



RE-PURPOSING OF MINE WASTE: AN ALTERNATIVE MANAGEMENT APPROACH TO GOLD TAILINGS IN SOUTH AFRICA

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ABSTRACT

The large volumes of waste generated during gold beneficiation are a major pollution concern in South Africa. To remove these potential pollution risks in perpetuity, non-conventional approaches to mine waste management are required which avoid land disposal of “unwanted” material. This dissertation explores the opportunities, drivers and barriers for the re-purposing of gold tailings in South Africa. The thesis draws on a comprehensive literature review, analysis of information and data in the public domain, and semi-structured interviews with relevant experts. The research findings identified numerous potential uses for gold tailings including reusing gold mine tailings in making bricks, ceramics, cement additives, backfill, stone paper and aggregate material for construction. The derelict tailing dumps can also be used for recreation purposes, tourism and many other land use applications. The study showed that despite existing opportunities, the application of mine waste as feedstock for other purposes in South Africa is currently constrained. According to the findings, this can be credited to numerous inter-related factors, such as inadequate technology development, lack of an enabling legislative framework, high short-term costs, and potential environmental risks associated with hazardous components in the waste. Overcoming these barriers will require innovative, transdisciplinary approaches, and effective partnerships with relevant stakeholders, including academia, private business entities (waste users) and regulatory bodies (government).

STATEMENT OF ORIGINALITY

I, Lesley Kudakwashe Sibanda, declare that this is my own work. This dissertation contains no material that has been written and or published by another person except where due acknowledgement is made.

Signed: Lesley Kudakwashe Sibanda

Signed by candidate

Date: 8 February 2019

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ACRONYMS AND ABBREVIATIONS

AMD	Acid mine drainage
CCT	Crushed classified tailings
CIL	Carbon-in-leach
CIP	Carbon-pulp
CPV	Concentrated photovoltaic
CSIR	Council for Scientific and Industrial Research
CW	Crushed waste
DEA	Department of Environmental Affairs
DHS	Department of Human Settlements
DMR	Department of Mineral Resources
DoH	Department of Health
DWA	Department of Water Affairs
DWS	Department of Water and Sanitation
EBE	Engineering and the Built Environment
EiRC	EBE Ethics in Research Committee
EPA	Environmental Protection Agency
FPT	Full plant tailings
GDP	Gross domestic product
GHG	Greenhouse gas emissions
HCl	Hydrochloric acid
HVMA	High volume mineral additive
IHRC	International Human Rights Clinic
MHSA	Mine Health and Safety Act
MPRDA	Mineral and Petroleum Resources Development Act
MRE	Department of Mineral Resources and Energy
NEMA	National Environmental Management Act
NEMWA	National Environment Management Waste Act
NEMAQA	National Environment Management Air Quality Act
NGO	Nongovernmental organization
NNR	National Nuclear Regulator
NREL	National Renewable Energy Laboratory
NWA	National Water Act
OES	One Environmental System
OPC	Ordinary Portland Cement
PGMs	Platinum group metals
PV	Photovoltaic
SABS	South African Bureau of Standards
WRC	Water Research Commission

CHAPTER 1

INTRODUCTION

1.1 Background

The mining and minerals beneficiation industry contributes significantly to the world economy as it supplies materials that are used in manufacturing of consumer goods. In South Africa, the first diamond was discovered in 1867 in Hopetown and since then, the mining industry has been pivotal in growing the South African economy and remains the cornerstone of the South African economy (Malherbe, 2000). South Africa has mineral resources in abundance and produces a substantial share of the world's minerals. It is estimated that South Africa accounts for approximately 11% of the world's gold reserves, manganese (26%), chromium (74%), platinum group (96%) and vanadium (26%) (Department of Mineral Resources, 2016). South Africa also extracts diamonds, iron ore, nickel, copper, coal and other non-metallic minerals. In 2017, the South African mining sector contributed a total of R312 billion towards the gross domestic product (GDP), signifying an estimated 6.8% of the overall GDP (Chamber of Mines, 2018)¹. Although its contribution to GDP has declined over the years (from 21% contribution to GDP in 1970), the mining sector continues to contribute significantly to the South African economy, most markedly in terms of job opportunities, economic activity and foreign exchange earnings (Antin, 2013, Chamber of Mines, 2014). According to statistics released by the Chamber of Mines (2018), the mining sector contributed R93 billion to fixed investments and employed a total of 464 667 individuals in 2017. In addition, the sector paid R16 billion and R5.8 billion in taxes and royalties respectively to the government in 2016/2017 (Chamber of Mines, 2018). Further to this, the industry still plays an essential role in attracting foreign

¹ Chamber of Mines was renamed the Minerals Council South Africa on 23 May 2018
(<https://www.mineralscouncil.org.za/>)

investment and the export of mineral resources brings in much needed foreign exchange earnings that enables the country to import critical goods and services (Antin, 2013).

Despite the industry's contribution to the economy, the industry has been plagued by labour disputes and is widely criticized for its negative impacts on the environment, both on a local and global scale (Antin, 2013). These environmental impacts destruction of productive topsoil and forest during initial clearing; soil erosion, dust, stresses to farm animals and wildlife during the blasting using explosives; soil and water (surface and groundwater) pollution from the leachates, loss of biodiversity (Zarsky and Stanley, 2011). These environmental impacts can be attributed, at least to a significant extent, to the fact that the ore extraction and beneficiation process results in large amounts of waste being produced and occur at each stage of the beneficiation as shown below in Figure 1.

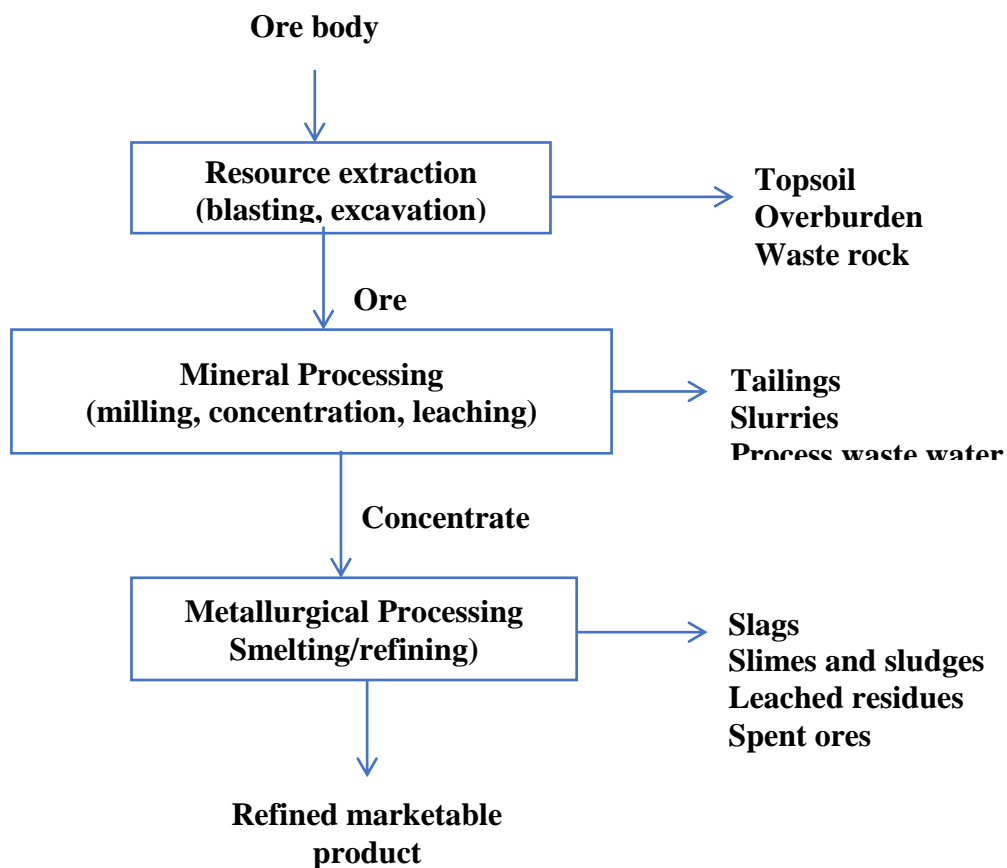


Figure 1: Schematic representation of waste streams from mineral extraction and primary beneficiation

The solid wastes from the extraction and beneficiation activities include overburden and waste rock from ore extraction (typically 42% of total waste); tailings from mineral processing (typically 52% of total waste); slags (typically 4% of total waste), flue dusts, slimes and sludges from metal recovery (metallurgical) operations; and residues from leaching and waste water treatment (Bellenfant et al., 2013, Broadhurst, 2005). The overburden is the surface material that consists of rock and topsoil that is removed in order to expose the mineral containing ore body. Waste rock typically consists of non-mineralized and or low-grade mineralized rock that has been removed during extraction to access the ore body (Lottermoser, 2010). Typically the overburden or waste rock is considered as material that is uneconomical to process as it contains too little minerals (Lèbre and Corder, 2015). The mineral processing waste, also referred to as tailings, constitutes the waste slurry and/or solids that result from the treatment processes that occur while separating the valuable minerals from the gangue in the ore body. These processes include “crushing, grinding, size sorting, flotation and other chemical processes” (Bellenfant et al., 2013, p.574). Together the wastes that are generated from the extraction and mineral processing of ores are generally referred to as mine wastes, and are characterized by large-volumes and naturally occurring (i.e. chemically unaltered) minerals. The legal definitions, however, vary and can have significant implications in terms of how such wastes are perceived and managed (see Section 2.5.1 and 2.5.3).

Godfrey et al. (2007) references a study done by the Department of Water Affairs in 1997 which documented that South Africa produced about 533 million tons of waste annually. Of this, approximately 468 million tons (87.7%) was all mineral waste constituting the single largest single source. The study also revealed that the gold sector waste accounted for 221 million tons which equates to approximately 47% of all mineral waste produced in South Africa. A more recent study revealed that approximately 42 million m³ of general waste is produced annually in South Africa with Gauteng Province contributing 42% of this (Nkosi et al., 2013). A further 5 million m³ of hazardous waste is produced annually across South Africa. A significant proportion of this hazardous waste is in Mpumalanga and KwaZulu-Natal provinces and this is attributed to the concentration of fertilizer production plants and mining activities in these two provinces (Nkosi et al., 2013). According to this research, waste from the mining sector accounts for approximately 72.3 % of the solid waste, making it the biggest contributor to solid waste streams (Nkosi et al., 2013). Other major contributors include pulverized fuel ash (6.7%), urban waste (4.5%), agricultural waste (6.1%), and sewage sludge

(3.6%) (Nkosi et al., 2013). The mineral waste quantities that are generated annually in South Africa from both the mining and beneficiation processes are presented in Table 1 below adapted from Godfrey et al. (2007).

Table 1: Waste generation from South Africa's mining industry adapted from Godfrey et al. (2007)

Sector	Quantities of solid waste (t/year)	
	CSIR 1992 study	DME 1997 study
Antimony	420 105	525 000
Asbestos	150 000	87 000
Base metal	59 600 000	70 000 000
Coal	45 600 000	42 000 000
Diamonds	23 000 000	31 000 000
Gold	191 726 070	221 000 000
Industrial minerals	-	43 500 000
Phosphate	10 920 000	4 000 000
PGM	45 181 701	56 000 000
Zinc	41 175	50 000

The data in Table 1 indicate that the solid waste generated by the mining industry is significant, particularly that generated in the early stages of ore extraction and processing (i.e. mine wastes). These mine wastes are traditionally disposed of, in impoundments such as waste rock dumps, slimes dams, tailings disposal facilities and other waste storage facilities. These facilities are also often unlined, located in near residential areas, perennial rivers and or sensitive agricultural areas (Pulles et al., 2005), and occupy valuable land that could be used for other productive uses (Malatse and Ndlovu, 2015). Many researches have documented that these mine waste facilities often contain toxic metals which can be mobilised through exposure to elements such as air and water thereby causing significant impacts such as biodiversity loss, environmental degradation, human health and socio-economic impacts on the local

community. This is a particular issue in the Witwatersrand goldfields of South Africa, which are characterised by numerous tailings deposits from gold mining operations, mostly defunct and abandoned and many in close proximity to local communities (Nengovhela et al., 2006, Oelofse et al., 2007). This landscape intercepts ecological systems, human settlements and freeways, posing a challenge for the spatial integration of the city of Johannesburg and its future development (Trangos and Bobbins, 2015). In addition, the generation of acid from the weathering of sulphide minerals inside these dumps is of concern as it results in contamination both surface and subsurface water resources, potential flooding resulting from burst tailings dams and dust, which leads to soil contamination and respiratory health impacts to the surrounding community (Nengovhela et al., 2006, Oelofse et al., 2007). Previous authors such as Oelofse et al. (2007) have reported that the contaminated water bodies arising from defunct gold mine workings and waste facilities are unsuitable for both human and animal consumption, potentially disrupting metabolic functions and leading to adverse health effects and the death of aquatic life (Oelofse et al., 2007). The contamination of soils can also lead to reduced soil fertility which affects crop productivity, growth and quality (Adler et al., 2007).

To date management of mine waste has mainly focused on rehabilitation to prevent generation and dispersion of dust and leachate with limited long-term effectiveness. In addition to these concerns, the storage of mine waste is counterproductive, as land is a valued resource in South Africa and thus land should not be used to store waste on land that can be used for other purposes. This has been a major driver to the research and development of alternative approaches which focus on the recovery of value from mine wastes and/or the re-use of bulk waste material for other purposes (Broadhurst et al., 2018; Godfrey et al., 2007). Such approaches are aimed at maximising resource efficiency and are well aligned with the principles of the circular economy. The recovery of value from defunct mine waste dumps approach is an alternate option that is gaining traction in South Africa (Godfrey et al., 2007). However, it is limited to extracting precious metals like gold and the range of platinum group metals (PGMs) where it is deemed to be economically viable. In addition, the bulk of the remained material is still sent to waste dumps, impoundments and/or tailings facilities and thus does not adequately tackle the problems that arise from the conventional disposal of mine waste. In contrast, the bulk re-purposing of unavoidable wastes focuses on the reallocation of waste as a feedstock of other uses, and aims at maximising efficient use of mined mineral resources whilst simultaneously removing the environmental impacts and risks associated with

the land disposal of mine waste. Potential applications of mine waste include use as construction materials, as backfill for mine workings or as additives in the production of ceramics (Harrison et al., 2013; Yellitshetty et al., 2008). However, despite the apparent opportunities and benefits, the effective utilisation of mine waste for other purposes appears to be relatively constrained, particularly in the South African context (Godfrey et al., 2007).

1.2 Problem statement

Mining activities generate vast quantities of solid waste which are typically disposed of in tailings dams. In particular, historical gold mining practices in South Africa have left a legacy of defunct and poorly rehabilitated tailings deposits. These deposits pose a significant pollution risk to the surrounding environment with concomitant risks to local human settlements, many of which occur in close proximity to the disposal facilities. Whilst the re-processing of gold tailings deposits for the recovery of gold is now common practice in South Africa, the majority of the mined material remains condemned to land disposal sites which occupy valuable land and represent a long-term and intergenerational risk and liability. Re-processing is, furthermore, limited to high value precious metals and still produces wastes. Little to no consideration is given to recovering the high value components and re-purposing the benign wastes simultaneously. A potential alternative approach, and one that is more in line with the principles of resource efficiency, cleaner production and sustainability, is to re-purpose the tailings for other uses. Although options for the re-use of mine tailings exist, application of this approach remains constrained. To overcome these constraints, and create a viable business case for an alternative approach to mining waste management, a clear understanding of the options available, and the factors influencing their uptake is necessary.

1.3 Research objective and scope

This research study aims to develop a better understanding of key enablers, barriers and opportunities for the effective re-purposing of bulk tailings and tailings deposits, with a specific focus on those generated by the South African gold industry. The study makes use of primary and secondary data sources generated through interviews with different stakeholders and a review of published literature respectively. No experimental work has been carried out as part of this research project.

1.4 Dissertation structure

This chapter provides the context and motivation for this project. Chapter 2 gives the background of the gold mining sector in South Africa. It details the current mine waste management practices and associated challenges before giving a review of the legislative framework that governs the South African mining industry. Chapter 3 outlines the research methodology used and the research questions that guided the research. The research findings are presented in Chapters 4 and 5. In Chapter 4, the different opportunities for utilizing mine waste from the gold industry are identified and outlined. Chapter 5 explores various factors that facilitate and/or hinder the use of mine waste.

Chapter 6 consolidates the findings of the study, drawing on the literature and findings presented in Chapters 4 and 5. This is followed by a discussion of the implications of the study findings with regards to the objectives of this thesis and the recommendations for future work. Figure 2 outlines the schematic structure of this research thesis.

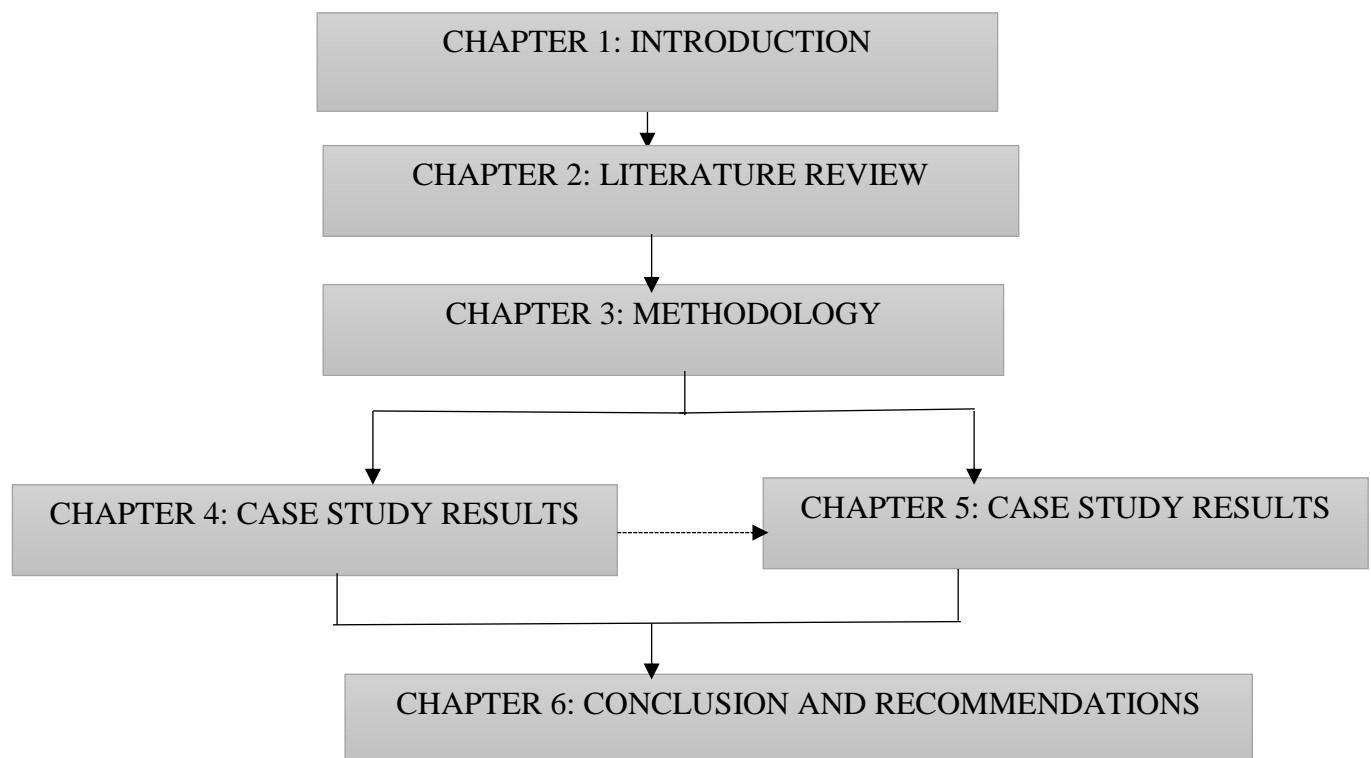


Figure 2: Schematic structure of this dissertation

CHAPTER 2

LITERATURE REVIEW

This chapter outlines the status of the gold mining sector in South Africa and details current mine waste management practices and associated challenges from gold tailings deposits. This is followed by an outline of the regulative framework that governs the mining industry.

2.1 The South African Gold Industry

World-class gold deposits were first discovered in the Witwatersrand region in the late 19th century and this attracted many prospectors and facilitated a change of South Africa's economy from an agriculturally based economy to a modern industrial economy (Malherbe, 2000, Trangos and Bobbins, 2015). The Witwatersrand Basin (Figure 3) consists of seven exploited goldfields and are the biggest known gold mineral deposits in the world and stretch over three provinces namely Gauteng, Free State and North West (Riemer and Durrheim, 2011, Rösner and Schalkwyk, 2000).

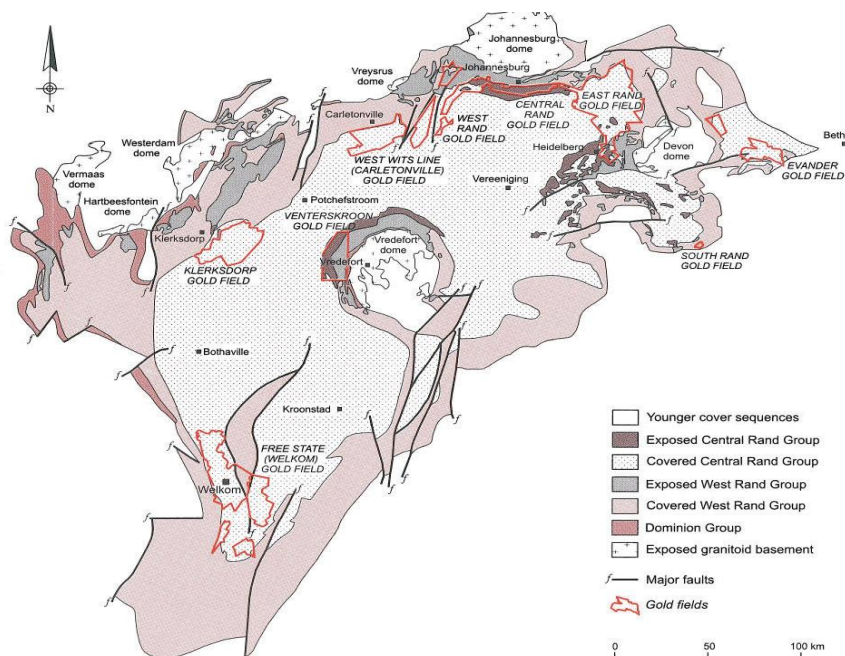


Figure 3: Map of the Witwatersrand Basin (Adler et al., 2007)

Since gold was discovered in the Witwatersrand, South Africa was for many years the world's leader in gold production with peak production of 1 000 tons of gold produced in 1970 (Chamber of Mines, 2017b). Since then, the amount of gold mined in South Africa has steadily decreased due to declining ore grades, increased mine depth as well as higher material input costs (Short and Radebe, 2008). Other contributing factors to the decline in gold production include labour strikes, increasing costs of water and electricity, safety stoppages and the ongoing energy crisis (Johnston, 2012). According to statistics given by the Chamber of Mines (2017a), 141.4 tons of gold was produced in 2016 in South Africa accounting for 4.4% of global gold production. Table 2 gives an overview of the South Africa's production levels of gold over a period of 10 years as documented by Chamber of Mines (2017a).

Table 2: Snapshot of South African gold production over a ten-year period (2006-2016) adapted from Chamber of Mines (2017a)

Year	Production (tonnes)	Global gold production (tonnes)	South African proportion of total gold production (%)
2006	272.1	2 495.4	10.9
2007	252.6	2 497.8	10.1
2008	212.7	2 429.9	8.8
2009	197.7	2 612	7.6
2010	188.4	2 739	6.9
2011	180.2	2 838.1	6.3
2012	154.2	2 860.6	5.4
2013	159.7	3 042	5.3
2014	151.6	3 131	4.8
2015	144.5	3 208.6	4.5
2016	142.0	3 222.3	4.4
2017	136.8	3 247.0	4.2

Despite declining production volumes, the gold mining industry directly employs approximately 120 000 people. While employee numbers within the sector have declined over time due to mine closures, restructuring and mergers (Short and Radebe, 2008), the total earnings have increased from R14.7 billion to R28.7 billion between 2007 and 2016 (Chamber of Mines, 2017b). However, compared to other major mining countries globally, the gold mining industry in South Africa employs significantly more people. This is mostly attributable to the fact that most gold operations in South Africa engage in deep-level hard-rock underground mining which are labour intensive (Short and Radebe, 2008). In addition, the gold mining sector recorded total sales of R62.7 billion and paid R0.61 billion in royalties to the South African government in 2016 (Chamber of Mines, 2017a).

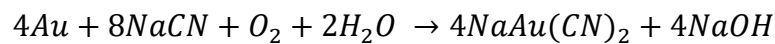
2.2 Gold beneficiation process

Typically, South African gold mines are deep level mines and can reach depths of over three kilometres and thus underground mining is common. The ore is hoisted from underground in skips and is transported to the surface by rail hoppers or conveyor belts. The ore then undergoes the first step of the gold recovery process, which is comminution. In this process, the ore-bearing rock undergoes crushing and grinding to reduce the size and to allow for the separation of valuable minerals from less valuable materials (Rosner, 1999). The small size particles of ore also provide a greater surface area necessary for the chemical processes to transpire in extracting the gold (Vermeulen, 2001). Typically the ore is reduced in size to less than 0.5 mm as this allows for the gold to be extracted through metallurgical processes (Vermeulen, 2001). The waste rock is deposited on a waste rock dump and sometimes sold as a construction material (Rosner, 1999). After the crushing, the ore undergoes various physical and chemical processes to separate and extract the gold.

There are numerous processing techniques that can be used for recovering gold and these are largely dependent on the suitability of the technique to the gold mineralogy (EIPPCB, 2009). Initially, gold was extracted from Witwatersrand ores using a process consisting of gravity concentration followed by mercury amalgamation (Naicker et al., 2003). Gold is then recovered by heating in open air with an oxygen flame to remove the mercury (Habashi, 2016). This technology is one of the oldest technologies and recovers relatively coarse gold with low gold recovery yields. This practice was widely used but is no longer popular due to mercury

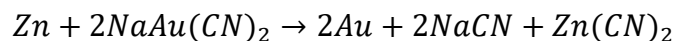
toxicity and pollution of the atmosphere, soils and rivers (Habashi, 2016).

Another technology that is common and has superseded the mercury amalgamation process involves cyanide dissolution. The use of cyanide technologies for gold extraction have been used worldwide but pose significant challenge for the proper handling and management of the wastes (Vermeulen, 2001). The main options for cyanide leaching include heap leaching or agitated tank leaching, with subsequent recovery of dissolved gold using carbon adsorption or zinc precipitation (Vermeulen, 2001). Typically, agitated tank leaching and heap leaching are applied to high-grade ores and to low-grade ores respectively (Durand, 2012, Vermeulen, 2001). The cyanide leaching process involves mixing the gold-bearing crushed ore with sodium cyanide, lime (also known as calcium hydroxide) and oxygen and the following reaction occurs:



The lime raises the pH of the solution to a value of approximately 11 before cyanide is added to dissolve the gold (Vermeulen, 2001). Following the leaching process, the pregnant liquor containing the dissolved gold is separated from the unreacted gangue using thickeners and/or vacuum filtration.

Recovery of soluble gold from the leach liquor may be conducted using either zinc precipitation or activated carbon adsorption in a carbon-in-pulp (CIP) or carbon-in-leach (CIL) configuration (Durand, 2012, Vermeulen, 2001). In the zinc precipitation method, gold is recovered through precipitation with zinc dust. The zinc displaces the gold in the redox reaction shown below:



The zinc-lead gold precipitate is filtered out from the solution. Sulphuric acid is then added to dissolve the excess zinc and impurities such as silver, platinum, copper and lead (Vermeulen, 2001).

In the alternate CIP/CIL methods, activated carbon is used to adsorb gold from the cyanide solution. The gold-enriched activated carbon is washed with dilute hydrochloric acid (HCl) to re-dissolve the gold and the carbon is regenerated and activated so it can be reused again in the

process (Durand, 2012). Lastly the gold is recovered from the eluate through electro-winning which entails the deposition of gold onto steel cathodes. It then undergoes smelting and refining to produce gold bars (Durand, 2012, Vermeulen, 2001).

The dewatered solid from the leach process, normally referred to as the cyanidation tailings, are washed to remove gold and cyanide and then pumped to tailings facilities where the solids settle and the liquid is allowed to drain and/or evaporate.

2.3 Gold tailings facilities and their impacts

In general, tailings refer to the fine grained mine waste material that is generated during the beneficiation of gold. Typically, tailings are very small particles ranging from between 0.001 to 0.62 mm (Netshiongolwe, 2018). The conventional land disposal of tailings can impact on the environment through geophysical failures or collapse as well as wind and water erosion, resulting in pollution of local water, air and soil (Franks et al., 2011). In addition, the construction of tailings facilities (also known as tailings storage facilities, impoundments, dams slimes dams or deposits) and their subsequent maintenance is very expensive (Franks et al., 2011). Globally, incidents of spills, seepage, and catastrophic failures due to poor construction and management practices remain one of the most evident features of the minerals industry (Franks et al., 2011). Often, these incidents have severe long-term environmental and social effects which can leave environmental, economic and social legacies for many years, thus impacting on both present and future generations (Franks et al., 2011). According to the European Environmental Bureau (2000), the environmental damage from mining activities results in irreversible destruction of ecosystems. This legacy of poor waste management poses a severe challenge to land restoration and the sustainability of mining activities (Franks et al., 2011). Further to this, it also continues to disproportionately shape the industry's reputation worldwide (Franks et al., 2011).

In South Africa, the gold mining industry has left the Witwatersrand region scattered with mine waste deposits and abandoned mine shafts (Pratt, 2011, Trangos and Bobbins, 2015). In particular about 270 tailings facilities, covering approximately 400 km² in surface area and containing approximately 6 billion metric tons of toxic and radioactive waste, have been identified (Oelofse et al., 2007, Olalde, 2015). These tailing facilities pose significant environmental, human health and socio-economic impacts on the local community as

articulated in the section below (Malatse and Ndlovu, 2015).

2.3.1 Radioactivity

The goldfields of the Witwatersrand basin all contain higher concentrations of uranium than gold (Coetzee et al., 2006, Durand, 2012), and as such uranium was initially mined as a by-product in the beneficiation of gold (Durand, 2012). Peak production of uranium in South Africa was recorded in 1980 with an estimated 7 000 tons of uranium being produced on a yearly basis (Coetzee et al., 2006). However, as more countries exploited their own uranium sources, the price of uranium on the world market dropped resulting in a decline in the production of uranium in South Africa. By the year 1994, only four out of the 26 uranium producing mines were in operation and production of uranium was down to 1 600 tons annually (Coetzee et al., 2006). Once recovery of uranium ceased, the majority of the uranium extracted during the gold mining process is dumped in tailings dams, along with other unwanted gangue minerals. This results in the elevated levels of uranium in these tailings dams (Trangos and Bobbins, 2015). According to Durand (2012), these facilities hold more than 100,000 tons of uranium as well as radium, thorium, polonium, and some lead isotopes which are toxic in nature and radioactive (Durand, 2012). These toxic metals leach out into water sources contaminating boreholes, streams and rivers putting the communities, who utilize these water sources for drinking, irrigation and watering of livestock, at risk (Durand, 2012). The uranium and associated metals also accumulate in the river sediment and soil which negatively impacts on the surrounding vegetation and any farming activities adjacent to contaminated mining areas (Durand, 2012). Prolonged exposure, absorption and inhalation of radioactive particles through the skin leads to radiotoxicity (Trangos and Bobbins, 2015). Other health effects include damage to tissues, kidney failure, blindness, paralysis and loss of coordination and cancer (Durand, 2012).

2.3.2. Acid mine drainage water pollution

Besides, uranium, the waste from the current gold beneficiation process normally contains sulphide minerals such as pyrite in large quantities (Rösner and Schalkwyk, 2000), which generate an acidic effluent known as acid mine drainage (AMD) through the natural weathering and oxidation of the sulphide-bearing materials on exposure to moisture and oxygen (Nengovhela et al., 2006, Oelofse et al., 2007). The acidic water that is produced during the

oxidation of sulphide minerals dissolves salts while mobilizing metals from residue deposits and mine workings (Oelofse, 2008). AMD from gold waste deposits and mine workings is often characterized by low pH; high electrical conductivity; high salinity; raised concentrations of iron, sulphate, aluminium and manganese; and toxic levels of arsenic, copper, cadmium, zinc and lead (Hove and Mangena, 2013, Oelofse et al., 2007). According to Nengovhela et al. (2006), the extent to which acid is generated and the exact nature of the drainage, is dependent on factors such as oxygen availability, mineralogy, pH and temperature.

AMD affects the water quality of groundwater, rivers and wetlands and pollutes surface and groundwater. It also results in soil quality degradation and researchers have documented a loss of biodiversity and the destruction of aquatic habitats aquatic life where AMD has occurred (Adler et al., 2007). This is because AMD affects the acidity, salinity, toxicity, turbidity, and radioactive nature of the receiving water bodies thus killing aquatic invertebrates, organisms such as fish, frogs and water birds and fish (Durand, 2012). Research has linked metal-rich AMD to increased rates of cancer due to high levels of radioactivity, skin lesions and decreased cognitive function (Adler et al., 2007, Oelofse et al., 2007, Ogola et al., 2002). These problems are not only confined to the Witwatersrand region but to other regions where mining activities have been taking place in South Africa (Pratt, 2011). Durand (2012) notes that many deaths and miscarriages of the animals in the Krugersdorp Nature Reserve have been documented since the first AMD incident was reported where polluted water from an old mine shaft contaminated a borehole upstream of the Krugersdorp Game Reserve. However, no autopsies have or no epidemiological studies have been conducted and as such the cause of death of the animals is speculative (Durand, 2012).

2.3.3 Cyanide toxicity

Gold extraction using the cyanide process as detailed in Section 2.2 threatens the environment, aquatic and terrestrial life and human health (Durand, 2012). After gold has been extracted, the slimes containing various chemicals as well as cyanide are pumped to tailings dams.

The degree of toxicity of cyanide and whether or not cyanide is stable or not is dependent on numerous factors. These include temperature, water, pH, salinity, dissolved oxygen concentration and the occurrence of other ions in solution (Rosner, 1999, Rösner et al., 2001). Four different classes of cyanides are common in gold effluents namely free cyanide; readily

soluble cyanides such as sodium cyanide, potassium cyanide and calcium cyanide; weak acid dissociable cyanides and strong acid dissociable cyanide (Bakatula et al., 2008). The weak acid dissociable cyanides are fairly unstable complexes consisting of cyanide and metals such as cadmium, nickel, copper and zinc (Bakatula et al., 2008). These complexes easily detach in mildly acidic and/ or neutral conditions. The strong acid dissociable cyanide complexes are made with metals like iron, silver, cobalt and gold that dissociate in conditions that are extremely acidic (Bakatula et al., 2008). Metal cyanide complexes are generally more stable, less toxic and do not readily degenerate.

Mining operations typically make use of simple cyanides for leaching as they dissolve easily. As such, mining leachate typically contains contains sodium cyanide which converts easily to a free cyanide ion (CN^-) and hydrogen cyanide (HCN) in water. The amount of free cyanide present in a solution determines the extent of toxicity. The higher the amount of free cyanide present in a solution, the more toxic the solution. Cyanide is not bio accumulative, degrades easily into non-toxic substances and quickly disperses (Zarsky and Stanley, 2011). It does not persist in the environment, mainly due to its chemical properties which results in it forming a cyanide complex with metals. Alternatively, the cyanide is lost due to volatilization and/or is degraded by microbes (Zarsky and Stanley, 2011). To this end, spills involving cyanide tend to not cause long-term toxic environmental effects unless other heavy metals are present which can result in heavy metal toxicity and/or the oxidation of metal sulphides to generate acid mine drainage (Zarsky and Stanley, 2011).

Typically, cyanide leachate from a fresh tailings dam poses a threat of pollution if the tailings dams walls are weakened or if there is a cyanide spill during transportation. This can lead to soil and water (ground and surface) pollution in the event of dam failure and or spills during transportation (Zarsky and Stanley, 2011). Great care is taken to prevent seepage through the lining of the tailings storage facilities with geosynthetic liners that are specifically designed as containment barriers (Durand, 2012). However, liner failures (tearing of the lining) can cause the cyanide to seep out of the facilities into the environment, streams and groundwater. Exposure to small concentrations ranging between 20-40 parts per million (ppm) can result in skin rashes, headaches, weak and quick pulse, nausea, vomiting burns, severe pain and ulcers (Zarsky and Stanley, 2011). However, the prolonged skin exposure and inhalation of high concentrations (i.e. 100-300ppm) of cyanide gas can lead to death (Zarsky and Stanley, 2011).

Cyanide also damages the nervous, respiratory and cardiovascular systems of animals that either ingest and/or inhale it.

2.3.4 Air pollution and dust control

The majority of the tailings dams in South Africa are intertwined with built-up areas and over the years, residential areas have encroached onto land that is very close to these tailings facilities (Kneen et al., 2014). Most tailing facilities are either not vegetated or have sparse vegetative cover and are generally open to wind elements. This, coupled with the fact that tailings are very fine materials that are easily blown by the wind, presents an intermittent and persistent environmental hazard for neighbouring communities (Kneen et al., 2014). A study commissioned by the International Human Rights Clinic revealed that communities located near to the gold tailings facilities in the West Rand and Central Rand are exposed to windblown mineral dust (IHRC, 2016). This wind-blown dust poses a health risk due to the dispersion of contaminants, often reduces visibility, and is a persistent nuisance to nearby communities. Air quality dispersion modelling has been undertaken in some of these communities and shows that occasional dust events can generate particulate matter (PM₁₀) which exceeds the 18 µg/m³ set by Department of Environmental Affairs. In addition, the particulate matter particles contain crystalline silica and quartz dust in high concentrations and this has been recorded up to 2km downwind of the tailings facilities (Kneen et al., 2014). The particulate matter can easily be transported to neighbouring agricultural used land due to its small particle size. The deposition of the radioactively contaminated dust onto plants, crops and vegetables can result in radiation exposures that far exceeds the inhalation of contaminated dust (Lieverink, 2016).

2.3.5 Soil pollution

Research conducted at the Tudor Shaft informal settlement indicates that soils that are close to gold tailings facilities are contaminated by heavy metals and this significantly affects the growth and quality of plants, crops and vegetables grown on the soils (IHRC, 2016). The Tudor Shaft informal settlement is located in Krugersdorp, approximately 30 km from Johannesburg. The community of Tudor Shaft live within 400 metres of a uraniferous tailings dam and some of the residents have built their shack dwellings on tailings soils. Radiation at the tailings dam was found to be at least 15 times greater than normal background levels in the region. The IHRC (2016) report documents failed efforts by residents to plant crops on land that is in close

proximity to tailings dams. According to this report, the vegetables did not grow and this was attributed to the fact that the soil had too many chemicals, was too acidic and general poor soil quality. The researchers further noted that the plants, crops and vegetables that survive on such soils are often not suitable for consumption by either humans or animals due to the elevated metal content and radioactive nature of the soil (IHRC, 2016). This is because the vegetables had adsorbed the high concentrations of uranium and other heavy metals thereby posing a potential health threat to residents who ingest the vegetables. (IHRC, 2016)

A research study by Kootbodien et al. (2012) investigated the potential contamination from heavy metals in a Johannesburg school vegetable garden. The vegetable garden was located approximately 500m from a gold-mine tailings facility. The soil from the school garden had high levels of arsenic and the vegetables had elevated concentrations of lead, mercury and arsenic. The researchers calculated the estimated daily intake (EDI) of heavy metals for a child weighing 30kg with an average intake of 100 g of school-garden vegetables daily consumption. The calculations showed that levels of lead, mercury and arsenic in vegetables fell within the acceptable limits. However, the levels of chrome and copper exceeded the acceptable intake limits (Kootbodien et al, 2012).

2.4 Current mine waste management approaches in South Africa

The environmental challenges articulated above and stricter environmental legislation has necessitated the need for more innovative methods of disposing and or utilizing mine tailings while simultaneously minimizing the environmental and social risks associated with conventional disposal (Malatse and Ndlovu, 2015). A review of available literature suggests that there are three main approaches to mine waste management in South Africa. These are namely rehabilitation, recovery and reuse. Godfrey et al. (2007) argues that the decision of how mine waste is handled is driven by different factors namely environmental policy, economic policy, and integrated waste policy respectively. Each policy favours different probable solutions, for instance rehabilitation, disposal in tailings facilities and reuse (Adler et al., 2007). Further to this, Adler et al. (2007) state that the need for environmental protection and economic development influences how mineral residues and mine wastes are managed (Adler et al., 2007). An overview of the main approaches to mineral waste management which have been explored in South Africa is provided in Sections 2.4.1-2.4.4.

2.4.1. Value recovery

Diminishing gold reserves have necessitated the need for turning this waste into a valuable resource by extracting the valuable metals from discarded waste (Trangos and Bobbins, 2015). Globally, mine waste containing residual high-value metal and minerals is now seen as a resource that is increasingly becoming accessed (Corder et al., 2015). Technological advancements have enabled the mining sector to extract low concentrations and lower mineral grades in an economically viable manner (Davis, 2014, Lottermoser, 2011). Recovery of minerals from waste has a potentially significant impact on current mineral reserves by deferring the exploitation of new deposits (Van Heerden, 2002). The reprocessing of waste to recover minerals and metals also has a significantly lower energy requirement and carbon footprint when compared to beneficiation of minerals from virgin ores (Corder et al., 2015). This results in reduced environmental impacts and promotes the efficient, sustainable and optimum resource use (Corder et al., 2015, Godfrey et al., 2007). The re-mining of mine waste has added benefits besides recovering residual gold as it offers the opportunity to re-position and re-engineer waste facilities and return previously impacted land to a higher social and economic use (Davis, 2014). However, the main driver is usually economic profit, and the viability of re-processing is thus largely dependent on factors such as processing efficiencies, scale of extraction and associated extraction costs, commodity price and grade in the waste (Godfrey et al., 2007). As such, this approach remains limited to extracting precious metals like gold and the platinum group metals (PGMs).

In South Africa, companies such as DRDGOOLD, Mintails, Goldfields, Sibanye Gold are undertaking this approach and re-mining gold dumps in Johannesburg to recover residual gold. The secondary gold tailings are then deposited in re-engineered “super-dumps”.

2.4.2. Rehabilitation

Rehabilitation refers to the process of restoring land that has been damaged by mining activities to a state that is sustainable and usable (Tanner, 2007). Rehabilitation of mine waste facilities is often undertaken to ensure environmentally appropriate mine closure and to lessen the environmental impacts associated with the facilities post mine closure (Godfrey et al., 2007). In certain instances, rehabilitation of mine waste facilities is undertaken to a standard which requires the area to be fenced off or used for limited grazing. Across the world, it is a common

practice, especially in densely populated areas, for rehabilitated mine dumps to be used as golf courses, football fields, parklands, open air theatres, artificial ski slopes, racing and quad biking sites (Lottermoser, 2011).

Nzimande and Chauke (2012) state that rehabilitation requires a holistic approach that considers the entire mine's life cycle, from planning right to the final end use of the mine. In line with this thinking, a mine site rehabilitation hierarchy was created to serve as a guide to prioritize rehabilitation approaches and strategies of waste dumps (Lottermoser, 2011). The focus of most rehabilitation strategies is to ensure that environmental harm is minimized and/or reduced (Lottermoser, 2011).

In South Africa, Godfrey et al (2007) argue that rehabilitation is largely driven by environmental policy that aims at ensuring that the tailings facilities pose little or no risk to the environment and does not negatively impact on the health of people affected by the dumps. Rehabilitation procedures often pose an economic encumbrance on the mine and are often perceived as costly investments with no financial returns (Godfrey et al., 2007). The biggest advantage of rehabilitation is that it reduces the contamination of surface and ground water as it provides better control of rainwater run-off and mine drainage that would otherwise contaminate water bodies (Nzimande and Chauke, 2012). Further to this, rehabilitation of tailings facilities also addresses issues such of erosion control and air quality, although it does not fully eliminate the challenges and the associated long-term pollution potential of mine waste (Godfrey et al., 2007). There is specific legislation in South Africa that relates to rehabilitation activities and this is discussed in Section 2.5.

Different methods of rehabilitation have been investigated and documented. The most popular method that has been documented is the use of vegetation cover. Rehabilitation through vegetation can be done through planting grasses and/or trees. Vegetation techniques offer a potential solution by minimizing wind and water erosion from tailing deposits. A previous review of studies that have been conducted on the rehabilitation of the tailings storage facilities around the Witwatersrand Basin by Umba (2013), has indicated that, while the use of vegetative cover provides an effective way of controlling and reducing dust, the maintenance of the vegetation is unsustainable both from an economic and ecological perspective.

Another method entails the rehabilitation of tailings storage facilities through chemicals. This

approach entails spraying the surfaces of the tailings facilities with various substances such as molasses, salt and hygroscopic material. These chemicals bind the loose particles thereby decreasing the amount of dust that gets blown by the wind from mine tailings. According to Umba (2013) the use of chemicals gives fast results but requires continuous application and thus becomes costly due to the high price of the chemicals used. Other methods that have been used include rock cladding or gravel mulching and rehabilitation through the use of biological organisms (also referred to as bioremediation).

Rehabilitation of mine lands offers endless possibilities for utilising the land. The opportunities include using the land for industrial and residential developments, agricultural activities, tourist attractions and leisure activities which are discussed in more detail in section 4.7.2. However, there is no guarantee that the rehabilitation of post-mining landscapes will produce land that is valuable, or be deemed as socially acceptable for redevelopment and economic activity.

2.4.3. Reuse

The reuse of mine waste involves finding other alternative uses for that mine waste that is different from its intended primary use. This approach is motivated by the integrated pollution and waste policy which promotes the reduction of material that is disposed of as mine waste, with disposal being considered as the last option (Godfrey et al., 2007). This approach is in line with national policy that promotes waste minimization. The reuse of mine waste has many advantages as it reduces the volume of virgin material that is extracted from the ground and decreases the quantity of mine waste disposed of to the environment. It also releases land for redevelopment and or other alternative land use options (Trangos and Bobbins, 2015). This transforms the physical landscapes that have been marred by mining activities and contributes significantly to removing the long-term environmental risks and liabilities of mining (Lottermoser, 2011, Trangos and Bobbins, 2015).

Several studies have investigated the reuse of mine waste worldwide. The most common application is using mine waste in producing construction material. In accordance with Yellishetty et al. (2008), the construction of railways, roadways, dams and rivers using mine waste as a substitute had increased steadily since the late 1980's. The numerous studies conducted have found that mine waste can be utilised for several purposes and this is highly

reliant on its chemical and physical properties (Van Heerden, 2002). Mine waste, and tailings in particular, have been used for construction of wetlands, production of ceramic products such as tiles and as a cement additive (Harrison et al., 2013). Incorporation of tailings in the making of building materials such as bricks and concrete blocks, as road aggregate, in ceramics, in agricultural applications and manufactured fillers has also been investigated (Vogeli et al., 2011, Yellishetty et al., 2008). Research also indicates that tailings facilities themselves can be used for various purposes. This includes using the dumps for generating clean energy (solar and wind farms), recreation and tourism purposes (Pearman, 2009). Mine dumps have also been re-purposed for leisure and sport facilities, and in some instances the land has been used for manufacturing, industrial and or residential redevelopments (O'Neill, 2015).

Despite the findings of numerous research studies that suggest that mineral waste can and has been successfully reused, the reuse of mine waste remains relatively constrained, especially in South Africa. Godfrey et al. (2007) cite five issues as hindering factors to the reuse of mineral waste. These are namely technology constraints, lack of enabling legislation, technical incompatibility, high cost and further environmental risks associated with downstream processing and use of mine waste.

2.4.4. Integrated waste management approaches

Increasingly, researchers (and, in some cases, practitioners are starting to recognise the potential advantages of waste management approaches which combine value recovery, risk removal and bulk waste re-utilisation in an integrated and holistic manner. Such approaches generally entail the pre-separation of waste components to recover value, remove harmful contaminants and simultaneously generate secondary wastes that are potentially suitable for downstream utilisation, ultimately resulting in a “zero-waste” scenario.

One such approach has been adopted by researchers at the University of Cape Town for AMD generating mine wastes from copper, gold and coal beneficiation. This approach makes use of the flotation process to recover value and remove acid-generating sulphide minerals, thereby preventing environmental risks associated with ARD (Harrison et al., 2013). A research study evaluated the use of froth flotation to physically separate sulphide minerals from gold tailings, as well as copper tailings and fine coal processing waste (Harrison et al., 2013). The researchers successfully demonstrated the feasibility of using froth flotation for the physical

separation of key component components in these wastes. The three output streams obtained include additional recovered product (gold, copper or coal), a sulphide rich concentrate and a sulphide-lean and a bulk sulphide-lean tailings fraction which was non-acid generating. The study also evaluated and identified numerous potential uses for these output streams. The findings suggest that the sulphide rich stream could be used to produce and manufacture sulphuric acid (H_2SO_4), wheat straw compost, ferric sulphate coagulant and ferrous sulphate heptahydrate (Harrison et al., 2013). The soluble sulphate stream could then be used to make inorganic pigments, coagulant and gypsum. Potential uses for the benign tailings were identified and included using the tailings to make backfill, for road construction, to construct wetlands and as a cement additive and to produce glass ceramics (Harrison et al., 2013).

In a similar approach, Benzaazoua et al. (2008) explored an integrated waste management approach to tailings management at a gold mine in Canada. The approach combines two processes namely environmental desulphurization process (i.e. the selective sulphide separation using flotation) and cemented paste backfill technology. The desulphurization process consisted of separating sufficient quantity of sulphides from the gold mine tailings through flotation. The flotation process has two output streams, the desulphurized tailings which are non-acid generating and the sulphide-rich tailings that are acid generating. The sulphide-rich concentrate was then used to successfully produce various cemented paste backfill (CPB) mixtures which can then be used underground returned. Detailed information on the process of making the cemented past backfill is discussed in section 4.4. Benzaazoua et al. (2008) argues that the use of integrated approach limits AMD generation from tailings and provides an alternative waste management to conventional tailings disposal methods while minimising the volumes of tailings to be stored at the surface.

Researchers at the Royal Melbourne Institute of Technology in Australia investigated the viability of recycling base metal mine tailings. The researchers proposed a four-stage integrated recycling system which consisted of metal retrieval, removal of potential contaminants, processing for construction materials and backfill, and development of 'soil' that is suitable for revegetation and landscaping from the benign final residue (Struthers et al., 1997). The recycling system was designed as an alternative to conventional tailings dam disposal and also to rehabilitate the tailings dumps. This process reduced the tailings volume and toxicity levels of the tailings. Struthers et al. (1997) argued that the recycling system removed the need to

have a tailings dam altogether. The feasibility of the systems depends on a continuous flow stream from one stage of the process to the next with no static treatments or double handling. Each stage has to be simple, quick and inexpensive (Struthers et al., 1997). Their research suggest that the recycling system is more suited for tailings at mine sites that were currently operating as opposed to historic mining sites. This is because the recycling system can be integrated into the mine planning and management strategies.

Integrated mine waste management approaches offer an alternative way of dealing with tailings that improve environmental, social and economic outcomes. This is because integrated approaches can be applied across the entire value chain from the early phases of exploration, ore body characterisation, processing, treatment, reprocessing, recycling and reuse in a way that mitigates environmental risks and increases the chance of successful rehabilitation (Edraki et al., 2014). The ultimate goal is to transform the perspectives of mine waste and highlight the need for total resource utilisation, where mine waste is exploited and converted into other valuable products while creating new economic value and moving toward zero waste and zero environmental footprint within the mining sector (Lottermoser, 2011).

2.5. Overview of the statutory law framework regarding mine waste in South Africa

The legal regime in South Africa promotes environmentally responsible mineral extraction and mine closure (McKay and Milaras, 2017). All mines are required to comply with the regulatory framework governing mineral and petroleum resources and ensure that all operational and closure procedures and activities to be conducted with due diligence and care for the rights of others (Pulles et al., 2005). This is articulated in section 24 of the Constitution (Act No. 108 of 1996) which states that “everyone has the right to an environment that is not harmful to their health or wellbeing; and to have the environment protected, for the benefit of present and future generations” (Constitution of South Africa, 1996). Section 24(b) of the Constitution directs “the state to take reasonable legislative and other measures to prevent pollution, and ecological degradation, promote conservation, and secure the ecologically sustainable development and use of natural resources while promoting justifiable economic and social development” (Constitution of the Republic of South Africa, 1996). To realize the objectives of the Constitution, a range of statutes has been enacted. The main statutes which have a direct

bearing on mining include the Minerals and Petroleum Resources Development Act 28 of 2002 (MPRDA); the National Environmental Management Act 107 of 1998 (NEMA), and the National Environmental Management: Waste Act 59 of 2008 (NEMWA). Collectively these statutes include comprehensive pollution prevention methods, minimization, remediation liability requirements. These are discussed in the more detail below.

2.5.1. Mineral and Petroleum Resources Development Act 28 of 2002

The MPRDA is administered by the Department of Mineral Resources and recognizes the state as the custodian of all mineral and petroleum resources. The Act promotes equitable access to mineral and petroleum resources through substantial and meaningful empowerment of persons who were historically disadvantaged including women and communities (Rogerson, 2011). It requires that these resources are developed optimally and in a manner that is ecologically sustainable (Cawood, 2004). According to the provisions in the MPRDA, mining rights holders must contribute to social and economic development of areas surrounding their operations and their host communities. Further to this, the Act provides security of tenure with regard to existing prospecting and mining operation, promotes investment, economic growth and job opportunities within the minerals industry.

The MPRDA defines minerals as “any substance, whether in solid, liquid or gaseous form, occurring naturally in or on the earth or in or under water and which was formed by or subjected to a geological process, and includes sand, stone, rock, gravel, clay, soil and any mineral occurring in residue stockpiles or in residue deposits”. Residue deposits are, in turn, defined as “any residue stockpile remaining at the termination, cancellation or expiry of a prospecting right, mining right, mining permit, exploration right or production right”. The Act also defines residue stockpile as “debris, discard, tailings, slimes, screening, slurry, waste rock, foundry sand, beneficiation plant waste, ash or any other product derived from or incidental to a mining operation and which is stockpiled, stored or accumulated for potential re-use, or which is disposed of, by the holder of a mining right, mining permit or production right”. From these three definitions, it is clear that the mine waste residue and stockpiles is seen as a resource that can has value and can be processed.

The MPRDA stresses that the holder of the mineral rights is liable for pollution, destruction of the environment and ecological deprivation (McKay and Milaras, 2017) and demands that

mines manage all waste, address and mitigate pollution and the impacts on the environment that are a result of mining activities. It also stipulates that the mineral rights holder is accountable for paying for the rehabilitation after the operation to either its normal state or an acceptable land use that adheres to sustainable development principles (Tucker, 2013).

In terms of residue stockpiles and deposits, regulation 73 of the MPRDA Regulations gives guidance on how residue stockpiles and deposits must be managed. According to regulation 73, impacts related to the management of residue stockpiles and deposits must form part of the environmental impact assessment report and environmental management programme. Mine residue stockpiles and deposits must be characterised and classified by a competent person.

2.5.2. National Environmental Management Act, 1998 (Act 107 of 1998)

The NEMA specifies the fundamental philosophies that have to be adhered to during any environmental decision-making. The Act demands for sound measures to avoid, control and rehabilitate the effect of substantial pollution and environmental degradation resulting from mining operations to be undertaken (McKay and Milaras, 2017). According to Rapson (2017), practical measures include (but are not restricted to) investigating, assessing and evaluating environmental impact; ceasing, modifying and or containment of any processes causing pollution and degradation and remediation of the pollution and degradation caused. Section 28 of NEMA states that this is the responsibility of the owner, the person who controls or the person who has the rights to use the land and or premises on which the activities are or have occurred (Rapson, 2017). This applies not only to processes or activities that are presently causing pollution or that possibly will cause pollution in the near future, but also to past activities that have caused environmental contamination and where that contamination remains evident (Rapson, 2017). In addition, NEMA includes comprehensive provisions regulating criminal liability and allows for the prosecution of environmental crimes. Humby (2017) argues that NEMA advocates for a weak form of rehabilitation of mining waste as it does not expressly require that residue stockpiles or deposits must be rehabilitated but rather states that residue deposits and stockpiles must be managed according to the provisions stipulated in NEMWA on a demarcated site.

2.5.3. National Environmental Management: Waste Management (Act 59 of 2008)

The NEMWA regulates the management of all waste so as to safeguard the environment and the health of humans. It does this by providing measures for pollution prevention and ecological degradation whilst ensuring sustainable ecological development. The Act advocates for a reduction of natural resource consumption; preventing and decreasing the amount of waste generated; and the reduction, reuse, recycling and recovery of waste and emphasizes that measures are to be developed to manage the treatment of hazardous wastes which cannot be avoided with disposal being the last resort. As such, this Act has the reuse of waste material and the recovery of minerals from waste as its core principles (Humby, 2017). To achieve the objectives of the Act, a National Waste Management Strategy was developed in 2011 with a primary focus of promoting the waste management hierarchy, ensuring effective service delivery, growing the waste economy through job creation and improved business development.

NEMWA defines waste as follows:

“any substance, whether or not that substance can be reduced, re-used, recycled and recovered

- a) that is surplus, unwanted, rejected, discarded, abandoned or disposed of; 30
- b) which the generator has no further use of for (he purposes of production;
- c) that must be treated or disposed of; or
- d) that is identified as a waste by the Minister by notice in the *Gazette*, and includes waste generated by the mining, medical or other sector, but
 - (i) a by-product is not considered waste; and
 - (ii) any portion of waste, once re-used, recycled and recovered, ceases to be waste;” (NEMWA, 2008)

The draft National Waste Management: Amendment Bill (B14 of 2017) provide clarity on how residue stockpiles and residue deposits must be managed in terms of NEMWA. The Bill also provides more certainty around definitions of residue deposits, residue stockpiles and waste and provides for the exclusion of residue stockpiles and residue deposits from the provisions of the NEMWA. The amendments make NEMWA the principal legislation that governs the environmental aspects of tailings dumps that were previously governed by the MPRDA

(Steenkamp, 2016). Mineral waste is predefined as hazardous and the Act stipulates the requirements for development and subsequent management of residue stockpiles and deposits as well as the recycling and treating of the waste (National Environmental Management Laws Amendment Bill, 2017). NEMWA requires a waste management licence for the creation of residue stockpile and applicants for the waste management licences must undertake an environmental impact assessment (EIA) process in accordance with NEMA. A basic EIA is required if the waste in question is generated from prospecting or activities requiring mining permits and a full scoping EIA is required if the waste is generated by activities requiring a mining right, exploration right or production right (National Environmental Management Laws Amendment Bill, 2017).

2.5.4. Other Relevant legislation

Other relevant legislation and policies are summarized in the Table 3.

Table 3: Summary of all other relevant legislation

Legislation	Summary of Act
National Water Act, 1998 (Act 36 of 1998)	The National Water Act (NWA) is administered by the Department of Water and Sanitation and promotes the protection, efficient use, development and sustainable management of water resources. The objectives of NWA include reducing and avoiding pollution and dilapidation of water resources (Odeku, 2014). Section 19 of the Act addresses pollution prevention and states that the owner, manager and/or occupier of land is required to take precautionary procedures to prevent and/or stop pollution (Odeku, 2014). Failure to prevent pollution might result in the persons or entities responsible for the pollution to be held financially liable for the steps taken by the catchment management agency to remedy the problem (Odeku, 2014). The Act was amended in 1999 and 2014 by the National Water Amendment Act No. 45 of 1999 and the Water Amendment Act, No. 27 of 2014.
Mine Health and Safety Act, 1996 (Act 29 of 1996)	The Mine Health and Safety Act (MHSA) is the principal health and safety legislation relevant to the mining industry. The objective of the act is to provide and promote the enforcement of health and safety measures in mines. It require both employers and employees to identify hazards and also makes provisions for effective monitoring systems, inspections, investigations and specific training that can eliminate and minimize the risk to health and safety of all persons who are on the mine.
National Environmental Management: Air Quality Act, 2004 (Act 39 of 2004)	The Act which falls under the mandate of the Department of Environmental Affairs (DEA) regulates air quality in order to protect the environment. It stipulates the national norms and standards regulating air quality monitoring, management, reporting and control measures to prevent pollution and ecological degradation. It establishes the air quality and local emission standards for the three spheres of government (i.e. national, provincial and local) who are answerable for monitoring and ensuring that the set standards are met. In support of the Air Quality Act, the National Dust Control regulations stipulate the maximum permissible dust fallout limits, measures to be taken with respect to dust control and the requirements for a dustfall monitoring programme and report. The Act has two amendments released in 3014 and 2014 respectively. These are the National Environmental Management Laws Amendment Act, No. 14 of 2013 and the National Environmental Management: Air Quality Amendment Act, No. 20 of 2014.

<p>National Nuclear Regulator Act, 1999 (Act 47 of 1999)</p>	<p>The National Nuclear Regulator (NNR) is the competent authority of the National Nuclear Regulator Act (Act No 47 of 1999). The Act regulates all nuclear activities and aims at ensuring that the environment, people and property are adequately protected against nuclear damage and any radiological hazards associated with using nuclear technologies. The NNR applies to all facilities that handle, treat, store condition and/or dispose of any radioactive material. The key functions of the NNR are to establish nuclear and radiation safety standards and regulatory practices; exercise regulatory control, grant nuclear authorisations and ensure necessary provisions are in place for nuclear emergency planning. For the reuse of mining waste to be feasible, the requirements stipulated within the Act must be adhered to prevent long-term impacts.</p>
<p>National Radioactive Waste Disposal Institute Act, 2008 (Act 53 of 2008)</p>	<p>The Act makes provision for the formation of a National Radioactive Waste Disposal Institute which manages the disposal of radioactive waste across South Africa. It provides the function of the institute, how it must be managed and regulates staff matters at the institute which became operational on 1 December 2009.</p>
<p>Hazardous Substances Act, 1973 (Act 15 of 1973)</p>	<p>This Act is overseen by the Department of Health and sets requirements that prohibit and control the importation, production, sale, use, handling, application, modification, disposal and or dumping of hazardous substances. hazardous substances are defined in the Act as substances that are toxic, corrosive, irritant, strongly sensitising, flammable and pressure generating under certain circumstances and may injure, cause ill-health or even death in humans. Waste from mining is likely to contain toxic metals and radioactive substances such as uranium. It is therefore imperative that this regulation stipulated within the act are adhered to.</p>

2.5.5. The One Environment System

The One Environment System (OES) was launched in December 2014. It aims to streamline all mining, water use and environmental authorisation processes for mining operations by integrating different aspects of mining activities management into one efficient and integrated mine environmental management system (Mapulane, 2017). The OES is an agreement between the three government entities that governed various aspects of mining activities, namely the Department of Mineral Resources and Energy, Department of Water Affairs and Sanitation and the Department of Environmental Affairs (Becker, 2015). The objective of the OES is to replace the fragmented and contradictory regulatory framework which has resulted an assortment of rules, regulations and institutional arrangements and to align the MPRDA, NEMA, NEMWA, NEMAQA and NWA (Mapulane, 2017). The OES is framed under the 'cooperative government' concept of the South African Constitution which promotes cooperation between all government spheres (Humby, 2015).

In the OES, all provisions relating to the environmental management of mining have been removed from the MPRDA and are regulated by the NEMA. The Minister of Environmental Affairs sets the regulatory frameworks, norms and standards for the sector with the Minister of Mineral Resources and Energy as the implementing authority. The Minister of Mineral Resources and Energy issues the environmental authorisations and licences for waste management for all mining and related activities in accordance to the NEMA and NEMWA while the Minister of Environmental Affairs is the appeal body for these authorisations. The Minister of Water and Sanitation handles all water use license applications. The three ministers agreed to synchronise and fix timeframes for issuing of authorisations and appeals. A 300-day turnaround period is stipulated for all application authorisations and all appeals must be lodged within 30 days of a decision been made. The OES is expected to simplify the process, avoid duplication in terms of requirements, negate the need for an applicant to deal with different regulatory approval processes and reduce the authorisation processing timeframes (Becker, 2015).

CHAPTER 3

CASE STUDY METHODOLOGY

The review in Chapter 2 details the background to the South African gold industry as a way to provide a context for the study and to highlight the status quo regarding tailings management in South Africa. This chapter begins by outlining the research objectives before outline the approach used to conduct this research and providing a justification on the choice of research methods used. Lastly the chapter details the participants of the research and briefly outlines the ethics of the research.

3.1 Research objectives

As indicated in Chapter 1, this study seeks to gain an enhanced knowledge regarding the opportunities, enablers and barriers to the utilization and down-stream processing of mine waste within South Africa, with a specific emphasis on gold tailings.

The review in Chapter 2 indicated that currently large-volume mine waste such as gold tailings are mainly disposed of in tailings facilities which are then rehabilitated, mainly through re-vegetation, in an attempt to stabilise the sites and minimise weathering through wind and water erosion. Options for reuse of these tailings appear not to have been rigorously explored, particularly in South Africa. As such the study's first aim is to *identify the potential alternatives for reusing gold tailings waste*. To achieve this aim, the following research questions have been formulated:

- i. What opportunities exist for reusing gold tailings?
- ii. To what level have these opportunities been developed (laboratory-scale; pilot scale; commercial plants)?
- iii. What technologies have been employed?
- iv. What are the key findings of developmental studies in terms of potential viability and feasibility, taking into consideration technical, economic and environmental factors?

The published literature has also alluded to a number of factors constraining the application of opportunities for re-use of mine wastes. A better understanding of these factors is imperative for the uptake of reuse opportunities and as such, the study also aims *to identify the factors influencing potential application of the alternatives for gold tailings in the South African context* using a barriers and enablers approach. To meet this aim, the following research questions have been formulated:

- i. What are the key drivers and barriers for the application of mine waste in general, and tailings from the South African gold sector in particular?
- ii. What are the perceptions and concerns in terms of the reuse of gold tailings amongst experts within, and external to, the industry in South Africa?

3.2 Data collection methodology

To formulate answers to the research questions above, the researcher used primary and secondary data sources. Primary data was obtained through semi-structured interviews and secondary data was obtained through a desktop study. These different approaches are discussed below.

3.2.1. Desktop study

The desktop study was the first phase of the research and was largely informed by secondary data obtained in previous studies that have been undertaken regarding the reuse of mine tailings. The focus of the study was on gold tailings; however, available literature on the development and application of alternatives for the re-use of mine waste with similar chemical properties was reviewed and informed the study. This included sulphidic tailings with quartz and kaolinite as major components, such as those generated during the processing of copper sulphide ores.

The desktop study reviewed publicly available literature including journal papers, post-graduate dissertations, published reports and media articles in order to identify existing opportunities for reusing mine waste and to highlight the drivers and barriers for mine waste reuse within the gold industry. In addition, various pieces of South African legislation, legal opinions and legal documents detailing the regulatory framework were also reviewed in order

to identify the current regulatory drivers and/or constraints for the implementation of the gold tailings reuse options in the local context.

3.2.2. Interview investigation

The second phase of the project made use of qualitative research techniques, namely semi-structured interviews, as interviews are a popular and effective means of data collection. The intent of the investigation was to determine stakeholder awareness, perspectives and concerns regarding the utilisation and processing of mine waste, with specific reference to gold tailings in South Africa.

For the interviews, participant selection was purposeful. Participants were selected based on how best they can inform the research questions and enhance understanding of research study. The selected participants were selected based on their expertise and in-depth knowledge of the gold mining industry, tailings management and tailings reuse. Potential candidates were sent an email requesting their participation. The email gave a background to the study and outline the research objectives and requested their involvement in the research. This was then followed up with a phone call to set up the interviews. Some potential participants declined the invitation and a total of nine participants accepted and as such a total of nine interviews were conducted. The number of participants was limited by the relatively small number of experts in this field as well as the reluctance of potential participants to be interviewed due to privacy concerns. While the number of participated might be considered low, all the participants have extensive experience and expertise in the gold mining industry and as such are considered to provide adequate representation. The stakeholders included individuals from various gold mining companies, legal experts, environmental consultants and government officials. More detailed information of the participants is presented in Table 4.

Table 4: Summary of research participants' details

Participant ID	Summary of expertise
Participant 1	Participant 1 works for a government institution and has significant experience in the waste sector.
Participant 2	Participant 2 has worked in the gold mining sector for more than ten years. This participant has expertise in the environmental issues associated with gold processing wastes.
Participant 3	Participant 3 works for a multinational mining company in a senior managerial position, with a specific focus on developing sustainability strategies for the company.
Participant 4	Participant 4 is a director of a consulting company that focuses on environmental consulting and mine waste management. The participant has expertise in the design and management of tailings storage facilities, rehabilitation and mine closure planning.
Participant 5	Participant 5 is a CEO of an environmental consultancy that provides environmental services to mining industry. The participant is considered an expert in environmental impact assessments, risk assessments, rehabilitation, mine closure issues affecting the mining industry.
Participant 6	Participant 6 has an environmental engineering background and holds a top managerial position in a large multinational mining company. Areas of expertise include environmental management and impact assessments, mine site rehabilitation and mine waste re-use.
Participant 7	Participant 7 is a director of an environmental consulting company and specialises in environmental pollution, mine wastewater treatment and tailings management, and environmental and social impact assessments.
Participant 8	Participant 8 works for a gold mining company working mostly on water management and is also a community liaison officer. Before joining the company, the participant worked for a NGO that aimed at creating awareness of mining risks and hazards to communities located closed to mines.
Participant 9	Participant 9 is an in-house legal practitioner working for a major environmental consultancy. Permission to record the interview was denied and so only scribbled notes from the interview are available.

Prior to the interviews, all participants were contacted by email requesting their participation in the study. Potential participants were provided with a brief project background and study objectives. This was then followed up by a telephonic conversation to provide more details,

answer any questions and to set up the interviews. A questionnaire was constructed in order to guide the interview process. The semi-structured nature of the interviews allowed for interaction and further questioning where necessary, and the questions were adapted where relevant in accordance with the interviewee's background and knowledge. It was imperative from the researcher's perspective that the questions probe the respondent's point of view without leading the interviewee towards predetermined answers. The set of questions used for the semi-structured interviews are provided in Appendix I.

All interviews were conducted face-to-face at each participant's preferred location and the period of each interview varied from between 45 and 90 minutes. All interviews, with the exception of the interview with stakeholder 9, were audio-recorded after permission was granted and later transcribed for purposes of accurate interpretation and quoting where applicable.

Each participant was assured about the anonymity. It was also pointed out to all participants that they could stop and withdraw from the interviews should they feel uncomfortable at any point in the interview. The participants were then given an informed consent form and asked to sign as an indication that they had understood the research objectives and also consented to being interviewed.

During the interviews, the researcher made notes of follow up questions and often asked the participants to clarify, elaborate and/or further explain the responses given. During the interviews, the researcher jotted down specific themes and made notes of key points being discussed for follow up questions and points of clarity. During the interview transcriptions, the researcher made note of recurring threads and these were captured in preliminary categories and themes as a means of interpreting the data. The transcripts were reviewed again to make sure that the data had been appropriately captured.

In order to protect the identities of the research participants, the transcripts have not been made available in the appendix as they contain confidential information which might reveal the identities of the participants. In addition, participants have been allocated numbers and are referred by that number in the results section of this dissertation.

3.3. Ethics

As the research made use of human participants as sources of data, an ethics review was carried out as per the requirements of the Engineering and Built Environment (EBE) faculty. This requirement ensures that the highest ethical standard is adhered to throughout the research process. Before the data collection commenced, the researcher submitted an ethics approval application to the EBE Ethics in Research Committee (EiRC). The EiRC granted approval for the research and the ethics form can be viewed in the Appendix II.

CHAPTER 4

RESULTS AND DISCUSSION: OPPORTUNITIES FOR GOLD TAILINGS REUSE

In recent years, utilization of mine waste has gained momentum and numerous studies have investigated the re-purposing of mine waste worldwide. This chapter addresses the first research objective by identifying and analyzing the various opportunities for reusing gold tailings and similar material in terms of their potential viability and feasibility. The information presented in this chapter is based on the literature review and interviews with various experts.

4.1 Bricks

In the last ten years, South Africa has seen a boom in the property development sector that has resulted in increased demand for construction materials. In addition, increasing population subsequently results in increased housing demand, thereby placing severe strain on the natural resources that are typically used as construction materials (Malatse and Ndlovu, 2015). The use of alternative raw materials offers massive opportunities for improving the sustainability of the brick making industry. As such, research has explored using alternative aggregates as input into brick making. This reduces the extraction of virgin materials thereby conserving clay, sand and shale resources used in brick. The use of mineral waste also has the added advantage of dealing with the associated environmental impacts of conventional tailings disposal (Shakir and Mohammed, 2013).

4.1.1 Overview of brick making

Conventional commercial bricks are produced from either ordinary Portland cement (OPC) concrete or clay which is fired in high-temperature kilns (Malatse & Ndlovu, 2015). The clay is typically mined in quarries resulting in adverse landscape alterations and high waste (Malatse & Ndlovu, 2015). Similarly, the production of cement is energy intensive and has a high carbon footprint. Research on the available technologies that have been used to produce bricks from mine waste include geo-polymerization, cementing and firing (Malatse & Ndlovu, 2015). Geo-

polymerization is a process in which solid aluminosilicates materials are dissolved in a concentrated alkali solution in order to form a stable inorganic polymer (Duxson et al., 2007; Zhang & Ahmari, 2014). Geo-polymerization “consist of 1) dissolving solid aluminosilicates in a highly concentrated alkali or silicate solution; 2) forming a silica-alumina oligomer as a gel followed by poly-condensation of the oligomer; 3) forming a stable inorganic material; 4) reorganization; and 5) forming a strong bond with any undissolved solid materials in the polymeric structure” (Kuranchie, 2015, pg. 96). The geo-polymerisation technology utilises industrial by-products including but not limited to kiln-dusts, slags and fly-ash (Klauber, Gräfe, & Power, 2009). Some of the advantages of geo-polymers over established ordinary Portland cement based concrete technology include excellent mechanical properties, an 80% reduction in overall CO₂ emissions intensity and superior capabilities of immobilising toxic metals (Klauber et al., 2009)

In the firing method, bricks are produced by mixing the virgin resources to form the bricks which are dried and the fired in high temperature kilns (Shakir & Mohammed, 2013). This technology has resulted in environmental contamination due to the high greenhouse gas emissions (GHG) which subsequently results in climatic variations, global warming, smog and acid rain and global warming (Shakir & Mohammed, 2013). In addition, the firing stage consumes a lot of the energy making is very expensive. Modifications to the conventional kiln-firing method have focused on the reduction of energy consumption and the environmental impacts of brick production through using waste materials to partially or entirely substitute the clay and follows the traditional method of kiln-firing (Malatse & Ndlovu, 2015; Shakir & Mohammed, 2013). Shakir and Mohammed (2013) reviewed published literature on the greenhouse gas emissions associated with bricks making. A Canadian study revealed that According to this investigation the energy consumption of the clay, sand lime and concrete bricks was approximately 6.5382, 1.16498 and 2.91483 GJ/tonne respectively (Shakir & Mohammed, 2013). The study also revealed that other pollutant gases were emitted and these included fluorine (0.7- 4ppm), hydrogen, sulphur dioxide (SO₂) and carbon dioxide (CO₂) (Shakir & Mohammed, 2013). Another study evaluated the energy consumption and associated GHG emissions of clay brick manufacture in the United States using fossil fuels. According to their findings indicate that fired clay bricks have an embodied energy of about 9.3MJ/brick and associated GHG emissions of around 0.6 kg of CO₂ per brick. Concrete bricks on the other hand emitted approximately 0.3kg of CO₂ per brick (Shakir & Mohammed, 2013). The

emissions include carbon monoxide (CO), nitrogen oxides (N₂O), and methane (CH₄) and carbon dioxide (CO₂) emissions. A Sudanese case study investigated the GHG emissions and the linkages between deforestation and the clay brick industry. The findings of the study indicated that the clay industry had annual emissions of approximately 378 028 tonne of CO₂, 15 554 tonne of CO, 1 778 tonne of CH₄, 442 tonne of NO_x, 288 tonne of NO and 12 tonne of N₂O (Shakir & Mohammed, 2013). In addition, the fired clay brick making industry resulted in the annual deforestation and loss of 508.4×10³ m³ of wood biomass, 267.6×10³ m³ round wood and 240.8×10³ m³ branches and small tree (Shakir & Mohammed, 2013).

4.1.2. Experimental studies of brick making using tailings

Different researchers have investigated the viability of brick making using tailings as a raw material. One such study, carried out in India by Roy et al. (2007), investigated the likelihood of making bricks from a mix of gold tailings and different additives which included Ordinary Portland Cement (OPC), black cotton soils and red soils. Depending on the additives used, the bricks were labelled as tailings bricks, cement–tailings bricks or soil–tailings bricks. All the brick samples were evaluated based on three parameters, namely compressive strength, linear shrinkage and water absorption. The mill tailings passed through a 300µm standard sieve and comprised of clay particles (33%), silt (17%) and sand (50%) (Roy et al., 2007). It was determined that the tailings did not require further processing but the tailings bricks could not be used for making bricks due to the absence of plasticity (Roy et al., 2007). The researchers also evaluated the soils' plasticity index and soil D was classified in the highly plastic category while soils A, C and D were categorized to be in the medium plastic grouping (Roy et al., 2007). As such, all the soils were suitable to be used as additives. The chemical properties of the mill tailings was also assessed and is presented in Table 5 below.

Table 5: Chemical compositions of the tailings used by Roy et al. (2007)

Constituents	Light coloured tailings (wt.%)	Dark coloured tailings Clay (wt.%)
SiO ₂	56.0	51.8
Al ₂ O ₃	11.9	8.2
Fe ₂ O ₃	10.2	18.9
CaO	8.4	7.6
MgO	8.6	6.3

Following the characterization, a batch of bricks were then produced which used cement as an additive and thus were termed cement–tailings bricks. These were made by mixing OPC with the tailings by weight in the quantities of 5%, 10%, 15%, 20% and 25%. For economic reasons, the proportion of cement was capped at 25% by weight. The cement-tailing bricks were cured in water for 3, 7, 14 and 21 day periods after which their resultant compressive strengths were ascertained (Roy et al., 2007). The researchers noted that increasing the percentage of cement and the curing times increased the compressive strength of the cement-tailings bricks. The cement-tailings bricks with 20% cement and cured for 14 days met the required compressive strength but were 2.4 times more expensive when compared to conventional bricks (Roy et al., 2007). The researchers then made soil tailings bricks in different proportions and using different soil types. The soil-tailings bricks were first dried at room temperature and then sun dried for 2 and 3 days respectively. After curing, the soil-tailings bricks were fired at differing temperatures then assessed for water absorption, compressive strength and linear shrinkage (Roy et al., 2007). The research findings revealed that bricks made with soils with a high clay content had minor cracks while the bricks made from soils with high silica content had no cracks. The economic analysis showed that the soil-tailings bricks cost between 0.72 to 0.85 times the cost of conventional bricks (Kunt et al., 2015). Roy et al. (2007) undertook a cost analysis study which also indicated that cement-tailings bricks are generally more expensive in comparison to the soil-tailings based bricks. As such, it was recommended that future test work should consider adding coarse particles from mining overburden as this would reduce costs.

Another investigation, conducted by Zhang and Ahmari (2014), investigated the viability of using copper mine tailings in the producing geo-polymer bricks. In their study, sodium hydroxide solution was used as an alkali activator and the bricks manufactured using different sodium hydroxide concentrations, water/solid ratios, forming pressure and curing temperatures. Their findings suggest that the tailings-brick geo-polymers had similar properties to those obtained using conventional cementitious binders such as OPC in terms of water absorption, shrinkage, density, compressive strength, thermal conductivity, fire and high acid resistance (Zhang and Ahmari, 2014). In addition to this, geo-polymers have significantly lower greenhouse gas emissions, excellent adherence to aggregates and are able to immobilize hazardous and toxic materials (Zhang and Ahmari, 2014).

Recently Kiventerä et al. (2016) investigated the geo-polymerization of sulphidic tailings from a gold mine in Northern Finland. In this study, an alkaline sodium hydroxide solution was used to activate the tailings and a co-binder, namely commercial ground granulated blast furnace slag, was added (Kiventerä et al., 2016). Different specimens with varying concentrations sodium hydroxide and varying quantities of co-binder were produced and tested for porosity and compressive strength. According to their findings, the specimens made from pure mine tailings had an unconfined compressive strength that ranged from 1.3 MPa to 3.5 MPa (Kiventerä et al., 2016). The addition of the co-binder increased the compressive strength of the specimens from 1.8 to 25 MPa. The alkali-activation of the tailings ensures the production of binders with adequate compressive strength which can be used as either backfill or as feedstock for construction materials (Kiventerä et al., 2016).

In South Africa, Malatse and Ndlovu (2015) evaluated the use of gold mining tailings from old mines in Johannesburg. The study explored the viability, from both a technical and economic point, of using gold mine tailings in making bricks (Malatse and Ndlovu, 2015). The gold mine tailings used for study had a particle size range of between 90 and 200 μm , with about 80% and 12% of the tailings passing the 200 μm screen aperture and 90 μm screen respectively. The tailings were found to portray similar chemical composition to clay material that is typically used in commercial brickmaking. Table 6 summarizes the chemical composition of the tailings used in the study.

Table 6: Chemical compositions of the tailings used by Malatse and Ndlovu (2015)

Constituents	Tailings (wt.%)
SiO ₂	77.7
Al ₂ O ₃	10.2
Fe ₂ O ₃	4.51
CaO	1.93
MgO	1.79
SO ₃	0.91
Na ₂ O	0.61
K ₂ O	1.19
TiO ₂	0.47
P ₂ O ₃	0.09
Cr ₂ O ₃	0.45

In addition, the tailings contained trace quantities of uranium oxide (0.0064%) which has safety implications and could pose a barrier to using gold tailings in brick making. The researchers made different samples of bricks from varying ratios of gold tailings from AngloGold Ashanti, water and cement as shown in the Table 7.

Table 7: Different mixtures used in Brickmaking (Malatse and Ndlovu, 2015).

Sample	Tailings (kg)	Cement (kg)	Water (L)
1	2	1	0.6
2	14	2	2.65
3	9	6	3.0
4	7	8	2.5
5	10	5	2.5
6	12	3	2.5
7	5	10	3.3
8	10	5	3

The bricks were cured by atmospheric sun drying, water curing for 24 hours, and oven drying at 360°C. The bricks were then tested to determine the compressive strength, water absorption rates and weight loss tests and the results compared to conventional commercial bricks, which were made from Ordinary Portland Cement (OPC) and clay and then fired in high-temperature kilns (Malatse and Ndlovu, 2015). All the brick samples were found to have a compressive strength lower than the value of 750 kN obtained for the conventional commercial bricks (Malatse and Ndlovu, 2015). The strongest tailings brick was found to have a compressive strength of 530 kN, which is below the standard South African specification for masonry bricks. The researchers also observed that the mixtures that were cured in water yielded a higher compressive strength, than those that were oven dried, which in turn was higher than that obtained by drying under ambient conditions (Malatse and Ndlovu, 2015). The researchers attributed this to using water for curing the bricks as this aids the cementation process, thereby increasing the bricks' compressive strength. In terms of economics, the tailings bricks were relatively more expensive than the commercial conventional bricks as they used more cement. The researchers recommended that more tests be conducted to identify the optimum tailings to cement ratio that would result in bricks that met the required compressive strengths. In addition, the researchers recommended adjusting the size of the tailings by adding overburden to the very fine tailings, and using additional additives that have higher plasticity and bonding

properties (Malatse and Ndlovu, 2015). A simple cost calculation for the mixture 7 which has the highest compressive strength indicates that the mixture requires 10 kg of cement and which costs R82 per 50kg of cement. This means that the bricks from mixture 7 would cost approximately 1.64 more than conventional bricks that does not require cement. This calculation, however, does not take account the cost of water or other materials. In line with the research findings of published data, at least eight of the respondents (participants 1, 2, 4, 5, 6, 7 and 9) mentioned brick making using tailings as a potential opportunity. All these respondents were aware of research studies that had been conducted worldwide on using tailings to make bricks and also mentioned South African case studies. Participant 2 mentioned that, while working for one of the top South African mineral research institutes, they investigated the feasibility of brick making from gold tailings using samples that were taken from different tailings dams within the Free State. The samples first underwent acid leaching to remove 85% of the uranium in the samples. After the leaching, brick specimens were made from tailings with different quantities of cement as an additive. From these bricks, the brick specimen that comprised of 65% cement and 35% fine tailings was the most competent brick when compared to conventional bricks in accordance with the South African Bureau of Standards (SABS) specifications for bricks. However, the cost of cement made this brick too expensive and this necessitated the need to explore other alternatives. Participant 2 stated that they then made alternative brick specimens containing a mix of clay, tailings and cement in varying quantities. Out of all the brick samples, the bricks that were made from clay and tailings (in a ratio of 1:1) and/or contained at least 50% clay with varying proportions of tailings and cement were found to be consistent with the SABS brick standards.

In general, most of studies on using tailings in brick making have been conducted on a laboratory scale and limited scaling up has been done. Zhang (2013) states that the limited commercialization of bricks from mining waste is “related to the methods for producing bricks from waste materials, the potential contamination from the waste materials used, the absence of relevant standards, and the slow acceptance of waste materials-based bricks by industry and public” (p. 643). In the media, a few cases of commercial brick making from tailings have been documented. One such case is of a brick manufacturing company that is located next to Lancaster Dam in Krugersdorp (Balch, 2015). The company reportedly makes bricks using tailings from the nearby tailings dump. However, this project received considerable bad

publicity, with environmental activists pushing to have the project shut down. This was mainly due to the fact that the tailings contained radioactive and toxic metals. Radiometric surveys done by the Department of Mineral Resources have revealed that the tailings had elevated levels of radioactivity (Balch, 2015). As such, the production of such bricks were seen by various environmental groups as inappropriate and risking the health and safety of both the brick manufacturers, but also the end users of the bricks (Balch, 2015). Another such case occurred in the West Rand where allegations were levelled against a brick manufacturing company operating within the area. The company was accused of using radioactive tailings to make bricks and for selling these bricks at a premium. However, interviews conducted by the IHRC (2016) with the Department of Environmental Affairs suggest that these allegations were not true. This is despite the fact that other sources and residents of Mindalore still contend that the production of bricks from radioactive tailings continues to be an ongoing practice (IHRC, 2016).

As part of the research, two Johannesburg companies that are said to use tailings in brick making were approached but both declined to participate. As such, no information could be obtained about the commercialisation of brickmaking from gold tailings in South Africa. Bricks were a well know opportunity highlighted by all the participants, however, the issue of radioactivity and financial viability were raised as potential problems that can be encountered. Participants 1, 5 and 7 emphasized that the tailings were radioactive and as such would need to go through pre-treatment to remove all contaminants before being reused. These participants also stated that reusing tailings in brick making was uneconomical and attributed this to the use of additives such as cement. According to the participants, the amount of additive required to ensure the bricks met the required compressive strength make it more expensive due to the cost of cement.

4.2 Ceramics

The production of ceramic bodies from gold mine tailings is a feasible option and numerous studies have been conducted to investigate this option. An exploratory research was carried out by Liu et al. (2015) in China and assessed the technical viability of utilising gold mine tailings as a clay substitute in the production of ceramic products. The composition of the tailings and clay is outlined in Table 8.

Table 8: Chemical compositions of the materials used by Liu et al. (2015)

Constituents	Tailings (wt.%)	Clay (wt.%)
SiO ₂	52.32	59.57
Al ₂ O ₃	13.00	30.73
Fe ₂ O ₃	7.80	3.22
CaO	9.96	0.68
SO ₃	2.91	0.23
Na ₂ O	2.46	0.63
K ₂ O	5.62	2.89
TiO ₂	0.71	1.56
P ₂ O ₅	0.26	0.06

The tailing's and clay particle diameters were found to be distributed within the range of 1 µm to 100 µm and 0.1 µm to 1000 µm respectively (Liu et al., 2015). Three different substrates, namely tailings (PW0), clay (PW5) and mixtures of clay and tailings in a mass ratio of 1:1, were mixed with clay and water at a ratio of 1:0.125, and then dried and sintered in an electric kiln at high temperatures ranging between 980 – 1020 °C (Liu et al., 2015). The research findings revealed that the PW5 (clay only based) and PW10 (tailings-clay based) products presented the basic characteristics of ceramic bodies; however, the PW0 (tailings only based) products did not. The researchers noted that when used together, the tailings and clay complement each other and the resulting ceramic products are rigid, ductile and can be shaped (Liu et al., 2015). Whilst the ceramic products made from tailings alone did not meet the required standard, the addition of clay improved the composition, particle gradation, and shaping property, generating mixtures that could be converted into ceramic tiles and household ceramics (Liu et al., 2015).

In Morocco, Yassine et al. (2016) explored the feasibility of using zinc tailings as an substitute material in the producing ceramic products. In the study, untreated and treated tailings were investigated. The treated tailings first underwent a flotation process to remove and recover lead

sulphide. Table 9 below shows the chemical composition of both the untreated and treated tailings.

Table 9: Chemical composition of tailings used by Yassine et al. (2016)

Constituents	Untreated tailings (wt. %)	Treated tailings (wt. %)
SiO ₂	12.2	13.4
Al ₂ O ₃	2.49	2.34
Fe ₂ O ₃	13.5	13.3
CaO	21.7	23.5
MgO	3.5	2.5
SO ₃	27.15	23.90
Na ₂ O	3.5	2.5
K ₂ O	3.5	2.5

In the study, both the treated and untreated tailings were then mixed with water to achieve a 14 % humidity by weight and then compressed in a hydraulic press. The samples were first air dried and then oven dried for 24 hours at 60°C and lastly were fired in an electric furnace at temperatures of between 950°C, and 1050°C. The products were tested to determine compressive strength, water absorption, porosity and bulk density. Despite their relatively low silica content, the findings suggested that both treated and untreated tailings could be used for making ceramic products. However, the samples produced from treated tailings had higher flexural strength and decreased water absorption and open porosity when compared to the samples produced from untreated tailings at high firing temperatures of 1050°C (Yassine et al., 2016). Leaching test results indicated arsenic (As), zinc (Zn) and lead (Pb) were mobilised after the firing process and as such present a safety risk in using the tailings to produce ceramic materials. However, the authors proposed that the addition of adsorbents such as magnetite on a zeolite and/or perlite matrix could potentially stabilize the metals, thereby reducing the risks associated with leaching (Yassine et al., 2016).

In the interviews conducted, participants 2 and 7 mentioned that while they were aware of the production of ceramics using gold tailings in the United States of America, they were not sure

if this opportunity had been explored within the South African context. Participant 2 stated that gold tailings typically contain silica which is required in ceramic production and that the technology was available and would work. However, the participant argued that there was no market for it and stated that there were abundant clay resources which are free and thus there was no incentive to using tailings especially when there is a possibility that the tailings can contain cyanide and uranium. Concurring with participant 2's thinking, participant 7 questioned why anyone would want to make ceramics from tailings when there were other non-contaminated raw materials that were also freely available. Participant 7 argued that the liability of using contaminated tailings (even if they were available) made no sense and did not think there was a viable market for it.

4.3 Cement additive

Globally, the development and application of alternative binders and the production of blended cements using either industrial by-products and/or mineral additives is gaining momentum (Sobolev, 2003). The use of tailings as a cement additive has numerous advantages such as lower carbon emissions, more thermal and chemical resistance and enhanced mechanical durability properties (Obonyo et al., 2011). Several studies have been done to investigate using additives, particularly fly ash, as an input into cement products. Most of these studies have been primarily focused on fly ash resulting in fly ash use in construction a common occurrence. Globally, limited research has been undertaken to evaluate the use of mine tailings, as cement additives, with no reported studies having been documented in South Africa. An investigation conducted by Çelik et al. (2006) in Turkey explored the feasibility of utilizing gold mine tailings as an additive material in the production of Ordinary Portland Cement. The additives tested in the study included two different samples of fly ash and silica fumes. The composition of the study materials are presented in

Table 10 below adapted from Çelik et al. (2006).

Table 10: Chemical composition and physical properties of materials used by Çelik et al. (2006)

Constituents (%)	Gold tailings	Silica fume	Fly ash (Soma Unit VI)	Fly ash (Seyitömer)	Clinker	Portland cement
SiO ₂	94.56	90.02	33.97	54.37	22.02	20.14
Al ₂ O ₃	1.67	–	19.53	19.46	5.9	5.79
Fe ₂ O ₃	1.87	0.3	4.53	11.17	3.61	3.34
CaO	0.39	0.33	32.27	4.64	65.1	65.8
MgO	0.27	2.36	1.48	5.58	1.21	0.84
SO ₃	0.09	0.85	4.95	1.15	0.24	2.69
Na ₂ O	0.31	0.29	0.61	0.74	0.23	0.43
K ₂ O	1.16	3.72	1.09	2.29	0.95	0.5
TiO ₂	0.11	0.64	0.8	0.8	–	–
P ₂ O ₅	–	–	0.185	0.075	–	–

Various mixtures were prepared using cement, tailings and additives in varying proportions. The mixtures were homogenized in a ball mill and different mortars produced from the blended mixture (450g), fine aggregate (1350g) and water (200ml). The compressive strength of the resulting mortars were tested after 2, 7, 28 and 56 days in accordance with the European Standard EN 196-1 (Çelik et al., 2006). The results indicated that up to 25% gold tailings within the clinker mix produced cement mortars of the required standard in terms of compressive strength. The addition of fly ash or silica fume improves the quality of the cement and results in mortars with a higher compressive strength values (Çelik et al., 2006). Based on their findings, the researchers concluded that gold tailings are a viable additive in the production of Ordinary Portland Cement.

Another study, conducted by Sobolev and Arikan (2002), explored making High Volume Mineral Additive (HVMA) cement. In their study, the HVMA cement is made from a mixture of Portland cement clinker, mineral additive, gypsum and a supersilica admixture (Sobolev, 2003). These materials are ground together in a ball mill and the resulting cement used for a range of concrete products. The mineral additives that were selected for the study and successfully applied in HVMA cement manufacturing included natural sand, pozzolanic materials, blast furnace slag, limestone, ceramic waste and fly ash (Sobolev and Arikan, 2002). Mortars were made and consisted of cement, sand and water (until a flow of 106-115 mm was achieved) and a sand to cement ratio of 1:1. The mortars were cured in a steam chamber at 80°C for 8 hours (Sobolev and Arikan, 2002). The study findings revealed that the optimum Supersilica content was 15% and this resulted in a high performance cement with a compressive strength of 135.4 MPa (Sobolev and Arikan, 2002). The findings also indicated that replacing the Portland cement component in the HVMA cement with the limestone, sand, fly ash and waste glass at optimal Supersilica results in increased compressive strength. The compressive strengths for the different mineral additives are shown in the Table 11 below adapted from Sobolev and Arikan (2002):

Table 11: Effect of different additives on compressive strength of HVMA - Cement adapted from Sobolev and Arikan (2002)

Mineral additive	Volume of mineral additive (%)	Compressive strength
Limestone	60	135.8 MPa
Sand	60	140.5 MPa
Fly ash	15	145.2 MPa
Waste glass	30	165.6 MPa

The additives increase the compressive strength of ordinary cement dramatically, while simultaneously dealing with the challenge of mineral waste (Sobolev and Arikan, 2002). Although their study did not include gold tailings, the researchers recognize the potential role of mine tailings to be used as an additive and thus suggests that tailings with high silica content

can be used to produce high strength eco-cement at a reduced cost and with low overall emissions, energy consumption and natural resource use (Sobolev, 2003).

No information could be obtained on using mine waste additives within South Africa and none of the respondents were aware of this opportunity except in the case of fly ash.

4.4 Backfill - Paste and thickened tailings

Worldwide, mine backfill is practiced in many modern mining operations and offers an alternative mine waste management method that results in reduced environmental impacts while also reducing mine waste volumes (Yilmaz, 2011). There are 3 main types of backfill commonly used and these are rock, hydraulic and paste fill (Yilmaz, 2011, Amaratunga and Yaschyshyn, 1997). Rock fills are made up of coarse aggregate and typically consists of blend of waste rock, sand, tailings and in some cases cement (Yilmaz, 2011, Amaratunga and Yaschyshyn, 1997). Rock fills are used largely to provide underground support and can be used with either a cemented filled slurry or in an un-cemented form (Yilmaz, 2011). The hydraulic fill consists of mixing appropriate-sized granular material (i.e. coarse tailings, grainy sand and binder) with water to produce a slurry mixture (Amaratunga and Yaschyshyn, 1997). The slurry mixture has a pulp density that ranges between 65 % and 75% solids by weight and the high water content ensures that the slurry can be easily transported and distributed underground by either gravity or pumping through boreholes and pipelines (Amaratunga and Yaschyshyn, 1997, Yilmaz, 2011). The use of coarse tailings improves the flow characteristics and strength of the hydraulic fill, and results in better consolidation of the hydraulic fill and thus consequent water drainage (Amaratunga and Yaschyshyn, 1997). The addition of the binder increases the strength properties of the hydraulic fill with high dosages resulting in higher strength (Amaratunga and Yaschyshyn, 1997). However, this has the disadvantage of being expensive due to the costs of binder.

Paste backfill has high solids content and a pulp density of between 75 to 85% solids weight for weight (Amaratunga and Yaschyshyn, 1997). It consists of dewatered mine tailings, a binding agent (commonly cement) and water mixed to the desired consistency (Edraki et al., 2014). Both fine and coarse tailings can be used for making paste fills and, in certain instances, large sized aggregates can be added. Paste fills that have comparative strengths to rock fills can be produced using less cement than hydraulic fills. In addition, paste fills have a reduced

porosity compared to hydraulic fills and as such water decantation from the fill is required (Amaratunga and Yaschyshyn, 1997).

A study conducted by Amaratunga and Yaschyshyn (1997) examined the use of gold tailings to produce a high modulus fill. The fine tailings were generated from a gold mine situated in Kirkland Lake, Ontario in Canada. In their study, paste fill specimens were made from agglomerated tailings pellets, unclassified tailings and binder. Different pellet to tailings ratios were investigated, namely 0:1; 1:2; 1:1 and 2:1. Binders at dosages of between 3 and 7% in varying Portland cement to fly ash ratio mixtures were investigated. Each sample was cured for 7, 14 and 28 days and then tested for different physical properties such as pulp density, slump, moisture content, elasticity, compressive strength, void ratio, bulk and apparent specific gravity (Amaratunga and Yaschyshyn, 1997). The researchers found that the poured density values for the different mixtures ranged from 1890 to 2115 kg/m³ and also observed that the pulp density increased as coarse aggregate tailings pellets were added to the mixtures (Amaratunga and Yaschyshyn, 1997). In terms of uniaxial compressive strength, all test samples had vertical cracks and the compressive strength increases as the binder dosage increased. The researchers found that the composition of the binder influenced strength development and the recommended binder combinations consisted of Portland cement and fly ash in a ratio of 80:20 and 60:40 (Amaratunga and Yaschyshyn, 1997). From the results, the researchers concluded that it was possible to produce agglomerated tailings paste with superior strength and stiffness characteristics that is suitable to be used as backfill material (Amaratunga and Yaschyshyn, 1997).

Another investigation was undertaken by Benzaazoua et al. (2008) and aimed at improving the management of gold tailings at Doyon mine in Québec, Canada. The study combined environmental desulphurization of the tailings with cemented paste backfill technology (CPB). The tailings first underwent desulphurization using a flotation process. The objective was to produce tailings with low sulphide concentrations and a sulphide concentrate which could then be used to produce cemented paste backfill. Froth flotation was used and the desulphurized tailings (about 85% of total tailings) were found to have less than 0.3 wt% sulphur. These were classified as non-acid generating based on a humidity cell test (Benzaazoua et al., 2008). Following this, various CPB mixtures were produced from the separated sulphide-lean tailings, the sulphide concentrate and a mixture of these two products in a ratio of 50:50 (Benzaazoua

et al., 2008). A binder consisting of approximately 30% Portland cement and 70% blast furnace slag was added in each case at a proportion of 5% by weight of total dry tailings. The samples were cured for 14, 28 and 90 days under controlled humidity and temperature conditions. After curing, the samples were assessed for uniaxial compressive strength and leachability (Benzaazoua et al., 2008). The study findings indicate that cemented paste backfills made from sulphide-rich concentrate had higher mechanical resistance. The uniaxial compressive strength values of 300, 400 and 500 kPa were observed for the CPB mixtures made of sulphide-lean tailings, 50:50 mix of sulphide-lean tailings and concentrate, and only desulphurized concentrate respectively (Benzaazoua et al., 2008). The researchers concluded that adding sulphide concentrate in the cemented paste backfill increases the mechanical strength of the cemented paste backfill and decreases the costs of the binding agent as lower cement quantities are required to make a cemented paste backfill of the same mechanical strength (Benzaazoua et al., 2008).

In South Africa, backfill is being utilized within the gold mining sector to alleviate problems such as rock falls and rock bursts in mines (Squelch, 1994). One such example where paste backfill is being used is at Harmony's Target Mine which is located about 270 km from Johannesburg. Previously the mine utilized a batching wetcrete underground system where the wetcrete material was made from a mix of conventional materials such as river sand, cement and chemical additives (Le Roux and du Plooy, 2007). Approximately 108 m³ of wetcrete material was required monthly which was then transported to the working areas of the mine. The long distances necessitated the need for an alternative wetcrete mix design that could be prepared on the surface and then pumped to the various working areas (Le Roux and du Plooy, 2007). The alternative was a surface batching plant that prepares a wetcrete mix from cyclone tailings, cement and additives. To investigate the feasibility of using the tailings as an alternative aggregate material to river sand, different mixes were created and tested to determine the most appropriate mix design (Le Roux and du Plooy, 2007). Five different types of fibre were then added to the mix design to establish the optimum composition that would attain the required strengths. The findings revealed that the samples has on average a uniaxial compressive strength of 38 MPa which exceeded the design criteria of 30 MPa (Le Roux and du Plooy, 2007).

Another South African example of backfill operations is at Gold Fields' South Deep Mine which commenced in 1993 when twin shafts of about 3km were sunk. Because of the location of the shafts, the main shaft pillar was mined out and had to be backfilled at a depth of 2.5km (Mining Weekly, 2012). The narrow tabular slopes required the use of a high strength backfill and a crushed waste/cyclone classified tailings (CW/CCT) backfill was utilized. However, high strength CW/CCT backfill proved too costly and financially unsustainable. This resulted in the use of a cyclone classified tailings (CCT) hydraulic backfill (Mining Weekly, 2012). The CCT hydraulic backfill was utilized mostly for the long-hole stopes and distress stopes (Gold Fields, 2012). As mining operations intensified, additional backfill was required and a cemented full plant tailings (FPT) backfill operation was commissioned. This was considered a more cost effective backfill production methodology for the mine and the product is used mainly for the backfill of general mining voids (Gold Fields, 2012). Tailings from the gold plant are stored temporarily in four storage tanks and then pumped to the backfill plant, with excess tailings diverted to the tailings dump. The plant was designed to produce approximately 148 000 m³ FPT backfill monthly. According to the Mining Review (2015), as of the June 2015, backfill production was approximately 80 000tpm and this is expected to increase with the conversion to hydraulic mining of surface tailings.

Four of the participants (namely 1,2, 7 and 8) noted that backfill is a viable opportunity and were aware of projects where backfill had been used in South Africa. According to participant 8, quite a number of mining companies in South Africa use tailings for backfilling to fill the void areas within the mines and for structural stability. Echoing these sentiments, participant 7 stated that backfill from gold tailings was feasible and helped to support the hanging wall underground. Participant 1 stated that it made sense to make backfill using tailings, saying it was one way of filling the massive voids underground, but cautioned that it might create a whole host of unintended environmental impacts which could have better been managed above ground. According to participant 1, there needs to be detailed analysis of the tailings to make sure that the tailings are benign and would not cause negative impacts before they can be used. The potential toxic nature of gold was flagged as a challenge but according to Participant 2, removing uranium, sulfide and other heavy metals can address that issue. Another participant, participant 1, noted that there was an issue with backfilling in terms of legislation. However, it must be noted that there are currently numerous projects making use of backfill and as such,

either this incident could have been an isolated incident or there is now an enhanced understanding of backfill, its advantages and disadvantages.

4.5 Stone paper

Stone paper first emerged in China when it became apparent that the present supply of fibers would not meet the paper demand in the emerging markets (Pauli, 2012). This, coupled with a massive supply of demolition construction waste and associated high removal costs, prompted the design of a new paper type (Pauli, 2012). The new paper type, referred to as stone paper or mineral paper, is a blend of crushed stones and/or tailings with polymers as a binding agent in a ratio of 80:20 by weight (Pauli, 2014b). The production of stone paper can be done in conjunction with extracting further amounts of gold and other materials such as sulphur, uranium and chrome (Pauli, 2014b). The use of tailings is more cost-effective compared to rock and is an opportunity to turn the liabilities of the mining industry into assets (Pauli, 2017). An economic study undertaken by the ZERI foundation indicates that the required investment costs for making stone paper is estimated at US\$150 million, which is 40% less than the costs of producing the same volume of paper in a conventional paper plant (Pauli, 2014a). In addition, stone paper is seen as a better alternative to the conventional pulp-based paper as it does not use water, does not require trees to be felled, and does not make use of chemicals such as chlorine, acids and/ or petroleum during its manufacture (Knopjes, 2015).

In South Africa, the City of Johannesburg is reportedly exploring the establishment of a stone paper factory (Knopjes, 2015). This factory will make use of tailings from the many tailings dams scattered across the city as well as rubble from illegal dump sites in making stone paper (Knopjes, 2015). Limited information is available in the public domain. Three of the interviewees (namely participants 1, 2 and 3) mentioned stone paper as a potential opportunity for gold tailings utilization. Participant 3 noted that he was aware of stone paper production projects planned within South Africa. According to the participant, there is currently a four-billion-dollar project underway in South Africa for making this stone paper (sometimes also referred to as rock paper). The participant stated that the paper is a much thicker and glossier type of paper and claimed that it was a better quality paper than paper made from wood. Participant 1 mentioned that stone paper was being explored in South Africa but was unable to provide further details on the project due to confidentiality reasons. According to participant

1, research was being undertaken by a top South African research institute but was also unable to give more information due to confidentiality reasons. The participant stated that stone paper is problematic and a cause of concern as it would not be easily recycled.

Further to this participant 1 noted that the inorganic waste material that is used as a filler during the production of stone paper jeopardizes the recycling of the end product at the end of its life. However, Pauli (2014b) argues that while stone paper is made of mineral sources and thus while it cannot be destroyed, it can be reconditioned and thus be used quasi-indefinitely, resulting in a higher material efficiency when compared to conventional paper. Pauli (2014b) further argues that stone paper from tailings reduces the risk for mining companies, lowers investment and operation costs of tailings facilities, creates jobs, generates cash income and frees up millions of hectares of land for food production and/or regeneration of biodiverse forests (Pauli, 2017).

4.6 Aggregate for road base and/or construction material

Mining and metallurgical waste has been utilized as aggregates for road construction and within the construction sector for making building materials (Yellishetty et al., 2008). According to six participants (participants 1, 2, 5, 6, 7 and 9) the use of tailings as a virgin aggregate replacement reduces the demand for natural aggregates and presents a practical solution in addressing the environmental liabilities of tailing dams. Participant 1 stated that the different types of waste streams including overburden, waste rock, slimes and tailings can be used as a replacement for natural virgin material that would otherwise be mined out of the ground. According to participant 1, this includes using the waste as backfill, making bricks and as basement material in road building. Several other opportunities where tailings can be used as a replacement for natural aggregate were identified by participants 2 and 6. These include using it for plaster sand, road construction, making concrete blocks, pavers, filling in foundations in the building and construction sector.

The use of tailings in making concrete blocks, paving material and in the construction of roads is seen as a more viable option than brick making in South Africa as these opportunities use little or no cement making it more economical. However, participant 1 argued that the volume of the tailings is so huge and only a small fraction of the tailings would be used as replacement

aggregate. In addition, all three participants stated that the potential contaminants in gold tailings is a challenge and as such tailings should be used with care to prevent long-term environmental problems from the contaminants.

4.7 Alternative uses of defunct gold tailings dumps

Over the past years, it has become increasingly apparent that mine land needs to be reusable post mine closure. Mining companies are under pressure to achieve environmental, social and economic sustainability and value-added land uses are key in delivering that (O'Neill, 2015). Globally, mine sites have been re-purposed for different uses such as manufacturing, industrial and residential redevelopments, industrial and heritage attractions and also used for tourism purposes (O'Neill, 2015). Other uses that were identified include using the sites as wildlife habitats, educational, leisure and sport facilities proving that the mining impacts of mining can be changed from liabilities to opportunities that are beneficial to local communities (Pearman, 2009).

In South Africa, very few of these initiatives are documented, although four of the interviewees (participants 1, 4, 7 and 8) indicated that defunct tailings facilities were being used for a number of (mostly informal and unregulated) activities, including agriculture, educational tours, recreation (quad biking, skate-boarding, off-roading), as well as photo and music video shoots. The various options are discussed in detail below:

4.7.1. Clean energy generation

Tailings storage facilities provide large, flat areas without significant vegetation that can be used for clean energy generation. Over the past years, research had been undertaken to determine the feasibility of using contaminated mine land, abandoned mine sites and tailings facilities to generate renewable energy. One such study was conducted at Sangdong mine in South Korea by Choi and Song (2016) and evaluated the photovoltaic (PV) potential of an abandoned mine tailings dam. The dam contained an estimated 4 million tons of mine tailings. The feasibility assessment consisted of field investigations to evaluate the surrounding topography and a regional shading analysis. The results showed that there was approximately 44 220 m² usable area for mounting a PV system with a design capacity of 3MW (Choi and Song, 2016). The design of the PV system took into account the spacing of the PV array,

specifications for the PV modules and inverters, onsite solar assessments. This was followed by a power generation simulation using site specific data such as hourly weather data, module and inverter characteristics. The simulation results indicated an annual electricity generation of 3509 MWh (Choi and Song, 2016). The study also assessed the economic feasibility and considered the income, costs and policies relating to renewable energy. The results indicated a net present value of 1.9 million US dollars over a 20 year period with a payback period of 11.5 years, and a 9.8% internal rate of return (Choi and Song, 2016). Based on the findings, it was recommended that a PV system with an installed capacity of 3 MW be installed on the tailings dam. This was deemed to be the most economically feasible option. In addition, installation of the PV systems promotes the redevelopment of a polluted abandoned mine site and creates new business models and jobs which could stimulate local economic growth (Choi and Song, 2016).

There are also reported cases globally where renewable energy generation is occurring at abandoned mines and tailings facilities. One such study was conducted in the United States of America and was a collaborative program between the National Renewable Energy Laboratory (NREL) and the Environmental Protection Agency (EPA) (Environmental Protection Agency, 2013). The project was titled “Re-Powering America’s Land program” and assessed the feasibility of generating solar, wind power, and hydroelectric systems on abandoned mine dumps and contaminated land (Environmental Protection Agency, 2013). As a consequence, renewable energy projects have been implementing and are operating across the United States. One such project is located on the Chevron Questa mine in New Mexico. The site includes two former molybdenum mines, a milling facility and tailing storage facility with a pipeline connecting the milling facility to the tailings dams (Environmental Protection Agency, 2013). The mine had operated sporadically from 1920 and consisted of open-pit mining operations. Over the years, the seepage and runoff from the tailings storage facilities resulted in ground water and soil contamination which necessitated a clean-up of the site (Environmental Protection Agency, 2013). As part of the clean-up activities, Chevron working with the EPA and other state agencies re-purposed the site into a solar field. The project which generates 1 megawatt of electricity (peak output) has a total of 173 solar panels and covers 21 acres. It is among the largest concentrating photovoltaic (CPV) systems in the United States and generates 80% of the community’s daytime power requirements (Environmental Protection Agency, 2013). The electricity produced is sold through a 20-year purchase agreement to a locally based energy cooperative (Environmental Protection Agency, 2013).

Other examples of renewable energy generation have been documented and include the Sullivan mine and Meuro mine in Canada and Germany respectively. There are also several large-scale wind farms in the United States of America including Somerset mine in Pennsylvania, Dave Johnston mine in Wyoming Buffalo Mountain mine in Tennessee the Zortman and Landusky gold mines in Montana (Choi and Song, 2016, Environmental Protection Agency, 2012).

In South Africa, no energy generation on abandoned mines and tailings facility has been recorded. However, participants 1, 2, 5 and 7 noted that generation of alternative renewable energies could be a viable option in South Africa, arguing that the existing energy infrastructure would make this a viable option. Participant 2 states that the tailings facilities offer vast spaces of land to erect solar panels and also mentioned that this could be used to supplement the cost of primary gold mining, especially in light of the declining gold reserves. In addition to this, participant 5 stated that tailings facilities are typically on mine land that has existing electricity infrastructure making it easy to feed in the renewable energy generated by the solar farms and/or wind farms into the grid. Echoing the sentiments of participant 5, participant 7 pointed out that old tailings facilities and abandoned mines can be used for generating energy and as such both solar and wind farms were a potential opportunity. Participant 7 argued that using old tailings dams and abandoned mines for generating energy as opposed to greenfield sites would leave arable land for other uses such as growing crops thus improving food security issues in South Africa.

4.7.2. Recreation, tourism and other alternative land uses

The use of defunct gold tailings dumps in South Africa for recreational use and other tourism related use often occurs on an informal basis due to the accessibility of defunct tailings dumps to the general public. According to participants 1, 4, 7 and 8, tailings facilities are being used for tourism and recreational purposes such as quad biking, skating facilities, off-roading, and shooting of music videos and photo. The participants also stated that other viable opportunities included turning the dumps into parks, agricultural land and educational tours respectively. According to participants 4,7 and 8, these opportunities had been trialed elsewhere with no documented uses in South Africa. In addition, cemeteries were mentioned as a viable land use by participants 1 and 7 with participant 1 arguing that we are currently short of areas to bury

people in South Africa. Other alternate land uses for the tailings dump mentioned by participant 7 includes turning the tailings facilities into either viable industrial land or residential land. According to participant 7, a different approach to laying foundations would need to be implored as the tailings are generally soft soils. This would have extra geotechnical costs but argued that the costs were minimal when considering the benefits that would arise from the use of tailings dumps. However, participants 1, 7 and 8 raised potential risks associated with such activities. The risks include mugging, tailings dam failures and exposure to toxic chemicals. According to participant 1, a couple of acquaintances who are photographers had been attacked, mugged and had their gear stolen while shooting on tailings dumps. The participant argued that while the use of tailings dumps for different land-use options was attractive, the potential of being mugged and robbed was a deterrent.

In addition, participant 7 and 8 acknowledged the risks from toxic material such as uranium, radon and arsenic but argued that the risks were minimal due to the limited exposure times. As such, both participants (neither of whom are health specialists) were of the opinion that there was very little to no health risks linked with the use of tailings facilities for recreation purposes. Participant 7 was of the opinion that someone would need to be exposed to the tailings for extended periods of time to suffer from arsenic and/or radon gas poisoning. The participant argued that the bigger risk to people using tailings facilities for recreational purposes was having tailings dams collapse under them or cave in. No evidence could be found to support these perceptions.

Further to this, participant 8 noted that the most concerning aspect was that often people from the surrounding communities used the tailings material as ‘cosmetics’ and sometimes eat the soils. According to the participant, some individuals from a community that is located near a gold mining area in the West of Johannesburg were reportedly smearing tailings slurry on to their faces and sometimes eating the tailings soils. Explaining these practices, participant 8 stated that the tailings slurry is used to treat acne, make skin lighter and is also believed to be an anti-aging treatment. The participant also stated that in some cases, pregnant women were eating the tailings-soil due to pregnancy related cravings and linked this to the tradition of eating soil to replenish iron in the body. According to participant 8, pregnant women believe that licking the tailings gives their body the necessary minerals required. Participant 8 stated that numerous workshops had been held at the specific mine to educate the community on the

risks of smearing tailings slurry and eating it and despite this community engagement, many of the women in the area were still using it especially as a skin lightening and acne treatment solution. Research by the IHRC (2016) revealed that residents (mostly women and children) of Tudor Shaft informal settlement often ate small blocks of the baked river sediments. These blocks are sold at the local shops contains tailings. The research also revealed that the locals have used the tailings to make traditional medicines and women specifically use the contaminated soil as a skin treatment (IHRC, 2016).

Other alternate in-situ uses mentioned included carbon sequestering and using the land to grow wood for firewood, crops and bamboo. However, it was noted by participant 7 that crops had associated risks and might not be suitable for human consumption and argued that firewood and bamboo were better options to minimize risk to humans as they are not suitable for human consumption. According to participant 4, bamboo can be used to remediate contaminated lands, specifically derelict mine land. Bamboo is a fast growing, versatile, drought-resistant and fire-resistant species that is well known for its capacity to purify contaminated water to potable water levels, and to regenerate water cycles and top soil (Pauli, 2012). It can be grown anywhere, performs well on poor and/or deficient soils and adapts easily to harsh conditions. Bamboo can be planted in sloppy land, arid land, windy areas and arid land. This makes it suitable for restoring degraded land. Another added benefit is that the bamboo covers the land which decreases the surface temperature and increases precipitation resulting in more rainfall (Pauli, 2012). Bamboo uses acid mine water for irrigation purposes and adsorbs unwanted heavy metals such as zinc, lead, iron and chrome.

The use of bamboo to rehabilitate derelict and ownerless asbestos mines has been tried in South Africa with relative success by Mintek which is a state-owned mineral processing and metallurgical research institute (Mothapo, 2017). Mintek researchers found that three bamboo types, namely *dendrocalamus asper*, *bambusa balcooa* and *phyllostachys edulis* are most suitable for rehabilitating the asbestos mine sites, as they can tolerate acidic soil types, increase pH levels and are able to survive harsh climatic conditions (Mothapo, 2017). Bamboo is also known to adsorb unwanted toxic substances such as mercury and uranium from soils, thereby reducing radioactivity levels. Besides the environmental benefits, cultivating bamboo on mine lands potentially provides a stable income for community producers, thus serving to uplift the

socio-economic conditions of communities living close to abandoned mines which undertake bamboo plantation (Mothapo, 2017).

4.8. Summary

This chapter has identified different reuse opportunities for gold tailings from both a review of literature review and interviews with expert stakeholders. These uses have been documented by different researchers across the world and also in South Africa. The major uses for tailings involves using tailings as a substitute for virgin material (i.e. clay, sand or aggregate) in making bricks, cement additive, backfill, construction materials, ceramics and stone paper. The study also identified opportunities for using tailings dumps for a range of uses including generating clean energy, for recreation purposes and agricultural purposes.

CHAPTER 5

RESULTS AND DISCUSSION: ANALYSIS OF FACTORS INFLUENCING THE REUSE OF GOLD MINE TAILINGS

The findings presented in the previous chapter suggest that reuse of gold tailings is possible and identified numerous reuse opportunities. It further articulated the numerous benefits of reusing tailings in the different applications, and these include replacing the use and quarrying of virgin material, freeing up land occupied by tailings, optimizing effective utilization of mined mineral resources (all consistent with the principles of resource efficiency) and preventing long-term and inter-generational impacts on the environment and local communities due to exposure to contaminated leachate and dust emissions. However, there are numerous factors influencing the viability and feasibility of options for the re-use of tailings. A review of the literature and interviews with stakeholders has indicated that these can be broadly defined as tailings' chemical properties, technology, corporate culture, economics and the legislation regulating the mine industry. These factors either hinder or facilitate the reuse of gold tailings.

This chapter explores the different factors that influence the uptake of the identified reuse options and aims to obtain a better understanding of these factors that both constrain and drive the development and implementation of approaches that eliminate the disposal of bulk mine waste and associated liabilities through re-allocating the waste as a resource for other uses. The information presented in this chapter is drawn from both a review of literature and interviews conducted.

5.1 Tailings properties

Mine waste and tailings in particular have different physical and chemical properties. These properties determine if the tailings are suitable to be used as feedstock for different applications, and also give rise to specific health and environmental risks during processing

and/or utilization. As such, before it can be reused effectively, it is imperative that the mine waste is comprehensively characterised prior to utilisation.

Numerous studies have assessed the physico-chemical characteristics of the tailings in the Witwatersrand gold tailings dams (Naicker et al., 2003, Rosner, 1999, Nengovhela et al., 2006). A study conducted by Rosner (1999) evaluated tailings samples obtained from five gold tailings dams across the Witwatersrand and the concentrations of the major elements found in the tailings samples are presented in Table 12.

Table 12: Major elements of the tailings samples adapted from Rosner (1999)

Constituents	Tailings 1 (wt.%)	Tailings 2 (wt.%)	Tailings 3 (wt.%)	Tailings 4 (wt.%)	Tailings 5 (wt.%)
SiO ₂	80.44	84.14	82.33	83.44	77.63
Al ₂ O ₃	8.24	6.33	8.05	5.68	9.77
Fe ₂ O ₃	3.66	3.23	3.65	3.66	3.60
CaO	0.28	0.55	0.12	0.43	0.20
MgO	0.94	0.77	0.6	0.29	0.60
SO ₃	0.1	0.12	0.02	0.08	0.06
Na ₂ O	0.15	0.21	0.19	0.17	0.22
K ₂ O	1.91	1.34	1.95	1.1	2.70
TiO ₂	0.49	0.48	0.47	0.27	0.60
P ₂ O ₅	0.03	0.04	0.04	0.03	0.03

Nengovhela et al. (2006) reported that the Witwatersrand tailings dams were acidic with a pH range of between 2.52 and 4.11. The composition of the tailings include quartz, pyrophyllite, chloritoid, mica, chlorite, jarosite, pyrite, gypsum, and clay minerals (Nengovhela et al., 2006). Similar compositions were obtained in research conducted by Naicker et al. (2003) which indicate that the Witwatersrand conglomerates comprise of quartz pebbles set in a matrix of quartz sand. The quartz pebbles have a diameter of between 1 and 3 cm. The matrix contains gold, pyrite (approximately 3%) and lesser amounts of various sulphide and oxide minerals

(Naicker et al., 2003). A more recent investigation conducted by MINTEK sought to characterise and assess the variability of samples obtained from twelve tailings dumps located in the East Rand, Central Gauteng, West Rand and Free State (Janse van Rensburg, 2016). The X-ray Diffraction (XRD) results indicate that the samples from the Witwatersrand gold basin had similar mineralogical properties shown in the Table 13.

Table 13: Mineralogical composition of the gold tailings used by Janse van Rensburg (2016)

Mineral	Chemical formula	Abundance of mineral %			
		East Rand	Central Gauteng	West Rand	Free State
Quartz	SiO ₂	81.0	76.4	71.8	70.7
Pyrophyllite	Al ₂ Si ₄ O ₁₀ (OH) ₂	12.2	13.7	14.7	16.2
Serpentine	Fe ₂₋₃ Si ₂ O ₅ (OH) ₄	0.9	-	2.2	0.6
Mica	KAl ₂ (Si ₃ Al)O ₁₀ (OH,F) ₂	4.6	3.8	5.9	9.9
Gypsum	CaSO ₄ •2H ₂ O	1.3	0.9	1.4	2.6
Aluminite	Al ₂ (SO ₄)(OH) ₄ •7(H ₂ O)	-	5.3	4.1	-

From the research studies, it seems that there is little variation in terms of their physico-chemical characteristics of the Witwatersrand gold tailings. The composition is constrained within a reasonably narrow compositional range (Abegunde, 2014). Pyrite, which is another constant constituent throughout all the dams, is a sulphide and major contributing factor to the generation of AMD (Abegunde, 2014). The generation of AMD can have multiple environmental consequences and undesirable implications for ecosystems such as contamination of water bodies, disruption of growth and reproduction of aquatic plants and animals as articulated in Section 2.3.2 (Nengovhela et al., 2006).

The gold tailings' composition presented in Table 13 indicates that the tailings are made up mainly of quartz with smaller amounts of clay and/or clay-like minerals such as phyllosilicates and serpentine. This confirms that the tailings have the potential to be used as substitutes (at

least partially) for clays and aggregates in some of the identified applications in Chapter 4. In addition, a comparison of chemical compositions indicates that the Witwatersrand gold tailings tend to have a higher Si content, and slightly lower Al, Ca and K concentration than most of the tailings indicated in the literature, possibly indicative of a higher quartz and lower clay mineral content. However, this would require further investigation.

Apart from major constituents such as quartz and silicates, the mine waste needs to be of an appropriate particle size and not contain high levels of impurities, contaminants and or toxic metals. To ensure the mineral waste is suitable, crushing and sizing prior to re-use may be necessary and often the tailings need to undergo pre-treatment to remove impurities (Godfrey et al., 2007). It is also important that the mine waste be compatible with the other materials as well as it complies with the relevant standards and specifications in the making of the end-product.

As indicated in Chapter 4, the issue of impurities was identified in the interviews by all the research participants. These participants stated that the perceived toxic and radioactive nature of tailings is a barrier and major constraint to reusing gold tailings in South Africa, particularly in the case of bricks, ceramics, backfill, aggregates. The use of tailings for recreation also posed a safety risk and potential health risk due to dermal contact. According to the participants, contaminants and heavy metals such as cyanide, mercury, uranium, arsenic, radon, lead and zinc pose a significant barrier to the effective utilization of gold tailings. As such, participant 6 argues that the geochemistry of tailings need to be considered and determined first to assess the feasibility of reusing tailings. According to participant 6, tailings from the Witwatersrand basin are typically radioactive and acid forming and argues that this is a major constraint to reuse. However, participants also pointed out that, in most cases health and environmental impacts could be avoided by removing impurities, such as uranium, sulphide and other metals, prior to converting the tailings into useful products.

5.2 Economics and markets

The research findings both from literature and by the research participants indicate that economics is both an enabler and impediment to the uptake of reuse options (Godfrey et al., 2007).

On one hand, many of the participants considered economics as a barrier to the uptake of reuse options. This was due to the fact that reuse options are considered financially non-viable on the basis of conventional financial indicators such as IRR, due to both the high direct costs entailed and the relatively low value of the products generated. Two of the interviewees (participants 1 & 6) emphasised (in the extracts below) that the uptake of the reuse options would only occur if it is deemed to be financially viable and/or there were economic incentives. This is compatible with the findings of Godfrey et al. (2007), which show that the potential is constrained and argue that reuse options will only be fully recognized if alternative waste management and treatment methods become more financially viable when compared to the conventional tailings dam disposal. Participant 1 highlighted that the costs associated with processing and transporting tailings was a hindrance to the uptake of mine waste reuse. This combined with the relatively low cost of virgin material locally provides little economic incentive. This thinking is consistent with Gericke (2014) who raised the issue that virgin aggregate is available at very low and/or no cost and thus renders the reuse of tailings uneconomic and provides no further incentives to reuse tailings accordingly (Gericke, 2014). Other direct costs associated with the use of tailings include the costs of required additives to amend the properties of the tailings, particularly in brick making, and the costs of additional treatment for removing deleterious contaminants. For example, a 50kg bag of cement costs about R82 which if required in large quantities pushes the costs up. Participant 1 stated that brick making using mine waste and tailings in particular had been explored for the past twenty years

Economics can, however, also serve as a driver and incentive for mine waste reuse. Pajunen et al. (2012) documented numerous effective drivers to improve waste reuse and these include the use of voluntary economic and market-based instruments, like taxes, competition for market share and environmental management systems and reporting. In addition, the escalating costs of complying with increasingly stringent legislation, particularly in terms of the land disposal of large-volume wastes, has the potential to provide financial incentives for companies to explore alternative uses (Godfrey et al., 2007). The provision of financial incentives was also identified by participants 1 and 6 as a driver to promote reuse options of gold tailing. According to participant 1, economics and incentives have a much greater opportunity to drive behavioural change when it comes to waste management than through legislation. The participant argues that South Africa's environmental legislation is among the best worldwide

and yet the state of the environment does not reflect it because of bad enforcement and implementation of legislation. As such, participant 1 states that there is no point of writing more legislation but the focus should rather be to ‘hang that carrot up’ for mining companies and give them economic incentives such as tax rebate as this is more likely to get them to do something.

However, Participant 1 also argued that there was currently no economic instrument to incentivise reusing gold tailings: “*Look, at the moment in South Africa we don’t have economic incentives or disincentives for waste management*” (Participant 1). According to this participant, the national pricing strategy is the only government document that looks at the potential suite of economic instruments that one could apply, both at the incentive and disincentive side. The participant stated that a virgin aggregate tax could be a potential incentive to support mining waste for use, but this has not been implemented yet in South Africa. This, coupled with the high demand for alternative aggregates, especially within the construction industry, is a potential enabler that can positively influence the uptake of mine waste reuse. Further to this, the reuse of mine waste frees up land, which can then be used for other uses resulting in different economic activities and the alternative uses of waste materials can also contribute to economic development and job creation (Godfrey et al., 2007). Taking these indirect benefits into account could assist in building a more economically robust business case for mine waste reuse.

Participants 1,5,7 and 8 also raised the issue of markets and stated that there were more tailings than there were marketable uses for it. Participants 5 and 7 stated that the amount of tailings that can be utilised for making bricks is relatively small, and that the local brickmaking industry will not be sufficiently large to consume all the gold tailings from historical and current operations. To elaborate this point, participant 5 used an example of an operation that produces approximately two million tons of tailings a month and stated that you could not possibly make that many bricks.

The issue of markets and economics needs to be explored further to determine market size and also explore how to create the business case for using tailings as a feedstock so as to influence the uptake of these opportunities. Currently there is insufficient process data to support a more comprehensive economic feasibility study and market survey.

5.3 Legislation

An in-depth review of literature on the legislation governing mineral waste, indicates that South Africa has robust legislation, policies and strategies which are on par with international legislation. From the interviews, participants 1 and 2 echoed the findings of the literature review, stating that South Africa has very well defined and good legislation. However, both participants noted that the implementation of the law and its subsequent enforcement was problematic. According to these participants, the main reason for the non-implementation and enforcement of legislation arises from the fact that there are multiple government entities mandated to act on mining related activities (IHRC, 2016). For instance, there are three main government entities that are key players in the mining industry. These are namely the Department of Mineral Resources, Department of Water and Sanitation and Department of Environmental Affairs. Each department has a distinct mandate with different goals and this can lead to conflicting priorities and different approaches of tackling the problems that arise from mining activities. In addition, the roles and responsibilities of each department overlap and sometimes conflict. According to Liefferink (2016), power delegation between the different departments and spheres of government is unclear. At national level, these government departments are tasked with administering policies, however, the enforcement occurs at both the provincial and municipal levels which further complicates the implementation and enforcement of legislation. Attesting to the complexities with legislation, participant 1 stated that “*the legislation is split across very different sectors from agricultural legislation to consumer goods legislation to environmental legislation to, you know, transportation legislation*”. According to participant 1, the different amendments to NEMA and NEMWA make it difficult for individuals that are not legal experts to stay up to date with the latest compliance requirements.

In addition, dealing with mining waste and tailings in particular often triggers multiple legislation acts. For instance, tailings might contain elevated levels of radioactive material such as uranium which then requires the National Nuclear Regulator to act. This can result in the tailings dump being classified as a ‘nuclear installation’ subject to the National Nuclear Regulator Act, (Act 47 of 1999) provisions. In addition to the radioactive material, the dust from the tailings dumps can exceed the air quality limits stipulated in the National Environmental Management: Air Quality Act, 2004 (Act 39 of 2004). The dust has a further

knock-on effect on the Department of Human Settlements (DHS) who are mandated to “create sustainable human settlements and improve the quality of household life” (IHRC, 2016, p.107). The involvement of multiple government agencies on a single site might result in the different mandates competing if there is no consistency within the regulations. An effect of the numerous regulators is that it results in confusion and becomes difficult to know the appropriate procedures to follow and which department to engage. Participant 7 echoed these sentiments and stated that the legislation is too complicated and involves too many different departments making it very difficult to know which departments to engage with and demonstrate compliance to. According to participant 7, it is for this reason that their organization has opted to invest and undertake certain projects in other countries than deal with the South African legislation which he terms a ‘mess’. This is aggravated by the fact that there is a lack of interdepartmental coordination between the several government institutions involved which further compounds the issue. Liefferink (2016) pointed out that there seems to be very little or no vertical and horizontal co-operation between the different institutions with some institutions operating in isolation. Liefferink (2016) uses an example of the radiotoxicity and chemical toxicity of uranium occurring in the Witwatersrand. According to (Liefferink, 2016), there has been little cooperation between the government arms which regulate radioactivity and chemical contamination. Instead of taking an integrated approach to solving the uranium challenges, the Department of Health has not been involved with assessing and mitigation the risks associated with uranium and the National Nuclear Regulator has had limited success in implementing the remediation of radioactive areas (Liefferink, 2016). Adler et al. (2007) argues that conflicts and the absence of coordination between the departments is further magnified by the high staff turnover in government as well as the shortage of governmental officials tasked with enforcing the relevant policies.

To address some of these complexities, the South African government implemented the ‘One Environmental System’ in December 2014 (see review in Chapter 2). Since the launch of the new system, there have been mixed feelings regarding its success. From the interviews, participants 1,3, 7 and 8 believed that the new system would be beneficial in bringing about regulatory clarity and synchronising timelines for environmental authorisations thereby avoiding unnecessary delays. However, in the media, some environmental advocacy groups and civil society groups that represent mining affected communities have raised concerns about the One Environmental System (Mpinga, 2017). The groups argue that the DMR’s main

mandate is to promote mineral resource exploitation and as such there is a conflict of interest in entrusting the environmental oversight function to the DMR (Mpinga, 2017). Further to this, these groups argue that the DMR lacks the necessary expertise and political will to enforce compliance which can compromise the environmental management of mining related activities (Mpinga, 2017,). Other contentious issues that have been raised regarding the One Environment System include the finalising of the MPRD Amendment Bill; the role of provincial government with respect to mining issues and the DMR's inadequate capacity to deal with the mining regulatory issues (Mapulane, 2017). There is no clear indication as yet from both a review of literature and the interviews to determine if the One Environmental System has been successful in addressing some of the legal complexities discussed in this section.

Another challenge that emerged from both the literature and the interviews as a legislative barrier to the utilisation of mine waste is the frequency of legislative changes. Participant 1 likens trying to understand the changes and keep to up to date with the latest legislation as *'tap dancing through a minefield'*. Over the years, there has been some restructuring of environmental management and mining related legislation and this has led to the regulations being revised and has shifted the roles and responsibilities of the different governmental institutes (IHRC, 2016). While the changes have been deemed necessary, the frequency interferes with the implementation and effective enforcement of these regulations especially in the area of environmental remediation (IHRC, 2016). This is largely due to the fact that the changes are often substantial and require upskilling and training for the various departments which requires time and money. The frequency of legislative changes means that revisions are released as amendments to the original act. The amendments have created uncertainty resulting in confusion among different stakeholders and compounded the administrative problems in the various departments (IHRC, 2016). According to participants 1 and 2, the frequency of the changes results in different pieces of legislation that are at different phases, some are gazetted, promulgated or out for public comment and argues that this results in uncertainties on compliance requirements. This aggravates uncertainties and confusion over what regulations are in draft and what are in effect. Participant 1 further states that there is potential danger for a company to get into trouble as there is a higher risk of being non-compliant as the legislation due to the ever-changing legislation. In addition, the uncertainties in the compliance

requirements were perceived as a potential risk by participant 2 as it makes the industry reluctant to invest in alternative or innovative approaches to waste.

Lastly, the waste classifications in the new waste act were noted by participants 1 and 8 as problematic and a potential barrier to mine waste reuse. According to the two participants, the classification of tailings is prohibiting the uptake of reuse options as it applies a blanket rule for normal, industrial, municipal and mining waste and requires that all tailings dumps are to be lined. Explaining this, participant 7 states that under the current legislation (i.e. Waste Act), mine waste is classified as waste and is required to undergo a classification and characterisation process. The process categorises it as one (hazardous), two, three or four (inert). According to participant 7, each type of class requires a certain standard of facility lining and approximately 90% of gold tailings in South Africa would be classified as a type three waste, and as such tailings dumps would require a basal geo-membrane lining to be legally compliant. The problem with this prescriptive approach, as articulated by participant 7, is that the lining does not take into account the lifespan of a tailings dam. According to the participant, over time, the lining gets broken down releasing any acid that will have formed. Echoing the same sentiments as participant 7, participant 8 argued that the various waste streams should be treated differently with less prescriptive measures. Further to this, participant 8 argues that by being prescriptive, the regulations hinder innovative approaches to tailings management and offer no incentive to develop alternative options to conventional tailings facilities disposal, mostly because of the costs associated with lining tailings dams. Both participant 7 and 8 questioned the effectiveness of the current prescribed solution relative to the problem and stated that lining the tailings dams just prolongs the problems without actually dealing with it. The sentiments of participants 7 and 8 are consistent with some law articles in the public domain. According to Becker (2015), disposing of mineral waste in the prescribed tailings facilities type design is problematic as it does not take into consideration the specific properties of that exact waste. Furthermore, Becker (2015) states that the use of geosynthetic material which is made mostly from plastic-based materials is not appropriate for mineral waste which can reach high temperatures and would specifically not work for coal discard dumps which are prone to spontaneous combustion. In addition, the weight of waste rock and tailings is likely to lead to linear failure thereby compromising the longevity of the tailings dumps designs.

5.4 Technology development

Over the years, studies have been conducted to test out the various technologies available for waste valorization on the market. In South Africa, technological advancements have resulted in the recovery of gold (and other minerals) from both low-grade ores and waste tailings (Gericke, 2014). Other technologies have been tried and have resulted in different products being made from tailings. These products include (but are not limited to) bricks, ceramics, cement additives and backfill. The technologies used to make the products seem to be well developed and in most of these applications, this includes simply replacing virgin material with tailings. However, the testing and demonstration of these technologies for the specific case of gold tailings is relatively limited. In most instances, the testing of these technologies has largely been done at laboratory scale and very few have been demonstrated at a larger commercial scale. As a result, the technology is not fully tried and tested and often is considered as “unproven” which further acts as a stumbling block. (Gericke, 2014). Pajunen et al. (2012) argue that the scale up to commercial applications is hindered by the fact that technologies often have to mature (which often takes years) to become industry standards or techniques. As a result, some technologies are seldom developed and/or implemented on operating sites as this requires massive investments. Further to this, Pajunen et al. (2012) state that the time required for technological innovations is normally not in line with the availability of capital investment. As a result, there are substantial delays in influencing technology changes resulting in most organizations being locked in to the current available technologies. In addition to the massive investment costs and time lags, another barrier results from the high risk and uncertainty associated with committing capital to unproven technology (Pajunen et al., 2013). This is consistent with the findings by Gericke (2014) that indicate that the lack of adequate funding for the scale-up of the options as well as lack of other necessary resources (human capital, skilled personnel, time) needed for technology transfer and implementation is a big hindering factor within South Africa (Gericke, 2014).

Generally, new technology is characterized by a degree of uncertainty and there is a risk that unproven technology may not perform to the required standard and specifications and/or be compatible to current technologies (Johnston, 2012). Uncertainties and risks associated with unproven technology have been identified as a key technological barrier to mine waste utilization (Pajunen et al., 2012). In addition, the mining industry is not always a conducive

environment for adopting research and development within the waste management sphere. This is due to a number of reasons, one being that mining companies often do not have advanced research and development departments or the technical expertise in-house to focus on technology development (Pajunen et al., 2012). Another factor which attributes to this is that sometimes, different teams within an organization have opposing mandates which then affects the uptake of new methodologies.

Lastly, an aversion to technological change and innovation within corporates is another possible hindrance to the uptake of some of these technological improvements (Bastein et al., 2014). This aversion is linked to the corporate culture, values and behaviours which is discussed in the next section and results from a lack of information on available technologies, the use of inappropriate technology, lack of available financial budgets for research and development and not having the having the appropriate expertise within the organization (Bastein et al., 2014).

5.5 Corporate culture and values

Globally, the mining industry is under tremendous pressure to improve its environmental, social, and developmental performance. Mining companies like other corporate companies are expected to perform to ever higher standards of behaviour that goes well beyond achieving the best economic rate of return for shareholders (Pauli, 2012, Pajunen, 2015). Significant demands and expectations from different stakeholder groups across the value chain, global disruptions and transformations towards a more sustainable and equitable future are factors that are challenging the traditional way of doing business. As a result, a culture of innovation is emerging and progressive mining companies are shifting from a business-as-usual way of doing things (Pauli, 2012, Pajunen, 2015). Progressive mining companies are realizing the distinct disadvantages of sticking to business-as-usual and are proactively preparing and adapting to a transforming business environment. The successful transition is heavily reliant on the organizational culture, leadership and how mining companies see themselves. Pauli (2012) argues that successfully transforming the business environment requires mining companies to focus on more than just the core business of extracting minerals from the ground. This requires a shift in management culture that enables mining companies to focus and identify the interconnections that exist beyond the core business of mining (Pauli, 2010). This,

according to participant 3, can be achieved if mining companies are able to determine the core competencies and skills within the organization and see the potential linkages with other sectors. According to participant 3, shifting from looking at the business as one product to looking at the business through a competency lens opens up many opportunities and ventures which a company would not originally consider. However, this is only possible if strategic partnerships are formed with key stakeholders and cooperatives who have similar interests, new set of capabilities and skillsets.

Corporate culture, leadership and overall company strategy influence how companies are run, the way tailings are classified, the uptake of waste reuse options, and the adoption of new technologies within the organization (Pauli, 2012, Pajunen, 2015). Depending on the company, the culture can be a barrier or an incentive and this comes down to how companies see themselves as an organization and how they view tailings. Participant 3 argued that there is also need for a mind-set change within mining organisations so that tailings and other mine waste can be seen as assets and not liabilities. According to participant 3, organizations who viewed tailings as an asset are more willing to explore reuse options and drive innovative solutions for dealing with waste; whereas organizations that view tailings as a liability or waste are often averse to the different waste reuse opportunities and likely to opt for conventional tailings disposal. Similarly, the findings from literature suggest that identifying tailings as an asset changes the norms of waste management and can potentially lead to the expansion and diversification of the mining industry's range of products resulting in economy diversification, job creation and fostering innovation in the industry (Pauli, 2012).

The mindset change articulated by participant 3 is necessary if businesses are to create entrepreneurial linkages and strategic partnerships with organizations that are likely to utilize the mine waste. Working with different partners and service providers is a practice that is already embedded in current business models. As such, forming strategic partnerships is not a foreign concept and can be easily implemented to address the challenges faced by mining companies in regard to waste. To demonstrate this, participant 3 gives one example of such strategic partnerships and says that a mining company can, as a way of dealing with the contaminants on a tailings dam, decide to grow bamboo which would help with removing contaminants in the dam that (if left) can potentially generate acid mine drainage. However, the company does not necessarily have all the technical skills in-house to effectively grow the

bamboo. In a case like that, the mining company can approach an entrepreneur or bamboo expert to set up a bamboo plantation on the dams. This would effectively empower the entrepreneur, create jobs for the surrounding community and help the mining company deal with the tailings issue. There are various linkages that can also arise from this scenario. The purified water can also be reused by the mining company thereby adding to their water supply. This new way of doing business looks at the operations holistically and determined the type of partners and partnership models that will create shared value for all (Participant 3).

Further to this, participant 2 stated that waste management strategies are normally part of the overall corporate strategy and as such are closely linked with the research and innovation strategies of an organization. This participant argues that these strategies are often confidential and as a result some organizations might not be willing to share any information related to the technologies in use and other alternate innovative mine waste management approaches. According to participant 2, many companies are not willing to share their trade secrets which significantly hinders the spread of innovative technologies and the uptake of alternative waste reuse options. The participant argues that there is need for more transparency and sharing of information within the industry. In line with this, Gericke (2014) states that there is need to develop collaborative efforts and partnerships between government, mining industry, academia and research institutes so that information on different waste technology development is shared and to ensure the technologies are affordable and accessible to the market (Gericke, 2014).

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

Gold tailings facilities are a major pollution concern in South Africa and pose significant, and often irreversible, impacts on the environment. These impacts include land and soil degradation, pollution of water sources, dust pollution and loss of biodiversity. These impacts, in turn, affect the health, quality of life and sometimes even the livelihoods of local communities. The facilities also represent a loss of mineral resources.

To address these potential long-term risks, alternate management approaches to the conventional land disposal are required. One such alternate approach involves re-allocating gold tailings as feedstock for other uses. This minimises the waste burden while maximising the efficient use of mined materials, which is consistent with the principles of resource efficiency and the circular economy. This thesis has identified (i) possible opportunities for reusing gold tailings in South Africa and (ii) the various factors that either enable and/or hinder the reuse of gold tailings in South Africa. This was done through an extensive literature review and interviews with various experts.

This chapter outlines the key findings and makes recommendations for further work.

6.1. Summary of key research findings

6.1.1. Identification of potential reuse applications

The research findings from both a review of published literature and interviews with selected experts identified potential in both ex-situ applications for gold tailings and in-situ applications for gold tailings facilities. The ex-situ reuse opportunities for current or defunct mine waste, such as gold tailings, mainly entails the replacement of virgin clay and sand in the production of cement backfill, brickmaking, cement additive, construction materials, ceramics and stone paper. Further to this, numerous

opportunities for utilizing mine tailings facilities in-situ have been identified. These opportunities include using the dumps for generating clean energy (solar and wind farms); recreation purposes and growing commercial crops such as bamboo and trees.

Each of the potential applications are discussed briefly below.

Bricks: The results of a number of experimental studies have indicated that mine tailings, including the Witwatersrand gold tailings in South Africa, are a viable alternate aggregate for brick making. However, it was noted that additives such as cement need to be included in the tailings brick mixture to improve the compressive strengths of the tailings bricks. The use of cement makes the tailings brick uneconomical which can hinder the uptake of this reuse option. Further to this, the potential radioactive nature of tailings material was highlighted as a significant challenge to reusing tailings. Although gold tailings have been reported to have been used to manufacture bricks on a commercial scale in the Witwatersrand, these operations are associated with significant controversy and no information could be obtained on these operations.

Ceramics: Internationally, research indicates that mine tailings from gold and base metal operations can be used as a substitute for clay in the production of ceramic products. However, the only commercial application appears to be in the United States. The potential use of South African gold tailings appears to remain unexplored in ceramic production.

Cement additive: Studies by international researchers have shown that mine waste and gold tailings in particular can be used as an additive in making blended cements and have identified the optimum cement-tailings ratios required to ensure that the produced cement achieves the compressive strength standards. No application of South African gold tailings appears to have been attempted, although the utilization of fly ash as a cement additive within the South African construction sector is common practice.

Paste backfill: Numerous gold mine companies in South Africa are known to have backfill operations onsite and use backfill from gold tailings to improve structural stability, filling mine voids and alleviating problems such as rock falls and rock bursts

in mines. However, publicly available data on these applications or any related research and developmental programmes is extremely limited.

Stone Paper: Stone paper, also referred to as mineral paper, is a blend of crushed stones and/or tailings with polymers. Reports suggest that the formation of a stone paper factory in Johannesburg is being explored and will make use of gold tailings and rubble from illegal dump sites in the stone paper making process. In addition, various research institutes are involved in experimental work around stone paper; however, limited information development of this opportunity is available in the public domain.

Aggregate for road base and or construction material: Mine wastes, such as tailings are commonly used as a replacement aggregate for road base, plaster sand, paving material and construction material. Although identified as a potentially feasible alternative for South African gold tailings by a number of participants, no commercial applications could be identified.

Alternative uses of defunct gold tailings dumps: In South Africa, gold tailings facilities are being used for a number of (mostly informal and unregulated) activities, including agriculture, educational tours, recreation (quad biking, skate-boarding, off-roading), as well as photo and music video shoots. Internationally mine waste facilities have been used for generating renewable energy, specifically wind and solar energy, but this option does not appear to have been explored in South Africa. It has also been proposed that gold tailings facilities could be used for cultivation of cash crops such as bamboo, but geotechnical stability and toxicity would need to be considered.

6.1.2. Influencing factors

The research identified five key factors which influence the use of gold tailings. These factors either facilitate and/or constrain the uptake of the identified opportunities. The identified factors are namely material properties, technology, economics, corporate culture and values, and legislation.

Material properties

According to the findings of the study, the physical and chemical properties of tailings determine their suitability to be used as feedstock for the different applications and can result in specific health and environmental risks during processing and/or utilization. In South Africa, gold tailings usually contain potentially radioactive and toxic metals such as uranium, lead, thorium and arsenic. In addition, tailings typically contain pyrite which is a source of acidic drainage. Fresh tailings also contain toxic levels of cyanide. These contaminants constitute a major barrier to reusing gold tailings, and in many cases would require pre-removal, using chemical or physical separation processes.

Technology

In most cases where tailings have been utilized, the tailings are typically used to replace (or partly replace) the virgin materials such as clays and aggregates that would have been used. The technologies for such applications are generally well developed. However, the testing and optimization for technologies for mine waste, and gold tailings, in particular has been limited. Most of the applications are laboratory scale and the only applications that have been applied on a commercial scale for gold tailings appear to be limited to brickmaking and paste backfill. In both these cases, there is limited evidence of any systematic technology development and transfer of applications. As such technologies and processes for the reuse of tailings can be considered as unproven. In addition, the uncertainty and risk of new and unproven technology also poses a technological barrier.

Besides the re-purposing of tailings, advancements in technology have made it feasible to extract gold (and other minerals) from both low-grade ores and waste tailings. This provides an ideal opportunity to simultaneously re-purpose the bulk material. However, this technology is mostly around on mineral recovery and limited technology has been fully tried and tested for the other re-purposing options.

Economics

Economics can be both an enabler and barrier to the uptake of the identified reuse options. Factors such as the escalating costs of complying with increasingly stringent legislation, particularly in terms of the land disposal of large-volume wastes, can potentially provide financial incentives for companies to explore alternative uses. However, the major economic barrier is that reuse options are considered financially non-viable on the basis of conventional financial indicators. This can be attributed to the high direct costs involved, particularly in terms of transport and the need for additional additives such as cement, as well as the relatively low value of the products generated. In addition, conventional virgin materials are readily available as they occur naturally in the environment and are relatively inexpensive. This therefore provides little incentive to use tailings, particularly where there is additional health, safety and environmental risks involved due to the presence of toxic components.

Another factor influencing the selection and feasibility of mine reuse opportunities, relates to local markets. The findings of the study suggest that there are more tailings than there were marketable uses for it. However, the market size would need to be investigated further.

Corporate culture and values

Corporate culture, leadership and overall company strategy influence how companies classify tailings and the uptake of waste reuse options. Classifying tailings as either a liability or an asset determines the approach an organization takes with respect to tailings management. Organizations which view tailings as an asset are more open to exploring reuse options and drive innovative solutions for dealing with waste. On the other hand, organizations that classify tailings as a liability and/or waste are often averse to the different waste reuse opportunities and likely to opt for conventional tailings disposal.

Legislation

Current legislation in South Africa was largely seen as barrier to the reuse of gold tailings. This is attributed to fragmented legislation and the fact that there is no uniting

policy which outlines how mining waste should be dealt with. As a result, there are no clear legislative guidelines on the procedure and requirements for reuse options, which is aggravated by the fact that the current regulatory environment focuses on a waste disposal approach. In addition, there is inconsistency to the definition of mine waste and coupled with the frequent changes to the legislation makes companies reluctant and impedes the willingness of companies to undertake new and innovated approaches to waste management. Lastly, increasingly stringent and costly regulations have to be met for the design and construction of disposal sites and this could provide an incentive for adopting reuse approaches.

6.2 Concluding remarks

This chapter has outlined the key research findings which were discussed and presented in Chapter 4 and Chapter 5. From the discussion, it is evident that gold tailings can be used for various applications and the tailings dumps can be re-purposed for numerous uses. However, in South Africa, this is not a common occurrence due to numerous inter-related factors, such as the absence of an enabling legislative framework, high short-term and direct costs, potential environmental risks related with hazardous components in the waste, inadequate technology development, and traditional corporate culture which views waste as unwanted material thus opting for conventional disposal of tailings as a waste management strategy. Unless these constraints are addressed, it is unlikely that there will be a significant uptake of reuse options without concerted collaborative effort between different stakeholders, underpinned by a sustained programme of Research & Development.

6.3 Recommendations for future work

The study findings indicate there is a business and ethical case for an alternative approach to mining waste management that is focused on the re-purposing of gold tailings. This subsection makes recommendations that can be implemented to improve the uptake of mine waste reuse opportunities for both the gold sector and the mining industry as a whole. It also looks at what further studies should focus on in order to address some of this research's shortcomings and limitations.

6.3.1. Further research and development studies

In the specific case of South African gold tailings, this study has indicated that limited research has been undertaken to explore and develop these opportunities for the case of South African gold tailings, and there is little data and information on reuse applications available in the public domain, particularly in the case of more innovative applications.

It is therefore recommended that a more detailed scenario study be undertaken with specific emphasis on markets, economic viability and environmental risks (as these seem to be the main factors) of the different opportunities. This should be supported by a systematic empirical test work campaign on the most viable options or combinations thereof, on an individual basis. In addition, there is a need to conduct research to investigate and identify the key stakeholders required to facilitate the uptake of these reuse options. This will also evaluate the roles that these different stakeholders need to play in the development of a sustainable approach to effective mine waste management and creating an environment that facilitated reusing mining waste.

6.3.2. Initiatives to promote commercial uptake

The study highlighted the need to establish initiatives aimed at creating investor and stakeholder confidence in order to drive the uptake of the various reuse options. Strategies to promote the commercial application of identified opportunities would also need to be developed. This entails laboratory and subsequent pilot-scale studies on the options identified as being potentially viable. The application of commercial applications will also require the establishment of partnerships between different stakeholders including the mining industry, business and government. These partnerships should look at the re-use of tailings and explore what kinds of incentives and other strategies are required to overcome the barriers.

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APPENDIX

Appendix I: Interview questions (Semi-structured)

1. What waste management practices are common in South Africa with respect to mine waste?
2. Which options are you using and why? How are decisions made about the relevant waste management options?
3. What opportunities are there for reusing mine waste? What are the available alternatives for reusing mining waste in South Africa?
4. What potential benefits (e.g. financial, socio-economic) can be gained from the reuse of mining waste?
5. What is your position (as an organisation) on reusing gold tailings for other purposes such as road construction, ceramic making etc.?
6. Have you ever undertaken or are aware of any projects that have reused gold tailings in South Africa?
 - a. If so what were the different options?
 - b. Was the project a success?
 - c. What was the most challenging aspect about the project?
7. What do you see as incentives and or barriers to reusing gold tailings in South Africa?
8. What would be the most important factors or drivers for reusing mine waste
 - a. Enabling legislation? Are there any policies or legislation governing the reuse of mining waste?
 - b. Technology advancement? Are there technological constraints (i.e. lack of technology, inappropriate technology etc.) to the reuse of mining waste?
 - c. Are financial benefits and avoiding extra costs important to encourage your organisation to act on environmental issues?
 - d. Social perspectives? What perceptions exist regarding the re-use of mine waste?

9. From a legal perspective, do you think the legislative promotes/hinders the reuse of gold tailings/mine waste?
10. What are the legal drivers and barriers for reuse? What can be done to promote the reuse of mine waste? What do you think are the appropriate structures (organisational, legislative) that need to in place to allow for reuse of gold tailings?

Appendix II: Ethics approval

Application for Approval of Ethics in Research (EiR) Projects
Faculty of Engineering and the Built Environment, University of Cape Town

APPLICATION FORM


Please Note:



Any person planning to undertake research in the Faculty of Engineering and the Built Environment (EBE) at the University of Cape Town is required to complete this form **before** collecting or analysing data. The objective of submitting this application *prior to embarking on research* is to ensure that the highest ethical standards in research, conducted under the auspices of the EBE Faculty, are met. Please ensure that you have read, and understood the **EBE Ethics in Research Handbook** (available from the UCT EBE, Research Ethics website) prior to completing this application form: <http://www.ebe.uct.ac.za/usr/ebe/research/ethics.pdf>

APPLICANT'S DETAILS		
Name of principal researcher, student or external applicant	LESLEY KUDAKWASHE SIBANDA	
Department	CHEMICAL ENGINEERING	
Preferred email address of applicant:	lesley.sibanda@uct.ac.za	
If a Student	Your Degree: e.g., MSc, PhD, etc.,	MPhil specialising in Sustainable Mineral Resource Development
	Name of Supervisor (if supervised):	ASSOCIATE PROFESSOR JENNIFER BROADHURST
If this is a research contract, indicate the source of funding/sponsorship	Click here to enter text.	
Project Title	Recycling and utilisation of mine waste: An alternative management approach to gold tailings in South Africa	

I hereby undertake to carry out my research in such a way that:

- there is no apparent legal objection to the nature or the method of research; and
- the research will not compromise staff or students or the other responsibilities of the University;
- the stated objective will be achieved, and the findings will have a high degree of validity;
- limitations and alternative interpretations will be considered;
- the findings could be subject to peer review and publicly available; and
- I will comply with the conventions of copyright and avoid any practice that would constitute plagiarism.

SIGNED BY	Full name	Signature	Date
Principal Researcher/ Student/External applicant	LESLEY K SIBANDA		21 Dec 2016

APPLICATION APPROVED BY	Full name	Signature	Date
Supervisor (where applicable)	JENNIFER BROADHURST		22 Dec 2016
HOD (or delegated nominee) Final authority for all applicants who have answered NO to all questions in Section 1; and for all Undergraduate research (Including Honours).	Click here to enter text.		Click here to enter a date. 22/12/16
Chair : Faculty EIR Committee For applicants other than undergraduate students who have answered YES to any of the above questions.	Click here to enter text.		Click here to enter a date.

Appendix III: Consent form

Informed Consent Form

Project title: Recycling and utilisation of mine waste: An alternative management approach to gold tailings in South Africa

I, the undersigned, confirm that (please tick as appropriate):

1.	I have understood the objectives of the project, as explained by the researcher.	
2.	I have been given the opportunity to ask questions about the project and my participation.	
3.	I voluntarily agree to participate in the project.	
4.	The procedures regarding confidentiality have been clearly explained to me.	
5.	I agree to the audio recording of this interview.	
6.	I understand that other researchers will have access to this data only if they agree to preserve the confidentiality of the data and if they agreed to the terms I have specified in the form.	

Participant name:	Researcher name:
Signature	Signature:
Date.....	Date: