locked in place and the counterbalance positioned correctly, the cover (hood) of the device was lowered and closed properly. At that point, the control panel was activated by the device itself. The required grinding time and speed were selected with the aid of the blue dial and menu options. Once that was captured, the device would start spinning and the timer would count down at the press of the start button.

To investigate the chipping phase in greater detail it was suggested to stop the device at regular intervals during the total 12 minutes grinding period. These intervals were after 1, 1.5, 2, 3, 4, 5, 6, 8, and 12 minutes respectively. At the end of each interval the device was stopped and the sample holder was unfastened. The holdup in the basket and the product in the sample holder were subsequently processed as described below. This procedure was repeated for each interval (9 per sample) and for every sample (16 in total).

3.4.3.3  ***Holdup processing***

After every interval, the basket was carefully removed from the sample holder and any excess fine product attached to it was brushed off into the sample holder. Then the basket and its contents were weighed and the mass recorded. After which the contents were sized with a $\sqrt[3]{2}$ series sieves with top size 9.5 mm and bottom size 4.0 mm. The mass and the number of particles retained in each size fraction were then recorded. Lastly, the entire holdup was placed back into the basket, ready to be abraded for the next interval. Unless it was the final interval (8 to 12 minutes) in which case the holdup was placed in a plastic bag and labelled.
3.4.3.4 Product processing

After every interval the product was brushed off the outside of the basket into the sample holder. Afterwards, the entire contents of the sample holder (the product) was transferred into a plastic vial and labelled. Only some of the product PSDs were analysed due to time constraints. These will be compared to the outcomes of the IMLATs.

3.4.3.5 Data analysis

The mass loss of the bed was determined after every intermission in the experiment. The cumulative mass loss per particle was then be plotted versus the cumulative input energy extracted from DEM simulations. These results were then compared to the IMLAT results to investigate any similarities or differences.

3.4.4 Scoping trials

There was uncertainty surrounding the size of particle to be used in the planetary mill for the abrasion tests. If the particles were too small, the amount of mass of fines produced at low speeds would be impractical. Results from a previous operator of the device (Walters and Weerasekara, 2012) suggested that -11.2+9.5 mm would be a suitable size to investigate. Having chosen the particle size and prepared the samples, another unknown had to be determined: when the steady state phase commenced. In other words, how much time is needed to sufficiently record the chipping and steady state phases of the abrasion profile? To that end, two scoping trials were conducted with 100 Beaudesert particles each at 300 RPM for 10 minutes stopping at regular intervals and measuring the mass loss of the charge.

3.4.5 Energy readings: DEM simulation

Because the energy readings provided by the device were unreliable, an alternative method of calculating the associated input energy was required. To that end, a DEM simulation of the device and relevant geometries were created by Weerasekara (2015) (Figure 40). Conventionally the ore particles were represented by spheres in the simulation, but as noted in the literature review, the particle shape can significantly affect the energy levels experienced in the device being simulated. Thus, it was decided to use a ‘realistic’ particle shape in the simulation (Figure 41) which consisted of a number of spheres of different sizes distributed randomly around a principal sphere. In this manner the contributions of asperities or edges of the real particles were incorporated into the simulation as well, producing more reliable results.
Figure 40 – Discrete Element modelling of planetary mill

Figure 41 – Particle shape used in DEM simulations
CHAPTER 4

Results and discussion

In this section the results of the experiments conducted to meet the objectives proposed earlier will be presented succinctly. Details of the data analysis methodologies followed to produce the final results were presented in chapters 3 and 5. The sections of this chapter were structured according to the objectives, starting with the error associated with using the SWAT device. Consequently the reader can assess if the objectives were met or not. All results will include a discussion on the trends observed and inferences drawn. All simplifying assumptions made during the analysis of the results will be stated also.

4.1 Error associated with the SWAT device

It is important to quantify the reproducibility of the results produced with a grinding device and recognizing the natural variability of ore particles. To determine the error associated with the SWAT device, an experiment was conducted with 10 rocks. To exclude the effect of the surface roughness, the rocks were cut in half and only the interior abraded. Thus, the differences in results could only be attributed to the error associated with the device (including the load cells and software), the operator, and natural variability of the ore. It was assumed that the interior of the rocks were identical with respect to their affinity to shear abrasion. An example of one of the samples is shown below. A normal load of 910 N was applied and each sample was abraded for 90 seconds.

Figure 42 - Beaudesert ore (a) before and (b) after abrasion with SWAT
The results are presented in Table 9:

<table>
<thead>
<tr>
<th>#</th>
<th>Mass loss [g]</th>
<th>Energy [kJ]</th>
<th>MLR [mg/kJ]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.2604</td>
<td>75.7</td>
<td>3.44</td>
</tr>
<tr>
<td>2</td>
<td>0.2877</td>
<td>76.9</td>
<td>3.74</td>
</tr>
<tr>
<td>3</td>
<td>0.3501</td>
<td>72.9</td>
<td>4.81</td>
</tr>
<tr>
<td>4</td>
<td>0.3457</td>
<td>77.3</td>
<td>4.47</td>
</tr>
<tr>
<td>5</td>
<td>0.3277</td>
<td>80.9</td>
<td>4.05</td>
</tr>
<tr>
<td>6</td>
<td>0.3994</td>
<td>84.8</td>
<td>4.71</td>
</tr>
<tr>
<td>7</td>
<td>0.3957</td>
<td>71.4</td>
<td>5.54</td>
</tr>
<tr>
<td>8</td>
<td>0.3573</td>
<td>57.2</td>
<td>6.25</td>
</tr>
<tr>
<td>9</td>
<td>0.2801</td>
<td>75.5</td>
<td>3.71</td>
</tr>
<tr>
<td>10</td>
<td>0.3922</td>
<td>81.1</td>
<td>4.84</td>
</tr>
</tbody>
</table>

| Average | 0.340 | 75.9 | 4.6 |
| Standard deviation | 0.050 | 7.4 | 0.87 |
| Standard error | 0.016 | 2.3 | 0.28 |
| 95% Confidence interval (CI) | 0.036 | 5.3 | 0.62 |

The standard error of the mean mass loss rate (MLR) was 0.28 mg/kJ which was 6.1% of the average. The 95% confidence interval (CI) of the average mass loss rate was 0.62 mg/kJ. The standard error of the mean energy was 2.32 kJ or 3.1% of the average. Also, the standard error of the mean mass loss was 0.016 g which was 4.7% of the average. The standard error of the mean and confidence intervals were calculated with the following equations respectively:

\[
\text{Standard error of sample mean} = \frac{\text{sample standard deviation}}{\sqrt{N}} \quad (4.1)
\]

\[
95\% \text{ confidence interval of mean} = 2.26^* \times \text{standard error of sample mean} \quad (4.2)
\]

*Assuming 9 degrees of freedom (N-1)

The 95% confidence interval defines a boundary around the sample mean such that there is a 95% chance of the population mean having a value within that bounded interval. In other words, the researcher can be 95% confident that the sample means of subsequent tests conducted with similar conditions will have a population mean within this interval.

The results showed that a researcher can expect a minimum error of 6% in the mean mass loss rate when conducting abrasion experiments on a reasonably homogeneous (low variability) ore type with the SWAT device. Any ore type with a larger degree of variability will result in larger errors. Experiments wherein the surfaces of the rock particles are abraded will result in larger errors too.
4.2 Low energy impact proxy

It was proposed (Leung, 1987) that the appearance function of low energy impact breakage could serve as a proxy for abrasion breakage. However, it was assumed at that time that the product resulting from tumbling ore particles in a sealed mill at slow speeds and low fillings was an abrasion product. As discussed previously in this thesis, it is unwise to make this assumption. The contribution of impact events and the degree of secondary breakage occurring in the tumbling mill are unknown. Conducting experiments in a sealed mill and assuming the products created were largely due to an abrasion mechanism is questionable. At best, the researcher can assume the appearance function was the product of surface breakage if the operating variables were in the optimum range, typically less than 40% critical speed and 25% filling. However, surface breakage can be the result of (repetitive) low energy impact events, shear abrasion, or both.

Since the SWAT device isolates the abrasion mechanism, experiments were conducted with the device and the JKRBT to investigate the possibility of using the results of (low energy) impact tests as a proxy for abrasion. This time, the products being compared will be solely due to two isolated independent mechanisms, contrary to the aforementioned proposition. However, a reoccurring dilemma kept presenting itself: on which basis should the results of the two devices or breakage mechanisms be compared? After all, the two mechanisms are distinctly different. In comminution, impact breakage is typically measured in kWh/t, but this unit of energy was not adequate for surface breakage mechanisms. Surface breakage is (as the term suggests) a superficial event, but relies predominantly on the hardness of the ore particle and the applied load as the results will show.

During an impact event the entire particle is given a certain amount of kinetic energy when it is propelled toward its surroundings. When it collides with an object, a fraction of the energy is transferred because work has been done on the particle also causing a change in its momentum. The amount of energy transferred (impulse) is equal to the change in the total momentum or change in kinetic energy (provided its potential energy remained constant and ignoring friction). During the collision, the energy is transferred to the particle across an area of contact. This apparent contact area varies widely depending on how the two objects collided. It is this area that drives the stress that the particle experiences. As a result, collisions result in a wide range of stressing events. The transferred energy will be absorbed and can result in breakage of the particle depending on various factors such as prior flaws and cracks, its competency, and the amount of energy absorbed.
However, contrary to impact breakage, during a shearing event the apparent surface area of the mating surfaces is not the primary driver of mass loss. However, the load and contact time are, as the results will prove. When the objects make contact all the energy transferred due to friction is concentrated across a small initial apparent contact area depending on the dimensions of the two mating surfaces. This area naturally evolves and grows as more material is removed from the surface of one or both particles, but does not vary in the same extent as what is possible with impact events. Even if the contact areas did vary, literature (Archard, 1953, Mulhearn and Samuels, 1962) showed that the wear rate was independent of the apparent contact area, but dependent on the sliding speed. Therefore, the contact area does not drive abrasion breakage. Also, abrasion can only occur if the particle can accommodate the stress applied to it and stay intact. If not, body breakage likely occurs. As a result, material properties like competency and hardness are key material variables in abrasion breakage, as in impact breakage. The difference is the required outcome. With impact breakage the breakage of the particle is the objective, but in abrasion it is a requirement that the particle remains largely intact during the event.

In summary, mass loss during impact events is driven by the localised stress the particle experiences when it collides with another object which in turn is dependent on its kinetic energy and the apparent contact area during the collision. Literature (Shi and Kojovic, 2007) has also shown that the mass or size of the parent particle affects the mass and size of the progeny since larger particles tend to have more inherent flaws compared to smaller ones. However, none of these variables are key drivers of mass loss during abrasion.

The results in the subsequent sections of this chapter will show that steady state mass loss during abrasion is primarily driven by the applied load, but is mass and contact area independent. It must be noted that neither the effect of contact area nor sliding speed were investigated in this project. It is assumed that the results from literature (Archard, 1953, Mulhearn and Samuels, 1962, Myshkin et al., 1997, Al-Samarai, 2012) apply in this project as well, but will be recommended for validation in future investigations. Since the breakage mechanisms of the two devices were completely different, it is argued that any frame of reference defined as a basis for comparison would be physically meaningless. Hence, the mass loss and appearance functions resulting from both devices (or mechanisms) were compared on face value. Each outcome will be discussed separately in the next subsections.
4.2.1 Mass loss

Figure 43 summarises the results from the low energy impact tests conducted with the JKRBT. The input energies ranged from 0.005 – 0.3 kWh/t or 38 – 2530 mJ. The stacked bars indicate the fraction of the samples (50 particles per sample) that experienced surface breakage (dark grey bars) or body breakage (light grey bars) respectively. It was assumed that any mass loss (ML) greater than 10% of the original particle’s mass was due to body breakage (Tavares and King, 1998) and the converse was due to surface breakage.

For example, all 50 particles lost less than 10% of their original mass when subjected to 0.005 kWh/t of energy, hence only surface breakage was recorded. A clear trend was observed: with increasing energy, more particles suffered body breakage. The red dots and smooth curve indicate the average mass loss per sample versus the energy. The average was determined from particles that experienced surface breakage only, i.e. those that lost less than 10% of their original mass. Another correlation was observed: on average, particles with increasing kinetic energy produced more product mass when subjected to an impact event. This trend coincided with a greater chance of body breakage illustrated by the larger light grey bars.

![Figure 43 - Average mass loss versus energy with JKRBT](image)
On the other hand, the IMLAT tests produced mass losses ranging from 0.09 – 0.36 g when subjected to energies ranging from 30 – 90 kJ. It should be noted that the energy ranges of the two devices (in J) were at least five orders of magnitude apart, emphasising again the differences in the breakage mechanisms present in each device. The minimum mass loss observed during the abrasion tests, 0.09 g, has been highlighted in Figure 43 by the dashed black line. The energy readings were also provided in kWh/t and were determined by the average masses of all the samples. When comparing the mass losses observed from both devices on face value, it was clear that only specific energies greater than 0.15 kWh/t applied in the JKRBT produced mass losses within the range of the SWAT device albeit at the lower end. However, these “comparable” mass losses witnessed in the JKRBT had a small chance (< 25%) of being the result of surface breakage.

In summary, on a purely quantitative basis, a low energy impact mechanism can produce similar mass losses compared to the abrasion mechanism, but the chance that the fines created were a product of surface breakage (as was the case with the IMLAT) was low, typically less than 25%. The results suggest that high energy impact (body) breakage should produce comparable mass losses compared to shear abrasion breakage, but at significant lower input energies.

4.2.2 Product PSDs (Appearance functions)

The products from the JKRBT had to be separated on a 1 mm screen. The oversize was sized with the Camsizer while the undersize was sent for optical size analysis in the CILAS device. This was performed to ensure consistency within results and a common frame of reference for the undersize. Also, the CILAS device could only accommodate a top size of 1 mm.

The -1mm PSD results (Figure 44) showed no clear trend with increasing energy, but a finer product was observed at higher specific energies in general. On the other hand, the finest distribution was produced by the lowest specific energy (0.005 kWh/t) applied. However, the +1 mm products produced a strong correlation. Figure 45 below illustrates that with increasing specific energy, the product PSDs became significantly finer.

To that end, it was decided to conduct two additional impact tests of 50 particles each at the highest possible energy the device could accommodate (3 kWh/t) for the same given particle size. The reasoning was that a higher input specific energy should produce a finer product, even finer than the current results. Another motivation for conducting the high energy impact tests was that none of the low energy appearance functions were comparable to the SWAT product PSDs. All the low energy JKRBT products were considerably coarser, with at least one order of magnitude difference in their P80s (Figure 46).
**Figure 44** – PSDs of -1 mm JKRBT product

**Figure 45** – PSDs of +1 mm JKRBT product
Since there was no obvious energy basis to compare the appearance functions of the two mechanisms with each other, it was decided to compare the coarsest SWAT product (910 N) with the finest low energy impact product (0.005 kWh/t) and the subsequent high energy product (3 kWh/t). The results are illustrated in Figure 46 below. The results showed that at the fine end (-1 mm) the 3 kWh/t experiment did not produce a finer product PSD compared to the 0.005 kWh/t test. However, the difference between the high and low energy impact product PSDs at the coarse end (+1 mm) was clearly noticeable (Figure 45). As noted in the earlier discussion, this +1 mm product can be attributed to superficial body breakage rather than abrasion – which correlates with a finer product as impact energy increases.

Nevertheless, both high and low energy impact test results (for the -1 mm) were still at least one order of magnitude greater than that of the SWAT device. Also, the high energy tests did not fall within the scope of this investigation, which was if a low energy impact mechanism could produce similar appearance functions to an abrasion mechanism. The results did suggest that the coarse end of the impact products PSDs became finer with increasing energy but the fine end (-1 mm) remained relatively constant.

Figure 46 - Comparison of PSDs of single impact vs abrasion breakage
A concern was raised that the results of the impact tests were biased because only a fraction of the total product (only -1 mm product) was analysed while in the abrasion tests the entire fines product was analysed excluding the parent particle. As a result, a fourth PSD was included in Figure 46 which illustrates the result of including the entire product PSD for the 3 kWh/t tests. The difference was even more apparent between the abrasion and high energy impact PSDs.

It should be noted here that the products from the impact tests were the complete product. That is, all the PSD results above included both the surface breakage and body breakage products.

In summary, none of the impact tests conducted with Beaudesert ore in the JKRBT (at low or high energy) produced similar appearance functions compared to the SWAT device. The mass loss and the product PSD results suggest that low energy impact breakage tests do not produce similar appearance functions compared to abrasion tests, at least not in the energy ranges that were investigated. It can therefore be concluded that a low energy single contact, single impact breakage mechanism cannot be used as a proxy for a shear abrasion breakage mechanism in comminution.
4.3  **Key drivers of abrasion**

Many experimental and material independent variables affect the mass loss rate of a rock particle when subjected to an abrasion mechanism. And some of them do not. A brief discussion of the common independent variables encountered during the IMLAT tests follows explaining their contribution to the mass loss rate, if any.

4.3.1  **Steel roughness**

The roughness of the steel wheel does affect the mass loss rate. However, it was assumed that the steel wheel used in the SWAT device had reached its stationary roughness phase, because it had been in use for over three years. Therefore, it was assumed that the roughness of the steel remained constant for all the experiments conducted with the SWAT device. The research of Myshkin et al. (1997: 5) supports this proposition: “The original roughness of working surfaces becomes significantly modified by friction and wear reaching the so-called stationary roughness which is apparently reproducible under normal friction conditions.” A detailed argument was presented in section 3.2.6.

4.3.2  **Parent particle mass**

As discussed in the section 4.2, the parent particle’s original mass has no bearing on the mass loss rate resulting from abrasion breakage provided the particle remains intact. During the IMLAT tests, the parent particle masses ranged from 84 to 250 g. Yet, the mass loss rates observed were comparable.

4.3.3  **Apparent surface area**

Even though this variable was not investigated during this project, literature shows that the apparent mating surface area does not affect the mass loss rate during abrasion. It was argued that for a given load, the localised stress increased with a decrease in surface area, but was counteracted proportionately by a decrease in the amount of asperities. Results from work conducted by Mulhearn and Samuels (1962) on metal cylinders showed that all the mass removal curves were coincidental regardless of the specimen area (0.27 to 2.7 cm²) having kept all other variables constant. Archard (1953) came to the same conclusion while deriving his theoretical wear equation (Equation 2.11 in Table 1). As a result, surface area did not appear in his equation.
4.3.4 Sliding speed

Findings from literature (Myshkin et al., 1997, Radziszewski et al., 2005, Al-Samarai et al., 2012) show that the mass loss rate is sliding speed dependent, because the sliding speed affects the coefficient of friction due to heating, especially in metals. Typically an increase in sliding speed causes a decrease in the wear rate. However, during the IMLAT tests, the rotational speed of the wheel was kept constant at 164 RPM with the aid of a powerful fixed speed motor. As such, the effect of different sliding or rotational speeds on the mass loss rate could not be investigated in the project. But, to confirm this assumption, the rotation of the wheel was recorded with a high speed camera at different compression loads. The results showed that even at the maximum load (910 N) the rotational speed of the wheel was a constant 164 RPM. Therefore, the effect sliding speed has on the mass loss rate can be excluded from this research since the speed remained constant.

4.3.5 Ore hardness (competency) and variability

Standardised tests conducted at the JKMRC provided the following results with respect to the hardness or competency of the two ore types used in the IMLAT tests:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Beaudesert</th>
<th>Cadia</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bond work index (BWi) [kWh/t]</td>
<td>18.5</td>
<td>19.5</td>
</tr>
<tr>
<td>A×b</td>
<td>29.4</td>
<td>35.1</td>
</tr>
<tr>
<td>tₘ</td>
<td>0.17</td>
<td>0.23</td>
</tr>
<tr>
<td>Density [kg/m³]</td>
<td>2850</td>
<td>2750</td>
</tr>
</tbody>
</table>

The results suggest that the Cadia East ore is more resistant to crushing and grinding compared to the Beaudesert quarry ore, because it required more energy to produce the same size reduction. It should be stated here that the Cadia ore was a ‘real’ ore with a larger degree of variability compared to the homogeneous Beaudesert ore. However, the ore impact parameter (A×b) suggests that the Beaudesert ore is more resistant to impact breakage (harder) compared to the Cadia ore. Moreover, the abrasion parameter (tₘ) also suggests that the Beaudesert ore is less amenable to abrasion breakage since a smaller fraction of the sample passed through a screen aperture 1/10 \(^{th}\) of the original geometric mean particle size compared to Cadia ore. Thus, according to the results, the Beaudesert ore was the harder (more competent) ore type and therefore more resistant to impact breakage and abrasion breakage.
4.3.6 Surface roughness

Every effort has been made to only abrade the ‘flat’ surfaces of the ore particles. This was performed to minimise the effect of surface roughness on the mass loss rate because the applied load was the primary independent variable under investigation. However, as the results will show, the roughness is a key driver of the initial chipping (running-in) phase of the abrasion mechanism. The initial mass loss observed during the first interval (30 kJ) was almost always higher than the subsequent two intervals. The initial mass loss was driven by the amount of asperities available to break off which in turn decreased as they were removed while the wheel abraded toward the interior dimension of the rock particle leading finally to a steady state mass loss rate.

4.3.7 Load (or compression force)

It was obvious that the amount of energy transferred influenced the mass loss. However, the load drives the energy input indirectly via the torque applied. So, is energy or load the key driver of abrasion? Literature showed that the applied load was the key independent variable as predicted by Archard’s equation. To investigate the key drivers of abrasion breakage in comminution, rock particles were given similar total input energies while varying the applied loads. If similar mass loss rates were observed for different loads, then energy must be the key driver of abrasion and not the load.

Figures 47 and 48 illustrate the results from the IMLAT tests conducted on the Beaudesert and Cadia ores respectively. The error bars indicate the 95% confidence intervals of the sample mean mass loss as defined in section 4.1. Some trends were evident: a linear increase in mass loss was recorded with increasing energy for all the loads. However, there was no evidence to suggest that a similar linear trend existed within the first interval (30 kJ). This was typically the chipping phase, driven by the surface roughness of the rocks. Literature (Queener et al., 1965, Gwyn, 1969) suggested that an exponential or power function would be appropriate here. This also explains why the linear fitted functions do not intercept the origin. It will be recommended that future research investigate this phenomenon in greater detail since it was outside the scope of this project.

Another trend observed was that the gradients increased with increasing load. That meant that the mass loss rates (g/kJ) were load dependent and that the total mass loss was driven by the compression load not the energy. For example, at 90 kJ, the 710 N and 310 N loads had statistically different total mass losses at the same amount of input energy. Therefore, even though energy drove mass loss, it was not the primary independent variable; the applied load was.
Figure 47 - Average cumulative mass loss - Beaudesert

Figure 48 - Average cumulative mass loss - Cadia
Similar results were found with the Cadia IMLA tests (Figure 48). The initial mass loss was driven by the roughness and the load. Interestingly, the minimum load (310 N) produced the most product mass during the first 30 kJ compared to the other loads. A similar result was recorded with the Beaudesert ore. Other physical surface properties and effects must have been present here, but that was outside the scope of this investigation.

The Cadia findings also showed an increase in mass loss rate (g/kJ) with increasing load. Due to the variability of the Cadia ore and the small sample sizes (20 particles), the confidence intervals were relatively large. This should decrease as the sample size increases. Notwithstanding, the relationship between the different loads, that is the mass loss rates, should still be valid regardless the sample size.

Mathematically, the observed trends can be expressed as follows:

\[
\frac{dm}{dE} = \alpha \text{ (load and ore type dependent)}
\]

but, \( \alpha = \beta \cdot L \)

therefore, \( \frac{dm/dE}{L} = \beta \text{ (ore type dependent)} \)

where \( dm \) is the mass lost (mg), \( dE \) is the applied energy (kJ), and \( L \) is the constant load (kJ). In the next section \( \beta \) will be defined as the Abrasion Index of the ore type.

A clear distinction between the two ore types was the magnitude of the mass loss rates observed. For equivalent loads, the mass loss rates recorded for Beaudesert ore were at least twice as large compared to Cadia ore. That meant that the Cadia ore was more resistant to abrasion (harder) compared to the Beaudesert ore. But this finding was not in agreement with the previous standardised test results (section 4.3.5) which showed that Beaudesert ore was more resistant to abrasion and impact breakage. This disparity stems from the test methodology followed to produce the abrasion (\( t_a \)) parameter and has been discussed at length in section 2.5.

In summary, while energy drives the mass loss, the primary independent variable for steady state abrasion breakage was the applied load. The findings showed that the mass loss rates (g/kJ) were load dependent. This was found to be in agreement with the literature. The initial chipping phase was primarily driven by the load and surface roughness, whereas the steady state phase was only load dependent.
4.4 Abrasion Index

The aim of this thesis was to develop a characterisation test for measuring the superficial breakage of ore particles. The entire methodology will be presented in chapter 5, but how are the results produced from this characterisation test useful? To that end, one of the objectives of this thesis was to propose a relationship to quantify the abrasion characteristic of a rock particle. In other words, propose an index or rating that classifies a specific ore type’s affinity to the abrasion mechanism, much like the $t_a$ parameter, and allows for comparison among different ore types.

Findings presented in previous subsection revealed that the mass loss rate ($g/kJ$) was load dependent. The mass loss rates increased with increasing load. This trend was observed for both ore types. To investigate the relationship between these variables, a plot of the mass loss rates versus load was produced (Figure 49). In this plot the variable mass loss over the running-in period was excluded as these are the steady state values. The trend observed for both ore types was unambiguous: the steady state mass loss rates were directly proportional to the applied loads. This finding was in agreement with the literature. Archard (Equation 2.11 in Table 1) predicted from a purely theoretical framework that the mass loss rate (grams per sliding distance) was directly proportional to the load.

![Figure 49 - Steady state mass loss rate vs load](image)

The findings showed that mass loss rates and loads changed proportionately. Thus, for a given load it is possible to predict the mass loss rates and therefore the average mass loss (in mg) if the amount of input energy (in kJ) is known.
For example, if a constant 0.6 kN of compression force was applied to the Cadia ore, every particle should lose on average 1.0 mg of mass for every kilojoule of energy transferred.

The results suggest that different ore types have different affinities to the abrasion mechanism, and this affinity can be quantified by plotting the mass loss rates versus the constant applied loads. The gradient of the least squares line fitted to the data (intercepting the origin) is then equal to that ore type’s abrasion index value. Therefore, the Beaudesert and Cadia ores have abrasion index values of 4.0 and 1.7 respectively, provided the mass loss rates were plotted in mg/kJ and the loads in kN. Figure 50 illustrates how the abrasion index value is determined.

![Figure 50 – Demonstration of abrasion index calculation](image)

The Beaudesert ore reported larger mass losses compared to the Cadia ore for the same applied load. Consequently, a large index value implies the ore type is more amenable to abrasion, or conversely, a small value implies the ore is more resistant to abrasion. Yet again, these findings are not in agreement with the $t_a$ values reported earlier for each ore type. From the $t_a$ values observed, it was concluded that Beaudesert ore was more resistant to abrasion and impact breakage. However, the newly created abrasion index values produced from the IMLAT tests, suggest that the Cadia ore is more resistant to abrasion breakage.

In summary, with the SWAT device and the IMLAT methodology it was possible to quantify a rock particle’s response to the abrasion mechanism. By isolating the mechanism in the SWAT, this response was now also comminution device independent, which means that comparable outcomes should be observed in any device that applies the same range of loads and energies provided the steel roughness was similar.
4.5 Mechanistic modelling contribution

Even though the IMLAT in itself is a powerful tool as an abrasion characterisation test, it also offers the opportunity of incorporating the results into a mechanistic model like the UCM. This was, after all, one of the motivations for conducting this research.

At the moment, the abrasion index is derived from the average mass loss observed from the IMLAT tests. But, the average values do not adequately account for the variability within an ore type or for surface effects. Therefore, a more prudent approach to predicting mass loss would be a distribution of possible results. Instead of assuming that every rock in a batch will lose a constant average amount of mass, it is possible to determine the likelihood of a specific outcome occurring from a cumulative mass loss probability distribution (MLPD) if enough rocks are tested.

The MLPD graphs were constructed by arranging all the mass loss results from smallest to largest. The largest value was then plotted against 100% and the rest of the results against evenly spaced percentage values determined by dividing 100 by the total amount of data points. For example, if 20 results were collected, then each mass loss result would be plotted against a multiple of 5%. That is, the smallest result corresponds to 5%, the second smallest corresponds to 10%, and so on, until the largest result corresponds to 100%. The distribution predicts the probability of any particle in a batch losing at most (but less than) a certain mass (normalised to the average). Once more tests are conducted and the sample size is large enough to characterize the population, this distribution will be a representative mass loss distribution. In other words, the probabilities on the y-axis will then represent the percentage of the entire population.

Figure 51 shows the MLPDs for the Beaudesert ore conducted at 310 N and 910 N respectively. These were the results from the scoping trials, and as such the tests ran continuously with 90 kJ of input energy as opposed to incrementally. The distributions were similar, yet, the 310 N load (black points) produced a wider distribution compared to the 910 N load. Since both distributions were the products of Beaudesert ore, it can be inferred that surface roughness and (to a lesser extent) load must have contributed to the differences in MLPDs.

A characteristic feature of both distributions was that their average values (1 on the x-axis) coincide with 60% on the y-axis. This would suggest that the frequency plots and the entire distribution were (positively) skewed.
To investigate the effect of ore type on the MLPDs, the incremental mass loss distributions for both ore types were plotted independently for the 510 N load. The results are presented in Figures 52 (Beaudesert) and 53 (Cadia). It was predicted that the initial distribution corresponding to 30 kJ would produce the biggest scatter in the BDS (Beaudesert) results. This could be due to the contribution of the roughness, which was highly variable and not controlled in this project, and the low energies corresponded to the wheel abrading the rock surface. As more energy was transferred to the rock, more of the surface was removed until the interior of the rock was reached.

The plots revealed that the distributions became narrower as more energy was transferred to the rock samples. The 30 kJ produced the widest distribution and 120 kJ the narrowest. These results supported the previous findings and predictions: the dispersion decreased with increasing energy. The Cadia results showed similar outcomes at 510 N (Figure 53), but the other loads produced no clear trend. However, the average mass loss (x = 1) corresponded to a y-value of 60% probability yet again.

![Figure 51 - Normalised mass loss probability distribution - Beaudesert](image-url)
Figure 52 - Cumulative normalised MLPD - Beaudesert @ 510 N

Figure 53 - Cumulative normalised MLPD - Cadia @ 510 N
One distinct difference between the MLPDs of the two ore types was the amount of scatter. The scatter was much larger for the Cadia ore compared to the Beaudesert ore for the same load and energy. Even though for both ore types it was observed that the dispersion decreased with increasing energy, the amount of dispersion was consistently larger for Cadia versus Beaudesert. Hardness does not account for the difference, because the hardness drives the amount of mass loss, not the scatter in the results. However, variability within the ore type itself could explain the findings. After all, it was known that Cadia was a ‘real’ ore compared to the homogeneous Beaudesert quarry rock.

The coefficient of variation (CoV) is a standardised statistical parameter that quantifies the amount of scatter (dispersion) of a frequency or probability distribution. It is equal to the standard deviation of the sample divided by the mean. As such, it is possible to compare the amount of dispersion between different samples. Motivated by the findings so far, it was decided to plot the CoVs of the mass losses observed versus the energy for every load and ore type. The results are presented in Figure 54. There was no apparent trend, however, the Cadia CoVs were distinctly larger than its counterpart in some cases even twice as large. This result was in agreement with the previous inferences drawn about the degree of scatter observed in the MLPD plots due to variability within the two ore types themselves.
The working assumption up to now has been that the relatively large scatter in mass losses observed at low energies was due to roughness and other surface properties. If there is variability within the ore type, the scatter should be even larger; as was found in the case of Cadia versus Beaudesert. Once the surface has been worn smooth (around 60kJ) and the interior being abraded (around 90 kJ), a pseudo steady state prevailed. However, this process takes longer for more abrasion resistant (harder) ores than for softer ones. Since the mass loss rates (g/kJ) and the subsequent abrasion index were both defined for the steady state, it was decided to only use the 90kJ CoV-values as a first approximation for the entire energy range. Besides, the low energy (unsteady) state did not fall within the scope of this project. Also, it will be recommended in the IMLAT methodology that harder ores be abraded for longer periods to ensure steady state has been reached.

When the steady state CoVs were plotted against the applied loads, the result was Figure 55. The findings suggested that there existed a strong correlation between the steady state CoVs and the loads. However, can this result be used to predict the steady state MLPD of the ores? And if so, how accurate is the prediction? To answer these questions, the author had to find a mathematical relationship that predicts the cumulative MLPD.

![Figure 55 - Steady state CoVs versus load](image-url)
The continuous MLPDs presented earlier (Figure 51) alluded to the possibility that the mass loss distributions were not normally distributed, but log-normally distributed. A log-normal distribution has the property that the logarithm of the random variable, \( \ln(x) \), is normally distributed, while the distribution of the variable itself, \( x \), is often skewed. A frequency distribution plot was prepared for the 310 N continuous abrasion test to investigate the distribution in greater detail. Figure 56a illustrates the results. It was evident that the distribution was positively skewed (long tail on the right). Results from a statistical analysis on the data showed that the kurtosis and skewness were 1.6 and 1.3 respectively. A normally (Gaussian) disturbed variable has both kurtosis and skewness equal to zero.

The findings clearly showed that the normalised mass losses were biased. Yet, the frequency distribution of the logarithmic normalised mass loss values (Figure 56b) produced a normal distribution. The kurtosis and skewness values were 0.17 and 0.20 correspondingly. The results now proved that the normalised mass loss distributions were log-normally distributed.

![Figure 56](image)

**Figure 56** - Frequency distribution plots of normalised mass losses (a), and logarithmic normalised mass losses (b)
The cumulative distribution function (CDF) for a log-normally distributed variable is defined by the following mathematical equation (Equation 4.1).

\[
F = 0.5 \left[ 1 + \text{erf}\left(\frac{\ln(x) - \mu}{\sqrt{2\sigma^2}}\right) \right]
\]

(4.1)

where \( \text{erf} \) is the error function, \( \mu \) and \( \sigma \) are the mean and standard deviation of the variable’s natural logarithm.

But, since the mass losses were normalised to the average mass loss (of the interval), a modified version of the above equation has been proposed for modelling the steady state cumulative MLPD prepared from the IMLA tests:

\[
F = 0.5 \left[ 1 + \text{erf}\left(\frac{\ln\left(\frac{x}{\mu}\right) - \ln(\alpha)}{\sqrt{2(COV)^2}}\right) \right]
\]

(4.2)

where \( \alpha \) is fitted by assuming that all distributions have similar skewness and therefore passes through a known point \((1;0.6)\), and the CoV will be approximated if unknown. The IMLAT methodology will suggest conducting tests at the minimum (310 N) and at the maximum loads (910 N) only. The CoVs for the intermediate loads need to be estimated from a similar graph as shown in Figure 56.

Results of the fitting of the proposed model (Equation 4.2) to the experimental MLPDs of the continuous scoping tests conducted are presented in Figure 57.
Results showed that the fit improved substantially when more than 40 particles were tested as was the case with Figure 57. Illustrated in Figure 58 below are the fitted steady state MLPDs of the IMLATs for the Beaudesert ore. The functions were forced to intercept (1;60%). The model predictions do not fit the experimental results to the same degree as with the continuous tests; largely, it is hypothesised, due to the small number of rocks abraded per interval. As expected, the maximum load produced the least scatter. This could be contributed to the fact that the lower loads abraded the surface of the rock for a longer period compared to the high loads. Hence, the roughness effects were more pronounced at the lower loads.

An alternative to using the CoVs determined empirically is to fit the model (Equation 4.2) by solving for both parameters (α and CoV) by least squares minimisation. Then the MLPD will not necessarily pass through (1; 0.6). However, when predicting the intermediate loads’ CoVs (510 and 710 N) it was found that the CoV’s calculated from the power function (Figure 55) fitted to the experimental results better compared to the CoV’s predicted by the power function fitted to the least-squares-determined CoVs for 310 and 910 N. IMLAT tests will only be conducted at 310 N and 910 N physically. Therefore, the outcomes for the intermediate loads must be inferred from these experimental results.

![Figure 58 - Cumulative normalised mass loss probability distributions - BDS at steady state](image-url)
In summary, statistically it is more realistic to assume that a distribution of mass losses will be observed in a comminution experiment instead of incorporating a single average. The challenge is to model this distribution accurately lest more error is introduced by using the model instead of the average. Therefore, a contribution to mechanistic modelling can be the introduction of a log-normal distribution function to model the range of mass losses observed, assuming the frequency distribution plots are skewed. If the data is normally distributed, the standard Gaussian distribution should suffice.

Since abrasion tests will only be conducted at 310 N and 910 N loads per ore type as recommended by the IMLAT methodology, a detailed schema is presented in chapter 5 illustrating how to produce the intermediate loads’ cumulative MLPD plots. It should be noted that only the steady state (90 kJ or more) MLPDs will be predicted by this method. The average mass loss rates should be used preferably to approximate the mass losses at low (unsteady state) energies.
4.6 **Single particle and particle bed tests comparability**

The last objective of this thesis was to investigate differences and similarities between single particle and particle beds surface breakage testing devices. That is, to compare the results of the IMLATs and the planetary mill. It was unknown which breakage mechanisms occurred in the planetary mill during operation. But, it was hypothesised that an abrasion breakage mechanism would prevail due to the dynamics of the device. The mill rotated at relatively high rotational speeds which exceeded the critical speed. The estimated critical speed of the mill was 156 RPM. It was understood that the mill operated much like a washing machine during the ‘spin’ cycle. The rocks would shear against the mill shell and against each other due to the centrifugal forces, but do not repetitively impact each other or the mill shell.

4.6.1 **Mass loss distributions**

Figure 59 illustrates the cumulative mass loss distribution of the charge (as a percentage of the original feed mass) versus the milling time. The results were similar to the single particle tests: an initial chipping phase was observed followed by a pseudo steady state. The scoping trial findings suggested that a steady state mass loss commenced after 6 minutes of grinding at 300 RPM.

![Figure 59 - Cumulative mass loss of batch tests in planetary mill](image-url)
The results suggested that there was an interaction between the rotational speed and filling. Since both these independent variables directly affect the energy transferred to the particles during operation, this result was to be expected. The particles in the 500 RPM-25% filling test would have received the most energy per particle, but did not produce the most mass loss. This was because there were too few particles to shear against each other and the mill shell to produce the mass loss. It was found that the 500 RPM-75% filling test produced the most mass loss as a percentage of the initial feed.

However, to compare with the IMLAT results, the batch test results had to be evaluated under the same conditions: steady state and single particle mass loss. To that end, Figure 61 was produced. It was assumed that all the batch tests had reached steady state after 6 minutes. Therefore, the last three data points of Figure 60 were plotted against the energy (predicted by DEM). For comparison, the results of the IMLATs were included as red lines (Beaudesert) and purple lines (Cadia). The four lines per ore type represent the four different applied loads. The results suggest that it is possible (in at least one scenario) for the planetary mill to produce similar steady state mass losses per particle compared to IMLAT. But the results were hardly conclusive.

![Figure 60 - Steady state mass loss per particle versus energy](image-url)
6.6.2 Appearance functions

Figure 61 illustrates the steady state appearance functions of some of the tests conducted in the planetary mill. For comparative purposes the coarsest IMLAT appearance function was also included (red line). The size distributions of the steady state products (after 12 minutes of milling) were analysed and the results compared with single particle abrasion. The results indicated that the size distributions became finer with increasing energy (rotational speed). Moreover, the planetary mill experiments can adequately produce similar appearance functions compared to the IMLAT. These results confirmed the initial assumption made regarding the dynamics of the mill: the breakage caused in the mill was due to abrasion and not repetitive impacts.

![Figure 61 – Steady state appearance functions of planetary mill experiments - 50% filling](image)

In summary, it can be inferred from the results of the experiments conducted with the planetary mill that the mill has the potential to produce similar mass losses and appearance functions compared to the single particle steady state IMLAT methodology. However, further investigation and development are needed to test its viability and the appropriate test conditions.
CHAPTER 5

IMLAT: Incremental Mass Loss Abrasion Test

One of the motivations for this project was to develop a methodology whose outcomes could be incorporated into the mechanistic UCM model. This model will eventually be able to predict the outcome of any comminution device without having to conduct any physical experiments in the device itself. However, certain characterisation inputs are required. For example, the responses of an ore particle to typical breakage mechanisms found in comminution are considered fundamental inputs. And the abrasion mechanism is one of them. To that end, an appropriate characterisation test had to be developed which isolated the mechanism and accurately captured the rock’s response to the abrasion mechanism under a wide range of controlled variables. It is proposed that the IMLAT is that characterisation test.

The schema presented in section 5.6 lies at the heart of the data analysis phase of the IMLAT and reveals yet another useful component of the IMLAT methodology that, if adopted, can produce valuable outcomes that can be incorporated into the UCM. It must be emphasised here that IMLAT is a tool whose outcomes could be used to establish a steady state abrasion index or model the dispersion in the mass losses observed. It is not the primary aim of this project to develop the models or generate the abrasion index of all ores. In other words, this thesis paves the road to a comminution abrasion index and a mechanistic abrasion model.

This chapter is the primary outcome of this project, i.e. the IMLAT methodology. The methodology will be presented in the same order as the methodology followed during experimentation. Starting with the ore sample preparation, then conducting the abrasion experiments with the SWAT device according to the SOP, product fines processing, parent particle processing, data analysis, and finally results presentation. Some of this methodology has been presented in chapter 3, and therefore, the reader will be referred to relevant sections in that chapter for the sake of brevity. However, in some cases the IMLAT methodology will be different to the experimental methodology followed during this project as presented in chapter 3. This is because the updated methodology will include recommendations and improvements made as a result of the lessons learned from conducting the experiments. Also, emphasis will be placed on the data analysis and results presentation. Further recommendations will be made in chapter 6.

Provided in Figure 62 is a pictorial process flow diagram of the IMLAT methodology.
Figure 62 – Process flow diagram of IMLAT methodology
5.1 IMLAT overview

Figure 63 illustrates the block flow diagram of the IMLAT methodology. The IMLAT consists of four processes: sample preparation, abrasion test, products processing, and data analysis which provides the results. Figure 62 illustrates the same processes, but with more detail. It summarises the remaining sections of this chapter in visual format.

```
Sample preparation
(90 samples per load, 30 per interval)

Abrasion Test
(310 N and 910 N loads)

Products
(Parent particle)

Results
(Mass loss rate, Abrasion index, MLPDs)

Products
(Fines)

Results
(Appearance functions)
```

Figure 63 - Overview of experimental methodology

5.2 Ore sample preparation

Crush the large rock samples and screen to the required size (-54+45 mm) after which the rocks must be cut with a saw to fit easily and securely inside the sample holder. Keep the sample holder at hand while sawing so that the individual rock samples can be tested to determine if they fit firmly in the holder. Wash the samples, then dry, label, and record their mass. Prepare 90 rock samples per compression load. Also prepare roughly 10 samples per ore type for scoping tests. Once all the samples are ready, the physical abrasion tests can be conducted with the SWAT.

5.3 Abrasion test

5.3.1 Calibration of SWAT

Calibrate both load cells according to the methodology described in section 3.2.5.

5.3.2 Scoping tests

The operator is not always certain when the steady state phase commences during the abrasion test. For that reason it is recommended that scoping tests be conducted for every load and ore type. The time needed to abrade the surface of the rock particle depends on many factors, mainly the ore
hardness and the applied load. It is recommended that the operator apply 50 kJ of energy initially and then investigate if the surfaces of the scoping rocks have been worn smooth. If so, the abrasion tests can commence. If not, apply more energy to the scoping rock sample especially if the ore type is hard or the load is low.

5.3.3 Test design

Once it is known what minimum energy is required to wear smooth the particle surface, the abrasion tests can commence. The abrasion test methodology consists of two phases. In phase 1 the surface of the particle is worn smooth as determined by the scoping tests. Phase 2 consists of abrading the ore samples at two compression loads (310 N and 910 N) while transferring a constant total amount of energy to every sample. The 310 N load will take roughly three times longer to transfer the same amount of energy as the 910 N. For both phases of the abrasion test the SOP must be followed as set out below.

Figure 64 illustrates the abrasion test procedure:

5.3.4 Standard operating procedure (SOP)

A standard operating procedure was available for the SWAT device when it was obtained from JKTech. However, it had to be modified to investigate the abrasion of rock samples instead of metal samples. Provided below is the standard operating procedure followed during every experiment with the SWAT device at the JKMRC. The risk assessment is available online in the UQ Risk Management Database at [https://www.risk.admin.uq.edu.au](https://www.risk.admin.uq.edu.au). The task ID was 48151.
I. Test preparation
   1. Prepare samples to be grinded: wash and dry test rocks.
   2. Mark the rocks and record their mass.
   3. Read the risk assessment and SOP.
   4. Calibrate both load cells.

II. Test procedure
   1. Wear appropriate PPE as prescribed by the risk assessment.
   2. Turn the power switch to “ON” on the side of the electrical box (see picture).
   3. Brush the steel wheel to remove dirt and rust.
   4. Place a bucket (“waste”) underneath the chute.
   5. Open the water mains.
   6. Open the water valve and flush the system for a minute cleaning the wheel and chute of dirt and grime in the process.
   7. Connect the DAQ device to a laptop via a USB port.
   8. Open SignalExpress™ on laptop.
   9. Fasten sample rock tightly in the sample holder ensuring that the rock’s surface is parallel with the sample holder. Also ensure that at least 1 cm of the rock is visible outside the holder.
   10. Fasten holder to lever arm by fastening the bolts ensuring that the centre of the rock is flush with the wheel and in line with the centre of the wheel. If not, adjust the holder height (see picture alongside).
   11. Lower the load cell gently against sample holder.
   12. Select required normal load by sliding metal pin into the correct weight slot. The small, medium and large weights are 1.3kg, 2.5kg and 5kg each respectively.
   13. Slowly lower weights support cam by rotating metal rod away from operator. There should be a clear gap between the weights above the metal locking pin and the unused weights.
   14. Check that the rock sample is in contact with the wheel but not the cam. If not, go back to step 9.
   15. Close the Perspex door properly.
   16. Place a clean bucket (“fines”) underneath the chute to collect the fines generated.
   17. Open the water valve such that a small continuous stream of water runs from it.
18. Switch power on at the mains (power point).

19. Press the Power “ON” button to switch on the power at the electrical box.

20. Press the “Run” button in the software when you are reading to start.

21. Start the motor by pressing the Drive “ON” button.

22. Start the stopwatch immediately.

23. Substitute the fines buckets according to test design, typically every third of the total time.

24. Once the required time has elapsed, switch off the motor by pressing the Drive “OFF” button. Also press the Power “OFF” button as a fail-safe.

25. Stop the stopwatch.

26. Press the “Stop” button in the software.

27. Open the door and return the weights support cam to the starting position by rotating the lever towards the operator.

28. Use a separate water bottle with spout and wash the sample and chute to ensure all the fines collect in the bucket.

29. Also wash the wheel to remove all fines and to cool it down.

30. Close the water valve completely.

31. Unfasten the sample holder by loosening the bolts.

32. Remove the rock from the sample holder.

33. Rename the recorded energy and load readings in the software according to predetermined convention and export to excel. Save the excel file in an appropriate folder.

34. (Repeat steps 9-33 for all other samples.)

35. Substitute buckets depending on requirement and/or test design.

36. Close the Perspex door properly.

37. Safely remove DAQ device from USB port and save results before shutting down.

38. Turn power switch to “OFF” on the side of the side of the electrical box.


40. Switch off the power at the mains.
5.4 Parent particle (sample) processing

After all 90 rocks have been abraded (per load), clean and dry them overnight. Then record their new masses.

5.5 Product fines processing

Follow the instructions as described in section 3.2.7.4.

5.6 Data analysis

At this stage in the experiment the researcher should have the following data sets:

i. Mass of sample (parent particle) before and after the abrasion test.


iii. Appearance functions as determined by available particle size analyser.

5.6.1 Mass loss versus energy

In a spreadsheet, determine the mass loss of every sample. Then, using the calibration curve, determine the energy transferred to every sample in terms of mass (kg) using the torque readings. These readings were the force the load cell (underneath the gearbox) experienced during the experiment. There will be 10 readings per second if the load cell was calibrated to 10 Hz. To determine the actual torque experienced by the gearbox, use equation 5.1:

$$\tau [Nm] = F[kg] \times 9.8 \times \ell [m] = F \times 9.8 \times 0.2$$

where $\tau$ is the torque experienced by the gearbox in Nm, $F$ is the force the load cell experienced in kg, and $\ell$ is the distance from centre of gearbox to the load cell in meter.

However, this is still not the energy transferred. To determine the energy transferred to the sample (assuming no losses in the gearbox and to surroundings), use equation 5.2:

$$E [kJ] = \frac{\tau[Nm] \times \sigma [RPM] \times 2\pi \times t [s]}{60 \times 1000} = \frac{\tau \times 163.6 \times 2\pi \times t}{60000}$$

where $\sigma$ is the rotational speed of the wheel in RPM and $t$ is the total abrasion time is seconds.

Now it should be possible to plot the mass loss versus energy graphs for the 310 N and 910 N loads. Fit the best least-square straight line through the data points (310 and 910 N) respectively.
5.6.2  Abrasion index

Plot the gradients of the mass loss versus energy (mg/kJ) against the compression loads (kN). There should be two points per ore type: one point at 310 N and the other at 910 N. Fit the best least-square straight line to these two points. The gradient will be the quantification of the rock’s affinity to abrasion; or abrasion index value [(mg/kJ)/kN]. The greater the value, the more amenable the ore type is to shear abrasion. Beaudesert ore had a value of 4 while Cadia east rocks (a much harder ore type) produced an index value of 1.7.

5.6.3  Cumulative mass loss probability distributions (MLPDs)

The last step in the analysis of the results is to model the mass loss as a cumulative probability distribution instead of assuming an average mass loss for every sample. Firstly, determine the coefficient of variation (CoV) for the 310 N and 910 N sets. Plot the results against the load. Fit the best least-square power function to the two points. The CoVs of the intermediate loads (between 310 and 910 N) must be determined from this function.

Model the MLPDs with equation 4.2 for every required load. Fit the $\alpha$-value such that the modelled function passes through (1;60%) on the cumulative probability plot. If there are significant discrepancies between the experimental MLPDs (for the 310 and 910 N) and the modelled functions (using equation 4.2), solve for $\alpha$ with least-squares minimisation.

5.6.4  Appearance functions

Determine the cumulative percentage passing versus size plots for every incremental time interval. In this project this was determined by the CILAS device. There should be 6 results per load if all of the product buckets were analysed. Typically the P80-values were in the range of 10 – 20 micron with the maximum load (910 N) producing the finest PSD.

5.6.5  Summary

The schema overleaf summarises the data analysis procedure. The primary outcomes are the average steady state abrasion index value, quantifying the rock’s affinity to shear abrasion, and the MLPD plots modelling the probability of maximum mass loss per test or simply representing the dispersion in the mass loss results visually.
i) Conduct IMLA experiments at 310 N and 910 N.

ii) Plot the mass loss versus energy graphs.

iii) Fit straight lines to the results in (ii).

iv) Plot the mass loss rates (mg/kJ) versus load (kN).

v) Fit straight lines to the results in (iv). The gradients are the abrasion index value.

vi) Determine the CoVs for the steady state phase.

vii) Plot the CoVs versus the applied load.

viii) Fit a power function to the results in (vii).

ix) Predict the CoVs for the intermediate loads with the result from (viii).

x) Model cumulative MLPD with equation 4.2.
CHAPTER 6

Concluding remarks & recommendations

This chapter summarises the key outcomes of this project as a whole. The first section will address the aim of the research, and therefore will comment on the validity of the hypotheses proposed in chapter 1. This chapter then concludes with recommendations for future research.

6.1 Hypotheses

6.1.1 Rock response to abrasion can be isolated from other breakage mechanisms and quantified with an appropriate testing methodology.

The introduction of a modified SWAT device to ore particle abrasion experiments has made it possible to investigate a rock’s response to an abrasion mechanism only. The device isolated the abrasion breakage mechanism by allowing single particle experimentation with the aid of a rotating steel wheel. The steady state response of a rock particle to abrasion can be quantified by following the IMLAT methodology as described in chapter 5.

6.1.2 The normal load (and not the total input energy) is the key driving mechanism of abrasion of ore particles.

Results from the IMLAT tests (Figures 47 and 48) have shown that for similar input energies, the same ore type produced statistically different average mass losses when subjected to different compression loads. This result was witnessed for two different ore types. Therefore, energy cannot be the key driving mechanism of abrasion breakage of ore particles. The compression load was the key driving mechanism. This result was also in agreement with the literature.
6.1.3 Low energy impact breakage mechanism does not produce an appearance function similar to abrasion breakage mechanism.

Figure 46 provided the evidence evaluate this proposition. The coarsest abrasion breakage appearance function observed did not coincide with any of the low energy impact breakage appearance functions. The P80 of finest impact breakage appearance function was at least one order of magnitude larger than the coarsest abrasion appearance function. It can therefore be concluded that a low energy single point, single impact breakage mechanism cannot be used as a proxy for a shear abrasion breakage mechanism in comminution.

6.1.4 Particle bed (batch) experiments in a planetary mill can produce similar appearance functions compared to IMLAT.

It can be concluded from Figure 60 that the planetary mill can produce similar appearance functions compared to the single particle steady state IMLAT methodology.
6.2 Recommendations

6.2.1 Single particle abrasion tests (IMLAT)

(a) Abrasion index

To date only two ore types have been tested with the IMLAT methodology. It is recommended that more ore types be tested to further validate the methodology and also expand the abrasion index chart.

(b) Media wear studies

The IMLAT methodology prescribes the removal all the metal fines collected with the rock fines. But, this gives the researcher an opportunity to investigate two outcomes simultaneously with only one experiment: the effect of shear abrasion of ore particles produced by a steel medium in conjunction with media wear studies. Not only will it be possible to predict the particle mass loss, but also the wear of the steel media causing the ore mass loss. This would have to be tested with the steel that will be used in the tumbling device to be of direct applicability.

(c) Chipping phase

Only the steady state phase of the abrasion mechanism has been investigated in this project. The results showed that when a 310 N load was applied, more mass loss was observed during the first abrasion interval compared to the higher loads. Why is this so? It is recommended that future work into abrasion breakage of ore particles investigate the dynamic chipping phase. Especially the effect of particle roughness and applied load on the mass loss and appearance functions during this stage.

(d) Mineral characteristics

Mineral characteristics such as mineral composition (quartz and equivalent quartz content), hardness of the constituents, and intergrowth of the grains (grain size) should be investigated. Especially their effect on the product size distribution of impact loads and shear loads.
(e) **Steel roughness**

It was assumed that the roughness of the steel wheel was a constant during this project. This would be the case for most worn-in media. However, it is recommended that future work investigate the effect steel roughness has on the rock mass loss and appearance function.

(f) **Sound proofing**

The SWAT device can produce a significant amount of noise during operation. A crude mobile application that determines the sound intensity of sound waves recorded values as high as 80 dB while the device was in operation. This is equivalent to a standard vacuum cleaner. Even though the SOP requires the operator to wear the adequate safety equipment, it is recommended that the device be made more sound proof or be relocated to a sound isolating room for future research.

(g) **Rotational (sliding) speed**

High speed camera footage proved that the rotational speed of the wheel remained constant during this project. However, literature has shown that the sliding speed does affect the mass loss rate of an abraded sample. It is therefore recommended that the effect of sliding speed on abrasion mass loss and appearance function also be investigated.

(h) **Apparent mating surface area**

Literature has shown that the apparent contact area between mating surfaces do not affect the abrasion mass loss rate of metal samples. However, no research has been done (to this author’s knowledge) on the effect of apparent mating surface area and abrasion mass loss of ore samples. Therefore, it is recommended that this subject be investigated in future research.

(i) **Common energy basis**

Much effort has been spent proposing appropriate energy frames of reference that will provide a fair comparison of the IMLAT and JKRBT results. None has been found thus far. Some of the suggestions (which included surface area) were either not measured during this project or were hard to measure physically, if not impossible. Since the two mechanisms were distinctly different, it stands to reason that a common basis simply does not exist. But, it is recommended that more resources could be invested into finding if there is a solution to this problem.
6.2.2 Impact tests (JKRBT)

(a) Different ore types and particle sizes

Only one ore type and one particle size range was investigated with this device. The literature has shown that impact breakage is particle size and ore type dependent. As such, it is recommended that more ore types and particle sizes be investigated with both the IMLAT methodology and the JKRBT and the results compared on an appropriate basis.

(b) Abrasion breakage proxy

With the exception of 0.005 kWh/t result, all the low energy impact breakage PSDs produced a coarser appearance function than the high energy (3 kWh/t) experiment. Therefore, it would be reasonable to assume that a researcher investigating an impact breakage proxy for the appearance function of an abrasion breakage mechanism should consider higher impact energies, definitely higher than 3 kWh/t.
6.2.3 Batch abrasion tests (planetary mill)

(a) IMLAT proxy

The results showed that the planetary mill could be used as a proxy for the IMLAT. The only limitations are that the energy values have to be predicted by DEM and that the researcher cannot apply a known load to the particles. And since the load is the primary driver of abrasion mass loss, this issue will need addressing. But on the other hand, the planetary mill is compact and fast. A suite of experiments with a range of rotational speeds and fillings can be conducted in a week making the planetary mill a cheap research tool with regards to time and labour intensity.

It is therefore recommended that more ore types be tested with the planetary mill and then to generate their mass loss rates versus load (as predicted by DEM) as well as the appearance functions. It would be prudent to compare these results to the IMLAT results of the same ore type initially, since only one ore type has been compared with both devices thus far. The planetary mill could prove to be the only batch grinding test device which isolates the abrasion mechanism and thus produces a pure abrasion product.

(b) Independent variables

Only one particle size range was tested in the planetary mill for this project. As discussed before, particle size does not affect the mass loss rate or appearance function of single particle shear abrasion breakage experiments. However, it is not certain if this is also valid for particle beds. Also, only four different speeds and four different fillings were investigated for this research. Hence, it is recommended that more particle sizes, speeds and fillings be investigated with the planetary mill in the future.

(c) Chipping phase

The chipping phase should also be investigated for batch abrasion tests. As an initial experiment, it is recommended that the researcher condition the ore particles in a small tumbling mill at low speed. This process will remove most of the sharp edges and asperities. Then conduct the same suite of experiments on both ores (original vs conditioned) in the planetary mill. When compared, the results (it is hypothesised) should show that the original PSDs were coarser and produced larger mass losses initially (during the chipping phase), but then once steady state had been reached they produced similar results compared to the conditioned particles.
(d) **Secondary breakage**

Secondary breakage was one of the primary limitations emphasised in the shortcomings of the literature review. But, the introduction of the steel basket into the planetary mill methodology ensured the minimisation of secondary breakage. However, this author could not find any published research on this topic to date. Therefore, it is recommended that equivalent tests be conducted with the planetary mill: one set of test with the basket, and one set without it. Then compare the appearance functions. The results should provide unambiguous proof of whether secondary breakage occurred for the ore type, particle size and energy range investigated.
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