

School of Mining Engineering



UNIVERSITY OF THE
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JOHANNESBURG

**THE FEASIBILITY OF WITWATERSRAND GOLD
TAILING AS AN ALTERNATIVE IN CEMENT
MANUFACTURING AS A POSSIBLE
CONTRIBUTOR TO THE CIRCULAR ECONOMY**

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A research report submitted to the Faculty of Engineering and the Built Environment, University of the Witwatersrand, Johannesburg, in partial fulfilment of the requirements for the degree of Master of Science in Engineering.

Johannesburg, 2024

DECLARATION

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ABSTRACT

Throughout mining history, there have been growing concerns about tailing storage facilities. Concerns include the vast space tailings occupy, and their mismanagement resulting in environmental impact and health implications. Tailings form the highest percentage of material remaining post extraction of mineral, which subsequently requires a deposition site. Only a small percentage of tailings is used in backfill filling in underground operations. The study investigated the viability of gold tailings as an alternative in cement manufacturing and in doing so contribute to the circular economy. The framework of this study used the Witwatersrand Supergroup gold tailings from the Klerksdorp area in North-West Province, South Africa. The mineralogical, chemical, and physical properties of the Witwatersrand gold tailings were investigated and compared to the Ordinary Portland cement and Hexi gold tailings in Shandong Province, China. The Witwatersrand gold tailings in this study had a noticeably lower calcium oxide content (0.98%) than what is required in cement manufacture (63.68%). The aluminosilicate minerals were reasonably high (above 70%) resulting in a pozzolanic nature, which implies that a certain percentage of the gold tailings can be used as supplementary cementitious material in the production of cement mortar. The study also explored ways of reducing or eliminating the identified hazardous substances such as cyanide and radioactive elements. The concentration of uranium radioactivity in Klerksdorp gold tailings is 931.6 Bq /kg above the regulatory limit of 500 Bq/kg for uranium in cement manufacturing. The uranium radioactivity

concentration can be reduced by incorporating a process of uranium extraction during gold extraction operations. Additionally, the South African policy on the valorisation of mining waste which only recognizes the retreatment of tailings under the Environmental Authorization under the National Environmental Management Act No. 107 of 1998 should be amended by including the use of mining wastes in other sectors of the economy through the circular economy framework.

DEDICATION

I dedicate this thesis to my late parents for the teachings they instilled in me.

In loving memory of my father Stemmer Mpati Maipushi and my mother Japhtaline Kedibone Maipushi.

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LIST OF UNITS

Bq/kg	Becquerel per kilogram (measures radiation emitted)
kWh/ton	Kilo Watts per tons
mSv	Millisieverts (measure of human exposure to radiation)
mm	Millimeters
MMt	Million metric tons
μm	Micrometers (microns)
ppm	Parts Per Million

LIST OF ABBREVIATIONS

A	Aluminum Oxide (Al_2O_3)
C	Calcium Oxide (CaO)
C_3A	Tricalcium Aluminate ($\text{Ca}_3\text{Al}_2\text{O}_6$ or $3\text{CaO}.\text{Al}_2\text{O}_3$)
C_4AF	Tetracalcium Aluminoferrite ($\text{Ca}_4\text{Al}_2\text{Fe}_2\text{O}_{10}$ or $4\text{CaO}.\text{Al}_2\text{O}_3.\text{Fe}_2\text{O}_3$)
CaCO_3	Calcium Carbonate
CO_2	Carbon Dioxide
C_2S	Dicalcium Silicate (Ca_2SiO_4 or $2\text{CaO}.\text{SiO}_2$)
C_3S	Tricalcium Silicate (Ca_3SiO_5 or $3\text{CaO}.\text{SiO}_2$)
F	Ferric Oxide (Fe_2O_3)
GTC	Gold Tailings Cement
LOI	Loss of ignition
OPC-SS	Ordinary Portland Cement Sandstone
PPC	Pretoria Portland Cement

SCM	Supplementary Cementitious Material
S	Silica (SiO ₂)
TSF	Tailings Storage Facilities

1 INTRODUCTION

1.1 Background

The gold mining industry in Southern Africa generates mine waste while mining ore from open pits, shallow, or deep-level mining. The waste generated after the extraction of metal through milling of host rock and leaching is called tailings, which is a fine-grained material mixed with process water and hazardous chemicals such as cyanide utilized in metal extraction (Simonsen et al., 2020). The inadequate management of tailings presents substantial environmental and human health risks as a result of the existence of hazardous chemicals. Tailings constitute the predominant proportion of mining residual material that requires a designated deposition area, though a minor fraction is utilized for backfilling purposes in underground operations (Nwaila et al., 2021).

As reported by Malatse and Ndlovu (2015), the Witwatersrand Supergroup Goldfield accounts for 98% of the gold production in South Africa. The extensive extraction of gold resources has resulted in the development of mine tailing storage facilities (TSF) distributed throughout the Witwatersrand Gold Basin (Malatse and Ndlovu, 2015). The current global pattern in gold mining reveals a noticeable decline in the quality of gold deposits over time. To maintain profitability, mining corporations are driven to mine larger volumes of low-grade ores (Morrison, 2022; Mudd, 2007). Consequently, there has been an observed augmentation in the quantity of tailings deposited in the environment, thereby heightening the ecological concerns associated with tailing storage facilities (TSF). These concerns encompass the extensive spatial footprint of TSF, as

well as its management practices, which have been associated with severe consequences such as catastrophic failures in tailings embankments, contamination of process water leading to groundwater pollution, and the occurrence of acid mine drainage (Morrison, 2022). The correlation between the efficiency and longevity of the mining sector and the well-being of global ecosystems is apparent, given the substantial risks currently faced by the latter. The occurrence of these risks can be ascribed to the depletion of high-grade ores and rising levels of air, water, and soil pollution and contamination (Morrison, 2022; Mudd, 2007).

The mining sector in South Africa is linked to notable environmental consequences as substantiated by its approximate 6% contribution to the country's greenhouse gas emissions (Mudd, 2007; Department of Forestry, Fisheries and Environment, 2022). Additionally, the industry contributes to around 5% of the country's overall water demand, and its production practices have significant impacts on soil quality and biodiversity (Department of Forestry, Fisheries and Environment, 2022). Furthermore, the presence of a significant quantity of mining wastes serves as evidence supporting the argument that the prevailing production methods are deficient in terms of environmental sustainability and circular economy.

Recently, there has been an increasing awareness of the environmental and health implications associated with tailings, which underscores the need for a paradigm shift in waste management strategies. According to Haywood et al. (2019), the prevailing strategy in the mining industry involves the ongoing

management of tailings during the entire lifespan of a mine, which includes the implementation of rehabilitation initiatives aimed at mitigating the environmental consequences. The approach under consideration is commonly referred to as cradle-to-grave, which is characterized as the "take, make, consume, discard" approach according to Haywood et al. (2019). To reduce and reclaim mining wastes, Haywood et al. (2019) emphasized the importance of transitioning the mining industry from a cradle-to-grave paradigm to a cradle-to-cradle framework that incorporates principles of circular economy.

Circular economy is an economic framework that is based on the principles of reutilization and regeneration of products or residual materials that are typically considered waste. This is achieved through the process of redesigning and reusing these materials to create new products (Stucki et al., 2023). The concept of a circular economy entails the redirection of resource cycles away from waste disposal towards the process of repurposing. Circular economy is aimed at closing the loop in any value chain, where the valorisation of wastes can be achieved through recycling them into more valuable products (Nwaila et al., 2021).

The incorporation of circular economy principles in the mining sector can reshape the value chain by broadening the Mine Value Chain to encompass post-processing and downstream production of value-added products, as advocated by Morrison (2022). This method would incentivize mining companies to implement strategies that facilitate the utilization of mining waste in many areas of the economy i.e., the implementation of actions aimed at

mitigating or eradicating impurities in tailings, facilitating their seamless integration into different industries. The evaluation of circular economy performance is conducted by employing various indicators of circularity (Smol, 2023). These indicators function as metrics for assessing the extent to which circular economy ideas have been effectively incorporated into products or services. The general consensus asserts that an increase in circularity is linked to an increase in environmental benefits; however, this assumption is not universally true. Therefore, further investigation is required to ascertain for a given industry the precise circumstances under which increased circularity leads to ecologically advantageous and economically effective industrial strategies.

The practical realization of the circular economy can be accomplished by establishing closed-loop supply or production networks, wherein reverse flows are redirected back to the original industries (Berlin et al., 2022; Braz and Marotti de Mello, 2022). In contrast, open-loop supply networks offer an alternate approach by redirecting reverse flows to other supply or production chains within the same industry or across various industries. This practice is sometimes referred to as open-loop or cross-sector supply/production chains (Berlin et al., 2022).

1.2 Problem Statement

The Witwatersrand basin consists of three goldfields, 1) the major strip found in the south of Johannesburg in the Gauteng Province, 2) Free State goldfields in the Free State Province, and 3) Klerksdorp, Orkney, and Stilfontein goldfields in North-West Province (Laker, 2023). The discovery and mining of gold from the

Witwatersrand basin since 1886 has led to the use of vast land for the tailing deposition of post-mineral extraction (McCarthy and Rubidge, 2005). Over 270 tailings have been identified to cover land along the Witwatersrand basin (Laker, 2023). The presence of tailings and their mismanagement have led to the environmental impacts that are significant in the vicinity of the tailings and can spread over several kilometres from the source. The majority of tailing storage facilities are unlined resulting in a higher threat to the quality of ground and surface water systems (Laker, 2023). The environmental impacts can include hazardous chemical-contaminated process water, acid mine drainage, and seepage associated with mine waste management. These impacts can persist even over 50 years after the dam is inactive (Rosner et al, 1998).

According to Statistics South Africa (2022), the Gauteng province occupies 1.4% of the country's surface area compared to the Free State and North-West (10.6% and 8.7% respectively). The 2022 Statistics accounted for a human population of 16.1 million compared to 12.7 million in 2013, in the Gauteng province alone. The increase in population is consequently associated with a high demand for land for housing, which will result in over usage of natural resources in the construction industry (Malatse and Ndlovu, 2015). Additionally, the Free State and North-West province are known to produce white maize contributing to over 75% of South African production in regions of unfavourable soil conditions and marginal rainfall (Nortje and Laker, 2021). Therefore, the land over the Witwatersrand basin has the potential to be used in agriculture, urbanization, and industrialization for economic development.

1.3 Justification for Research

The study will investigate the feasibility of readily accessible mine waste for the benefit of reducing environmental and health effects surrounding tailings storage and management. The research will contribute to a better understanding of the use of gold ore tailings in cement production, specifically the Witwatersrand gold tailings. The study also aims to explore ways of reducing or eliminating the presence of hazardous substances to levels safe for the usage of tailings in cement manufacturing.

The use of tailings as a replacement in cement production has the potential to decrease the use of natural raw materials such as sandstone, limestone, gypsum, clay, and alumina, which are usually used in cement production. Furthermore, reusing tailings frees up land for use in other parts of the mining company's operations while lowering rehabilitation costs. It is projected that using tailings as substitute materials in cement production may contribute to a more sustainable path (Morrison, 2022).

1.4 Research Objectives

The main aim of the research is to evaluate the feasibility of using Witwatersrand gold tailings in cement production and compare the results with those of other case studies conducted involving comparable materials. The framework of this study will be the use of Witwatersrand Supergroup Reef tailings from mining operations as an alternative in cement manufacturing. The following are the objectives for this research:

- Understanding the physical, mineralogical, and chemical parameters of existing case studies in cement manufacturing using gold tailings material;
- Investigate the nature of Witwatersrand Supergroup gold ore tailings composition and their reliability as a substitute in cement manufacturing;
- Investigate hazardous chemicals, impurities, and the presence of radioactive mineral uranium that could influence the use of Witwatersrand gold tailings as a substitute in cement manufacturing; and
- Lastly, review the South African legislation to determine whether it caters to the reuse or recycling of mine waste for usage in other sectors of the economy.

1.5 Research gaps

There is a growing interest in studies aligned to attempt in reducing or eliminating mine waste through repurposing. The interest is mainly driven by mitigation plans to eliminate environmental hazards associated with mine waste, especially tailings. It has been established that the current use of mine waste in backfilling within the underground operations is a minor solution since a small proportionality can be utilized resulting in higher quantities occupying land (Nwaila et al., 2021). Globally, numerous studies have investigated the viability of tailing material in use in ceramic, bricks, cement paving, concrete, and stone paper ((Méndez et al., 2022; Maruthupandian et al., 2021; Simonsen et al., 2020; Wang et al., 2019). In the South African context, tailing material is limited to backfilling within the underground operations and very few of the tailing repurpose research initiatives have been documented. Research studies in the

South African context explored alternative ways of managing tailings through interview-based investigations (Sibanda, 2019; Sibanda and Broadhurst, n.d. and viability studies on the usage of tailings in other industries to contribute to the circular economy (Aderinto and Ikotun, 2023; Ikotun et al., 2022; Mhlongo et al., 2022). Therefore, this research aims to contribute towards the viability of the gold tailings in cement production, specifically on the Witwatersrand gold tailings from a South African based ore deposit.

1.6 Research Methodology

The research methodology includes the following:

- Literature review to investigate the physical, mineralogy, and chemical parameters of material used in Ordinary Portland cement manufacturing;
- Compare Ordinary Portland Cement physical, mineralogy, and chemical parameters with existing research work on the utilization of gold tailing in cement production;
- And lastly use mineralogical quantitative data from Witwatersrand gold ore tailing samples collected by Harmony tailing operations in Klerksdorp compared to ordinary cement production and other successful research in cement production using gold tailings material.

1.7 Structure of the Research Report

The research structure consists of five chapters.

- Chapter 1 introduces the research project, research problem, justification, aims, and objective of the research.

- Chapter 2 reviews the literature on the viability of tailing in cement manufacturing, mineralogy, and chemical composition of the Witwatersrand Gold Ore, Legislation of tailings,
- Chapter 3 reviews the cement manufacturing process and finally a case study on the use of tailing in cement manufacturing.
- Chapter 4 presents the methodology used in data collection.
- Chapter 5 presents the mineralogy, chemical composition, and physical properties of Witwatersrand gold tailings in comparison to case studies on the use of tailing in cement manufacturing. Finally, discuss the feasibility of Witwatersrand gold tailings in cement production, challenges in the implementation of gold tailings, and challenges Identified as per South African Legislation in the usage of tailings.
- Chapter 6 concludes the study and provides recommendations.

2 LITERATURE REVIEW

2.1 Introduction

The deposition and storage of tailings material has resulted in environmental and health-related risks throughout mining history. The majority of tailing storage facilities are unlined resulting in a higher threat to the quality of ground and surface water systems (Laker, 2023). In some instances, environmental and social-related issues can be felt for over several years. The most significant being the mismanagement of tailings that led to catastrophic events with the impact stretching out over several kilometers leaving behind damage to the surrounding community to an extent, losses in human life. The influence of tailings on the surroundings requires a change in mining strategy from cradle-to-grave to cradle-to-cradle through the principle of circular economy (Haywood et al., 2019).

Over the years, there has been a growing interest in research work on the reduction of potential health and environmental pollution through the reduction of tailings material or removals from land through alternative usage in other sectors of the economy (Morrison, 2022; Maruthupandian et al., 2021). The growing interest resulted in an increase from less than five research papers in 2010 to over 120 papers in 2020 (Maruthupandian et al., 2021). Existing work reviewed the application of tailings ranging from bricks making (Veiga Simão et al., 2022); Malatse and Ndlovu, 2015), ceramic (Liu et al., 2015), sand substitute in concrete blocks (Méndez et al., 2022), fine aggregates (Andrews et al., 2022), and cement in the construction industry (Maruthupandian et al., 2021; Simonsen

et al., 2020; Wang et al., 2019). Within the South African context, tailing material is limited to backfilling within the underground operations. However, Malatse and Ndlovu (2015) utilised the Witwatersrand gold tailing in brick making. The use of gold tailings in cement manufacturing is not broadly addressed in the open literature within the South African context.

Most researchers have been focusing on utilizing tailings as a supplementary cementitious material in cement mortar in place of sand. This includes the study by Ince (2019) that investigated the use of gold tailing from the Lefke Xeros mine area, Lefke town in Cyprus, which was a copper and gold extraction mine. Simonsen et al. (2020) also investigated the utilisation of tailings as an effective supplementary cementitious material (SCM) to reduce carbon dioxide (CO₂) emissions during cement manufacturing. Different mine tailings were assessed based on their physical (grain size and morphology), chemical, and mineralogical properties for compatibility as SCM. The latter highlights the importance of understanding the mineralogy, chemical and physical properties of the considered material in order to understand its viability.

Although tailings are said to be theoretically usable, Morrison (2022) lists three types of obstacles: first, transportation costs resulting from the mining operation to market radius; second, the physical and chemical properties of tailings, which include potential impurities and radioactivity that can affect their usage; and third, the availability of space for on-site stockpiling in anticipation of preferred market prices.

2.2 Tailing as Engineering Material

The characterization of tailings material is critical to understand the potential process of valorisation that the tailings may go through in downstream beneficiation as a value-added product (Morrison, 2022). Nwaila et al. (2021) emphasized the importance of implementing a proper sampling, classification, and resource modelling framework in understanding the nature of tailings before their usage through the waste valorisation concept. Key parameters that are commonly investigated are the mineralogical and chemical properties of tailings. In addition, physical properties such as particle size analysis are examined to understand the behavior of tailings in cement and other construction material manufacturing (Ince, 2019; Malatse and Ndlovu, 2015; Maruthupandian et al., 2021).

2.2.1 Chemical Properties

The required chemical properties include hydraulic, pozzolanic, and potential activator properties. Hydraulic property is the ability to harden during the hydration of calcium silicates and it is measured by CaO and SiO₂ content (Simonsen et al., 2020). For potential hydraulic activity to take place, the sum of CaO and SiO₂ content must be greater than 50% by weight according to European standards (EN 197-1, 2011; Simonsen et al. 2020).

The pozzolanic nature is the formation of calcium silicate hydrate (C-S-H) along with other cementitious compounds due to the reaction between fine-grained siliceous or aluminosilicate, calcium hydroxide (C-H) and water (Simonsen et al., 2020). In this reaction, insoluble calcium silicate hydrate and calcium

aluminate hydrate compounds are formed possessing cementitious properties. The use of pozzolan material provides the ability to construct structures such as bridges under water. The measure of pozzolanic nature is based on the sum of key oxides (SiO_2 , Al_2O_3 and Fe_2O_3) greater than 70% (Simonsen et al., 2020).

The activating nature is attained during the chemical reaction between silicate and the source with alkaline metal that can be calcium-rich aluminosilicates such as furnace slags or calcium-poor aluminosilicates obtained from fly-ash (Maruthupandian et al., 2021; Torres-Carrasco and Puertas, 2017). In the case of gold tailing with lower calcium oxide, the process will require blast furnace slag, a by-product from iron production with high calcium oxide. Slag in the cement manufacturing supplement limestone material required in the process of calcination to produce lime (CaO) and CO_2 in the kiln section. In addition to chemical release of CO_2 , this part of the process using limestone emits 40% CO_2 as a result in fossil fuel used to produce heat during calcination in cement manufacturing (Ige et al., 2024).

According to Karim et al. (2011), the energy required using natural raw limestone in the calcination process is 1587 kWh/ton. The use of 30% slag requires 1206 kWh/ton energy compared to the use of raw natural material (24% lesser kWh/ton). At 75% slag, the energy saving is 62% resulting in 602 kWh/ton required. The higher the percentage of slag used, the lower the energy required resulting in a reduction in CO_2 emission in the atmosphere, which is an upside on the environment during cement manufacturing (Ige et al., 2024; Torres-Carrasco and Puertas, 2017).

The presence of silica content in cement manufacturing provides strength during its reaction with lime to form dicalcium silicate (C_2S) and tricalcium silicate (C_3S). However, excess of SiO_2 can prolong the setting time (Hills et al., 2002). The study by Ince (2019) identified that the incorporation of gold tailings as cement replacement and sand replacement results in high compressive strength due to reduced porosity and denser microstructure. The study also revealed that the compressive strength increases with an increase in the fraction of gold tailings from 10% to 30%. Beyond 40% tailings material addition, the compressive starts decreasing. Therefore, it was found that 30% is roughly the optimum percentage weight of gold tailings to use in place of cement or sand. The study by Andrews et al. (2022) reported that the optimum tailing replacement is 25% by weight. In addition, Ince (2019) found that the use of gold tailings as supplementary cementitious material reduces CO_2 emissions. For instance, the incorporation of 30% gold tailings as supplementary cementitious material SCM induced a decrease in CO_2 emission by 22%.

2.2.2 Physical Properties

According to Simonsen et al. (2020), the physical properties in cement manufacturing are dependent on grain size distribution, specific surface area and grain morphology (sphericity or angularity of grains). The grain size has an influence on the required water, hydration reaction, setting and curing time. It is evident that the reactivity of supplementary cementitious material can be influenced by grain size distribution. The reactivity increases with the finer particle size. However, excess water usage can result in lower workability

(Andrews et al., 2022; Simonsen et al., 2020). In addition, grain morphology affects the strength development of mortar. Ince (2019) reported that the distribution of particle size below 75 μm is referred to finer particles. These particles act as filler material and can form a denser microstructure and more consolidated matrix. The grain size distribution of cement is comparable to that of gold tailings. More than 80% of their particles fall below 75 μm . Gold tailings have high fineness compared to the sand, which can reduce the total voids in concrete or cement mortar considerably.

2.2.3 Activation Properties

Simonsen et al (2020) indicated that some mine tailings might require pre-treatment, such as size reduction and/or thermal treatment for their effective usage in cement manufacturing. The majority of the gold tailings are in the crystalline phase rendering them incapable of chemical reaction. The amorphous fraction of silica is considered to be more important for an effective chemical reaction than the total silica content (Maruthupandian et al., 2021; Simonsen et al., 2020). The process of rearranging the crystalline phase to a reactive amorphous phase is called activation, which can be mechanical, chemical or thermal activation (Maruthupandian et al., 2021).

Mechanical activation can be achieved by introducing pressure and shearing through milling the material. The latter decreases the particle size and improves the surface area for effective chemical reaction. Thermal activation also known as calcination, consists of high-temperature treatment of the material to change its crystal structure. Finally, the chemical activation involves the use of an

activator to stimulate a chemical reaction which unlocks the crystalline ions for further reaction. The widely used chemical activators for tailings are sodium/potassium hydroxide, sodium/potassium sulphate, sodium/potassium silicate, and sodium carbonate/potassium carbonate (Maruthupandian et al.,2021).

2.3 Witwatersrand Gold tailing

2.3.1 Tailings Deposits and Mineralogy

The gold ore mined in the Witwatersrand basin originates from the fluvial sedimentary rocks of the West Rand Group and Central Rand Groups of the Witwatersrand Supergroup (Robb and Robb, 1998). The West Rand Group forms the lower portion of the Witwatersrand Supergroup, with a thickness of five kilometres and covers an area of 43, 000 km². It is subdivided into Hospital Hill Subgroup, Government Subgroup, and Jeppestown Subgroups (McCarthy and Rubidge, 2005). The upper portion of the Witwatersrand Supergroup is Central Rand Group with two kilometres thickness, covering 9750 km². It is subdivide into the Turffontein Subgroup and the lower Johannesburg Subgroup (McCarthy and Rubidge, 2005). The Wits gold mines target the economically mineralised gold-bearing conglomerate reef bands mostly confined to the Central Rand Group. The conglomerate band reefs are mined in major goldfields from Evander east of Johannesburg, the East Rand, West Rand, South Rand, Central Rand, West Wits, Klerksdorp, and Free State goldfields. The location of goldfields within the Witwatersrand Basin is shown in Figure 1.

The gold mineralisation within the conglomerate layer mined is associated with uranium and pyrite (Robb and Robb, 1998).

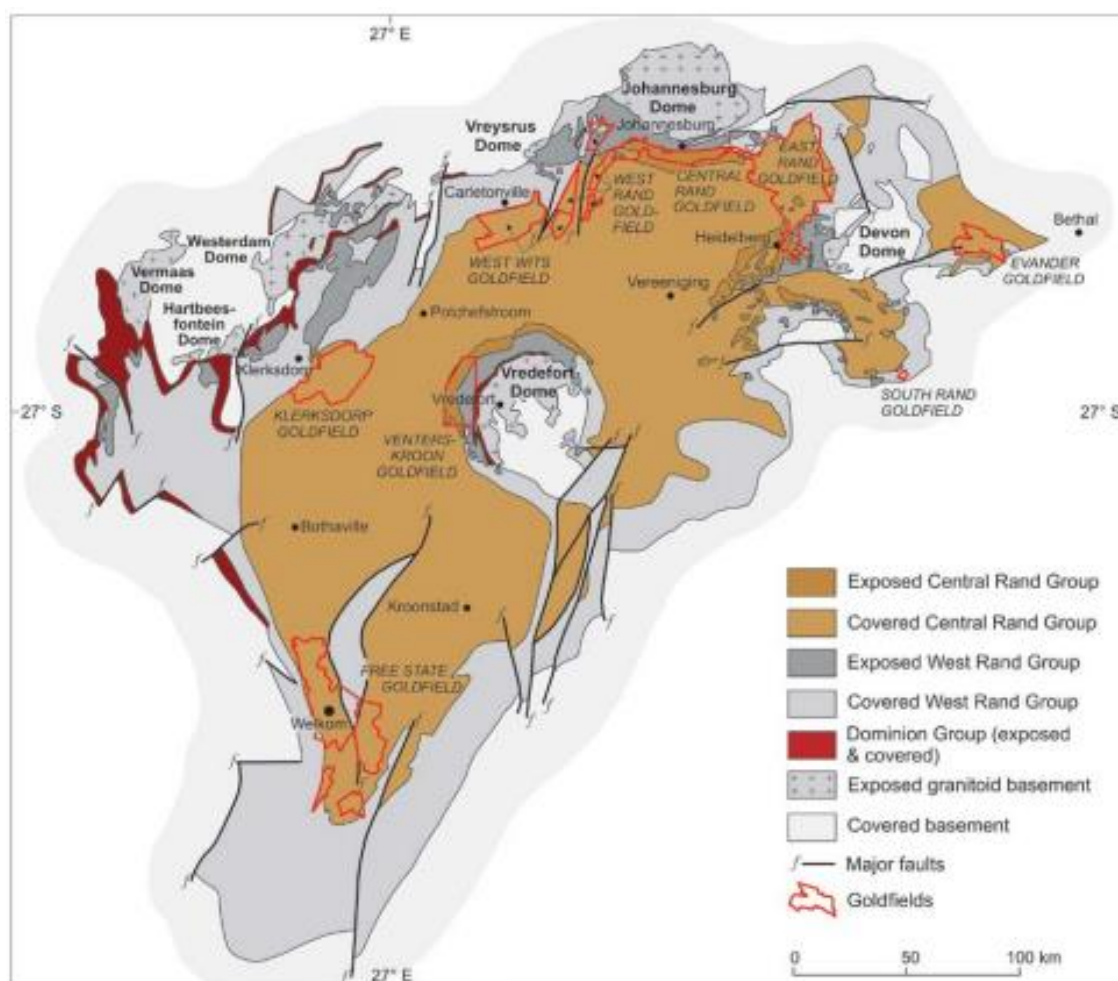


Figure 1: The location of the goldfields in the Witwatersrand Basin (after Robb and Robb, 1998)

The residue material, from gold extraction consisting of pyrite and uranium is deposited into tailing dams. The chemical compositions of Witwatersrand gold mine tailings include silica, alumina, magnesium oxide, calcium oxide, sulphur trioxide, haematite, potassium oxide, and trace quantities of uranium (Malatse

and Ndlovu, 2015; Nwaila et al., 2021). The chemical composition of the Witwatersrand gold tailings according to Malatse and Ndlovu (2015) is given in Table I.

Table I: Chemical composition of Wits gold tailings (Malatse and Ndlovu, 2015)

Chemical Name	Chemical Formulae	Wits gold tailings
Alumina	Al_2O_3	10.2%
Lime	CaO	1.9%
Chromic oxide	Cr_2O_3	0.5%
Ferrite	Fe_2O_3	4.51%
Potassium Oxide	K_2O	1.19%
Magnesia	MgO	1.79%
Manganese Oxide	MnO	0.05%
Sodium oxide	Na_2O	0.61%
Phosphorus pentoxide	P_2O_5	0.07%
Silica	SiO_2	77.7%
Titanium Oxide	TiO_2	0.46%
Sulphur trioxide	SO_3	0.91%
Nickel oxide	NiO	0.02%
Copper (II) oxide	CuO	0.01%
Zinc oxide	ZnO	0.01%
Arsenic Trioxide	As_2O_3	0.01%
Lead oxide	PbO	0.00%
Strontium oxide	SrO	0.02%
Zirconium dioxide	ZrO_2	0.03%
Uranium	U_3O_2	0.01%

2.3.2 Toxic and Hazardous Substances in gold tailings

Gold tailings deposited into dams are in the form of a slurry from mineral processing and metal extraction. These tailings consist of toxic and hazardous substances: cyanide as leaching agent, heavy metals (Cu, As, Pb) and

radioactive elements (Th, Ra, U). Some iron sulfide minerals such as pyrite and chalcopyrite from raw materials can be found in gold tailings. When pyrite or chalcopyrite is exposed to oxygen and rainwater, sulphuric acid is produced resulting in the phenomena called acid mine drainage (AMD) affecting the surrounding environment (Dong et al., 2021; Rosner et al., 1998).

Heavy metals are naturally occurring metallic elements with a density more than five times compared to water (Okewale and Grobler, 2023). Major heavy metals including zinc (Zn), arsenic (As), nickel (Ni), cobalt (Co), copper (Cu), chromium (Cr), lead (Pb) and manganese (Mn) are found in tailing dams. High concentrations of heavy metals may become hazardous after mixing with water, soil or air and can build up in living organisms through the food chain (Mitra et al., 2022). Heavy metals including Cu and Cr in gold tailings are harmful and can pose an ecological and human health risk to the environment and residents near tailings dams (Okewale and Grobler, 2023).

The total cyanide in tailings dams comprises free cyanide and metal cyanide (Chen et al., 2007; Dong et al., 2021). The free cyanide accounts for 10-40% of total cyanide, contributing to an increase in cyanide toxicity depending on the temperature, pH, dissolved oxygen versus salinity, and occurrences of ion in solution (Dong et al., 2021; Rosner et al., 1998). The half-life of cyanide on tailing is 3 years (ATSDR, 2006). The law permits less than 5 mg/L (5 ppm) concentration of cyanide before being discharged into a tailings dam (Dong et al., 2021). The quality of water for free cyanide concentration must be ≤ 0.001 mg/L (≤ 1 μ g/L), and the chronic health influence occurs at 0.004 mg/L (Rosner

et al., 1998). The acceptable limit (5mg/l) permitted for deposition on tailing for material with cyanide is more than 0.004 mg/L, which means exposure can result in chronic health issues. The process of removing cyanide and heavy metals in tailings consists of a method called chlorination electrolysis which uses hypochlorite to safely remove cyanide and heavy metals (Chen et al., 2022).

Gold tailings contain radioactive elements that are associated with isotopes or radionuclide emitting alpha- and beta particles and γ -rays (NNR, 2006). The naturally occurring radioactive materials (NORMs) form part of elements in the Earth's crust, and radionuclides form cosmic ray in the atmosphere that ultimately reach the water supply through rain and radioactive decay products (Moshupya et al., 2022). Gold Mining activities introduce underground radioactive materials from the Earth's crust post the deposition of tailings material and waste rocks after gold extraction (Moshupya et al., 2019). Numerous studies assessed the radioactivity in tailings dams from the Witwatersrand gold mining, the soil affected by tailings, and in some studies, the catchments area in the vicinity of tailings dams. According to the National Nuclear Regulator (NNR, 2006), materials with radioactivity concentrations greater than 500 Bq/kg for uranium (^{238}U) and thorium (^{232}Th), and 50 000 Bq/kg for Potassium (^{40}K) require monitoring the control of exposure to hazardous and radioactive substances.

The study on the gold tailings of the West Rand District by Moshupya et al. (2022) indicated radioactivity concentration levels range from 209.95 - 2578.68 Bq/kg for uranium, 19.49 - 108 Bq/kg for thorium and 31.30 - 626 Bq/kg for

potassium. Tailings material with a lower concentration of uranium could indicate that the metallurgical process included uranium extraction as a by-product or re-treatment of tailings resulting in lower uranium concentration (Moshupya et al., 2019). The process of uranium extraction consists of the photocatalytic uranium extraction and photo-electrochemical method (Ye et al., 2021). In the current gold extraction process, uranium extraction is mothballed or completely discontinued in tailing retreatment due to low uranium grades and low price of uranium. Moshupya et al. (2022) reported that West Rand gold tailings have effective dose limits between 0.14 – 1.09 mSv. In this study, the average effective dose is 0.51 mSv. These dose values are above the acceptable limit for human exposure, which is approximatively 0.25 mSv per year.

2.4 Legislation On Tailings Material

The South African Legislation Mineral and Petroleum Resources Development Act 28 of 2002 (MPRDA), requires the management of tailings storage sites during the life of the mine through environmental management (Haywood et al., 2019). According to the South African law under the National Environmental Management Waste Act amendment in 2014, Schedule 3, hazardous waste includes waste generated from the exploration phase, mining extraction, to the physical and chemical treatment of minerals (National Environmental Management: Waste Amendment Act, 2014; Haywood et al., 2019). This implies that mine waste must be managed according to the requirements of the National Environmental Management Waste Act.

In terms of the National Environmental Management Act No. 26 of 2014, *“hazardous waste is any waste consisting of organic or inorganic elements that may harm health and the environment due to the inherent physical, chemical, or toxicological characteristics of that waste, and including business waste, residue stockpiles, and residue deposits”*. The amended Act further distinguished between residue deposits and residue stockpiles. A residue deposit is defined as any residue stockpile remaining after mine closure. Whereas residue stockpile is any material derived from a mining operation, stockpiled within the mining boundary for possible re-use, or discarded by mining, permit, or production right holders including historic dumps formed before the enactment of this Act (National Environmental Management: Waste Amendment Act, 2014). The Act includes products such as waste rock, slimes, tailings, slurry, or mineral processing waste as residue stockpiles (National Environmental Management: Waste Amendment Act, 2014). In terms of the National Environmental Management Act No. 26 of 2014, tailing materials were classified as hazardous waste. However, the retreatment of tailing material is covered under the Environmental Authorization under the National Environmental Management Act No. 107 of 1998. The purpose of a regulation or legislation in the use of tailing waste in cement manufacturing would be to ensure the incorporation does not pose any environmental or health risk.

3 CEMENT MANUFACTURING AND CHARACTERISATION

3.1 Overview of the cement process

Cement is a chemical substance in a dry powder form used in construction to bind with other materials and harden (Mohammed et al., 2021). It is categorised into hydraulic and non-hydraulic cement based on hardening and the cement setting mechanism (Mikulčič et al., 2016). Hydraulic cement requires the presence of water to harden whereas non-hydraulic requires dry conditions such as carbon dioxide to harden (Mohammed et al., 2021). Ordinary Portland cement is a hydraulic cement that predominately comprises calcium silicates, aluminates, and ferrites (Dalton et al, 2004). The process of cement production summarised by Mikulčič et al. (2016) is shown in Figure 2. The process involves the following sub-processes, namely: mixing of raw material, crushing to the required size particle, preheating of mixed raw material, calcination, burning of clinker, cooling it off and finally grinding to produce cement (Fidaros et al., 2007).

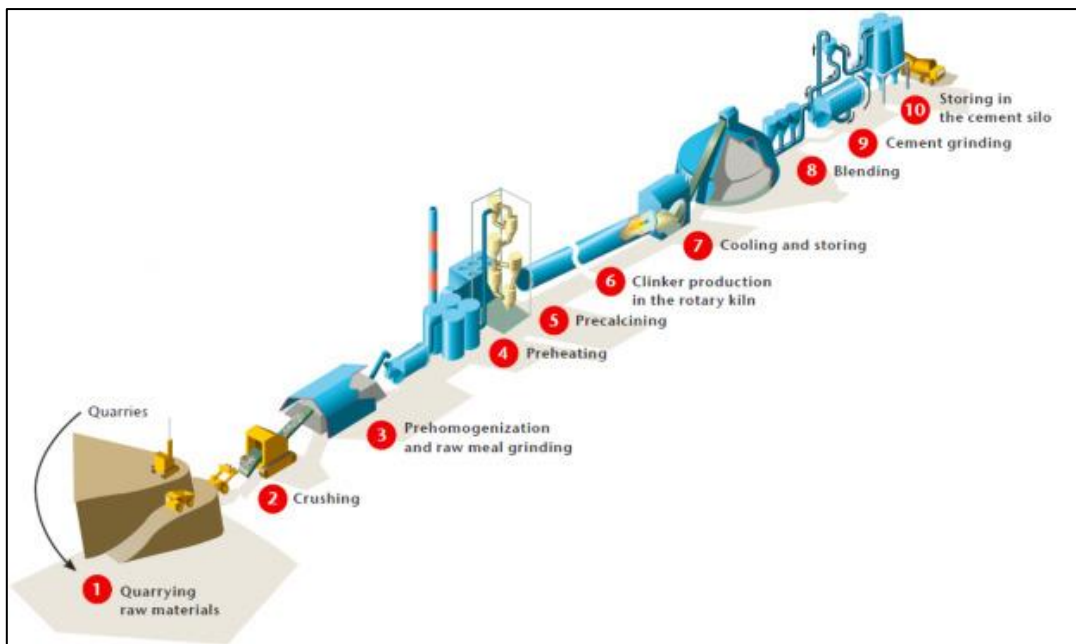


Figure 2: Process of cement manufacturing (After Mikulčič et al., 2016).

In South Africa, there are six major contributors to the cement industry with a production capacity greater than 15.6 million metric tons (MMt) per year in 2014 (Edwards, 2014). The cement market growth is driven by the demand in urban and rural development and the growth in construction activities in the country. The production statistics of 2014 indicated Pretoria Portland Cement (PPC) as the major contributor to the cement industry with a capacity of 4.75 MMt per year from eight integrated cement plants across South Africa (Edwards, 2014). Natal Portland Cement (NPC) is second producing 3.15 MMt per year between one integrated cement plant and two grinding plants situated in KwaZulu Natal (NPC, n.d.). The third largest producer at 2.05 MMt per year is AfriSam with two integrated plants and one grinding facility. Lafarge Africa is in fourth place producing 2.0 MMt per year using one integrated plant and grinding facility (Edwards, 2014). The other players in the cement market are Sephaku and Mamba. Dangote Cement from Nigeria is the major shareholder of Sephaku Cement at 64% shareholding (Edwards, 2014). The Sephaku Cement consists of one integrated cement plant and a grinding plant (Sephaku Cement, 2020). Mamba Cement currently consists of one integrated plant in Northan, Limpopo Province.

Preferably, the raw materials are located close to the market or the cement plant to ensure low cost of transportation (Morrison, 2022). The further the raw material the more expensive it is to produce cement due to logistics costs. The South African context is aligned with the proximity between the source of major raw materials required and plant facilities. The majority of the cement plants are

in areas close to enough resource supply for cement manufacturing as illustrated in Figure 3, based on the location of the current cement plants in South Africa (DME, 2003; Edwards, 2014).

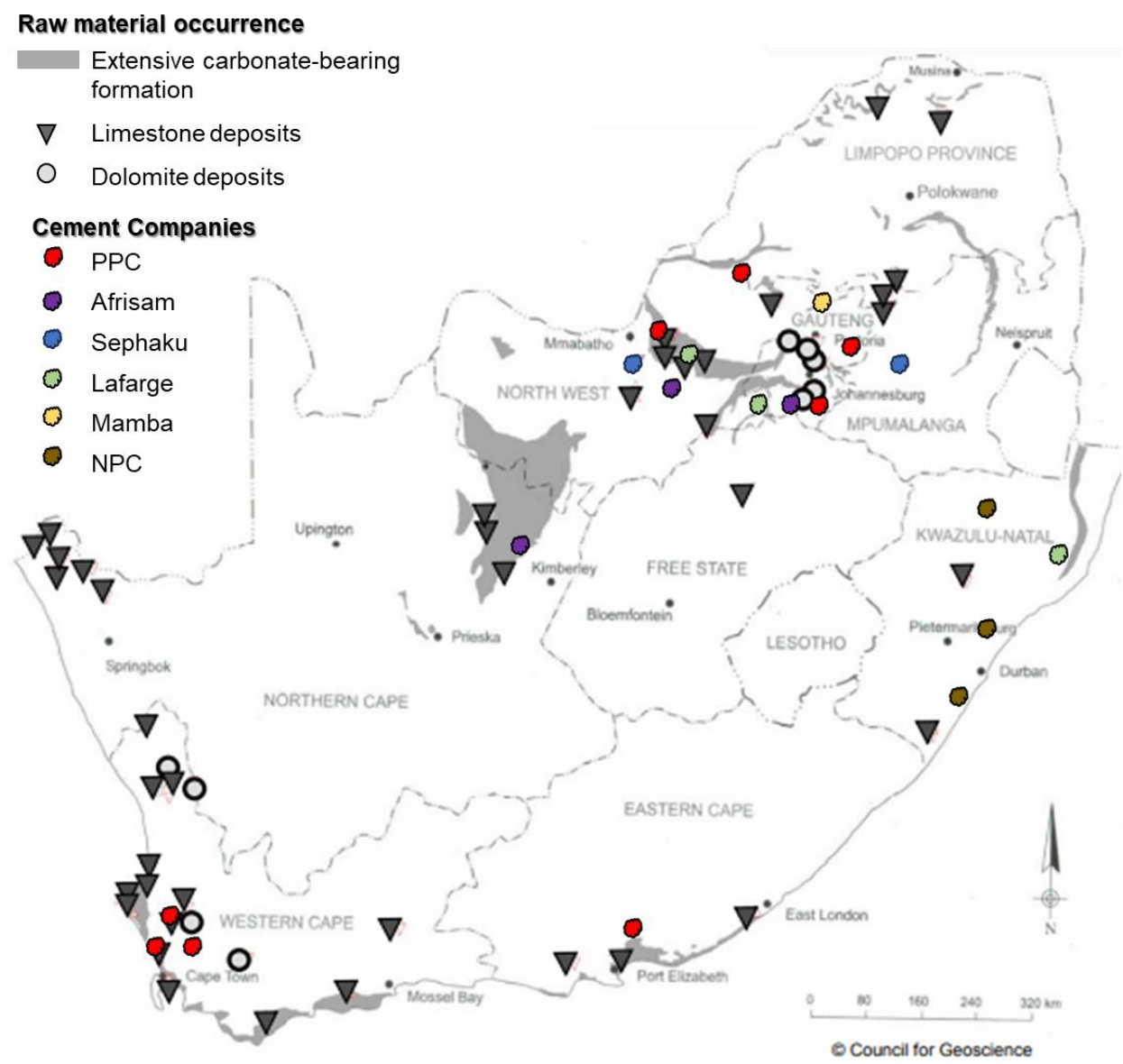


Figure 3: The limestone, carbonate-bearing, and dolomite deposits in South Africa (modified after The Department of Mineral and Energy, 2003).

3.2 Physical chemistry of cement manufacturing

The cement process is mostly influenced by the raw material performance and clinker production stage. This stage involves multiple reactions dependent on the material reactivity and burnability of raw materials in the Kiln (Chatterjee, 2018). The sequence of chemical reactions at different temperatures during the clinker production is shown in Figure 4. The identified major reactions are as follows (Chatterjee, 2018; Hills et al., 2002; Mujumdar and Ranade, 2006).

- Dehydration of the clay minerals between 27 to 600°C.
- Above 85% of calcium carbonate (CaCO_3) calcination or decarbonation occurs in the preheating and recalcining section. The chemical reaction results in CaO (lime) formation and removal of carbon dioxide (CO_2) during temperatures between 550-1000°C.
- The breakdown of aluminosilicates and solid-state reactions forming compounds such as dicalcium silicate (C_2S) due to oxides (CaO , Al_2O_3 , SiO_2 , Fe_2O_3) in the kiln feed upstream. (which temperature?)
- Liquid phase sintering and melt formation occur above 1280°C in the burning zone. Therefore, tricalcium silicate (C_3S) is formed from C_2S and free CaO in the liquid.
- Stabilisation of clinker and microstructure reorganisation during the cooling process forming tricalcium aluminate (C_3A) and tetra calcium aluminoferrite (C_4AF).
- The combustion of fuels and emission of gases occur throughout the cement process including pre-calcining and burning stages.

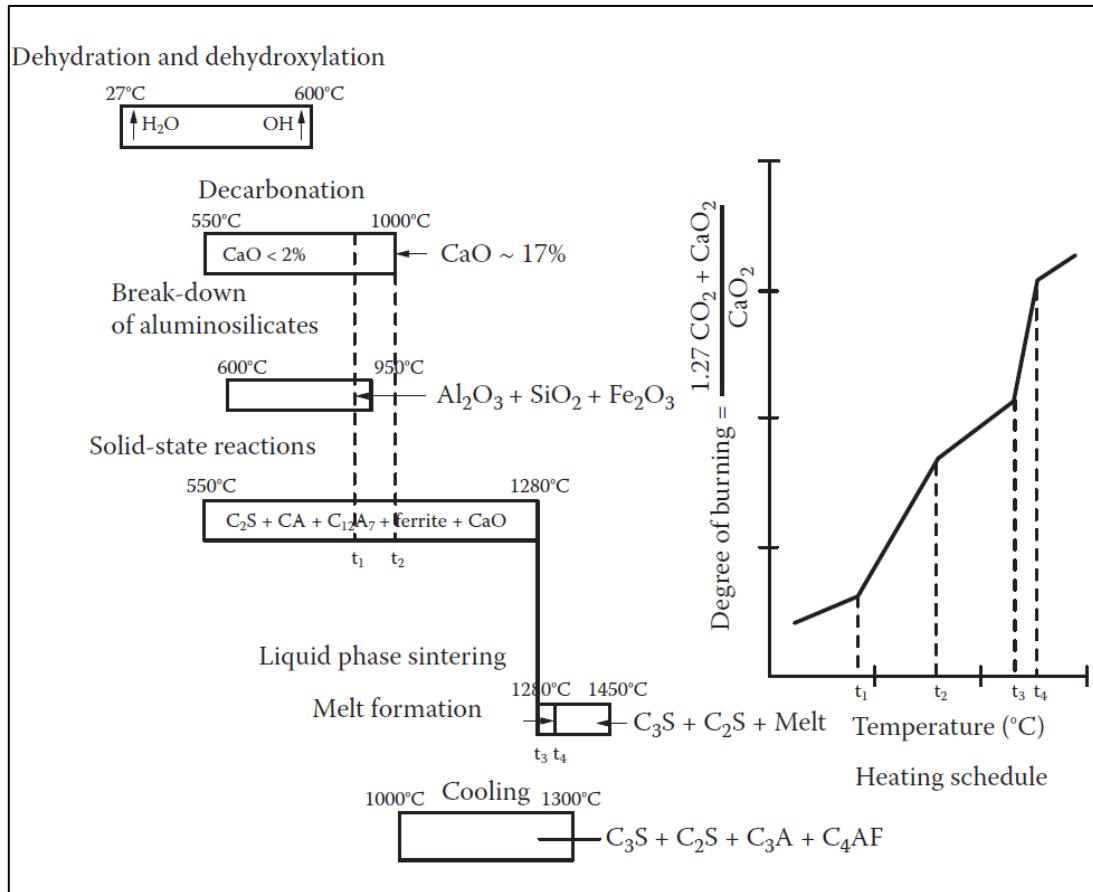


Figure 4: Reactions within the Kiln during clinker production (After Chatterjee, 2018).

3.3 Wet, Dry and Semi-dry process

The three processes of cement manufacturing are identified as wet, dry and semi-dry processes. The wet process involves mixing crushed raw material with water to form a slurry before the kiln section. The slurry is thoroughly mixed to ensure an even chemical reaction which is mostly effective in slurry form. The wet process also reduces dust emissions during the process but requires more energy to eliminate excess moisture (Dalton et al., 2004). The dry process involves mixing crushed blended material in dry form by preheating before the kiln section. The combined material is dried in the pre-heating stage to remove

moisture and break down the limestone into lime and carbon dioxide. (Fidaros et al., 2007; Mikulčić et al., 2016). The semi-dry process is a combination of the wet and dry processes. In this process, the moisture is sensibly reduced to about 1% by weight, which is necessary to moisten the ground dry and form nodules that are fed to the kiln. The semi-dry process requires less water than the wet process but more than the dry process (Macfadyen, 2006).

3.3.1 Raw Material and Crushing

The raw material in cement manufacturing includes the following natural resources: limestone (source of calcium oxide – CaO), sandstone (source of Silica – SiO_2), iron ore (Fe_2O_3), bauxite (source of alumina- Al_2O_3), clay (SiO_2 , Al_2O_3 , Fe_2O_3), and gypsum (CaSO_4) (Madani-Hosseini et al., 2011; Mikulčić et al., 2016). At this stage different raw materials are crushed into 2-5 cm size pieces separately, milled to fine grain material, and stored into silos before mixing to the required proportion and heated in Kilns (Fidaros et al., 2007). Portland cement clinker production requires fine-grained siliceous materials hence the need to crush the material to the required grain size. Natural resources used are selected based on the chemical and mineralogical composition required for cement manufacturing. The mineralogical composition of Portland cement is shown in Figure 5 with lime (CaO) as the dominant chemical composition at 63.68% by weight. In some cement-producing processes, Fly ash from coal-fired power plants is used to stabilize the chemistry by balancing chemical compositions required for cement manufacturing (Mashifana, 2018).

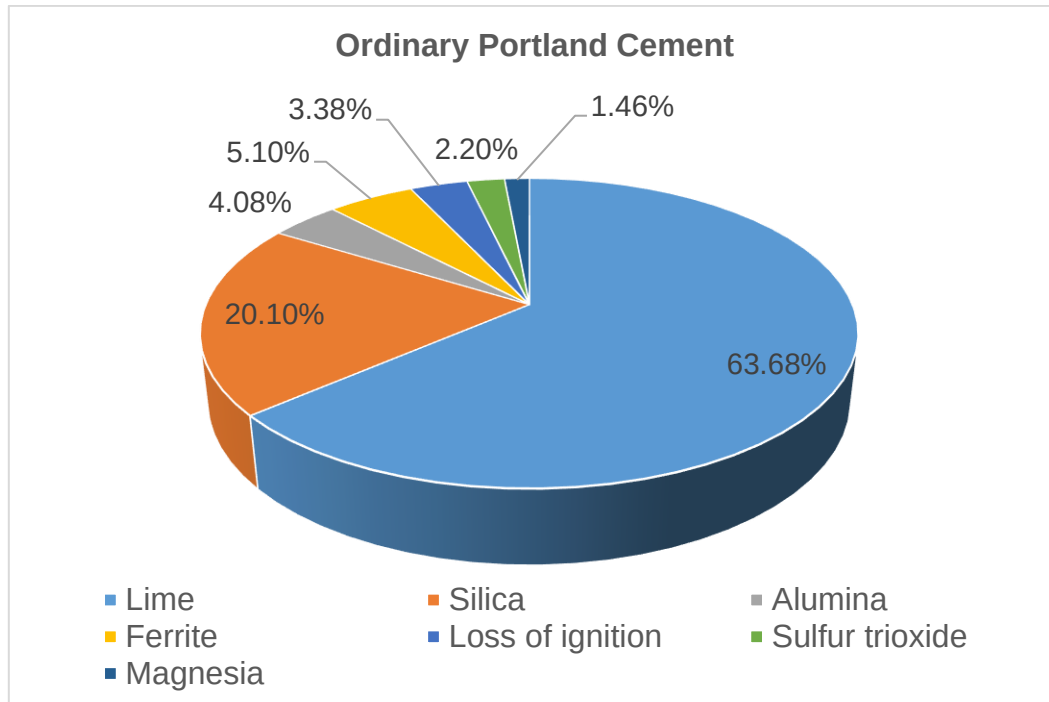


Figure 5: Chemical composition of Portland cement (after Mahmood et al., 2021)

3.3.2 Clinker Production

The mixed raw material is heated at temperatures of about 1450°C in the rotary kiln with a multi-stage cyclone. In this stage, the chemical composition at the correct proportions produces calcium silicate compounds, which are granulated grains called “clinker” (Madani-Hosseini et al., 2011). Different oxides (lime, silica, alumina and iron oxide) interact with one another in the kiln at high temperature to form more complex compounds. Tricalcium silicate and dicalcium silicate are the most important compounds responsible for required properties of cement such as strength (Mikulčić et al., 2016). The subsequent clinker is then cooled down before being ground by a ball mill and finally mixed with 5% gypsum to regulate setting time (Madani-Hosseini et al., 2011; Mikulčić

et al., 2016). Additionally, silica in cement imparts strength and in excess, the setting time is prolonged (Ince, 2019).

The chemical composition required in cement manufacturing is important to serve as a base for the comparative study that will take place in this research. Table II summarises the percentage composition of materials (clinker phases) used in cement manufacturing based on Portland cement (PPC Africa, n.d.; Wang et al., 2019). The highest is with the tricalcium silicate (55-70%), and the lowest being the calcium oxide (<1.5%) and gypsum (2-5%) (Madani-Hosseini et al., 2011; Mikulčić et al., 2016; PPC Africa, n.d.). The chemical reaction of lime and silica in the kiln at higher temperatures produces dicalcium silicate (C_2S), tricalcium silicate (C_3S) called belite and alite, respectively. The formation of tricalcium silicate is the hardest step in the clinker production, while tricalcium aluminate (C_3A) and tetracalcium aluminoferrite (C_4AF) form at low temperatures of less than $1350^{\circ}C$ (Hills et al., 2002).

Table II: Chemical composition of Portland cement. (After Wang et al., 2019, PPC Africa, n.d.)

Composition	Chemical formula	Composition range
Tricalcium silicate (C_3S)	$3CaO \cdot SiO_2$	55 – 70%
Dicalcium silicate (C_2S)	$2CaO \cdot SiO_2$	5 – 20%
Tricalcium aluminate (C_3A)	$3CaO \cdot Al_2O_3$	2 – 10%
Tetra calcium aluminoferrite (C_4AF)	$4CaO \cdot Al_2O_3 \cdot Fe_2O_3$	5 – 15%
Gypsum	$CaSO_4 \cdot 2H_2O$	2 – 5%
Calcium oxide (Lime)	CaO	< 1.5%

3.4 Characterisation of cement

3.4.1 Physical properties of cement

The key physical properties used to classify cement include fineness, soundness, strength, consistency, heat of hydration, setting time, loss of ignition, bulk density, and specific gravity. The fineness of cement is measured by grain size and grain size distribution. Finer cement offers a greater surface area for hydration and hence faster the development of strength. In general, the higher the fineness the higher the strength of the cement (Elbagermi et al., 2020). The fineness test involves passing the cement samples through sieves of standard mesh sizes of 150 μm and 75 μm (Jillavenkatesa, 2001).

Soundness is the ability of cement to resist expansion after hardening. A good cement would mean cement with less or no change in volume after it converts into a hardened state. Soundness is measured using Le-Chatelier and autoclave method (Zhang, 2011). Le-Chatelier method assesses the cement expansion by measuring lime content in cement. High lime content will make the cement unsound, resulting in a delay in cement setting. The test measures the distance between indicator points after it had been immersed in water and then boiled. Quality cement should not exceed 10mm for distance between indicator points (Elbagermi et al., 2020). The autoclave method uses an autoclave, which is a high-pressure steam container, to determine cement expansion. As soundness refers to the ability to resist volume expansion, a quality cement should have 0.80% volume expansion (Zhang, 2011).

Cement strength refers to compressive, tensile, and flexural strength. These strengths can be affected by a number of items such as water-cement ratio, cement-fine aggregate ratio and curing period (Elbagermi et al., 2020). Compressive strength is the most common test conducted in practice. The standard test is carried out according to American Society for Testing and Materials, ASTM-C109 and American Association of Highway and Transportation Officials, AASHTO-T106, where a 50mm cement mortar cube is compressed until failure (Zhang, 2011).

Cement consistency is the ability of cement to flow consistently, and it is influenced by the water-cement ratio. The consistency is measured with the Vicat test apparatus. A good consistency is achieved when the plunger of the Vicat can penetrate the 10 ± 1 mm (Elbagermi et al., 2020).

The heat of hydration is the heat generated during the reaction of water and cement. It is measured by the heat conduction calorimeter. The cement fineness, C_2S , C_3A and water-cement ratio affect the hydration rate (Zhang, 2011).

Loss of Ignition is a measure of loss of weight post heating of cement between $900 - 1000^\circ\text{C}$ until a consistent weight is achieved. The incorrect storage of cement resulting in more than three percent loss of ignition, which is a result of the cement carbonation and pre-hydration (Leco, n.d.).

The setting time of cement is classified as the initial and final setting time. Initial setting time (up to 45 minutes) is the time it takes for the cement to mix with other materials such as aggregate and water to form a solid. The final setting time (below 10 hours) is the time it takes for the cement mortar to harden and be able to take load. The Vicat apparatus is used to determine the setting time (Zhang, 2011). In addition, cement is characterised by bulk density and specific gravity. The bulk density is the weight of cement particles per unit volume of cement sample (Helsel et al., 2015).

3.4.2 Radioactive Elements in Cement

The raw materials used in the process of cement manufacturing contain radioactive materials. The measure of natural radioactivity is in becquerel (Bq) and curie (Ci). To assess the effective and equivalent dose for human exposure to radiation and medical influence of the radiation category post-exposure, the radioactivity can be measured in sieverts (Sv) and roentgen equivalent man (rem), respectively. The global average specific radioactivity for construction materials is 50 Bq/kg for radium, 50 Bq/kg for thorium, and 500 Bq/kg for potassium (UNSCEAR, 1993; Stojanovska et al., 2010). In the case of radium, the material is considered unsafe when the equivalent activity is greater than 370 Bq/kg (Norloch et al., 2019). Human exposure to radiation from cement used in construction must be below 0.3 mSv per year according to the European Commission (1999).

The radioactivity content of the raw material used in cement manufacturing was studied by Narloch et al. (2019) and Stojanovska et al. (2010). Both studies used

gamma-ray spectrometry to investigate the radioactivity content of raw materials used in Portland cement. Stojanovska et al. (2010) investigated the radioactivity content in Portland cement with less than 97% clinker and 3% natural gypsum, with a maximum of 15% and 30% component of pozzolan, fly ash and limestone (CEM II/A-M and CEM II/B-M, respectively). The following radioactive elements (nuclides) were identified, uranium (^{238}U) and thorium (^{232}Th), radium (^{226}Ra), lead (^{210}Pb), and potassium (^{40}K).

Stojanovska et al. (2010) revealed that Portland cement with natural gypsum has the lowest radioactivity concentrations: 42 ± 10 Bq/kg for ^{226}Ra , 28 ± 6 Bq/kg for ^{232}Th ; 264 ± 50 Bq/kg for ^{40}K . The equivalent activity for cement with pozzolan and fly ash was higher than the global average specific activity: 107 ± 45 Bq/kg for ^{226}Ra , 109 ± 30 Bq/kg for ^{232}Th , and 685 ± 171 Bq/kg for ^{40}K . Stojanovska et al. (2010) also found that the effective and equivalent dose for human exposure to Portland cement is at a lower level, 0.111 ± 0.022 mSv per annum.

Narloch et al. (2019) similarly quantified the radioactivity levels of radium, thorium, and potassium in Portland cement, phosphogypsum mortar, natural gypsum, and sand. The study focused on the concentration of radon released in the atmosphere by building materials, equivalent and effective dose, and absorbed dose rate. Some parameters related to the hazard index such as alpha hazard, gamma, internal and external hazard index were also investigated. Narloch et al. (2019) found radium levels within acceptable range (11.4 – 41.27 Bq/kg), whereas the radon levels found in the air were above 300

Bq/m³ for Portland cement (854 Bq/m³) and sand (427 Bq/m³). However, the application of paint on the wall is required in residential areas to reduce the radon concentration where the atmospheric concentration is above 300 Bq/m³.

3.4.3 Heavy Metals in Cement

The raw materials used in the process of cement manufacturing contain heavy metals like chromium (Cr), nickel (Ni), cobalt (Co), lead (Pb), potassium (K), thorium (Th), uranium (U) and mercury (Hg) (Stojanovska et al., 2010). Some of these metals Cr, Ni and Hg, are known as toxic and carcinogens. Other elements including Th, Pb, Hg and U are radioactive (Okewale and Grobler, 2023).

Ince (2019) and Dalton et al. (2004) reported that the presence of heavy metals in natural raw materials has an impact on the clinker phase and the hydration time of the cement, which determines the setting time and strength development. The presence of zinc influences the strength of cement by forming zinc silicate that influences the setting time and the ability to resist harsh environmental conditions such as freezing and melting resistance. Chromium influences the viscosity of clinker and hydration process, and it improves the curing time by introducing earlier strength of cement. However, chromium in the Cr (IV) compound is toxic compared to Cr (III). The exposure of humans to Cr (IV) compounds through inhalation affects the respiratory system (Okewale and Grobler, 2023). The presence of pyrite in the material causes the production of sulfur dioxide emissions. However, due to the limestone ratio to the pyrite, the emission of sulfur dioxide is mitigated with carbon dioxide in the kiln (Dalton et

al., 2004). In addition, Bhatti (1995) highlighted the presence of heavy metals as a possible influence in the increased cement plant maintenance due to the different ways the metal reacts in the cement process and the output material produced.

3.5 Gold Tailings as a Substitute in Cement Production

A feasibility study on gold tailings as a substitute in cement production was conducted using gold tailings from Hexi Gold Mine, in Shandong Province of China (Wang et al., 2019). The study compared the mineralogical phases of the clinker, hydration products of cement, and physical properties of cement using gold tailing as a substitute in cement production compared to Portland cement produced using natural raw materials. In addition, the study investigated setting time, consistency, bending strength, compressive strength of cement, and burnability analysis on the ordinary raw material used in cement manufacturing. The latter was compared to cement manufactured using gold tailings material.

The mineral composition of cement is depended on the control of ratios of oxides materials added to achieve the desired cement clicker modulus during the process of sintering at 1450 °C (Xu et al., 2018 cited in Wang, 2019). The XRD pattern of the gold tailings indicates the presence of quartz, feldspar, and mica. The chemical compositions of raw materials used in the manufacturing of Portland cement and gold tailings from Hexi Gold Mine are shown in Table III (Wang et al., 2019). The Hexi Gold tailings have a high percentage of silica or quartz content and can substitute the natural sandstone. Additionally, gold tailings can provide Al_2O_3 from feldspar and mica, which is required in cement

manufacturing. This can potentially reduce the use of natural bauxite, commonly added during Portland cement production.

Table III: The chemical composition of the Hexi gold tailing and the natural raw material used in Portland cement (Modified after Wang et al., 2019).

Chemical Formulae	Hexi Gold tailing	Sandstone	Limestone	Bauxite	Iron correction material
SiO₂	72.9%	91.6%	5.7%	39.1%	56.0%
CaO	1.1%	0.3%	48.3%	0.9%	1.9%
MgO	0.08%	0.37%	2.81%	1.34%	3.89%
Fe₂O₃	1.11%	1.69%	0.42%	11.13%	35.32%
Al₂O₃	13.7%	3.2%	1.2%	33.8%	2.1%
K₂O	5.32%	0.2%	0.4%	0.3%	0.0%
Na₂O	3.04%	0.2%	0.1%	0.1%	0.0%
SiO₃	0.16%	0.6%	0.2%	1.5%	0.2%
LOI	2.0%	1.1%	40.9%	11.7%	0.5%

The effortlessness of raw materials to be converted into clinker phases is measured by the burnability index, quantified by the amount of unreacted lime (free lime) remaining in the Kiln with an increase in temperature (Hills et al., 2002). The higher the free lime, the more difficult it is for raw material to burn. Wang et al. (2019) reported that the amount of free CaO in both Portland cement and gold tailing cement decreases with an increase in temperature during the formation of alite (C₃S) and belite (C₂S), indicating higher burnability. However, the free lime content is lower in gold tailing cement than in the ordinary Portland

cement produced from sandstone. Therefore, clinker production using gold tailings indicates higher burnability (high reaction). Wang et al. (2019) claimed that high burnability index with gold tailings as SCM results from the presence of Al_2O_3 in feldspar which poses the likelihood of silica in feldspar reacting with the lime compared to sandstone-manufactured Portland cement. Furthermore, larger particle sizes have a negative impact on the calcining process of the clinker. Therefore, the milling of raw materials would be required to produce fine particle sizes which are beneficial in the burnability of raw materials in cement manufacturing.

Wang et al. (2019) reported that physical properties such as fineness, soundness, consistency, and setting time are similar for the gold tailing cement (GTC) and ordinary Portland cement using raw sandstone (OPC-SS). In addition, the maximum particle size for the gold tailings is 67.51 μm , which is below 75 μm similar to OPC-SS and sandstone used in cement production. The study further indicated that compressive and flexural strength for both GTC and OPC-SS increase with an increase in curing time. The physical properties of gold tailing cement were found to align with the Chinese standard (GB/176, 2017). The Hexi gold tailing was therefore considered as a suitable substitute according to Chinese Legislation on the use of tailings in cement production.

4 METHODOLOGY

The methodology was aligned to provide directions to answer the research objectives as directly linked to the research questions. The research methodology is predominantly desktop study with a combination of data obtained from previous research studies conducted on cement production using tailings and data obtained from the Harmony tailing operations. The mineralogical and chemical analysis was carried out on seven samples of gold tailings in the Klerksdorp Goldfield near Klerksdorp town in North -West Province (South Africa).

4.1 Sample collection

Different samples were collected through auger drilling using 1.5 meters of sample extraction down the drill hole, from the top to the bottom of the TSF (full meaning of TSF). The auger drill advances using the downward force from the drill rig combined with a clockwise rotation. The drill-hole samples were dried at 60°C and deagglomerated to remove lumps. The samples were extracted at every 12 - 15 meters intervals down the drill hole from the upper bench of the TSF to the bottom. The drilling resulted in 3 maximum composite samples for a TSF with an average depth of 45 meters. The composite samples were subjected to 10-way rotary splitter to blend and obtain representable sub-samples. The first sub-sample was pulverised for qualitative mineral composition (XRD) and the second was for chemical composition analysis to determine the major and minor elements in the sample. The third sub-sample was prepared for 100 normal polished sections for trace mineral search (TMS)

and two 90°-transverse polished sections for the bulk mineralogy analysis (BMA). An illustration of the preparation of respective polished sections is shown in Figure 6 (SGS, 2020).

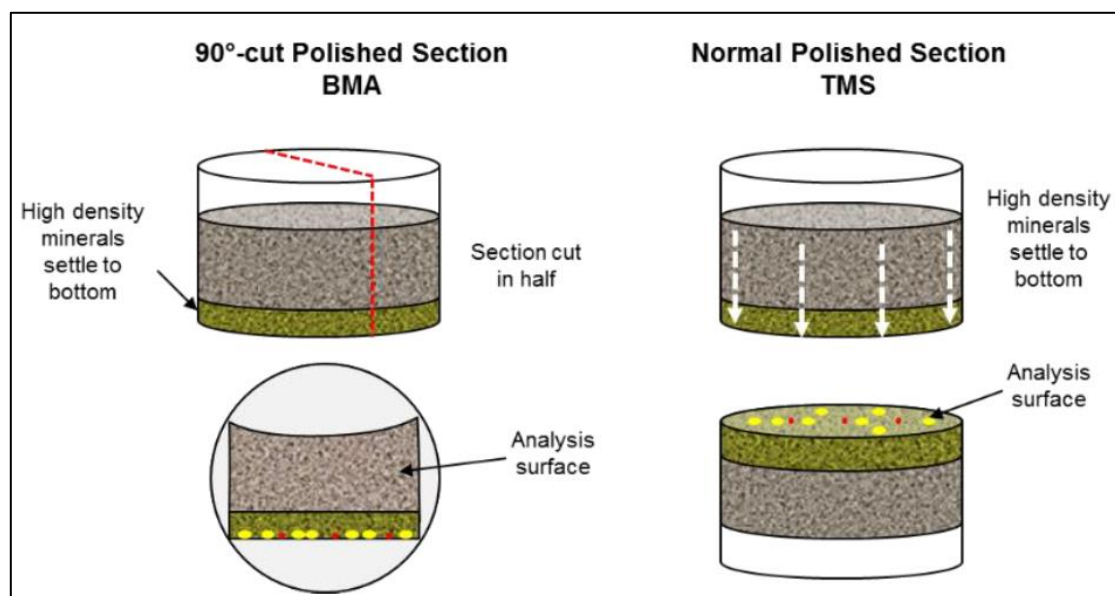


Figure 6: An illustration of the preparation of 90° transverse and normal polished sections (SGS, 2020).

4.2 Sample characterisation

TESCAN Integrated Mineral Analyzer (TIMA), in conjunction with qualitative X-ray diffraction (XRD) analysis, were used for BMA, TMS, chemical composition. The X-ray fluorescence technology (XRF) was used to determine the uranium in parts per million (ppm).

4.2.1 TESCAN Integrated Mineral Analyzer (TIMA)

TESCAN Integrated Mineral Analyzer (TIMA-X) is an automated scanning electron microscopy mineralogy solution that provides rapid chemical

compositions and textures of solid material using four energy-dispersive X-ray detectors. The TIMA is used to scan the polished sections prepared from the composite samples. The TIMA in conjunction with the XRD were used to identify and quantify the mineralogical characteristics of the composite samples. The Bulk Modal Analysis (BMA) determines mineral composition of the composite samples.

4.2.2 X-ray diffraction (XRD) analysis

The XRD method is a tool used to identify and quantify the mineralogy of crystalline compounds to provide bulk mineralogy of the sample. The XRD results confirmed the presence of the gangue minerals and agreed with the data obtained using the TIMA. The XRD analysis was limited to identifying crystalline minerals with concentrations greater than 3% (mass) in the sample.

4.2.3 X-ray fluorescence (XRF)

The XRF machine is an analytical tool used to determine the qualitative and quantitative elemental composition of the composite samples. This technique uses the primary X-ray source to excite the atoms to emit secondary fluorescent X-ray that produces certain signature unique to that specific element. The composite sample material was first pulverized before being pressed into a pellet for Uranium analysis. The pressed pellet was then taken in for elemental analysis of uranium or other trace elements.

5 RESULTS AND DISCUSSION

5.1 Mineralogy and Chemical Composition

In Portland cement production, the typical raw minerals contain 75% limestone (CaCO_3) and 15% clay (SiO_2 , Al_2O_3 , Fe_2O_3). The remaining 10% consists of sand (SiO_2), iron ore (Fe_2O_3), bauxite (Al_2O_3) depending on the clay used, and 5% gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) after the clinker is cooled and pulverised (Madani-Hosseini et al., 2011). Table IV shows the mineralogical results obtained from seven gold tailings collected from the Klerksdorp gold tailings near Klerksdorp town.

Silica (SiO_2) accounts for 69.1 – 84.6 % of the bulk mineral as a result of the nature of the original ore mined underground consisting of quartz and chert pebbles within the conglomerate reef band. Clay minerals range between 1.8 – 7.4%, typically utilised for its source of aluminosilicate. The presence of mica minerals (9.9% maximum) and small amounts of feldspar (2.7% maximum), particularly in the form of plagioclase mineral, has a notable impact on the formation of Al_2O_3 in cement. The carbonate minerals representing natural raw material for lime (CaO), has a very limited range within the gold tailings, typically spanning from 0.1 to 2.0%.

Table IV: Mineralogical results of the Wits gold in the Klerksdorp area

Mineral	Chemical Formula	Klerksdorp Gold Tailings							Mean
		East	MWS 5	MWS 4	Buffels 5	Buffels 1	Abandon	Ariston Gully	
Pyrite	FeS ₂	1.0%	1.3%	1.5%	1.0%	0.6%	0.3%	0.9%	0.9%
Arsenopyrite	FeAsS	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Quartz	SiO ₂	69.1%	83.9%	82.4%	80.9%	81.2%	84.6%	82.3%	80.3%
Plagioclase	(Ca,Na)AlSi ₃ O ₈	2.7%	0.5%	0.6%	0.4%	0.7%	0.3%	0.3%	0.8%
K-Feldspar	KAlSi ₃ O ₈	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Micas	K(Mg,Fe) ₃ (AlSi ₃ O ₁₀)(OH) ₂	9.9%	5.8%	6.0%	6.4%	6.1%	4.7%	5.6%	6.5%
Amphiboles/Pyroxene	Ca ₂ [Mg ₄ (Al,Fe)]Si ₇ AlO ₂₂ (OH) ₂	3.1%	0.1%	0.2%	0.1%	0.2%	0.0%	0.1%	0.6%
Clays	Al ₂ O ₃ 2SiO ₂ 2H ₂ O	7.4%	2.4%	2.1%	2.8%	2.5%	1.8%	2.5%	3.1%
Chlorite	(Fe,Mg,Fe) ₅ Al(Si ₃ Al)O ₁₀ (OH,O) ₈	3.8%	2.3%	2.2%	3.6%	3.8%	3.1%	3.5%	3.1%
Other Silicates	(Mg,Fe) ₃ (Si,Al) ₄ O ₁₀ (OH) ₂	0.7%	0.7%	0.6%	1.0%	1.1%	0.9%	1.0%	0.8%
Fe-Oxides	Fe ₂ O ₃	1.2%	1.4%	2.6%	0.9%	0.6%	2.7%	1.3%	1.6%
Other Oxides	-	-	0.2%	0.3%	0.5%	0.3%	0.2%	0.3%	0.3%
Carbonates	(Ca, Mg,Fe,Mn) (CO ₃) ₂	0.1%	0.5%	0.5%	1.2%	2.0%	0.6%	0.7%	0.8%
Apatite	Ca ₅ (PO ₄) ₃ (OH,F,Cl)	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Titanite	CaTiSiO ₅	0.0%	0.0%	0.1%	0.0%	0.3%	0.0%	0.0%	0.1%
Ti-Oxides	TiOx	0.5%	0.4%	0.4%	0.4%	0.3%	0.4%	0.4%	0.4%
Other		0.2%	0.8%	0.5%	1.2%	0.6%	0.8%	1.5%	0.7%
Gypsum	CaSO ₄ .2H ₂ O	0.5%							0.5%

The mineral gypsum, which is often used in small amounts in cement, is observed on East TSF at less than one percent. The purpose of gypsum is to control the setting time of cement after water is added during building (Madani-Hosseini et al., 2011). Sulphide minerals in the form of pyrite (FeS_2) are present at low levels (0.3%–1.5%) in all seven gold tailings. However, the exposure of sulphide minerals to atmospheric oxygen and water may likely result in formation of sulphuric acid (called acid mine drainage) and dissolved iron. The acid runoff can dissolve heavy metals into groundwater while dissolved iron can precipitate to form the sediments in the bottom of streams containing mine drainage.

The chemical compositions of Wits gold tailings from Klerksdorp gold mine are shown in Table V. For comparison purposes, the chemical compositions of Portland cement and Hexi gold tailings are listed in Table V. The typical chemical composition of Portland cement for clinker production is 63.7% CaO , 20.1% SiO_2 , 4.1% Al_2O_3 , 5.1% Fe_2O_3 , 1.5% MgO and LOI at 3.4% (Mohammed et al., 2021). The Klerksdorp gold tailings contain a lower CaO of 0.5%, and a higher SiO_2 of 83.3% similar to Hexi gold tailings. The Al_2O_3 content is high at 6.2% and 13.7 % in Klerksdorp and Hexi gold tailings, respectively, while the Portland cement contains 4.1% Al_2O_3 .

The presence of MgO influences the volume instability by delayed expansion due to its expansion property Simonsen et al.(2020). Higher MgO content has the potential to aggravate the volume shrinkage in clinker production, reduce cement strength and extend setting time (Liu and Li, 2005). The required

amount of MgO within cement production should be between 2 – 3% (Simonsen et al., 2020). The MgO content for the Klerksdorp gold tailings spans between 0.2 – 0.9% as shown in Table V. The solution to lower MgO can be resolved during the calcination of carbonate mineral or by adding bauxite mineral with reasonable MgO content as shown in Table III and that comes in with additional benefit of Fe_2O_3 , Al_2O_3 and SiO_2 .

Wits gold tailing is pozzolanic in nature due to the sum of the dominant oxides (Al_2O_3 , SiO_2 , and Fe_2O_3) that is greater than 70% (Morrison, 2022; Ince, 2019). The pozzolanic material is a fined-grained aluminosilicate that can harden as a result of moisture reacting with calcium hydroxides to produce cementitious properties (Simonsen et al., 2020). The effective use of gold tailings from Klerksdorp mines still requires a calcium-rich material to produce cementitious properties during cement manufacturing.

For potential hydraulic activity to take place, the sum of CaO and SiO_2 content must be greater than 50% by weight. It is evident that Wits gold tailings can exhibit hydraulic properties because the sum of CaO and SiO_2 content, as specified in Table V is above 50%. Portland cement and Hexi gold tailings also indicate hydraulic properties with the sum of CaO and SiO_2 that is more than 50%. In terms of contribution of each oxide, Wits gold tailings are significantly low in CaO content required in cement manufacture while the aluminosilicate minerals are reasonably high resulting in pozzolanic nature.

Table V: Chemical Compositions of Wits gold tailings from the Klerksdorp area, Portland cement and Hexi Gold tailing

Chemical Name	Chemical Formulae	Portland cement (Mahmood et al., 2021)	Hexi Gold tailing (Wang et. Al, 2019)	Vaal River and Stilfontein Gold Tailings							Mean
				East TSF	MWS 5	MWS 4	Buffels 5	Buffels 1	Abandon	Ariston Gully	
Alumina	Al ₂ O ₃	4.1%	13.7%	8.4%	7.0%	9.1%	8.4%	8.5%	6.2%	7.7%	7.9%
Lime	CaO	63.7%	1.1%	1.1%	0.9%	0.5%	1.0%	0.9%	1.1%	0.9%	0.9%
Chromic oxide	Cr ₂ O ₃	-	-	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Ferrite	Fe ₂ O ₃	5.1%	1.1%	3.3%	2.8%	3.3%	2.8%	2.6%	3.3%	2.9%	3.0%
Potassium Oxide	K ₂ O	-	-	1.6%	1.5%	1.2%	1.3%	1.6%	1.0%	1.3%	1.3%
Magnesia	MgO	1.5%	0.1%	0.5%	0.5%	0.5%	0.3%	0.9%	0.5%	0.5%	0.5%
Manganese Oxide	MnO	-	-	0.1%	0.1%	0.0%	0.1%	0.1%	0.3%	0.1%	0.1%
Sodium oxide	Na ₂ O	-	3.0%	0.2%	0.2%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%
Phosphorus pentoxide	P ₂ O ₅	-	-	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Silica	SiO ₂	20.1%	72.9%	80.2%	83.0%	81.9%	82.4%	82.2%	83.3%	82.4%	82.2%
Titanium Oxide	TiO ₂	-	-	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%
Vanadium pentoxide	V ₂ O ₅	-	-		0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Loss of Ignition (LOI)	LOI	3.4%	2.0%	2.7%	2.9%	2.7%	3.4%	2.6%	3.3%	2.8%	2.9%
Pozzolanic character	Sum (Al ₂ O ₃ , SiO ₂ , Fe ₂ O ₃)	29.3%	87.7%	91.9%	92.9%	94.3%	93.5%	93.3%	92.8%	93.0%	93.1%
Hydraulic activity	Sum (CaO, SiO ₂)	83.8%	73.9%	81.3%	83.9%	82.4%	83.4%	83.1%	84.4%	83.3%	83.1%

5.2 Comparison between Portland Cement, Wits and Hexi Gold Tailings

An averaged composition of gold tailings was calculated based on data reported in Table V and compared to the chemical compositions of Portland Cement and Hexi gold tailings (Figure 7). Comparing Hexi and Wits gold tailings reveals that some oxide contents are similar. Both gold tailings have high silica content (SiO_2), high alumina content (Al_2O_3), and low lime content (CaO). The pozzolanic nature is high for both tailings, Wits gold tails is also Hexi gold tailings. The silica content provides strength during its reaction with lime to form dicalcium silicate (C_2S) and tricalcium silicate (C_3S). Silica in excess improves the cement strength but affects the setting time by prolonging it (Hills et al., 2002).

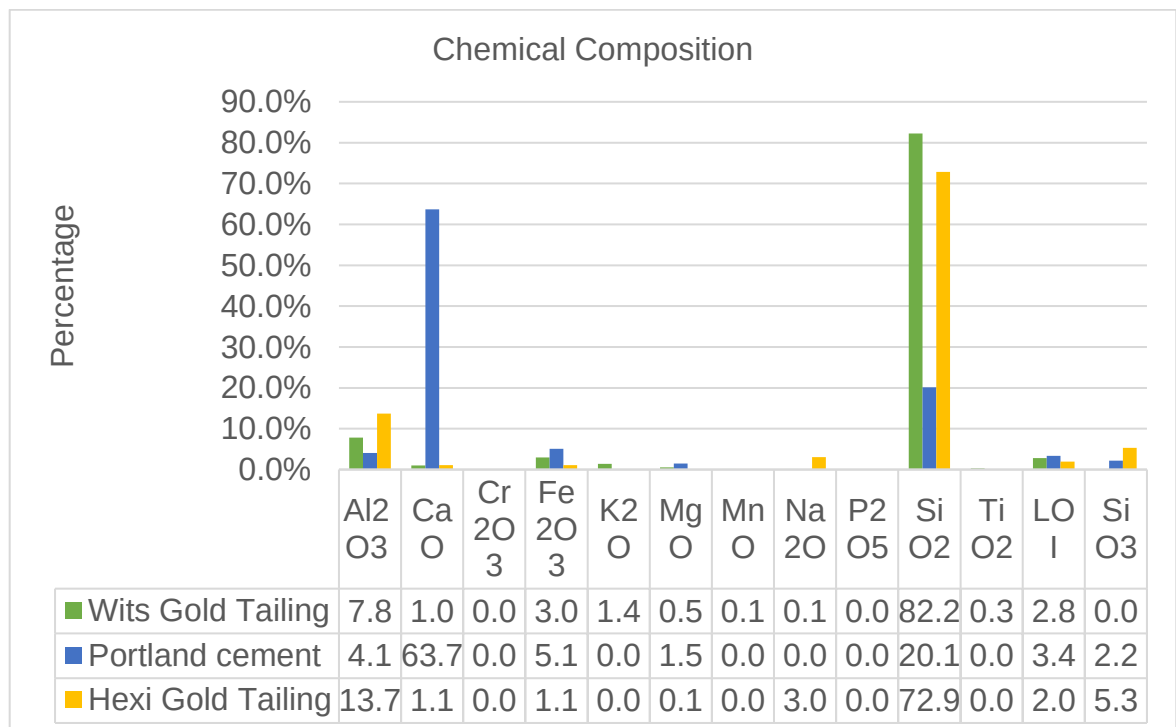


Figure 7: The chemical composition of Wits gold tailing in Klerksdorp, Hexi gold tailing and Portland cement.

The CaO is the major contributor to Portland cement manufacturing. The lime concentration of Wits and Hexi gold tailings is lower in comparison to the Portland cement content. The deficiency in CaO is associated with an increase in the proportions of alumina and ferric oxide, resulting in quick setting of cement. The comparison between chemical compositions of Portland cement and Hexi and Wits gold tailings is represented in a CaO-SiO₂-Al₂O₃ ternary phase diagram (Figure 8). The compositions of Klerksdorp, Hexi and Wits gold tailings fall in the higher SiO₂ section of the ternary phase diagram. As gold mine tailings are composed mainly of granular sand (SiO₂), it will require upgrading the chemical composition of Klerksdorp gold tailings and rearranging the crystalline phase of silica to an amorphous phase using an alkali activator. In addition, CaO content of gold tailings can be increased by adding fly ash and blast furnace slag with high CaO content as shown in Figure 8 (Torres-Carrasco and Puertas, 2017).

LEGEND

- Klerksdorp Gold Tailing (Wits Tailings)
- Hexi Gold Tailings (Wang et al., 2019)
- Wits Tailings (Malatse & Ndlovu, 2015)
- ▲ Portland Cement (Mahmood et al., 2021)
- Blast Furnace Slag (Torres-Carrasco and Puertas (2017)
- Fly-ash (Torres-Carrasco and Puertas (2017).

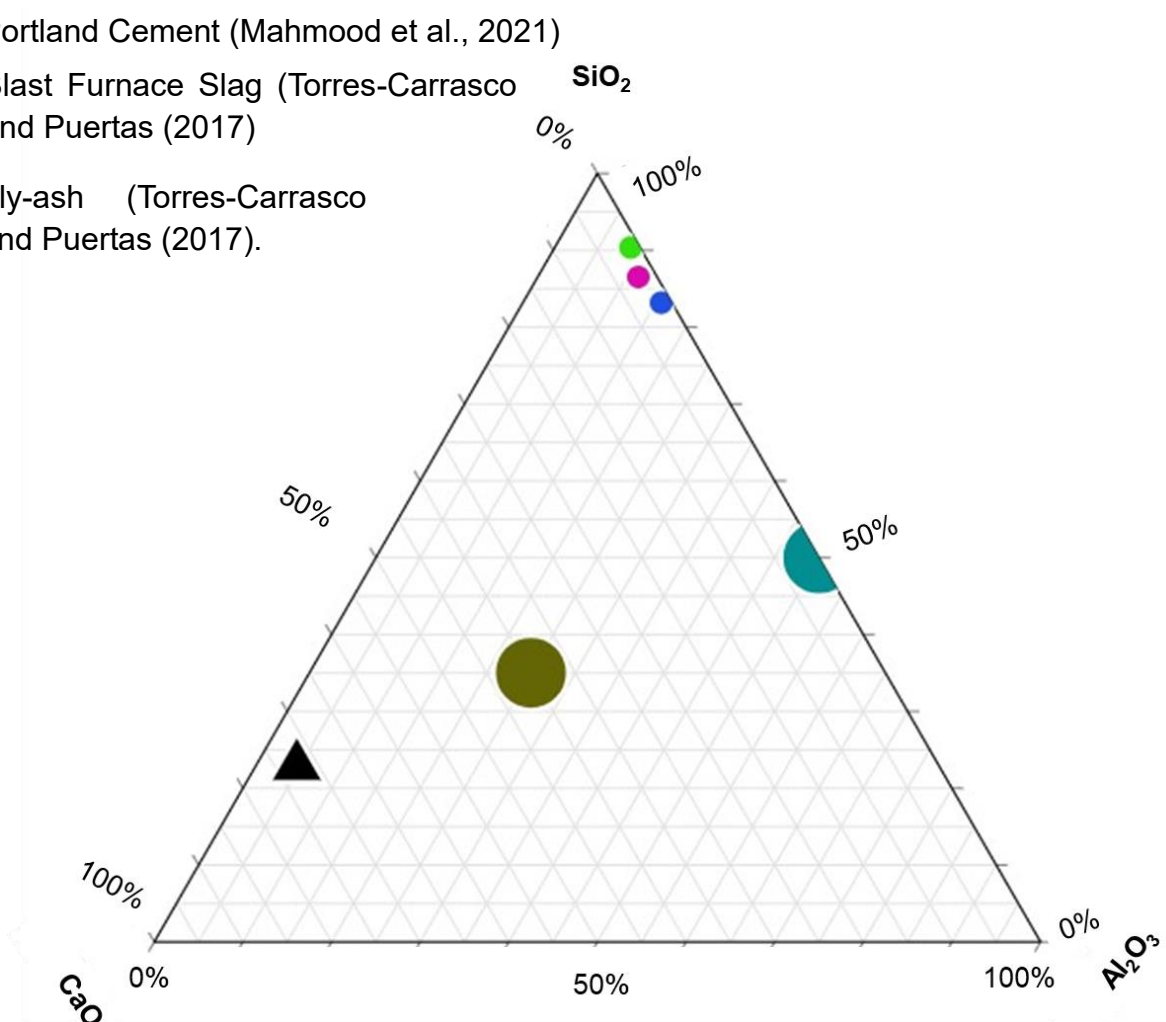


Figure 8: Ternary plot of the chemical compositions for Wits gold tailing, Hexi gold tailing, Portland cement, Blast furnace slag and Fly ash.

The Wits gold tailings can be used as sand or as cement replacement in the production of cement mortar as a result in the pozzolanic nature of the material. The high silica content in Wits gold tailings enables the material to be used as a binder substitute in cement production without exploiting natural

resources. However, excess of SiO₂ can prolong the setting time (Hills et al., 2002). The study by Ince (2019) showed not all the silica can be used since beyond 30% gold tailing resulted in a drop in compressive strength. Ince (2019) therefore recommended an optimum of 30% use of gold tailings as a supplementary cementitious material.

5.3 Physical Properties of Wits Gold Tailing

The physical properties of raw materials required in cement manufacturing depend on grain size distribution, specific surface area and sphericity or angularity of grains (Simonsen et al., 2020). The reactivity of supplementary cementitious material can be influenced by grain size distribution. The finer the particles size, the higher the reactivity, with excess water usage resulting in lower workability (Andrews et al., 2022; Simonsen et al., 2020). Coarse particle sizes can trigger inhomogeneity in cement raw material, resulting in local volumes with chemical compositions deviating from the average composition. In this research, the study was limited to the particle size distribution to determine the coarseness and fineness of the Wits gold tailing material and potential to be reactive in cement manufacturing process.

Four sieves namely, 150, 106, 75 and 25 µm were used to determine the particle size distribution of Wits gold tailings. From this sieving, five size fractions were produced namely (1) +150 µm, (2) +106 µm, (3) +75 µm, (4) +25 µm and (5) -25 µm. The particle size distributions of Klerksdorp gold tailings are plotted in Figure 9. An average particle size distribution was drawn in Figure 10, where above 88.7% of gold tailings material passed

through a 150 μm sieve, classifying the retained 11.3% as sand and 63.6 % of gold tailings passed through a 75 μm sieve, and this size fraction is classified as silty-clay. In the study by Wang et al. (2019), the maximum grain size found for the Hexi gold tailings is 67.51 μm , classifying 100% of the tailings material as silty-clay. Hexi gold tailings is finer than the Wits gold tailing with all their material passed through the 75 μm and there are no grains retained above 150 μm . Finer particles affect the early strength development of cement mortar while coarse particles contribute to later strength development (Andrews et al., 2022). In addition, a finer size fraction of gold tailings can be used as filler material as reported in open literature (Andrews et al., 2022; Simonsen et al., 2020).

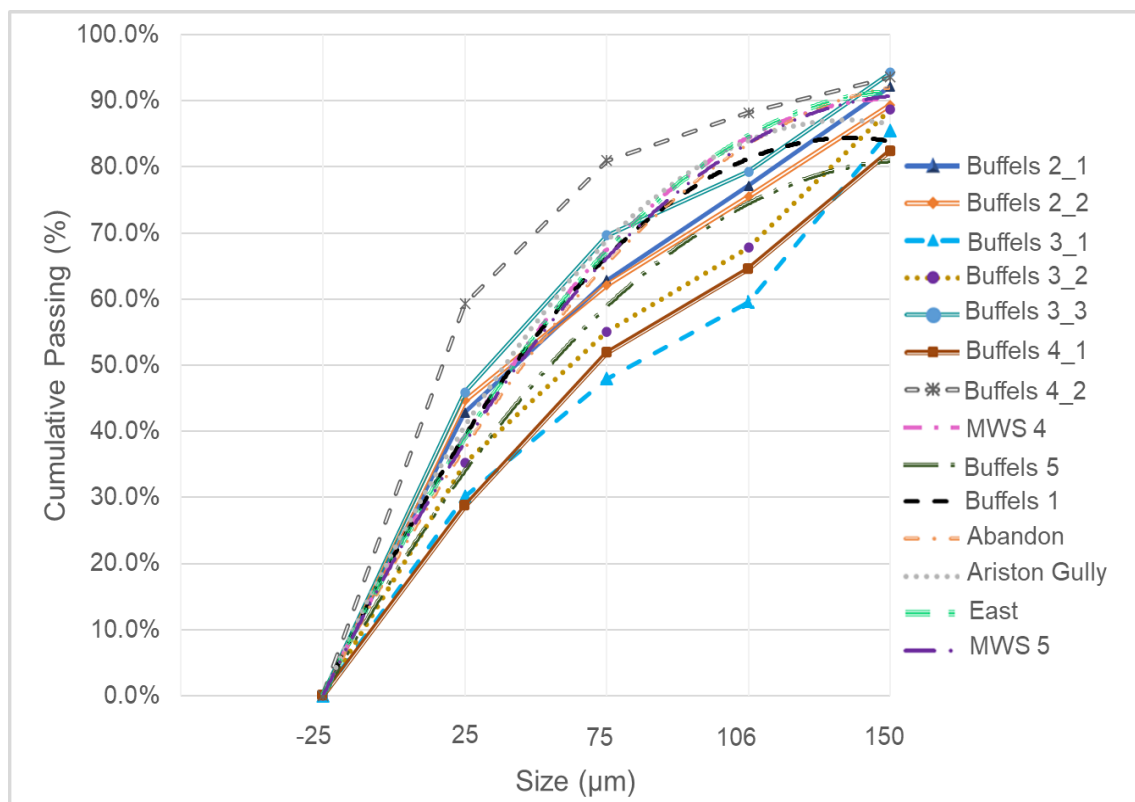


Figure 9: The particle size distribution for the Klerksdorp gold tailings

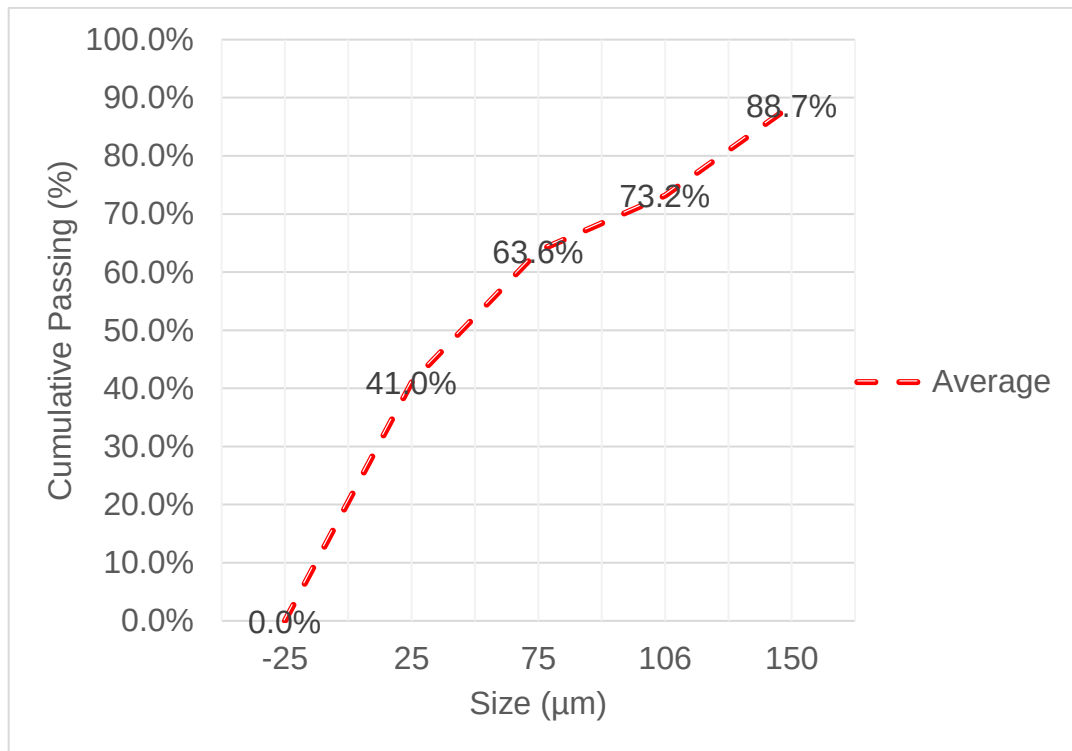


Figure 10: The average particle size distribution for the Klerksdorp gold tailings

5.4 Gold Tailings as alternative in cement production

The analysis of chemical compositions and physical properties of Wits gold tailings showed that Wits gold tailings can be successfully used as replacement for both cement and sand in cement manufacturing. Table VI summarizes the key parameters of Wits gold tailings compared to required properties of Portland cement. Wits gold tailings have high quartz and low lime minerals. The presence of silica, alumina and ferrite gives Wits gold tailings a pozzolanic nature. The lower CaO can be compensated by the addition of calcium-rich aluminosilicate such as a slag. The pozzolanic nature of Wits gold tailings combined with the addition of calcium-rich aluminosilicate triggers a chemical reaction to take place when water is added to produce

cementitious binding hydrate. However, the chemical reaction can only take place post the activation of Wits gold tailings to change from crystalline to an amorphous phase. The properties of Hexi gold tailings are also comparable to those of Portland cement. Both Wits and Hexi gold tailings can be used as cement or sand replacement during cement production.

Table VI: Requirements for gold tailings as cement replacement

	Mineralogy	Chemical	Physical	Comparison with Portland cement	Optimising pretreatment or requirements
Klerksdorp gold tailings	High Quartz Crystalline minerals	Pozzolanic activity – 93.1%	Silty clay with minor sand. (61.6 % pass through the 75 µm & 10 % retained above 150 µm).	Lower CaO (0.98%) but higher SiO ₂ (82.2%) Moderate Al ₂ O ₃ (7.3%) and Fe ₂ O ₃ (3.0%)	Requires Ca-rich aluminosilicate to use in cement.
		Hydraulic activity – 83.1%			Requires activation to change to the amorphous phase
		Low MgO – 0.5%			Add MgO mineral rich content
Hexi Gold Tailings	High Quartz Crystalline minerals	Pozzolanic activity – 87.7%	Silty clay (max grain size 67.51 µm)	Lower CaO (1.1%) but higher SiO ₂ (72.9%) Lower Al ₂ O ₃ (13.7%) and moderate Fe ₂ O ₃ (1.1%)	Requires Ca-rich aluminosilicate to use in cement.
		Hydraulic activity – 73.9%			Requires activation to change to the amorphous phase.
		Low MgO – 0.1%			Bauxite added to mitigate MgO content

5.5 Radioactivity within Wits Gold Tailings

The radioactivity concentration in Wits gold tailings was determined using XRF spectroscopy. The determination of other elements including heavy metals was carried out in aqua regia-dissolved samples using in ICP-OES (Inductively coupled plasma-optical emission spectrometry). The identified harmful heavy minerals were Cu and Cr at 47 ppm and 200 pm, respectively. The concentration of uranium was given in parts per million (ppm) and then converted to Bq/kg as shown in Table VII (Moshupya et al., 2022).

Table VII: Conversion of radioactive element.

Element	Conversion
Uranium (^{238}U)	1ppm = 12.35Bq/kg

The usage of Wits gold tailings will depend on the suitability of the gold material in terms of radioactivity. According to the National Nuclear Regulator NNR (2006), materials with ^{238}U nuclide concentration that is greater than 500 Bq/kg require monitoring and exposure control. The uranium (^{238}U) radioactivity concentration for the seven-gold tailing within the Klerksdorp area is shown in Table VIII. Based on these results, the average radioactivity concentration for ^{238}U in Wits gold tailings is approximatively 931.6 Bq /kg. This concentration level is above the regulatory limit of 500 Bq /kg. High uranium concentration in Wits gold tailings reveals that uranium was not extracted during the gold extraction process but deposited in tailings dams. The remedial action would be the reduction of radioactive element uranium through the process of photocatalyst or photoelectrochemical.

Table VIII: Identified radioactive elements.

Radioactive elements	East	Abandon	Ariston Gully	Buffels 1	Buffels 5	MWS 5	MWS 4	Mean
U²³⁸ (ppm)	115.7	62.9	73.0	31.4	55.2	89.1	100.8	75.4
U²³⁸ (Bq/kg)	1,428.5	776.2	900.9	387.8	682.0	1,100.6	1,244.9	931.6

In terms of human exposure, radiation from cement used in construction must be below 0.3 mSv per year according to the European Commission (1999) and 0.25 mSv per year according to NNR (National Nuclear Regulation, 2006). According to the study by Moshupya et al. (2022), Wits gold tailings from the West Rand site contain an effective dose of 0.51 mSv, which is above the acceptable limit. However, no effective dose was detected in this study.

6 CONCLUSION AND RECOMMENDATION

6.1 CONCLUSION

This study investigated the potential incorporation of Wits gold tailings from Klerksdorp in cement production. Based on the chemical composition, gold tailings are silica-rich (82.23%), with reasonable alumina (7.81%) and ferrite (2.98%) compared to Portland cement (20.10% silica, 4.08% alumina and 5.10% ferrite), therefore contributing to pozzolanic characteristics. The pozzolanic nature of Wits gold tailings make the material an effective supplementary cementitious material (SCM). The Wits gold tailing indicated lower CaO (0.98%) which is detrimental for cementitious properties. The deficiency in CaO in Wits gold tailings can be balanced with the addition of calcium-rich aluminosilicate from blast furnace slag, which is a waste from the Iron industry.

Approximately 64% of Wits gold tailings are fine material ($< 75 \mu\text{m}$), which can be identified as fine silty – clay grains. The fineness can predict a higher reactivity and suitability of gold tailings to act as fillers for compressive strength development in the cement mortar.

The study explored ways of reducing or eliminating the presence of hazardous substances to safer levels for the usage of tailings in cement manufacturing. The radioactivity concentration can be reduced by extracting uranium during the gold extraction process. The safe removal of heavy material and cyanide in tailing can be implemented with chlorination electrolysis which uses hypochlorite.

6.2 RECOMMENDATION

The policy in valorisation of mining waste in the South African context is still lacking and further work needs to be considered to create a framework for the usage of mining waste material in other sectors of the economy. The South African policy can incentivise mining companies to implement strategies that facilitate the utilization of mining waste to other sectors of the economy. The incorporation of circular economy principles in the mining sector has the capacity to reshape the Mining Value Chain with the aim of seamless integration of post processing material to the cement industry.

Though the usage of tailings can be possible in principle, there are costs associated with pre-treatment processes, which are required to ensure the safety of using gold tailings in the cement industry. These costs were not investigated during this study. Additional economic challenges can include transport costs when transferring tailing material to operating cement plants in various locations across South Africa. To mitigate the latter costs, it is recommended that mining companies consider entering long-term contracts or forming partnerships with potential customers.

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APPENDIX A: Mineralogical results per Klerksdorp gold tailings per bench

Mineral	Chemical Formula	Klerksdorp Gold Tailings												
		EAST TSF			MWS 5		MWS 4	Buffels 5		Buffels 1	Abandon		Ariston Gully	
		East Bench 2	East Bench 3	East Bench 4	M5 Bench 1	M5 Bench 2	M4 Bench 1	B5 Bench 1	B5 Bench 2	B1 Bench 1	WCM Bench 1	WCM Bench 2	ARM Bench 1	ARM Bench 2
Pyrite	FeS ₂	1.30%	0.70%	0.90%	1.10%	1.40%	1.50%	0.9%	1.1%	0.6%	0.2%	0.3%	1.3%	0.5%
Arsenopyrite	FeAsS	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Quartz	SiO ₂	68%	71%	69%	81%	86%	82%	79%	83%	81%	84%	85%	84%	81%
Plagioclase	(Ca,Na)AlSi ₃ O ₈	3%	2%	3%	0%	1%	1%	0%	0%	1%	0%	0%	0%	0%
Micas	K(Mg,Fe) ₃ (AlSi ₃ O ₁₀)(OH) ₂	8%	12%	10%	7%	5%	6%	7%	6%	6%	6%	3%	6%	6%
Amphiboles/Pyroxene	Ca ₂ [Mg ₄ (Al,Fe)]Si ₇ AlO ₂₂ (OH) ₂	4%	2%	3%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Clays	Al ₂ O ₃ 2SiO ₂ 2H ₂ O	8%	6%	8%	3%	2%	2%	3%	3%	3%	2%	2%	2%	3%
Chlorite	(Fe,Mg,Fe) ₅ Al(Si ₃ Al)O ₁₀ (OH,O) ₈	6%	3%	3%	3%	1%	2%	4%	3%	4%	2%	4%	4%	3%
Other Silicates	(Mg,Fe) ₃ (Si,Al) ₄ O ₁₀ (OH) ₂	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%
Fe-Oxides	Fe ₂ O ₃	1%	2%	1%	2%	1%	3%	1%	1%	1%	2%	3%	1%	2%
Other Oxides		-	-	-	0%	0%	0%	1%	0%	0%	0%	0%	0%	0%
Carbonates	(Ca,Mg,Fe,Mn) (CO ₃) ₂	0%	0%	0%	1%	0%	1%	1%	1%	2%	0%	1%	1%	1%
Ti-Oxides	TiOx	1%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Other		0%	0%	0%	1%	1%	1%	2%	1%	1%	1%	1%	1%	2%
Gypsum	CaSO ₄ .2H ₂ O	0%	1%	1%	-	-	-	-	-	-	-	-	-	-

APPENDIX B: Chemical results per Klerksdorp gold tailings per bench

Chemical Name	Chemical Formulae	Portland cement (Mahmood et al., 2021)	Hexi Gold tailing (Wang et. Al, 2019)	Klerksdorp Gold Tailings													
				EAST TSF			MWS 5		MWS 4	Buffels 5		Buffels 1	Abandon		Ariston Gully		
				East Bench 2	East Bench 3	East Bench 4	M5 Bench 1	M5 Bench 2	M4 Bench 1	B5 Bench 1	B5 Bench 2	B1 Bench 1	WCM Bench 1	WCM Bench 2	ARM Bench 1	ARM Bench 2	Mean
Alumina	Al ₂ O ₃	4.1%	13.7%	7.9%	8.8%	8.4%	7.1%	7.0%	9.1%	8.0%	8.7%	8.5%	6.8%	5.5%	7.3%	8.1%	7.8%
Quick Lime	CaO	63.7%	1.1%	0.8%	1.3%	1.2%	0.7%	1.2%	0.5%	1.0%	1.0%	0.9%	1.0%	1.2%	0.6%	1.3%	1.0%
Chromic oxide	Cr ₂ O ₃	-	-	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Ferrite	Fe ₂ O ₃	5.1%	1.1%	3.8%	2.9%	3.3%	2.7%	3.0%	3.3%	3.0%	2.5%	2.6%	3.0%	3.7%	3.1%	2.8%	3.0%
Potassium Oxide	K ₂ O	-	-	1.3%	1.8%	1.6%	1.4%	1.5%	1.2%	1.6%	1.0%	1.6%	1.1%	0.9%	1.2%	1.3%	1.4%
Magnesia	MgO	1.5%	0.1%	0.7%	0.4%	0.4%	0.7%	0.4%	0.5%	0.4%	0.2%	0.9%	0.4%	0.7%	0.6%	0.4%	0.5%
Manganese Oxide	MnO	-	-	0.1%	0.2%	0.1%	0.1%	0.1%	0.0%	0.1%	0.1%	0.1%	0.2%	0.4%	0.1%	0.2%	0.1%
Sodium oxide	Na ₂ O	-	3.0%	0.1%	0.2%	0.2%	0.2%	0.2%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%
Phosphorus pentoxide	P ₂ O ₅	-	-	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Silica	SiO ₂	20.1%	72.9%	81.2%	79.6%	79.8%	83.7%	82.3%	81.9%	82.3%	82.5%	82.2%	83.1%	83.5%	84.0%	80.8%	82.1%
Titanium Oxide	TiO ₂	-	-	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%
Vanadium pentoxide	V ₂ O ₅	-	-	-	-	-	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Loss of Ignition (LOI)	LOI	3.4%	2.0%	3.0%	2.2%	2.8%	2.3%	3.5%	2.7%	3.1%	3.7%	2.6%	3.4%	3.2%	2.5%	3.2%	2.9%
Pozzolanic character	Sum (Al ₂ O ₃ , SiO ₂ , Fe ₂ O ₃)	29.3%	87.7%	92.9%	91.4%	91.5%	93.5%	92.2%	94.3%	93.3%	93.7%	93.3%	92.9%	92.7%	94.4%	91.6%	92.9%
Hydraulic activity	Sum (CaO, SiO ₂)	83.8%	73.9%	81.9%	80.9%	81.0%	84.4%	83.5%	82.4%	83.3%	83.5%	83.1%	84.1%	84.7%	84.6%	82.1%	83.0%

APPENDIX C: PSD for the Klerksdorp gold tailings (SGS, 2019)

Anglo Comp 1	Mass				Gold				
	Discrete		Cumulative		g/t	Discrete		Cumulative	
	g	%	% Retained	% Passing		mg	%	% Retained	% Passing
+150 µm	48.9	5.0	5.0	95.0	0.86	0.04	9.1	9.1	90.9
+106 µm	158.7	16.3	21.3	78.7	0.46	0.07	15.8	24.8	75.2
+75 µm	146.4	15.00	36.3	63.7	0.41	0.06	13.0	37.8	62.2
+25 µm	221.6	22.7	59.0	41.0	0.38	0.08	18.2	56.0	44.0
-25 µm	399.9	41.0	100.0	0.0	0.51	0.20	44.0	100.0	0.0
Total	975.5	100.0			0.47	0.46	100.0		

Anglo Comp 2	Mass				Gold				
	Discrete		Cumulative		g/t	Discrete		Cumulative	
	g	%	% Retained	% Passing		mg	%	% Retained	% Passing
+150 µm	109.4	10.6	10.6	89.4	0.44	0.05	11.5	11.5	88.5
+106 µm	143.1	13.9	24.4	75.6	0.46	0.07	15.7	27.3	72.7
+75 µm	139.2	13.47	37.9	62.1	0.33	0.05	11.0	38.2	61.8
+25 µm	179.2	17.3	55.3	44.7	0.41	0.07	17.6	55.8	44.2
-25 µm	462.1	44.7	100.0	0.0	0.40	0.18	44.2	100.0	0.0
Total	1033.0	100.0			0.40	0.42	100.0		

Anglo Comp 3	Mass				Gold				
	Discrete		Cumulative		g/t	Discrete		Cumulative	
	g	%	% Retained	% Passing		mg	%	% Retained	% Passing
+150 µm	143.6	14.4	14.4	85.6	0.46	0.07	18.2	18.2	81.8
+106 µm	259.3	26.0	40.5	59.5	0.27	0.07	19.3	37.4	62.6
+75 µm	114.8	11.53	52.0	48.0	0.47	0.05	14.8	52.3	47.7
+25 µm	177.5	17.8	69.8	30.2	0.30	0.05	14.6	66.9	33.1
-25 µm	300.4	30.2	100.0	0.0	0.40	0.12	33.1	100.0	0.0
Total	995.6	100.0			0.37	0.36	100.0		

Anglo Comp 4	Mass				Gold				
	Discrete		Cumulative		g/t	Discrete		Cumulative	
	g	%	% Retained	% Passing		mg	%	% Retained	% Passing
+150 µm	115.8	11.3	11.3	88.7	0.31	0.04	7.9	7.9	92.1
+106 µm	215.1	20.9	32.2	67.8	0.47	0.10	22.4	30.3	69.7
+75 µm	131.8	12.82	45.0	55.0	0.43	0.06	12.5	42.9	57.1
+25 µm	203.1	19.7	64.7	35.3	0.36	0.07	16.2	59.0	41.0
-25 µm	363.0	35.3	100.0	0.0	0.51	0.19	41.0	100.0	0.0
Total	1028.7	100.0			0.44	0.45	100.0		

Anglo Comp 3	Mass				Gold				
	Discrete		Cumulative		Discrete			Cumulative	
	g	%	% Retained	% Passing	g/t	mg	%	% Retained	% Passing
+150 µm	143.6	14.4	14.4	85.6	0.46	0.07	18.2	18.2	81.8
+106 µm	259.3	26.0	40.5	59.5	0.27	0.07	19.3	37.4	62.6
+75 µm	114.8	11.53	52.0	48.0	0.47	0.05	14.8	52.3	47.7
+25 µm	177.5	17.8	69.8	30.2	0.30	0.05	14.6	66.9	33.1
-25 µm	300.4	30.2	100.0	0.0	0.40	0.12	33.1	100.0	0.0
Total	995.6	100.0			0.37	0.36	100.0		

Anglo Comp 4	Mass				Gold				
	Discrete		Cumulative		Discrete			Cumulative	
	g	%	% Retained	% Passing	g/t	mg	%	% Retained	% Passing
+150 µm	115.8	11.3	11.3	88.7	0.31	0.04	7.9	7.9	92.1
+106 µm	215.1	20.9	32.2	67.8	0.47	0.10	22.4	30.3	69.7
+75 µm	131.8	12.82	45.0	55.0	0.43	0.06	12.5	42.9	57.1
+25 µm	203.1	19.7	64.7	35.3	0.36	0.07	16.2	59.0	41.0
-25 µm	363.0	35.3	100.0	0.0	0.51	0.19	41.0	100.0	0.0
Total	1028.7	100.0			0.44	0.45	100.0		

Anglo Comp 5	Mass				Gold				
	Discrete		Cumulative		Discrete			Cumulative	
	g	%	% Retained	% Passing	g/t	mg	%	% Retained	% Passing
+150 µm	55.9	5.8	5.8	94.2	0.38	0.02	6.6	6.6	93.4
+106 µm	144.8	14.9	20.7	79.3	0.28	0.04	12.7	19.3	80.7
+75 µm	93.5	9.65	30.4	69.6	0.29	0.03	8.5	27.8	72.2
+25 µm	229.9	23.7	54.1	45.9	0.27	0.06	19.4	47.2	52.8
-25 µm	444.8	45.9	100.0	0.0	0.38	0.17	52.8	100.0	0.0
Total	968.9	100.0			0.33	0.32	100.0		

Anglo Comp 8	Mass				Gold				
	Discrete		Cumulative		Discrete			Cumulative	
	g	%	% Retained	% Passing	g/t	mg	%	% Retained	% Passing
+150 µm	156.7	17.6	17.6	82.4	0.44	0.07	19.9	19.9	80.1
+106 µm	158.5	17.8	35.4	64.6	0.39	0.06	17.9	37.8	62.2
+75 µm	112.9	12.68	48.1	51.9	0.31	0.03	10.1	47.9	52.1
+25 µm	206.1	23.2	71.2	28.8	0.34	0.07	20.3	68.2	31.8
-25 µm	256.0	28.8	100.0	0.0	0.43	0.11	31.8	100.0	0.0
Total	890.1	100.0			0.39	0.35	100.0		

Anglo Comp 9	Mass				Gold				
	Discrete		Cumulative		Discrete			Cumulative	
	g	%	% Retained	% Passing	g/t	mg	%	% Retained	% Passing
+150 µm	58.8	6.4	6.4	93.6	0.59	0.03	6.8	6.8	93.2
+106 µm	49.7	5.4	11.8	88.2	0.48	0.02	4.7	11.4	88.6
+75 µm	66.5	7.22	19.0	81.0	0.43	0.03	5.6	17.0	83.0
+25 µm	200.0	21.7	40.7	59.3	0.43	0.09	16.8	33.9	66.1
-25 µm	545.6	59.3	100.0	0.0	0.62	0.34	66.1	100.0	0.0
Total	920.5	100.0			0.56	0.51	100.0		