The viability of using Gold mine tailings as a substitute for fine aggregate in concrete mixes

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Name: Saajidah Abdool Rehman Gani

Student number: GNXSAA001

Supervisor: Prof Hans Beushausen

Co-supervisor: Jaziitha Simon

Date: June 2025

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Executive summary

The rapid rates of urbanisation in recent years have increased the demand for building materials, some of which require mined natural resources. The increased demand for natural resources, among other increased market demands for various minerals, such as Gold, diamonds, coal and other mined resources have resulted in increased extraction of natural resources, subsequently increasing the volume of mine waste (also known as tailings) produced worldwide. Tailings are conventionally stored in tailings storage facilities (TSFs), which have major environmental and economic implications. This increase in mine waste and demand for building materials has prompted research to find alternative uses for these solid wastes in the construction industry. This dissertation explores the potential of recycling tailings, specifically, the viability of using Gold mine tailings from the Witwatersrand region as a substitute for fine aggregate in concrete mixes.

Testing done in this study was separated into two parts. Firstly, the fine aggregates were characterized in terms of density and particle size distribution (PSD). Secondly, Gold mine tailings were used as a replacement for Philippi dune sand (one of the fine aggregates used in this study) at different replacement ratios in concrete and tested in terms of fresh and hardened properties, with a specific focus on compressive strength.

It was found that the Gold mine tailings were similar to the Philippi dune sand in terms of the PSD and Fineness Modulus (FM) when compared to the other fine aggregates used. The Gold mine tailings contained particles with a maximum size of 0.6 mm, with 68.3% of the particles falling within the 0.3 mm – 0.6 mm range comparable to the Philippi dune sand which contained 53.6% of particles falling within this range. The Philippi dune sand contained 0.6% of particles that were larger than 1.18 mm in size and 7.1% of particles which were between 0.6 mm – 1.18 mm. Furthermore, the Gold mine tailings contained a higher percentage of particles that were smaller than 0.15 mm when compared to the Philippi dune sand. The Greywacke crusher sand contained a larger range of particle sizes, including 66.8% of its mass being made up of particles larger than 1.18 mm.

For the compressive strength test, two (2) sets of concrete mixes were tested. Mix A used a water to binder ratio (w:b) of 0.45 and 10-mm Greywacke as the coarse aggregate. Mix B used a w:b of 0.6 and 19-mm Greywacke as the coarse aggregate. The Philippi dune sand was replaced with Gold mine tailings at various ratios of replacement. It was found that at 28-days, all mixes reached at least 76% strength of the reference mix.

The compressive strength of the concrete cubes tested in this study had variable results in Mix A, with a decrease in compressive strength at 14-days, followed by an increase in compressive strength at 28-days. Through the literature, this trend is inexplicable, and the tests were redone on Mix B which generated a more linear trend in that an increase in the ratio of replacement of Philippi dune sand with Gold mine tailings resulted in a decrease in compressive strength.

It has been documented in literature that concrete made with low ratios of replacement of fine aggregates with finer material results in an increase in compressive strength due to the filler effect which is the action of finer particles moving into the voids of the existing concrete mortar and filling in the gaps, thus increasing the mechanical resistance of the concrete.

At higher ratios of replacement, finer particles fill the voids between the aggregate and mortar and interferes with the cement-paste interface thus reducing the cohesiveness and compressive strength of the mix. Furthermore, previous studies have shown a loss in compressive strength which can be attributed to several factors namely an increase in water demand which affects the workability of the concrete mix and reduces the amount of water available for hydration reactions. Mine tailings are poorly graded with flaky and angular particles which increases the number of micropores in the concrete mix and reduces the mechanical resistance of the concrete at a microscopical level. These factors of compressive strength loss are mainly attributed to the physical properties of the material used however, mine tailings are non-homogenous and differ depending on the type of mine tailings and the method of extraction used. Some mine tailings contain heavy metals which can have a retarding effect on the compressive strength development of the concrete resulting in lower early age strengths.

The Oxygen Permeability Index (OPI) tests were done on Mix A and all OPI values were within the excellent range and had a variance of 0.01 with the OPI values all above 10. The negligeable differences in OPI values indicated that regardless of the level of replacement, the Gold mine tailings had good resistance to oxygen permeability.

Experimental studies reported in the literature highlight the differences between different tailing types in terms of the physical and chemical properties of the tailings and the varying results when used in concrete mixes, which motivates that further research needs to be done on different tailings types. However, the method of testing is similar between the experiments aiding in the development of a testing method that can be applied to different tailings.

Qualitative and quantitative studies need to be conducted on tailings to develop a method that can be used in practice. Recommendations include further research be done beyond the scope of this dissertation in terms of the chemical composition of the tailings and the effects of the chemical constituents on the environment and human health. Furthermore, legislative requirements need to be developed to put this method into practice and technological advancements to make this method of recycling more accessible and the economic implications of using mine tailings in this way need to be investigated to develop a viable method that can be implemented in the industry.

The aim of this study was to test the viability of using Gold mine tailings as a substitute for fine aggregate in concrete mixes through laboratory testing which was achieved through the objectives, including a detailed literature study and acquiring the Gold mine tailings and using it to conduct characterization tests on the material as well as determining fresh and hardened properties of the concrete mixes.

The outcome of the laboratory testing addressed the research questions “Can Gold mine tailings from the Witwatersrand region be used as a replacement for fine aggregates in concrete mix designs and create concrete products of adequate strength and quality?” and “What percentage of Gold mine tailings can be used in concrete mixes such that adequate strength is maintained?”. This study indicated that the decrease in workability and compressive strength of the concrete using Gold mine tailings as a replacement for fine aggregate in concrete mixes is unideal and will not be accepted by the industry at any ratios of replacement. However, the literature suggests that the possibility of using other mine tailings as a partial replacement for fine aggregates should be explored as a possible solution. This partial replacement can be achieved through the manufacturing of blended fine aggregates which incorporates mine tailings at appropriate percentages prior to being supplied to the market.

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List of abbreviations

°C	Degrees Celsius
AMD	Acid Mine Drainage
ASTM	American Society for Testing and Materials
C&CI	The Cement and Concrete Institute
CH	Calcium Hydroxide
CSH	Calcium Silicate Hydrate
DI	Durability Index
FM	Fineness Modulus
g	grams
ℓ	litres
ℓ /m^3	litres per cubic metre
m^3	cubic metres
ISAT	Initial Surface Absorption Test
kg/m^3	kilogram per cubic metre
mℓ	millilitre
MPa	Megapascal
OPI	Oxygen Permeability Index
m^2/kg	Square metre per kilogram
mm	millimetre
PC	Portland Cement
PCE	Polycarboxylate Ethers
PPC	Pretoria Portland Cement
pH	Potential of Hydrogen
ppm	parts per million
PSD	Particle Size Distribution
SANS	South African National Standards
SCM	Supplementary Cementitious Material
SDG	Sustainability Development Goal
TSF	Tailings Storage Facility
UN	United Nations
US EPA	United States Environmental Protection Agency
w:b	water-to-binder ratio
XRD	X-Ray Diffraction

1. Introduction

1.1 Background

Tailings are the ground ore produced during the extraction process of mining activities (Méndez et al., 2022). Mining of natural resources generates wealth within economies and aids development (Adiguzel et al., 2022). However, increased urbanisation rates in recent years have placed immense pressure on the mining industry and subsequently caused an increase in solid waste production around the world (Benzaazoua & Taha, 2020).

Portland cement (PC) in combination with water and aggregates make up concrete which is used in the building industry (Adiguzel et al., 2022). Appropriate natural resources are mined for this purpose, which is costly and time-consuming (Maruthupandian et al., 2021). Mining activities generate large amounts of tailings which are typically stored in TSFs and South Africa, being rich in mineral resources is notoriously known to largely contribute to global solid waste production statistics (Kudakwashe, 2019).

The increasing demand for raw materials around the world has resulted in increased mining activity, and subsequently contributed to the production of tailings, most of which is managed using TSFs (Maruthupandian, Chaliasou & Kanellopoulos, 2021). These tailings pose contamination risks and are harmful to the environment due to the physio-chemical composition of the tailings, and the radiation emitted from some tailings (Méndez et al., 2022). Furthermore, TSFs must be professionally designed and constructed to ensure stability and effective waste and water management systems (Méndez et al., 2022). This process is costly and time-consuming (sgu.se, 2024).

In recent years, environmental awareness has increased around the world and conventional construction and mining practices have been placed under scrutiny. This has driven researchers to focus on more sustainable ways of managing mine waste while still meeting the demands created by urbanisation (Méndez et al., 2022). The reuse of mine tailings in concrete can potentially reduce the amount of mine waste stored in conventional TSFs and all problems associated with it. (JXSCmachine, 2024). Table 1-1 summarises the social, economic, and environmental issues associated with conventional TSFs.

The primary focus of this study is to test the effect of using Gold mine tailings as a substitute for fine aggregate in concrete mixes in terms of the compressive strength and OPI of the concrete. This aligns with United Nations (UN) development goals by reusing mine wastes in a sustainable way that focuses on environmental conservation (Méndez et al., 2022). Furthermore, reusing mine tailings for alternate uses helps generate revenue for mining companies as opposed to storing mine wastes in TSFs (Méndez et al., 2022).

Table 1-1: Problems associated with conventional TSFs

Social	Economic	Environmental
Radiation emitted from tailings is a major concern for human health of the population in nearby communities (Méndez et al., 2022).	There is a high cost related to designing and constructing TSFs (Maruthupandian, Chaliasou & Kanellopoulos, 2021).	Mine tailings can potentially cause leachate which mixes into groundwater sources (Benzaazoua & Taha, 2020).
The footprint of TSFs and the zone of influence affect the development of towns/cities in terms of their regions of expansion (Kneen, Ojelede & Annegarn, 2015).	Legal procedures may be costly for the commissioning and maintenance of TSFs (Méndez et al., 2022).	Chemical contaminants from tailings can affect biodiversity and wildlife in the area (Benzaazoua & Taha, 2020).

Existing research on using tailings as a substitute for fine aggregate in concrete mixes shows varying results. The literature indicates that the use of tailings in this manner is dependent on the geological origin and method of extraction of the tailings used (Vermeulen, 2001; Maruthupandian, Chaliasou & Kanellopoulos, 2021). Generally, trends have shown that the compressive strength of concrete using Gold mine tailings is adequate when used in certain percentages of replacement for fine aggregate, but the long-term durability of concrete mixes containing Gold mine tailings has to date not been investigated thoroughly (Vermeulen, 2001; Malatse & Ndlovu, 2015; Sibanda, 2019)

Other types of tailings that have been repurposed and tested in this way include Copper tailings, Iron tailings, Hematite tailings and Kimberlite from various geological regions (Otieno & Ndoro, 2020; Maruthupandian, Chaliasou & Kanellopoulos, 2021; Adiguzel, Tuylu & Eker, 2022; Méndez et al., 2022). These studies indicated large variances in concrete compressive strength when used as fine aggregates. The variances are on account of the particle size, relative density, porosity, and water absorption differences between these tailings (Maruthupandian, Chaliasou & Kanellopoulos, 2021; Adiguzel, Tuylu & Eker, 2022).

Industry and consumers are hesitant to move away from using conventional concrete as it has been used for decades and the applications and complications of conventional concrete are well documented. Research can mitigate the hesitancy of the industry to move away from conventional concrete and address the concerns regarding the health implications of using tailings in concrete mixes (Maruthupandian et al., 2021). To reach this point, and align with sustainability goals of the UN, the International Energy Agency, and the European Cement Association among others, which all promote greener uses for solid wastes, repetitive testing focused on each type of tailings from a common source needs to be conducted to generate reliable results (Maruthupandian, Chaliasou & Kanellopoulos, 2021).

Gold mine tailings were chosen for this study as they are abundant in South Africa, with the country contributing to approximately 11% of the world's Gold reserves (Kudakwashe, 2019). The study was limited to Gold mine tailings from the Witwatersrand region to ensure uniformity between the concrete samples. The scope includes using existing data on the chemical composition of the Gold tailings used and testing the fresh and hardened properties of concrete produced with the tailings, using the ratio of tailings substitution in the mix as the independent variable.

1.2 Research problem

Existing research on using different mine tailings as a substitute for fine aggregate in concrete has shown varying results in terms of the compressive strengths and durability of the concrete. Compressive strength and durability results from these tests differ even where the type of tailings used is the same, but the geological origin or method of extraction differs. These studies are limited in that different mine tailings have been studied, which have different physical and chemical properties, such that conclusions cannot be quantitatively drawn and repetitive testing is required to determine the viability of each type of tailings to be used as a replacement for fine aggregate in concrete mixes. With a specific focus on Gold mine tailings, there is a lack of information on how Gold tailings impact the compressive strength and durability of hardened concrete when used as a replacement for conventional fine aggregates. A common trend noted in the review of existing literature is that mine tailings fill micropores within the matrix of concrete due to the particle grading and reduce the number of pores within the concrete, thus impacting the permeability of the concrete. In this context, the OPI test is included to assess the potential impact of Gold mine tailings replacement on oxygen permeability, as an indicator of durability.

1.3 Research motivation

Using Gold Mine tailings as a substitution for fine aggregate in concrete mixtures reduces the demand for conventional natural resources while disposing of tailings in a safe and sustainable manner (Maruthupandian, Chaliasou & Kanellopoulos, 2021). This could also reduce the adverse effects that raw tailings have on the environment, reduce financial pressures on mines to expand TSFs, and comply with environmental and legal requirements (Adiguzel, Tuylu & Eker, 2022). Furthermore, this solution relieves the pressure on the building industry to supply natural aggregates for concrete (Maruthupandian, Chaliasou & Kanellopoulos, 2021). Through research, it has been noted that Gold mine tailings, when mixed with binder, can achieve desired strength properties (Malatse & Ndlovu, 2015; Sibanda, 2019; Adiguzel, Tuylu & Eker, 2022).

1.4 Aim

This study aims to test the viability of using Gold mine tailings as a substitute for fine aggregate in concrete mixes through laboratory testing by determining the compressive strength and OPI of concrete using different replacement ratios of fine aggregate with Gold mine tailings.

1.5 Objectives

This investigation was conducted on the physical properties of the fine aggregates used in this study and focused on the compressive strength and OPI of concrete made using Gold mine tailings at different ratios of replacement of the conventional fine aggregate. Therefore, the following objectives were investigated to achieve the aim of the study:

- Performing a detailed literature review on replacing fine aggregates in concrete with mine tailings and determining the impact of these mine tailings on the compressive strength and durability properties of concrete.

- Sourcing Gold mine tailings and characterizing the material in terms of its relative density and PSD.
- Designing and testing concrete mixes using different replacement ratios of conventional fine aggregate with the sourced Gold mine tailings.
- Determining the physical properties of Gold mine tailings and comparing them to those of the conventional fine aggregates used in the study.
- Determining the influence of different replacement levels of fine aggregates with Gold mine tailings on the workability, compressive strength, and OPI of concrete made using conventional fine aggregates.
- Identifying if Gold mine tailings can be used as a replacement for fine aggregate in concrete mixes and what ratios of replacement can be used without resulting in a decrease in compressive strength.

1.6 Research questions

The primary research question is "Can Gold mine tailings from the Witwatersrand region be used as a replacement for fine aggregates in concrete mix designs and create concrete products of adequate strength and quality?". The secondary research question is "What percentage of Gold mine tailings can be used in concrete mixes such that adequate strength is maintained?".

1.7 Research assumptions

Tailings are primarily made of crushed rock and will not cause further chemical reactions that will affect the strength of the concrete after it has reached its 28-day strength. This research assumption was made to fit the scope and limited timeline of this study, and following a successful outcome, compressive strength testing beyond 28-days is a potential area for improvement to this study.

1.8 Scope and limitations

The scope of this study includes the following:

- Material characterisation of fine aggregates and Gold mine tailings used in this study.
- The effects of adding Gold mine tailings to concrete mixes as a replacement for fine aggregate on the workability, compressive strength, and OPI of the concrete produced.

This study was limited in the following ways:

- The type of Gold mine tailings used in this study was from a single source which would differ when compared to other tailings in terms of the physical and chemical properties (Adiguzel, Tuylu & Eker, 2022).
- The chemical composition of these mine tailings was not assessed, and the environmental implications were not included in this study. To determine if the replacement is truly viable, it needs to be assessed in terms of applicability as well as sustainability. This study focuses on determining whether Gold mine tailings can successfully be used as a replacement for fine aggregate in concrete in terms of applicability such that it would achieve structural objectives. If it is determined that Gold tailings is a potential replacement for fine aggregate in this regard, environmental sustainability should be a

key area of focus to determine if this replacement is actually viable. This includes determining the chemical composition of the Gold mine tailings due to the potential of leachate from heavy metals within the Gold mine tailings, which may make this an unviable replacement.
- The Gold mine tailings were dried and used as acquired from the mine and did not include any further refining as suggested by some literature.
- There are no standards to be followed on the test methods that should be conducted on concrete when fine aggregate is replaced with mine tailings.

1.9 Structure of the dissertation

This dissertation comprises the following chapters:

- Chapter 1: Introduction – this includes a summary of the topic, identifying the key research indicators such as the problem statement, the aims and objectives, and the limitations of the study.
- Chapter 2: Literature review – this includes the development of the problem being addressed through this study, the constituents of conventional concrete, and previous studies in which the fine aggregates in concrete were replaced similarly as done in this study.
- Chapter 3: Methodology – this includes the test methods and materials used in this study.
- Chapter 4: Results and discussion – this includes the results from this study and the discussion based on the literature.
- Chapter 5: Conclusion and recommendations – this includes the overall findings of the study and recommendations for further studies to implement the reuse of mine tailings in the industry.

2. Literature review

2.1 Introduction

This chapter addresses the problems associated with increased mining activities and the use of conventional TSFs. The growing demand for concrete, driven by development needs, has accelerated the extraction of natural aggregates (Maruthupandian, Chaliasou & Kanellopoulos, 2021). Concrete comprises a binding agent mixed with water and aggregates. To reduce the depletion of natural resources, fine aggregates in concrete have experimentally been replaced with different mine tailings in the past and it has been found that generally mine tailings can be used as a substitute for fine aggregates in concrete mixes when replaced partially. The varying results from different experiments encourage further research to be conducted (Adiguzel, Tuylu & Eker, 2022). This chapter highlights the physical and chemical properties of mine tailings that contribute to varying compressive strengths when used in concrete with a particular focus on Gold mine tailings. Furthermore, the experimental procedures done in previous experiments were used as a framework for this study.

2.2 Mining wastes

The current world population of 8 billion has seen a substantial increase throughout history, doubling from 4 billion in the 1970s and continually growing exponentially (Worldometer, 2024). It is estimated that the number of people living in urban areas will double in the next 26 years (Maruthupandian, Chaliasou & Kanellopoulos, 2021). The increasing population living in urban areas has prompted the need for infrastructure development which requires large quantities of construction materials such as concrete (Adiguzel, Tuylu & Eker, 2022). The increasing demand for natural aggregates which is a constituent of concrete has led to an increase in extraction of natural aggregates which increases the rate at which natural resources are being depleted. The increase in demand for natural resources including natural aggregate and Gold has subsequently resulted in increased mining wastes (Maruthupandian, Chaliasou & Kanellopoulos, 2021). More natural resources are being mined, however the amount of natural resources available is finite and if not controlled, will eventually get depleted (Maruthupandian, Chaliasou & Kanellopoulos, 2021). Where natural minerals are concerned, it takes millions of years to form naturally and thus replenishment of these resources once used is not possible (Adiguzel, Tuylu & Eker, 2022). This imbalance between demand and supply is evident as mining companies have begun extracting minerals from low-grade mineral ore, generating even greater amounts of mine wastes (Maruthupandian, Chaliasou & Kanellopoulos, 2021).

Mine wastes (also known as tailings) are typically stored in TSFs which are notoriously known for their cost factor, environmental implications associated with acid leachate, stability issues, and potential failure (JXSCmachine, 2024). Mining activities not only exploit the natural resources available but also generate large quantities of CO2, enhancing the natural greenhouse effect of the earth and subsequently contributing to global warming and all associated problems (Lindsley, 2024). This means that increased rates of mining line up with development goals but contradict sustainability goals.

TSFs are constructed in one of three ways, as shown in Figure 2-1 namely upstream, downstream and, centreline construction (sgu.se, 2024). In these construction methods, a barrier wall is constructed using natural aggregates or tailings and expanded over time (Vermeulen, 2001). Tailings are deposited within the perimeter using open-ended pipes or cycloning, which splits the coarser and finer fractions of the tailings by means of gravity and is achieved by high-speed rotational movements (Vermeulen, 2001). The tailings are mixed with water and fed into the delivery pipes in the form of a slurry (Vermeulen, 2001). These structures are carefully designed using engineering calculations for volume, lifespan and stability requirements (Bhanbhro, 2017). This means that the storage capacity of TSFs is finite.

Figure 2-1: TSF Construction methods

Mine tailings may contain chemical additives such as Cyanide and Sulphur used in the extraction processes and sometimes contain heavy metals that can cause acid leachate and lead to acid mine drainage (AMD) (Bhanbhro, 2017).

In summary, TSFs are costly to construct and maintain, and comprise mine wastes that have little to no economic value. TSFs are also known to have environmental and social implications but are increasing in size and quantity to meet increasing demands. Increased mining and subsequently increased mine wastes results in an increased need for TSFs and TSF expansion.

2.3 Concrete constituents

Concrete is comprised of different ratios of cement, aggregates, and water with controlled proportions of each constituent to achieve specific strength and durability requirements (Adiguzel, Tuylu & Eker, 2022). The different constituents of a typical concrete sample are presented in Figure 2-2.

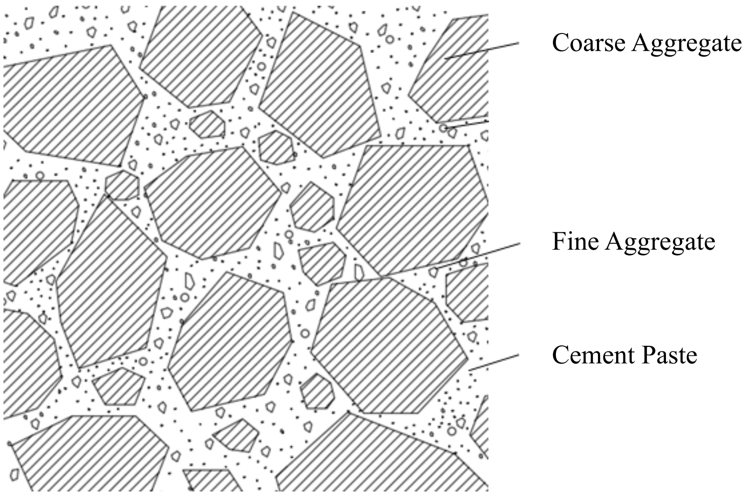


Figure 2-2: Typical image of concrete sample (Zhao et al., 2019)

2.3.1 Cement

Cement is comprised of sedimentary ore from the Earth's crust which is put through thermochemical and physical processes to form a finely ground powder that acts as a binding agent when activated with water (Adiguzel, Tuylu & Eker, 2022). The parent material that undergoes these processes produces different grades of cement which are used for different applications (Lords Builders Merchants, 2021).

Table 2-1 summarises the general chemical composition of PC which indicates a high Silica and Alumina content. The Silica and Alumina help in the development of strength in concrete by forming Dicalcium and Tricalcium silicates during the hydration reactions and contribute to the setting and hardening properties of concrete (HSA Silica Fume, 2024).

Table 2-1: Chemical composition of cement (Shambharkar, 2019)

Constituent	Content (%)
CaO	62 – 65
$Al2O_3$	3 – 8
$CaSO_4$	3 – 4
S	1 – 3
SiO_2	17 – 25
Fe_2O_3	3 – 4
MgO	1 – 3
K_2O	0.2 – 1
Na_2O	0.2 – 1

2.3.2 Water

Potable water is used in concrete to activate the hydration reactions of cement to hold the constituents together (Lords Builders Merchants, 2021). The activation of cement creates a malleable compound that can be cast into any shape before hardening occurs (Lords Builders Merchants, 2021). An appropriate w:b must be chosen to ensure proper activation of cement, contributing to the strength development of the concrete. Furthermore, the w:b contributes to the setting time, void ratio, and workability of the concrete (Roxburgh, 2021).

2.3.3 Fine and coarse aggregates

Aggregates make up to 80% of the volume of the concrete and add to the dimensional stability and compressive strength of the concrete (Bonser & Alexander, 2021). Aggregates used in concrete can be either natural or manufactured. The PSD of coarse and fine aggregates is one of the properties described in SANS 3001-AG1 guidelines. The standard indicates that if at least 90% of the mass of the aggregate is smaller than 4.75 mm it is classified as fine aggregate and if at least 90% is greater than 4.75 mm, it is classified as coarse aggregate (Bonser & Alexander, 2021). Aggregates that do not meet the criteria of either coarse or fine aggregates in terms of its PSD is unclassified in terms of SANS 3001-AG1.

The most common type of natural aggregate used in concrete is derived from igneous rocks, which are formed from molten lava or magma that has cooled down and usually comprises crystalline lattices and glassy matter (Bonser & Alexander, 2021). Other types of natural aggregates include those derived from sedimentary rocks (which are formed from physical or chemical weathering of larger rock particles to form fine rock particles that accumulate together) and metamorphic rocks (which are formed from high temperatures or pressures that change the compounds within existing rock bodies to form new compounds) (Bonser & Alexander, 2021).

The choice of aggregate used in concrete affects the packing capability and hence the void content of the concrete. Aggregates also affect the water requirement and absorption capabilities of the concrete. Where there is a presence of organic impurities in the fine aggregate, the setting time and strength development of concrete may be affected (Bonser & Alexander, 2021). The PSD of the coarse and fine aggregates needs to comprise particle sizes that clearly distinguish between the coarse and fine fractions to ensure adequate workability and cohesiveness. Typically, when there is inadequate distribution of particles between the coarse and fine aggregates, the concrete mix is harsh in the fresh state and may result in bleeding of the concrete (Bonser & Alexander, 2021).

Fines (particles that are less than 0.075 mm in size) have the greatest impact on the workability and cohesiveness of the concrete mixture and are controlled by guidelines such as ASTM C33 and SANS 1083. A very high content of fines makes the mixture harsh and sticky. Adiguzel, Tuylu and Eker (2022) found that concrete mixtures with replacement ratios greater than 40% of fine aggregate with mine tailings led to a very sticky consistency. This was attributed to the high percentage of particles smaller than 0.3 mm (Adiguzel, Tuylu & Eker, 2022). Furthermore, high levels of fines increase the water demand and drying shrinkage rates of the concrete. In contrast to the negative impacts of having high levels of fines in concrete, their presence in small amounts aids with compressive strength, bonding capabilities, and void contents in concrete (Katz & Baum, 2006).

When looking at the PSD of aggregate, the FM is an important calculation and is used to develop concrete mix designs. The FM is a measurement of the fraction of particles between 0.150 mm and 4.75 mm in size (Bonser & Alexander, 2021). SANS 1083 recommends using a fine aggregate with an FM value between 1.2 – 3.5 for adequate strength and durability of the concrete mixture.

2.3.4 Admixtures

Chemical admixtures are compounds that are added to fresh concrete to alter physical properties in the fresh and hardened state and are governed by SANS 50934. The use of fines in concrete mixes makes the concrete less workable which can be mitigated by using admixtures such as superplasticizers (Adiguzel, Tuylu & Eker, 2022). Superplasticizers make the concrete more workable in the fresh state by increasing its flowing capability (Cement and Concrete SA, 2015). Superplasticizers need to be used with caution as an excessive amount can lead to increased air entrainment, increased bleeding and, retarding of strength development in concrete mixes (Brouard, 2021).

2.4 Gold mining in SA

Gold was first discovered in South Africa in 1806 between the Witwatersrand and Magaliesburg regions (Vermeulen, 2001). South Africa is still well-known for its rich Gold deposits which span over three (3) provinces and contain seven (7) Goldfields (Sibanda, 2019). The Goldfields within South Africa are depicted in Figure 2-3 (Minerals Council South Africa, 2024). These Goldfields are comprised of Archaean Granite Greenstone (a sedimentary rock) which has undergone metamorphosis over billions of years (Vermeulen, 2001).

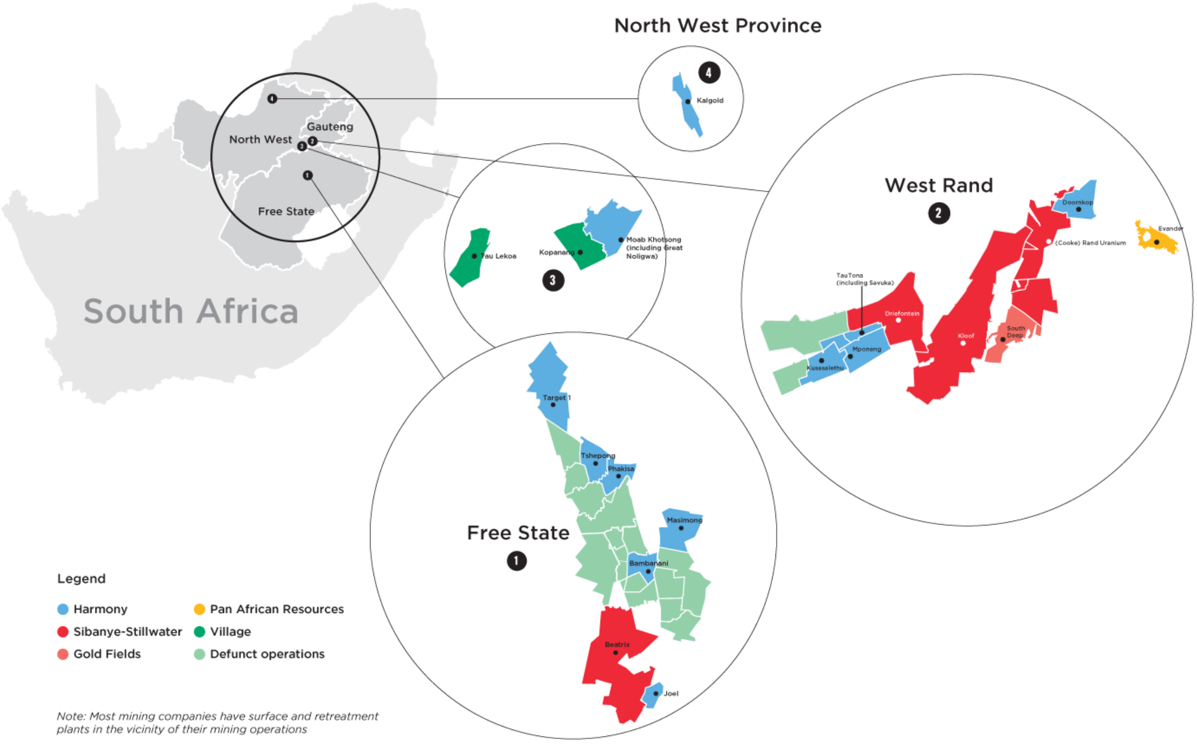


Figure 2-3: Witwatersrand Gold mining operations in South Africa (Minerals Council South Africa, 2024)

Gold is extracted from underground mining operations and typically contains between 70% – 90% of Quartz, 10% – 30% of Muscovite and phyllosilicates, and other compounds. This Gold is usually found at a concentration of about 45 parts per million (ppm) (Vermeulen, 2001). The extraction processes of Gold are both physical and chemical, with the chemical process of Cyanidation being the most common method of extraction in South Africa (Sibanda, 2019). Wherein Calcium Hydroxide, Oxygen, and Cyanide are added to the ore, after which the Gold is extracted through precipitation reactions (Sibanda, 2019).

Once the Gold has been extracted from the ore, the remainder of the mixture (which includes rock particles, water and extraction chemicals) is transported to TSFs. These mine wastes are known as tailings. Tailings in South Africa is typically stored in TSFs which are notoriously known for potential environmental and failure hazards that may bring about irreversible damage to the environment and human health (Vermeulen, 2001). The abandoned mine waste dumps, adverse effects of TSFs, cost factors of TSF construction and maintenance, and the low economic value of mine tailings have prompted experimental research in South Africa to determine alternate disposal methods for tailings in recent years (Vermeulen, 2001; Sibanda, 2019).

2.5 Gold mine tailings

Gold mine tailings are the waste produced during the extraction process of Gold from rock ore and generally comprises of the ground ore mixed with water and chemicals used in the extraction processes (Vermeulen, 2001). Gold mine tailings have high concentrations of oxides (namely, SiO_2, Al_2O_3, CaO, and Fe_2O_3), which are also found in great quantities in building materials such as cement, natural aggregates, and supplementary cementitious materials (SCMs) (Maruthupandian, Chaliasou & Kanellopoulos, 2021).

Gold mine tailings are primarily made up of Quartz, Pyrite, Mica, and Talc and contain hard and angular grains ranging in size from 0.001 mm – 0.65 mm (Sibanda, 2019). The relative density of Gold mine tailings ranges between 2.7 – 4.9 (Maruthupandian, Chaliasou & Kanellopoulos, 2021). Gold mine tailings are generally more compressible as opposed to natural sands due to the grading and angular shape of the particles, which contribute to the presence of voids between particles. Furthermore, Gold mine tailings have low plasticity indices and are non-cohesive in nature (Vermeulen, 2001). The consolidation of tailings applied in the design of TSFs is highly dependent on the excess pore pressure and the ability of particles to rearrange themselves (Vermeulen, 2001).

The mine tailings have little to no economic value and environmental regulations and rehabilitation of mined land needs to be done in line with stringent legislation to ensure that the land can be restored as sustainably as possible (Benzaazoua & Taha, 2020). Historically, mined land has been rehabilitated successfully, but there is no guarantee that post-mining, the land would hold much economic benefits (Sibanda, 2019).

In the South African context, there are more than 270 registered tailings dams in the Witwatersrand basin which spans an area of more than 400 km^2 and as of 2023, the approximate quantity of Gold tailings in South Africa was approximately 800 million tons (Oelofse et al., 2010; miningweekly.com, 2023). South African studies have shown that the reuse of Gold mine tailings is dependent on the physical and chemical properties of the tailings which differ from operation to operation (Vermeulen, 2001; Sibanda, 2019). Gold tailings have successfully been used in the production of building materials (namely ceramics, concrete blocks, bricks, and aggregates) on an experimental scale (Sibanda, 2019; Maruthupandian, Chaliasou & Kanellopoulos, 2021).

2.5.1 Chemical composition of Gold mine tailings

The Goldfields in the Witwatersrand contain high concentrations of Uranium ore that do not always get extracted during mining processes and are often dumped in TSFs (Sibanda, 2019). This has resulted in Gold mine tailings often containing Uranium, Radium, Thorium, Polonium and Lead isotopes which make the material potentially hazardous and can contribute to acid mine drainage (AMD) (Sibanda, 2019).

Gold extraction often follows the process of Cyanidation which threatens the environment. The toxicity of Cyanide is dependent on the stability of the Cyanide used, the temperature, pH, salinity and the presence of Oxygen, and other interactive ions (Vermeulen, 2001). The toxicity of a solution from Cyanide is based on the amount of free Cyanide in the solution and it is important to note that Cyanide dissolves easily into non-toxic substances and can quickly disperse without having any adverse effects on the environment (Sibanda, 2019).

The oxide composition of Gold mine tailings as per the research studies conducted by Sibanda (2019) and Méndez (2022) is summarised in Table 2-2. These studies were limited in that they did not test for the presence of potentially hazardous materials that may be present in the Gold mine tailings.

Table 2-2: Summary of Gold mine tailings composition from the literature

Constituent	**Composition (%)** (Méndez et al., 2022)	**Composition (%)** (Sibanda, 2019)
CaO	14.89	1.93
SiO_2	44.62	77.7
Al_2O_3	8.64	10.2
Fe_2O_3	26.1	4.51
SO_3/S	2.31	0.91
MgO	0.51	1.79
K_2O	0.55	1.19
Ti_O2	0.41	0.47
Na_2O	1.63	0.61
MnO	0.09	-
Cl	0.02	-
ZnO/Zn	0.11	-
SiO_2/Al_2O_3	0.29	-
P_2O_3	-	0.09
Cr_2O_3	-	0.45

From these studies, Gold mine tailings are generally found to comprise primarily of CaO, SiO2, Al2O3 and Fe2O3 with smaller proportions of other oxides. This chemical composition is attributed to the parent material of the Gold tailings. However, these tailings differ vastly between different sources and samples. Each source of tailings should therefore be tested in terms of its composition and viability prior to using it for alternative uses. It has also been observed that Silica, Iron, and Carbonate are present in some Gold tailings and act as bonding agents. The physical and chemical composition of Gold tailings generally makes it suitable for civil engineering applications (Maruthupandian, Chaliasou & Kanellopoulos, 2021).

2.6 Recycling mine tailings

Recycling mine tailings is the process of recovering mine wastes to be used in other applications as opposed to conventionally disposing of them in TSFs (JXSCmachine, 2024). This approach is done to reduce the environmental impacts of conventional disposal methods, optimise natural resources, and extend the life of mine facilities by reducing the rate at which facility volumes are filled (JXSCmachine, 2024). In general, recycling mine tailings aligns better with social and environmental regulations and expectations, reduces the running costs of TSFs, and aids in alleviating the demand pressures on the building industry (Maruthupandian, Chaliasou & Kanellopoulos, 2021).

The increased production of mine waste and the cost implications associated with effective maintenance and closure of mine facilities alongside stringent environmental and management laws of conventional TSFs have prompted studies towards finding alternative uses of mine wastes, such as using mine tailings in the manufacturing of construction materials (Sibanda, 2019; Benzaazoua & Taha, 2020; Maruthupandian, Chaliasou & Kanellopoulos, 2021; Adiguzel, Tuylu & Eker, 2022).

Mine tailings have been used in experimental studies in the production of construction materials such as porcelain tiles, as fine aggregates in concrete, and as a substitution for SCMs in concrete (Sibanda, 2019; Maruthupandian, Chaliasou & Kanellopoulos, 2021; JXSCmachine, 2024). Mine tailings have also experimentally been used as a backfill for mine goaf areas and as mineral fertilisers in agricultural applications (JXSCmachine, 2024).

People tend to prefer to use conventional concrete as it is robust under different exposure conditions and can be tailored for specific strength and shape requirements with historical problems being well-documented with already existing solutions. Furthermore, the current supply of concrete is not challenged and alternatives to conventional concrete has little existing knowledge, with possible long-term effects that are not yet known (Maruthupandian, Chaliasou & Kanellopoulos, 2021).

By using tailings as fine aggregates in concrete, less raw material will be required to meet the current demand, preserving natural reserves and generating less waste (Adiguzel, Tuylu & Eker, 2022). Due to the high demand for building materials and high CO2 production associated with mining practices and the production of cement, even partial replacements in concrete mixes will positively help the demand for naturally mined aggregates.

2.7 Fine aggregates in concrete

The fine aggregates refer to all particles less than 4.75 mm in concrete. The amount of fines in concrete, which is defined as particles less than 0.075 mm, is quantitatively limited to about 5% of the mass of the aggregate by most standards such as ASTM C33 guidelines and 10% in SANS 1083 guidelines. It has been noted that the use of fines in concrete mixes improves cohesiveness, workability and reduces segregation and bleeding when added in controlled amounts (Al-Harthy et al., 2007).

Mine tailings generally contain very fine particles that do not align with ASTM C33 and SANS 1083 guidelines when used as a fine aggregate in concrete (Katz & Baum, 2006; Gou, Zhou & Then, 2019; Maruthupandian, Chaliasou & Kanellopoulos, 2021; Adiguzel, Tuylu & Eker, 2022). The studies relating to the replacement of fine aggregates in concrete with materials comprising of finer particles have been included in this literature review since the Gold mine tailings used in this study contains a larger quantity of finer particles when compared to the Philippi dune sand which is being replaced. The studies presented in Table 2-3 highlights the effects of using finer materials in concrete as opposed to conventional fine aggregates.

The use of an excessive amount of fines, however, has been limited by most standards as it increases the water demand of the concrete mix due to a larger surface area of the particles, making it less workable and prone to shrinkage cracking. Furthermore, the drying and shrinkage action of fines in a concrete mix when wetted and dried causes volume changes which can cause further cracking in the concrete matrix. Excessive amounts of fines also weaken the bond between the cement paste and aggregates by lodging between the aggregates and making the concrete mix less cohesive (Katz &

Baum, 2006; Maruthupandian, Chaliasou & Kanellopoulos, 2021; Adiguzel, Tuylu & Eker, 2022). mixes.

Table 2-3 summarises the experimental procedures and findings of experiments relating to using materials with finer particle sizes as compared to the fine aggregate being replaced in the concrete mixes.

Table 2-3: Summary of the impact of fine aggregate in concrete

Experiment	Experimental Procedure	Findings
Effect of high levels of fines content on concrete properties (Katz & Baum, 2006)	The fine aggregate in a control mix was replaced with different ratios of different types of fines and tested in terms of the PSD and relative density, wet concrete properties, and strength and durability properties of the hardened concrete.	• The compressive strength of the samples increased up to a replacement ratio of 30% of conventional fine aggregate with fines, followed by a decrease in compressive strength. • There is a greater change in volume when using higher ratios of fines as opposed to conventional fine aggregates in concrete. • Higher dosages of the superplasticizer are required to maintain the workability in concrete mixes as the ratio of fines increases. • The current ASTM C33 guidelines on the amount of fines allowed in concrete mixes is very low and higher ratios can be used without significantly affecting the compressive strength of the concrete.
The properties of concrete made with fine dune sand (Al-Harthy et al., 2007)	Concrete samples were prepared by means of direct replacement of fine aggregate in concrete mixtures with fine dune sand in different ratios and tested in terms of the PSD, relative density and absorption, modulus of elasticity, slump, initial surface absorption test (ISAT) and compressive, tensile and flexural strengths.	• The fine dune sand used in this study had FM values between 0.45 – 0.88. • The relative density of the fine dune sand ranged between 2.49 – 2.62. • The workability of the concrete mix decreased with higher levels of replacement of fine aggregate with fine dune sand. • When compared to the reference mix, the replacement of fine aggregate with dune sand showed compressive strengths of between 0.76 to 1.00 of the reference mixture when compared in terms of a ratio.
Replacement of cement and fine aggregate by ceramic powder and Copper slag in concrete (Chitra, 2015)	Ceramic powder and copper slag are fine-grained particles that have experimentally been used in concrete as a direct replacement for both cement and fine aggregates respectively, at different replacement ratios and scenarios. The concrete was tested	• The compressive strength of the samples increased up to an optimum replacement ratio of cement with ceramic powder and fine aggregate with copper slag. • The optimum replacement ratios of cement and fine aggregate with ceramic powder and copper slag were 20% and 40%, respectively.

Experiment	Experimental Procedure	Findings
	for compressive strength at 7, 14, and 28-days.	
Replacement of fine aggregate by using construction demolition waste (Padmanaban, Nithila & Reshma Jahaan, 2019)	Steel slag is a by-product of the steel manufacturing process and was used as a direct replacement for fine aggregate in concrete in different ratios of replacement (10% to 50% at 10% intervals). This was measured in terms of the slump, strength properties and durability properties, following the Indian Bureau of Standards.	• Steel slag has a relative density of between 2.5 – 3.0 and ranges in particle sizes between 2.36 mm and 4.75 mm comprising of a coarse and fine fraction of particles. • The compressive strength of concrete containing steel slag increased up to a fine aggregate replacement of 40% and then decreased as the replacement levels increased. • The slump and workability decreased with an increase in replacement of fine aggregate with steel slag due to the higher water demand of the mixture.

The materials used as replacements for fine aggregates in concrete in these studies were derived from different sources but exhibited common behaviours when used in concrete as partial replacements. It is important to note that in these studies, a reference concrete mix was developed and the fine aggregate was replaced with different ratios of a material containing finer particles than the fine aggregate in the concrete mix (Katz & Baum, 2006; Al-Harthy et al., 2007). These common behaviours aid in understanding the effects of the particle size of the fine aggregate in concrete.

In terms of the physical characteristics of the materials used in these studies, the relative densities of the materials ranged between 2.49 – 3.00 (Al-Harthy et al., 2007; Padmanaban, Nithila & Reshma Jahaan, 2019). The particle sizes varied between the studies, but all measured less than 1.00 mm in size, except for the steel slag which contained coarser particles. The FM values were below 2.00 and a low FM of 0.45 for one of the fine dune sands was noted (Katz & Baum, 2006; Al-Harthy et al., 2007; Chitra, 2015; Padmanaban, Nithila & Reshma Jahaan, 2019).

The low FM values noted in these studies indicate poorly graded fine aggregate with a proportion of fines that do not comply with ASTM C33 guidelines. The results of these studies are representative of the behaviours to expect based on the physical characteristics of the Gold mine tailings when added to concrete mixes, as the Gold mine tailings are expected to be poorly graded with a high proportion of fines and thus a low FM value (Vermeulen, 2001; Sibanda, 2019; Maruthupandian, Chaliasou & Kanellopoulos, 2021; Adiguzel, Tuylu & Eker, 2022).

The studies described in Table 2-3 all follow a similar experimental procedure in that the fine aggregates are replaced by means of direct replacement with alternative materials in concrete mixes and tested at different ratios of replacement of fine aggregate in concrete in terms of the physical properties of the materials and the fresh and hardened properties of the concrete.

Generally, the inclusion of finer particles in these concrete mixes results in harsher concrete mixes with low slump values and subsequently low workability, which can be attributed to the increase in surface area of the particles which results in a higher water demand for the concrete mixture (Padmanaban, Nithila & Reshma Jahaan, 2019). To correct the increase in water demand in these concrete mixtures, wherein the w:b remains constant, a superplasticizer was used in the concrete mixtures with higher levels of fine aggregate replacement with finer materials as the ratio increased (Katz & Baum, 2006; Al-Harthy et al., 2007; Padmanaban, Nithila & Reshma Jahaan, 2019). The studies noted that up to a replacement ratio of between 20%- 40% of fine aggregate with finer particles, lower dosages of superplasticizer were required however, at higher replacement ratios, the amount of superplasticizer required increased exponentially (Katz & Baum, 2006; Al-Harthy et al., 2007; Chitra, 2015; Padmanaban, Nithila & Reshma Jahaan, 2019).

The compressive strengths of the concrete in these experiments had an initial increase when replaced with lower ratios of finer materials, followed by a decrease in strength (Katz & Baum, 2006; Chitra, 2015; Padmanaban, Nithila & Reshma Jahaan, 2019). Overall, these research studies have the common conclusion that finer materials can effectively be used as a fine aggregate replacement in concrete mixes up to a certain percentage of replacement without adversely affecting the compressive strength and workability of the concrete. However, the ratio at which finer particles can be used is dependent on the physical characteristics of the material and must be determined for each material.

2.8 Mine tailings as fine aggregate in concrete

The use of mine tailings as a replacement for fine aggregate in concrete has been done experimentally using different mine tailings. These experiments used a fixed concrete mix design, and the ratio of fine aggregate replaced with mine tailings was adjusted in each concrete mix. Table 2-4 summarises the findings of these experiments in terms of the influence of Gold mine tailings being used in concrete mixes and the effects of this replacement on concrete properties. Table 2-4 summarises the findings of different experiments on concrete properties when using different mine tailings as a substitute for fine aggregate in concrete mixes.

Table 2-4: The influence of mine tailings on concrete properties

Property	The effect when using mine tailings as a substitution for fine aggregate in concrete
Workability	Decreased
Slump	Decreased
Setting Time	Increased
Density	Increased
Water Absorption	Increased
Compressive Strength	Increased initially, then decreased (based on the substitution ratio)
Tensile Strength	Decreased

The tailings used in these experiments are derived from different mining procedures and thus contain different mineralogical and chemical compositions however, they share similar physical properties in that they are very fine-grained particles that exhibit similar behaviours when used in concrete mixtures as a replacement for fine aggregates. These materials were used as a direct replacement for fine aggregates in concrete mixtures at different ratios of replacement and in all the studies, it was found that the compressive strengths of these concrete mixtures increased at lower ratios of replacement up until a percentage of between 30% - 50%, which was followed by a decrease in compressive strength (Otieno & Ndoro, 2020; Adiguzel, Tuylu & Eker, 2022; Li et al., 2023).

Table 2-5: Summary of findings of experiments using mine tailings in concrete

Experiment	Experimental Procedure	Findings
Utilization of tailings in concrete products: A review (Adiguzel, Tuylu & Eker, 2022)	This study presents findings from existing research studies and describes the physical and chemical properties of different mine tailings as well as the environmental implications of these mine tailings assessed in terms of the US EPA method (1311).	• The compressive strength of concrete generally decreases when fine aggregate is replaced with mine tailings in ratios higher than 30%. • The water demand increases as the ratio of tailings increases beyond 10% and superplasticizers are often required to maintain the desired workability of the fresh concrete. The superplasticizer requirement for concrete using mine tailings as a replacement for fine aggregate is linear up to the optimal percentage replacement but increases exponentially thereafter. • The fine particles in tailings provide a filler effect in the concrete, reducing the permeability and increasing the mechanical resistance of the concrete when used in smaller ratios, but interfere with the cohesiveness of the cement paste and aggregates when using higher ratios of replacement. The filler effect can be described as the finer particles filling in the voids between larger particles within the concrete matrix. • The physical and chemical properties of tailings directly affect the mechanical properties of the concrete with a focus on PSD, porosity, water absorption and contents of MgO, Cl and SO_4. • The porosity of concrete mixes increases as the ratio of mine tailings increases, making it less resistant to harsh environmental conditions. • The clay-like nature of very fine particles makes the concrete more susceptible to drying and shrinkage cracking. • Tailings can be used as a replacement for fine aggregate or cement replacements but need to be assessed in terms of pozzolanic activity. • Chemical ions and compounds react differently when mixed with cement and water and should be assessed both as a material on its own and as a mixture in concrete. The chemical reactions within the concrete can affect the strength development of the concrete and retard early-age strength development.

Experiment	Experimental Procedure	Findings
		• CaO in mine tailings can dissolve in water to create a saturated $CaOH_2$ solution that acts as a lubricant and makes the concrete more workable. The presence of CaO therefore can increase the workability of the concrete. • The presence of heavy metals in tailings can cause a retarding effect on concrete by delaying hydration reactions. • The Gold mine tailings tested had traces of heavy metals (Namely Ni, Cu, As, Cd and Pb) which were reduced to values below 12 mg/L when mixed in concrete.
Use of tailings as a substitute for sand in concrete blocks production: gravimetric mining wastes as a case study (Méndez et al., 2022)	Gold mine tailings from Ecuador from gravimetric mining processes were used as a substitution for fine aggregate in concrete blocks using different concrete mix designs and tested in terms of PSD, density and compressive strength following ASTM standards. Furthermore, an XRD (X-ray diffraction) analysis and toxicity analysis were done on these tailings. The use of Gold tailings as a fine aggregate replacement is relative to this study however, the compressive strengths have not been considered as this experiment focuses on Masonry concrete, whereas the focus of this dissertation is on structural concrete.	• The potentially toxic elements present in the Gold mine tailings were Cr, Cu, Pb, V and Zn. • The primary constituent of Gold mine tailings was found to be Quartz, followed by a Phosphate Group and Andradite, with smaller percentages of Epidote, Feldspar and Calcite. • The chemical composition of Gold tailings described in this experiment has been presented in Table 2-2.
Utilization of kimberlite tailings as aggregates in concrete – strength and selected	Kimberlite tailings is a by-product of diamond extraction which follows a mechanical process, thus eliminating the incorporation of extraction chemicals and	• The tailings had an FM of 2.8 and comprised of particles which ranged from 0.075 mm – 20 mm in size. • The slump of the fresh concrete decreased as the ratio of kimberlite increased and can be attributed to both the fine particles and porous nature of these tailings.

Experiment	Experimental Procedure	Findings
durability properties (Otieno & Ndoro, 2020)	making it a more viable option to be used in concrete (Otieno & Ndoro, 2020). This experiment uses a combination of Kimberlite tailings and Andesite crusher sand at different replacement ratios for both coarse and fine aggregates in concrete to determine the effects of this replacement on the compressive strength and durability of the concrete.	• The Kimberlite tailings were separated into fine and coarse fractions, and it was found that the finer material had a higher impact on the water demand of the concrete as opposed to the coarser fraction. • The use of Kimberlite tailings as a coarse and fine aggregate in concrete causes a decrease in compressive strength and durability but can be replaced up to a percentage of 40% without impacting these properties significantly.
Recycling Mine tailings as precursors for cementitious binders – methods, challenges and future outlook (Maruthupandian, Chaliasou & Kanellopoulos, 2021)	A review of experiments done on the use of tailings as a substitute for cementitious binders in concrete in terms of the physical and chemical properties. The physical characteristics from these experiments have been used as a basis for the expected results for this dissertation.	• Mine tailings are generally loose and porous with a crystalline microstructure and have a relative density of between 2.70 – 4.29. • Mine tailings are generally comprised of very fine particles within the silt and clay range. • Mine tailings have a high water-absorption of up to 7.15%. • Mine tailings generally have a pH between 6.70 – 10.00. • The porousness of mine tailings and water absorption can cause additional hydration reactions in concrete. • Mine tailings generally have high sulphide and carbonate contents which may partake in oxidation reactions within the concrete. • The presence of heavy metals can be hazardous to the environment and retard strength development of the concrete.
Research status and prospects for the utilization of Lead–Zinc tailings as building materials (Li et al., 2023)	Lead-Zinc tailings from crushing and flotation mining methods in China have been used as a replacement for fine aggregates in concrete mixes by means of direct replacement and tested in terms of the physical and	• These tailings are very similar to natural sand as they are comprised of Quartz, Feldspar and Clay which is true for most tailing types. • The presence of angular particles because of mining activities could aid in the strength development of the internal pore structure of the concrete but also increase the presence of micropores which will reduce the compressive strength of the concrete.

Experiment	Experimental Procedure	Findings
	chemical properties of the concrete. The chemical composition of these tailings is similar to the chemical composition of Gold mine tailings in that they comprise primarily of Quartz (Méndez et al., 2022), making this study suitable for the expected behaviours from using Gold mine tailings as a substitute for fine aggregate in a similar manner as presented in this study.	• The compressive strength of concrete made with Lead-Zinc tailings can optimally be used for replacement levels up to 50%. • Replacement levels greater than 50% significantly increases the water demand and reduces the compressive strength of the concrete. • Lead-Zinc tailings have a high content of Silica-Alumina-Oxide and the composition of SiO_2, Fe_2O_3, and Al_2O_3 makes it a potential replacement for SCMs.

The initial increase in compressive strength has been attributed to the filler effect such that the fine particle nature of tailings acts as a filler that fits into the smaller voids in the concrete matrix at low levels of replacement, but at higher levels of replacement interferes with the cement-aggregate interface (Maruthupandian, Chaliasou & Kanellopoulos, 2021; Adiguzel, Tuylu & Eker, 2022). This filling effect decreases the voids in the concrete accounting for the increase in compressive strength, and when the ratio surpasses an optimal percentage, the interference with the cement-aggregate matrix results in a concrete mixture that is coarse and non-cohesive in nature. The adverse effect of the fine aggregates occurs when the fine particles fill the voids between the aggregate and the cement paste, thus interfering with the binding of the cement paste to the aggregate. This causes a decrease in the cohesion of the mix and separates the aggregates from the cement paste, resulting in the segregation of the concrete constituents and a decreased compressive strength (Maruthupandian, Chaliasou & Kanellopoulos, 2021; Adiguzel, Tuylu & Eker, 2022).

Furthermore, another common trend between the concrete mixes is that the water demand increases with the addition of mine tailings and according to one study, the water demand can be as high as 7.15% (Otieno & Ndoro, 2020; Maruthupandian, Chaliasou & Kanellopoulos, 2021; Adiguzel, Tuylu & Eker, 2022; Méndez et al., 2022). This increase in water demand begins as early as a 10% ratio of replacement and results in a decrease in slump which indicates a concrete mix that is less workable This increase in water demand can be attributed to the increase in surface area that needs to be wetted by introducing finer particles which in the case of mine tailings generally measure less than 1.00 mm in size (Maruthupandian, Chaliasou & Kanellopoulos, 2021; Méndez et al., 2022).

The small particles also fall within the clay range of particles in terms of sizing and exhibit a similar nature of absorption and drying which makes the concrete more susceptible to drying and shrinkage cracking (Adiguzel, Tuylu & Eker, 2022). In the case where there were both fine and coarse fractions of the same material used in one study, the finer particles had a more significant impact on the water demand of the concrete (Otieno & Ndoro, 2020). This finding reinforces the literature that particle size is a significant contributing factor to the water demand in these concrete mixes. The use of superplasticizers was noted in all the studies to correct the effects of the higher water demand of the concrete mixes to correct the workability of the concrete at higher replacement ratios of fine aggregate with mine tailings.

The increase in water demand of the mixture contributes to a loss in compressive strength such that the consumption of water by the aggregates means that less water is available for hydration reactions and therefore strength development of the mix (Padmanaban, Nithila & Reshma Jahaan, 2019). Furthermore, less cohesive and less workable concrete means that compaction becomes difficult which can lead to a further loss of compressive strength in concrete (Otieno & Ndoro, 2020).

The strength of the aggregates used in concrete mixes is also a distinguishing factor and aggregates derived from softer rocks can adversely affect the compressive strength of the concrete as compared to aggregates derived from harder rock (Otieno & Ndoro, 2020).

The chemical properties of mine tailings that affect the behaviour of the concrete include the pozzolanic oxides (namely SiO2, Al2O3, and Fe2O3) which react with the CH in cement to form CSH gels (Adiguzel, Tuylu & Eker, 2022). The amount of pozzolanic oxides helps determine whether the mine tailings are better to be used as a fine aggregate or SCM in concrete mixtures. The CaO content acts as a lubricant when combined with cement and the Sulphate content contributes to volume changes in concrete. Furthermore, mine tailings contain potentially toxic metals, such as Ni, Cu, As, Cd, and Pb which are found in trace amounts in Gold mine tailings and can retard the strength development of the concrete (Adiguzel, Tuylu & Eker, 2022).

Generally, tailings have a neutral pH however, the chemical reactions between the mine tailings with cement and/or water may result in acid leachate which is harmful to the environment, and it is therefore important that tailings be tested both as a material on its own and within the concrete matrix when assessing the environmental implications of using mine tailings as a substitute for fine aggregate in concrete.

Different tailings lack homogeneity in terms of physical and chemical properties which is affected by the source of the tailings and method of extraction. Therefore, construction guidelines and technology need to be developed to incorporate the use of tailings in concrete mixtures which requires repetitive research to be performed focusing on the type and source of tailings being assessed.

2.9 Summary

Conventional mine waste disposal includes the use of TSFs which is costly and requires ongoing monitoring and maintenance even after the facility is no longer in use (Maruthupandian, Chaliasou & Kanellopoulos, 2021). Furthermore, with rapid urbanisation rates, TSFs are reaching capacity at increasing rates as the demand for raw materials rises with development (Adiguzel, Tuylu & Eker, 2022). To meet the demands of development, sustainable alternatives need to be studied to preserve the environment while catering to these demands. By using mine tailings as a replacement for aggregates which are typically stored in TSFs, both the demand for natural resources for construction and the pressures on TSFs are reduced (JXSCmachine, 2024). There have been studies presenting ways in which this can be achieved, and in specific a large focus has been placed on methods in which tailings can be recycled.

This chapter discussed the impact of using replacements of fine aggregate with finer material in concrete and the impact of replacing fine aggregate with different mine tailings in concrete mixes. The relevance of the fine aggregate replacement with finer materials is that Gold mine tailings generally comprise particle sizes that are smaller than that of conventional fine aggregates (Vermeulen, 2001; Sibanda, 2019; Maruthupandian, Chaliasou & Kanellopoulos, 2021; Méndez et al., 2022).

The studies pertaining to the replacement of fine aggregate in concrete with materials containing finer materials include the use of fines, fine dune sand, ceramic powder and copper and steel slag (Katz & Baum, 2006; Al-Harthy et al., 2007; Chitra, 2015; Padmanaban, Nithila & Reshma Jahaan, 2019). It was found that even though these materials were derived from different sources, the concrete produced using these materials exhibited similar trends which can be attributed to the decreasing particle size. These concrete mixes experienced a reducing slump as the ratio of replacement increased and an initial increase in compressive strength, followed by a decrease in compressive strength as the ratio of replacement increased. Similar trends were observed in the experiments using mine tailings as a replacement for fine aggregate in concrete mixes and different mine tailings including Gold, Kimberlite, and Lead-Zinc tailings among others were considered (Otieno & Ndoro, 2020; Maruthupandian, Chaliasou & Kanellopoulos, 2021; Adiguzel, Tuylu & Eker, 2022; Méndez et al., 2022; Li et al., 2023).

However, in terms of the real-world context, these studies are small-scaled and limited, and to steer people away from conventional methods of solid waste management, further studies needs to be conducted (Gou, Zhou & Then, 2019; Maruthupandian, Chaliasou & Kanellopoulos, 2021; Adiguzel, Tuylu & Eker, 2022). The methods of testing the applicability of using these alternative materials can be standardized but need to be conducted on different tailings as they are non-homogeneous depending on the type of tailings and method of extraction (Adiguzel, Tuylu & Eker, 2022). The recycling of tailings to be used in building materials aligns with the sustainability goals set out by most "green" associations. Continuous research will aid in technological and legislative advancements to incorporate recycling methods into common practice which will contribute to a better future in terms of environmental, economic, and social contexts (Adiguzel, Tuylu & Eker, 2022).

3. Research methodology

This chapter describes the experimental procedures followed in this study to determine the viability of using Gold mine tailings from the Witwatersrand region as a replacement for fine aggregate in different proportions in concrete mix designs. The experiments were conducted in the Civil Engineering materials laboratory at the University of Cape Town and consisted of the following:

1. Characterisation of fine aggregates.
2. Slump test on fresh concrete mixtures.
3. Concrete compressive strength and OPI testing on hardened concrete.

The tests conducted in this study were done in accordance with the South African National Standards (SANS) and American Society for Testing and Materials (ASTM) Standards, which are stipulated for each test.

3.1 Experimental Investigation

The phases of the experimental investigation are summarised in Figure 3-1 and are further described in this chapter.

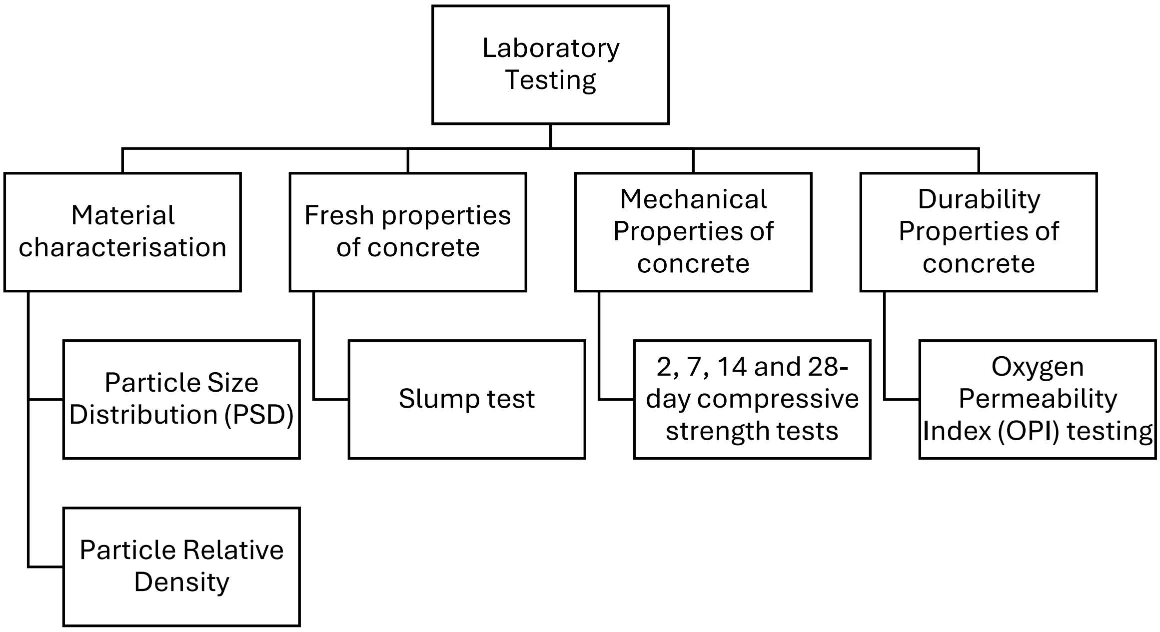


Figure 3-1: Experimental programme for testing the viability of using Gold mine tailings as a substitute for fine aggregate in concrete mixes

3.2 Materials and resources

The following resources were required for successful execution of this study:

- Homogeneous Gold mine tailings from a single TSF in the Witwatersrand region.
- Concrete constituent materials (namely cement, water, fine aggregates and coarse aggregates).
- Chryso Premia 550 superplasticizer.
- Equipment required for material characterisation (namely oven, scale, PSD sieves, sieve shaker, and pycnometer).
- Equipment required for sample preparation (namely oven, scale, mixing bowl, slump cone, metal rod, and vibrating table).
- 50 mm and 100 mm concrete casting cubes.
- A temperature controlled concrete curing bath controlled at 23°C.
- Compressive strength testing machine.
- Concrete cutting and coring machines.
- OPI testing apparatus.

The concrete material constituents are described in Sections 3.2.1 – 3.2.5.

3.2.1 Cement

CEM II/A-L 42.5 N Surebuild Cement from Pretoria Portland Cement (PPC) was used in this study. This cement is commonly available in South Africa, Botswana, and Zimbabwe and comprises a combination of clinker and extender (PPC, 2020). The Limestone-based PC complies with the 42.5 N strength class as stipulated by SANS 50197-1 (PPC, 2016). Table 3-1 summarises the physical and chemical properties of the cement.

Table 3-1: Physical and chemical properties of CEM II/A-L 42.5 N (PPC, 2016)

Property	Value
Chemical composition	55% – 70% Tricalcium Silicate ($3CaOSiO_2$) 5% – 20% Dicalcium Silicate ($2CaOSiO_2$) 2 %– 10% Tricalcium Aluminate ($3CaOAl_2O_3$) 5% – 15% Tetra Calcium Aluminoferrite ($4CaOAl_2O_3Fe_2O_3$) 2% – 5% gypsum ($CaSO_42H_2O$) <1.5% Calcium Oxide (CaO)
Relative Density	3.08
Bulk Density	1500 kg/m^3
Specific Area (Blaine)	400 m^2/kg
Compressive Strength	20 MPa (3-day strength) >45 MPa (28-day strength)

3.2.2 Water

Potable tap water was used for the mixing and curing of the concrete samples.

3.2.3 Natural fine and coarse aggregates

Greywacke was used as the coarse aggregate in this study. Greywacke stone (also known as hornfels) is a type of shale rock from the Malmesbury and Peninsula regions in the Western Cape which has undergone thermal metamorphism to form a fine-grained, glassy structure containing Quartz, Feldspar, Mica, Iron oxides, and Alumino Silicates. The parent rock undergoes industrial crushing to achieve desirable sizes (Bonser & Alexander, 2021). Mix A used a nominal size of 10-mm Greywacke aggregate and Mix B used a nominal size of 19-mm. The use of 19-mm Greywacke in Mix B was chosen due to the timeline of this study which spanned over a 2-month period, and the availability of the 19-mm Greywacke. The initial experimental investigation did not include Mix B, which was added to the experimental programme following a trend of decreased compressive strength at 14-days in Mix A. The addition of Mix B to the experimental programme was added to verify or dispute this decrease in strength at 14-days. Furthermore, the 19-mm Greywacke aggregate was readily available at the UCT Materials Laboratory whereas the 10-mm would not be available in time to include the results of Mix B in the experimental programme. The Greywacke used in this experiment was acquired from Afrimat in Cape Town, South Africa.

The fine aggregates used in this experiment comprised of Philippi dune sand, 5-mm Greywacke crusher sand, and Gold mine tailings, such that the proportion of crusher sand remained constant, and the Philippi dune sand was replaced by different ratios of Gold mine tailings. The combination of Philippi dune sand and Greywacke crusher sand was chosen to achieve an adequate distribution of particle sizes between the aggregates in the concrete mix (Kahabi et al., 2022). A ratio of 1:1 for the Phillipi dune to crusher sand was used in the reference mixes in this study. Furthermore, the sources of natural pits in the Western Cape have seen immense pressures in terms of supply, hence a combination of these fine aggregates has been widely adopted (Kahabi et al., 2022). Figure 3-2 presents a summary of the aggregates used in this study.

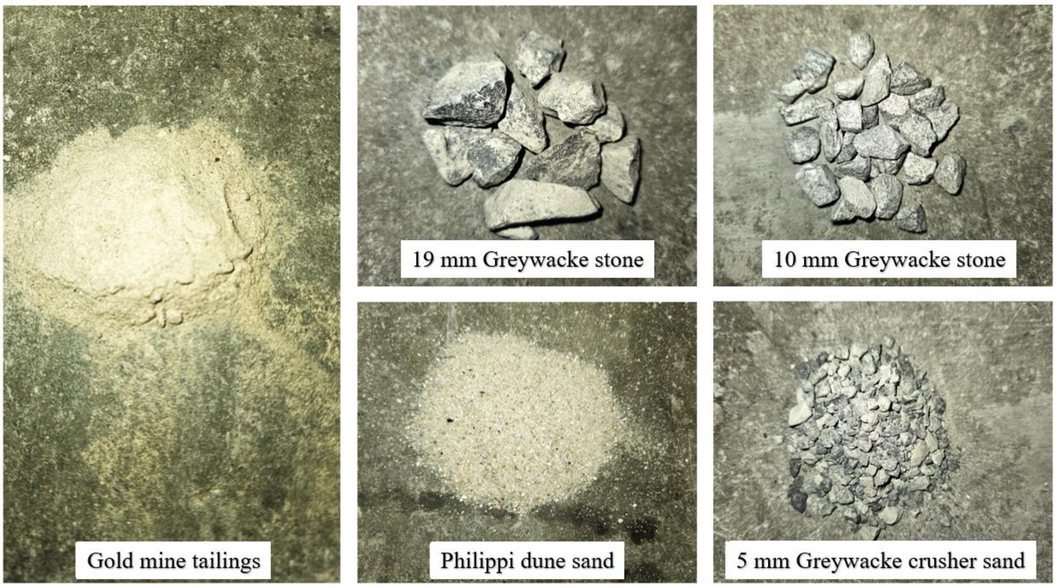


Figure 3-2: Aggregates used in this study

The crusher sand used in this study was manufactured using Greywacke rocks which underwent mechanical processes to achieve desired particle sizes. The mechanical processes cause the crusher sand to have more angular particle shapes and a larger distribution of particle sizes ranging from 0.075 mm – 5 mm. This manufacturing process has increased the availability of well-graded fine aggregates which alleviates the pressures on natural sand pits in the Western Cape and is often used in combination with other fine aggregates in practice (Kahabi et al., 2022).

Philippi dune sand is found in coastal regions and is specifically found in abundance in Cape Town, South Africa. The particles of Philippi dune sand are well-rounded due to the wind action that moves the particles to dune deposits. The grain size of Philippi dune sand ranges between 0.1 – 1.0 mm. The well-rounded shape of the Philippi dune sand aids in particle movement within the fresh concrete. Dune sand is found in heaps that have formed naturally in low-lying coastal areas and have a relatively uniform particle size, shape, and density (Kahabi et al., 2022).

3.2.4 Mine tailings

The tailings used in this experiment come from a Gold mine reclamation project that falls within the Witwatersrand region in the North-West Province of South Africa. The Gold mine tailings were acquired from a facility that remines tailings from existing facilities and deposits them in a single TSF by means of a slurry and cyclone system. The extraction process used at this facility is Cyanidation which is described in Chapter 2 of this dissertation. Figure 3-3 shows the Gold mine tailings used in this experiment at different stages of the study.

Gold mine tailings after oven drying used in this experiment

Gold mine tailings being weighed for use in this experiment

Figure 3-3: Gold mine tailings used in this study

3.2.5 Admixtures

The high water-absorption characteristics associated with fines in concrete required that a superplasticizer be used in the concrete mixtures to maintain the desired workability for all concrete mixes. The superplasticizer used in this study was Chryso Premia 550. The amount of superplasticizer used in each concrete mix design varied based on the required and actual slumps achieved during the mixing process. The maximum allowable dosage of this admixture is 3% of the binder weight (Chryso, 2015).

3.3 Material characterization of fine aggregates

Basic indicator testing was performed on the fine aggregates used in this study using the following methods:

- PSD in accordance with SANS 201.
- Relative density in accordance with SANS 3001-AG23:2014.

3.3.1 Particle size distribution

For the PSD, 500 g of fine aggregate was used for each test following the sieve analysis test method as per SANS 201 guidelines. The aggregate was oven-dried at 50°C for 48 hours, placed into the sieve apparatus and shaken, followed by the masses of each sieve being recorded. The results were used to develop a PSD curve which was used for the analysis of each aggregate. The masses of each particle size were recorded in terms of the percentage of aggregate retained by the sieve and used to calculate the percentage passing and FM for each fine aggregate. This was used to calculate the concrete mix design. Figure 3-4 and Figure 3-5 illustrates the sieve test analysis as done in this study.

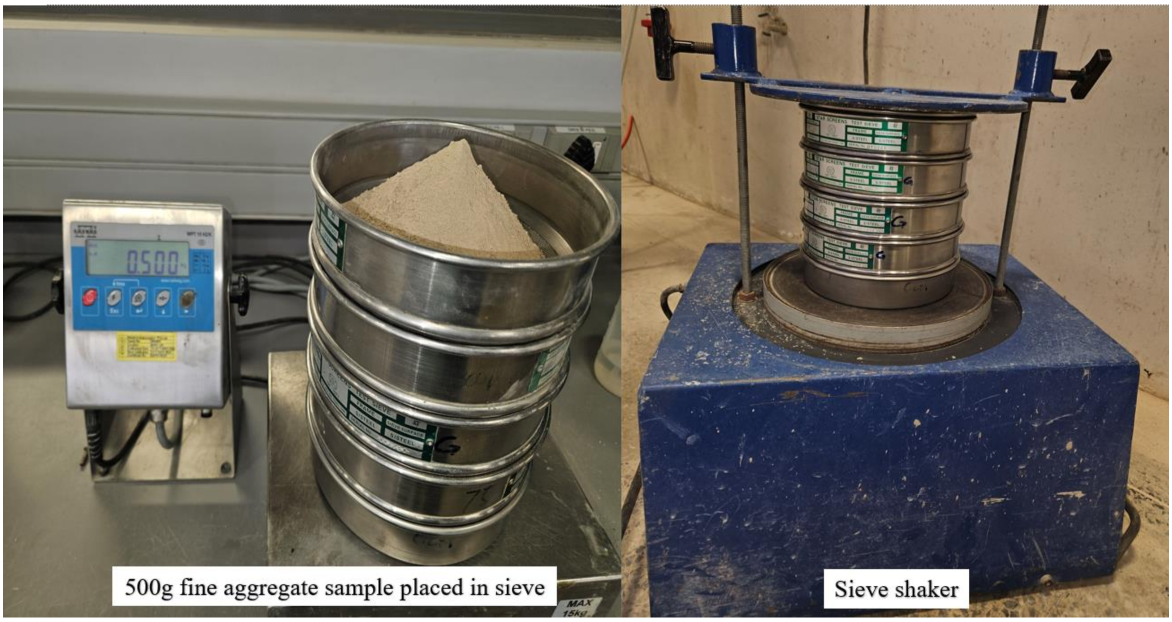


Figure 3-4: Apparatus used in particle size distribution test

3.3.2 Relative density

Relative density testing was done three (3) times per fine aggregate sample and an average value of the three (3) tests was used to determine the relative density of each fine aggregate. The aggregates were tested following the SANS 3001-AG23:2014 procedure using 300 g of fine aggregate which was placed in a pycnometer and filled with water. The mass of the aggregate mixed with water and the mass of only water filled in the pycnometer to the same level was recorded and used to determine the relative density of each sample. Figure 3-6 illustrates the procedure used in the relative density test of the Gold mine tailings in this study.

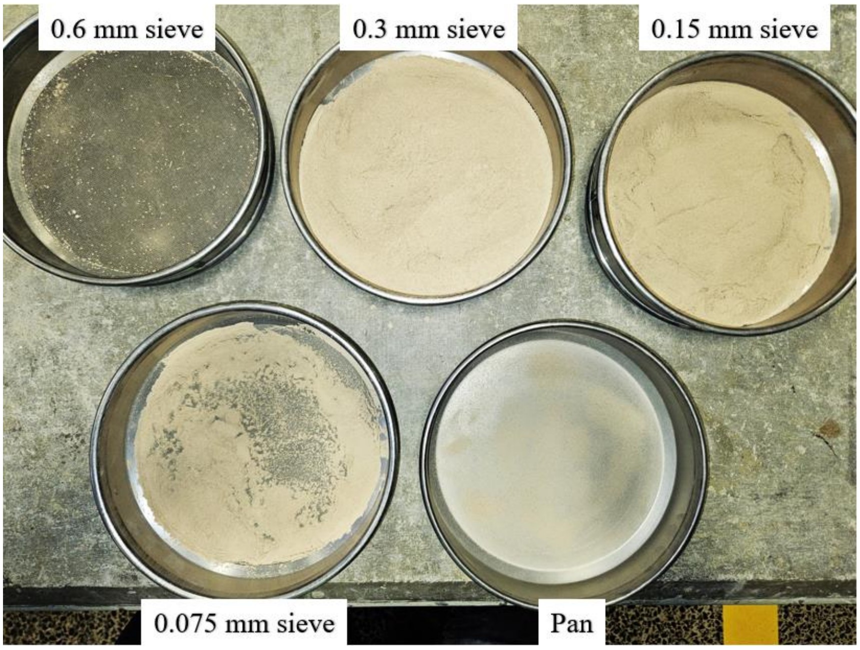


Figure 3-5: Aggregates retained on each sieves size after sieve analysis of Gold mine tailings

300g fine aggregate in Pycnometer

Water sample in Pycnometer

Saturated tailings sample in Pycnometer before filling with water

Figure 3-6: Relative density testing of Gold mine tailings

3.4 Concrete mix designs

The workability of concrete is a function of the w:b and the fines in the mixture (Kahabi et al., 2022). The fine content in concrete mixes affects the amount of water required to achieve a specific slump which is attributed to the increase in surface area of the particles that need to be wetted (Adiguzel, Tuylu & Eker, 2022).

Two reference concrete mix designs were used in this study and were developed using the C&CI method. The first concrete mix design was developed using a w:b of 0.45, as this ratio yields higher strengths as opposed to a higher w:b, aligning with the focus on compressive strength in this study. This concrete mix used 10-mm Greywacke stone as the coarse aggregate as the compressive strength testing was done on 50 mm cubes which limits the coarse aggregate to a maximum size of 10-mm as per SANS 5861 guidelines.

The second reference mix was developed following a trend in the compressive strength results of Mix A which showed a consistently abnormal trend in that the compressive strengths for the concrete with a ratio of replacement of 20%, 40% and 60% resulted in an increased compressive strength between 2 and 7-days and then a decreased compressive strength at 14-days, only to increase beyond the compressive strength of 7-days at the 28-day compressive strength test. This decrease in strength, followed by an increase in strength does not align with concrete strength development theory, which is that the compressive strength of concrete increases with time, at a decreasing rate (Boshoff, Combrinck & van Zijl, 2021).

Conventional concrete reaches about 40% of its full-age strength at 3-days, 65% at 7-days, 90% at 14-days and 99% at 28-days of curing (Converge.io, 2022; theconstructor.org, 2024). It is expected that the use of Gold mine tailings as a replacement for fine aggregate in concrete may cause a retarding effect on the strength development of the concrete however, it should still follow a trend of continuous increase in compressive strength over the 28-day period (Adiguzel, Tuylu & Eker, 2022; Méndez et al., 2022). The compressive strength results on Mix A can therefore be described as a deviation from what is expected, unless further testing can verify this trend. This trend of compressive strength development prompted the inclusion of Mix B into the experimental procedure to verify or dispute these results. In this mix, a few changes were made to improve the test results as follows:

1. A w:b of 0.6 was used to reduce the amount of superplasticizer required to maintain the workability of the concrete, as it was found that the higher replacement ratios of fine aggregate required exponentially increasing dosages of superplasticizer.
2. 100 mm concrete cubes were used for compressive strength testing to ensure that each cube was cast individually and not in a tray as with the 50 mm cubes. This was done since the 14-day concrete cubes for all replacement ratios of Mix A were cast on the same location of the tray, which could potentially have produced different degrees of vibration which was consistent across the mixes and could potentially have contributed to the results.
3. A 19-mm Greywacke stone was used as the coarse aggregate in this mix due to a limited experimental programme in terms of time which spanned over 2 months. The 19-mm Greywacke was available at the time of casting and getting a supply of 10-mm Greywacke aggregate would cause delays in the experimental programme. This also aligns with SANS 5861 guidelines on coarse aggregate sizing for 100 mm concrete cubes.

The mix designs were calculated using the w:b, the FM, and relative densities of the aggregates for a 1 m^3 mix and reduced to produce 10ℓ of the relevant mixes. A combined relative density for fine aggregate was calculated using the relative densities of each fine aggregate at the relevant replacement ratios and used to calculate the mass of each constituent. The mix designs adopted for this study are presented in Table 3-2 and Table 3-3.

Table 3-2: Mix Design A

Mix Design A: **w:b = 0.45** **Coarse aggregate = 10 mm Greywacke**						
		Mix 1	**Mix 2**	**Mix 3**	**Mix 4**	**Mix 5**
Replacement level of dune sand		0 %	20 %	40 %	60 %	80 %
Ratio of Crusher:Dune:Tailings		50:50:0	50:40:10	50:30:20	50:20:30	50:10:40
Combined density of fine aggregate		2.50	2.60	2.60	2.70	2.80
Dosage of superplasticizer	**mℓ**	30	30	30	80	85
Material	**Particle relative density**					
Water (ℓ /m³)	1.00	180	180	180	180	180
Cement (CEM II-A-L 42.5 N) (kg/m³)	3.08	400	400	400	400	400
Coarse aggregate (10-mm Greywacke) (kg/m³)	2.7	909.2	920.9	932	942.4	952.3
Total fine aggregate (kg/m³)	-	895.3	902.9	911.5	921.1	931.7
Fine aggregate (crusher sand) (kg/m³)	2.79	447.7	451.5	455.7	460.5	465.8
Fine aggregate (Dune sand) (kg/m³)	2.32	447.7	361.2	273.4	184.2	93.2
Fine aggregate (Tailings)	2.86	0	90.3	182.3	276.3	372.7

The reference mix design was developed following C&CI guidelines, using a 50:50 ratio of Philippi dune sand and Greywacke crusher sand. The reference mixes were then re-calculated using a method of direct replacement of the Philippi dune sand with Gold mine tailings at ratios of 20%, 40%, 60%, and 80% replacement levels for Mix A and 20% and 60% replacement ratios for Mix B. The replacement ratios of 20% and 60% were chosen for Mix B as this was an additional component to the original experimental programme following the results of Mix A as mentioned, and the limited availability of homogenous Gold mine tailings.

Table 3-3: Mix Design B

Mix Design A: **w:b = 0.60** **Coarse aggregate = 19 mm Greywacke**				
		Mix 1	**Mix 2**	**Mix 3**
Replacement level of dune sand		0%	20%	60%
Ratio of Crusher:Dune:Tailings		50:50:00	50:40:10	50:20:30
Combined density of Fine Aggregate		2.50	2.60	2.70
Dosage of superplasticizer	**mℓ**	10	8	28
Material	**Particle relative density**			
Water (ℓ/m³)	1	180	180	180

Mix Design A: **w:b = 0.60** **Coarse aggregate = 19 mm Greywacke**				
		Mix 1	**Mix 2**	**Mix 3**
Cement (CEM II-A-L 42.5 N) (kg/m³)	3.08	400	400	400
Coarse aggregate (10-mm Greywacke) (kg/m³)	2.7	909.2	920.9	942.4
Total fine aggregate (kg/m³)	-	895.3	902.9	921.1
Fine aggregate (crusher sand) (kg/m³)	2.79	447.0	451.5	460.5
Fine aggregate (Dune sand) (kg/m³)	2.32	447.7	361.2	184.2
Fine aggregate (Tailings)	2.86	0	90.3	276.3

3.5 Mixing and casting procedure

The casting and curing procedure used during this experiment was done in accordance with SANS 5860 and SANS 5861-1, respectively. The concrete samples were cast in 50 mm x 50 mm moulds and 100 mm x 100 mm moulds for the different tests. The use of 50 mm x 50 mm cubes was chosen due to the limited amount of Gold tailings material available at the time of casting. A minimum of three (3) 50 mm moulds and two (2) 100 mm moulds were required for each compressive and OPI test, respectively for Mix A, and three (3) 100 mm cubes were required for the compressive strength tests of Mix B. The concrete cubes were cured in a temperature-controlled water bath at 23°C until testing.

All specimens were left in their respective moulds for 24 hours prior to the demoulding process and were covered with a plastic sheet which reduces the surface water evaporation rate. Once the specimens were demoulded, they were cured for their respective curing times before being removed for testing. This was done at the UCT Materials Laboratory. The specimens were tested for compressive strength and cored and cut as per SANS 3001-CO3-1:2015 for the OPI test. Figure 3-7 and Figure 3-8 illustrates the mixing and casting procedures followed in this experiment. The number and size of the specimens used in the tests are summarised in Table 3-4.

Concrete mix in 10 l mixing bowl   50 mm and 100 mm cast concrete cubes

Figure 3-7: Mixing and casting procedures

50 mm concrete cube tray moulds   100 mm concrete cubes

Figure 3-8: Concrete cube moulds used in this study

Table 3-4: Concrete sample sizing and tests done

Concrete mix design	50 mm cubes	100 mm cubes	Tests done (50 mm cube)	Tests done (100 mm cube)
Mix A (0% replacement)	9	1	Compressive strength (2,7 and 14-days)	OPI
Mix A (20% replacement)	12	4	Compressive strength (2,7,14 and 28-days)	OPI and compressive strength (28-days)
Mix A (40% replacement)	12	4	Compressive strength (2,7,14 and 28-days)	OPI and compressive strength (28-days)
Mix A (60% replacement)	12	4	Compressive strength (2,7,14 and 28-days)	OPI and compressive strength (28-days)
Mix A (80% replacement)	12	4	Compressive strength (2,7,14 and 28-days)	OPI and compressive strength (28-days)
Mix B (0% replacement)	-	9	-	OPI and compressive strength (28-days)
Mix B (20% replacement)	-	9	-	OPI and compressive strength (28-days)
Mix B (60% replacement)	-	9	-	OPI and compressive strength (28-days)

3.6 Fresh properties of concrete

The workability of the concrete was tested in accordance with the slump test specified by SANS 5862-1:2006 and was executed before casting the concrete. The concrete mixes were found to be less workable with an increase in the content of the Gold mine tailings, and the superplasticizer was added in doses of 5 mℓ until the desired slump was reached. The target slump for these concrete mixes was 100 mm with a 25 mm allowance on either side.

It was found that the addition of superplasticizer in dosages of 5 mℓ had an impact on the slump such that a very low slump would be achieved with a certain dosage of superplasticizer, and when adding an additional 5 mℓ dose, the slump collapsed in some cases. This can be attributed to the lack of cohesiveness observed in the mixes which caused the heavier coarse aggregates to settle at the bottom of the mix by gravity. The segregation of the fines and coarse aggregate is due to the interference of the cement paste-aggregate by means of the filler effect (Adiguzel, Tuylu & Eker, 2022).

During the slump test, the slump cone was filled in 3 equal layers and tampered with a metal rod prior to filling the next layer. The slump cone was removed, and the slump was measured. Where a very low slump was achieved, the concrete was placed back into the mixer and an additional dose of superplasticizer was added, and the concrete was mixed for an additional 5 minutes. This procedure was repeated until an acceptable slump was achieved. Figure 3-9 illustrates the slump test done during this study.

Figure 3-9: Slump tests done in this study

3.7 Compressive strength testing

The compressive strength testing was done in accordance with SANS 5863-2006 procedures using an Instron 1000RD-E4 H2 compressive strength testing machine. The compressive strength testing investigated the strength development of the concrete samples and the effect that the addition of Gold mine tailings as a substitute for fine aggregate would have on the compressive strength at various ages of curing.

The compressive strength testing was conducted on both 50 mm and 100 mm concrete cubes samples. The compressive strength testing was done after the samples were cured in a temperature-controlled curing bath at 2-days, 7-days, 14-days and 28-days, and the compressive strengths for three (3) samples were recorded for each test. Furthermore, an additional two (2) 100 mm samples were tested for compressive strength on Mix A at 28-days.

An early-age testing of 2-days was chosen in this study instead of 3-days as this allowed for concrete mixes to be cast between Monday and Wednesday due to the tight experimental programme and allowed for a 2-day compressive strength testing that would remain consistent throughout all concrete mixes as access to the UCT laboratory is limited over the weekend. The 2-day compressive strength results are illustrative of early strength development and can easily be compared when kept consistent between the mixes.

3.8 Oxygen Permeability Index Testing

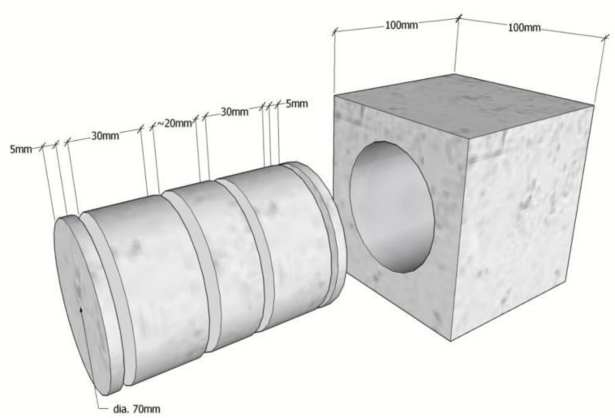
The OPI test measures the hardened concrete's resistance to the ingress of oxygen and measures the permeability of the concrete sample when exposed to a dropping pressure head (Alexander, 2018). This test was conducted in accordance with SANS 3001-C03-1:2015 and investigated the pores within the concrete on a microstructural level relating to the deterioration of the concrete because of using Gold mine tailings as a replacement for fine aggregate in concrete.

The OPI test was done in accordance with SANS 3001-C03-1:2015 on four (4) concrete discs measuring 70 mm in diameter and 30 mm in thickness which were prepared as per the UCT Durability Index Testing Procedure Manual (Alexander, 2018). Table 3-5 summarises the OPI values relating to the quality of the concrete.

Table 3-5: A guide to the quality of the concrete using the OPI values (Alexander, 2018)

OPI log scale	Quality of concrete
>10.0	Excellent
9.5 – 10.0	Good
9.0 – 9.5	Poor
<9.0	Very Poor

For this test, two (2) concrete cubes were prepared, giving a total of four (4) concrete samples per test Figure 3-10 to Figure 3-12 illustrates the OPI testing that was done in this study.



Concrete disc preparation

Figure 3-10: Diagrammatic representation of OPI testing sample preparation (Alexander, 2017)

Concrete cores in oven during sample preparation

Concrete cores in desiccator during sample preparation

Figure 3-11: Sample preparation of cores for OPI testing

Figure 3-12: OPI testing apparatus

3.9 Summary of test methods

This chapter comprised of the research methodology and experimental procedure programme as set out by this study, the materials used and the material characterisation and associated test methods including the PSD and relative density testing procedure. Furthermore, this chapter specifies the mix designs used in this study and the mixing and casting procedures followed in preparation of the concrete samples.

The test methods included in this chapter are the slump test which is measured on fresh concrete and the compressive strength and OPI testing methodology used in this study which was executed on hardened concrete.

4. Results and Discussion

4.1 Introduction

This chapter summarises the experimental results of this study which followed the testing methods described in Chapter 3. Furthermore, the results are discussed in relation to the viability of using Gold mine tailings as a substitute for fine aggregates in concrete mixes.

4.2 Characterisation of materials

4.2.1 PSD of fine aggregates

The percentage passing of particles through the PSD sieves of the fine aggregate used in this study are presented in Table 4-1 and their PSD graph are illustrated in Figure 4-1 with the particle size envelope showing upper and lower limit guidelines as per SANS 1083 guidelines.

Table 4-1: Cumulative passing of fine aggregates used in this study

Sieve opening (mm)	Cum. % passing (%)		
	Gold mine tailings	Philippi dune sand	Greywacke crusher Sand
4.75	100.0	100.0	86.9
2.36	100.0	100.0	50.6
1.18	100.0	99.4	33.2
0.6	99.0	72.3	22.7
0.3	30.7	18.7	12.2
0.15	3.7	1.0	2.4
0.075	0.3	0.0	1.0
PAN	0.0	0.0	0.0

None of the fine aggregates used in this study fell within the guideline envelope on its own. Figure 4-1 highlights that the Gold mine tailings contained a high proportion of particles in the 0.075 mm – 0.6 mm range which accounted for 98.7% of the total mass of the tailings, whereas the Philippi dune sand contained 71.3% of its mass being made up of particles between 0.15 mm - 0.6 mm in size. The Greywacke crusher sand contained 22.7% of fine particles measuring 0.075 mm – 0.6 mm in size. The predominant particle sizes of the Gold mine tailings and Philippi dune sand was in the 0.3 mm – 0.6 mm range whereas the predominant particle sizes of the Greywacke crusher sand fell within the 0.6 mm – 4.75 mm range, with 13.1% of the particles measuring larger than 4.75 mm.

The non-compliance of these fine aggregates with SANS 1083 guidelines forms the basis of using the blend of these fine aggregates to create a more well-graded natural fine aggregate and is common practice in the Western Cape region of South Africa (Kahabi et al., 2022).

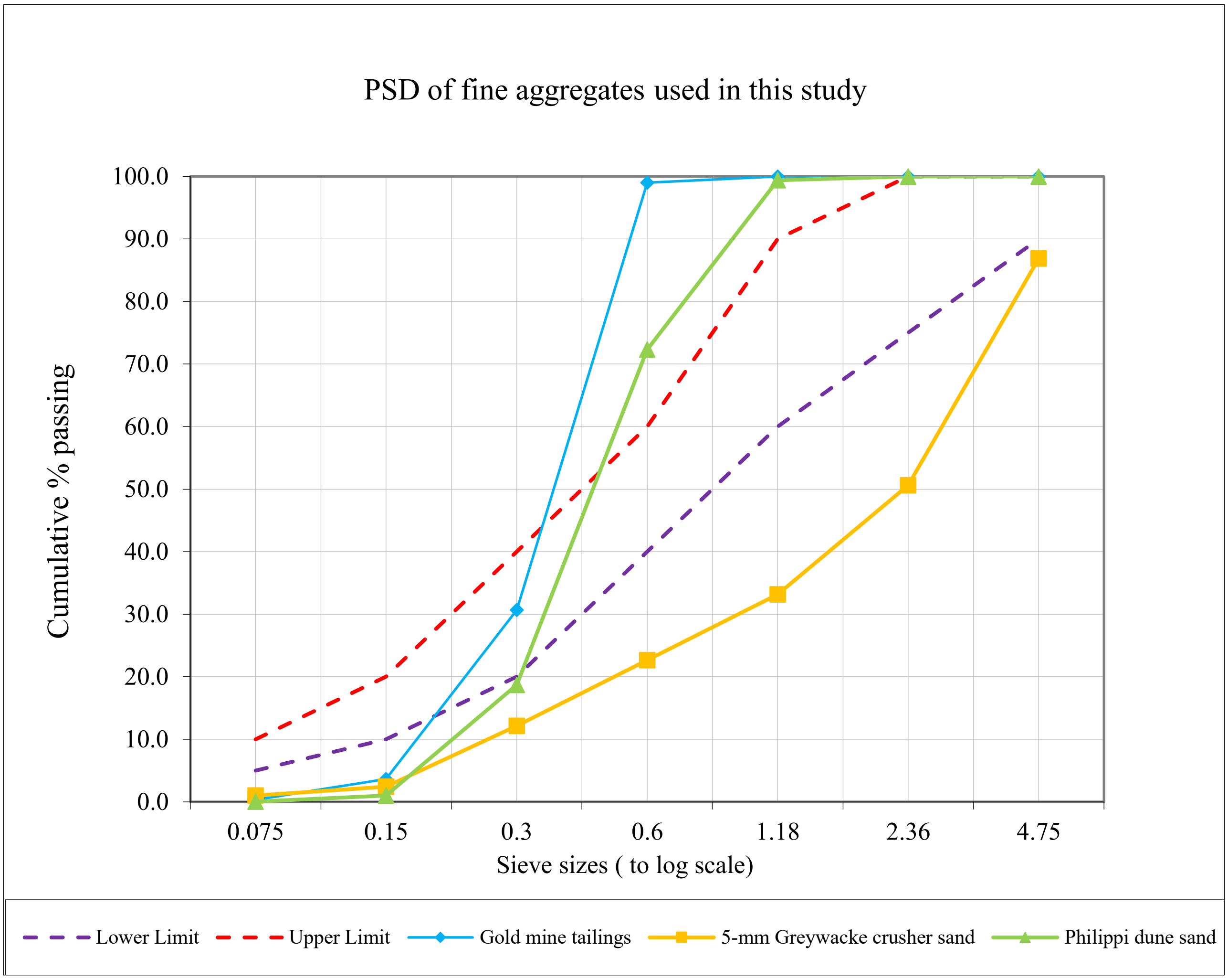


Figure 4-1: PSD graphs of fine aggregates used in this study

The Gold mine tailings contained predominantly particles sized smaller than 0.6 mm with only 1% of particles measuring greater than 0.6 mm. The Philippi dune sand had a similar gradation, with a higher percentage accounting for 27.7% of particles being larger than 0.6 mm. The Greywacke crusher sand contained particle sizes larger than 1.18 mm which accounted for 66.8% of the total mass of the aggregate whereas only 0.6% of the total mass of the Philippi dune sand and 0% of the Gold mine tailings fell within this range. The Greywacke crusher sand contained particles smaller than 0.075 mm which accounts for 1% of the total mass of the aggregate which is classified as fines and aids with the cohesiveness and workability of the concrete mix (Al-Harthy et al., 2007). The Gold mine tailings only contained 0.3% of fines and the Philippi dune sand did not contain any fines.

The blends of the fine aggregates used in this study were assessed in terms of the PSD and how well they fit in the SANS 1083 guidelines and can be seen in Figure 4-2. It was found that the Philippi dune sand and the Greywacke crusher did not comply with the SANS 1083 guidelines in terms of the quantity of fine particles less than 0.30 mm in size which should account for 20% - 40% of the concrete mix. The Gold mine tailings had more material within the 0.15 mm – 0.3 mm range. This result was expected as the quantity of particles less than 0.3 mm was 12.2%, 18.7% and 30.7% for the Greywacke crusher sand, the Philippi dune sand and the Gold mine tailings, respectively. The fine aggregates used in this study do not fall within the SANS 1083 envelope guidelines for fine aggregates as seen in Figure 4-1 however, from Figure 4-2 it can be seen that all the fine aggregate blends used in this study comply with the SANS 1083 guidelines for particle sizes greater than 0.3 mm which create a more suitable fine aggregate grading to be used in concrete mixes.

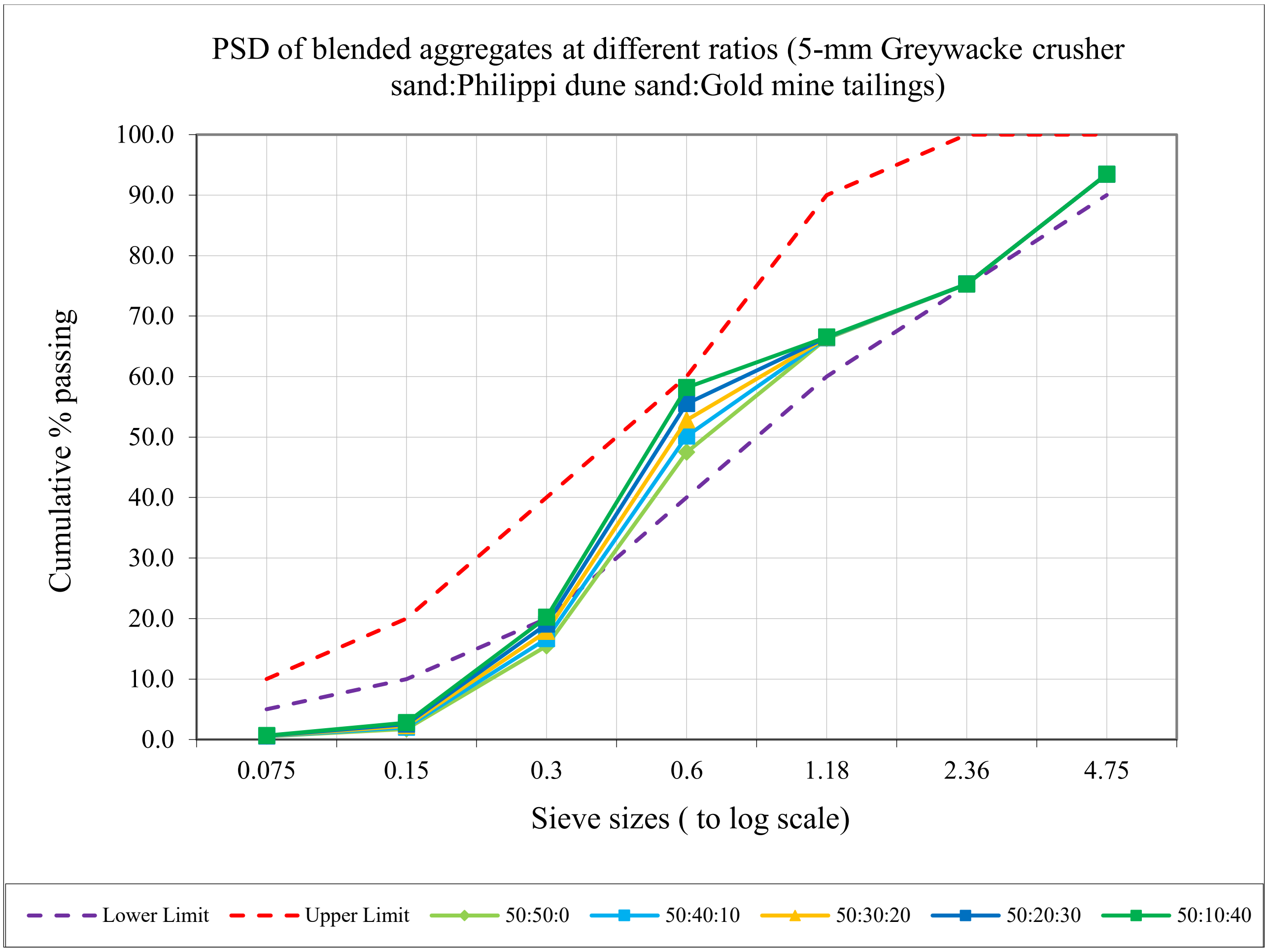


Figure 4-2: PSD of blended aggregates used in this study

The finer particles of the Gold mine tailings when compared to other fine aggregates used in this study was expected as the particle sizes of Gold mine tailings typically range between 0.001 mm - 0.65 mm (Vermeulen, 2001; Sibanda, 2019).Although the particle sizes of Gold mine tailings fall within the range documented by the literature, most of the particles from the Gold mine tailings used in this study fall within the higher fraction of the range, making the material similar to the Philippi dune sand in terms of its PSD. The PSD of the Gold mine tailings was predominantly made up of particle sizes between 0.3 mm – 0.6 mm, accounting for 68.3% of the mass of the aggregate, with 0.3% measuring smaller than 0.075 mm.

The particle sizes of the Philippi dune sand were expected to have a variable PSD as the properties of dune sand are dependent on the source material and the strength of the wind or water action that moves it to dune deposits. However, the Philippi dune sand from the Western Cape is described to have coarser fractions due to the strong wind action in the Western Cape (Bonser & Alexander, 2021).

Overall, the physical grading of the Gold mine tailings was similar to the Philippi dune sand, making its substitution with Gold mine tailings more suitable than substituting the Greywacke crusher sand with Gold mine tailings sand used in this study.

The PSDs of the fine aggregates used in this study were used to calculate the FM values which were used to quantify the average size of particles in concrete aggregate between 0.15 mm - 4.75 mm and were used to calculate the concrete mix designs (Bonser & Alexander, 2021). The FM value provides an indication of the proportion of these particle sizes such that a lower FM value indicates that a higher amount of paste is required in a concrete mix and indicates that the concrete has a higher water demand due to the increased surface area of the particles (Kahabi et al., 2022). SANS 1083 guidelines indicate that a fine aggregate with an FM of 1.2 – 3.5 should be used in concrete mixes. FM values within the acceptable range as per SANS 1083 guidelines should produce concrete that is workable, cohesive and has good compatibility with aggregates. The FM values of the fine aggregates used in this study as indicated Table 4-2 shows that the Gold mine tailings and Philippi dune sand can be considered as a good fine aggregate to be used in concrete on their own when only looking at the FM value, but the crusher sand did not fall within this range and would need to be blended with a fine aggregate with a lower FM value to achieve an FM that complies with SANS 1083 guidelines.

Table 4-2: Fineness Modulus of fine aggregates

Material	Fineness Modulus
Gold mine tailings	1.7
Philippi dune sand	2.1
5 mm Greywacke crusher sand	3.9

Lower FM values indicate higher water demand and from the results of this study, the FM values indicated the Gold mine tailings have the highest water demand when compared to the other fine aggregates and will therefore result in a decreased slump and lower workability of the concrete. This finding is in line with the literature that states that the use of finer particles in concrete mixes results in concrete that is less workable and has a reduced slump when compared to a reference mix that uses conventional fine aggregates that contains larger particles, and that higher doses of superplasticizer would be required to maintain the target slump of the concrete (Katz & Baum, 2006; Al-Harthy et al., 2007; Padmanaban, Nithila & Reshma Jahaan, 2019; Otieno & Ndoro, 2020; Maruthupandian, Chaliasou & Kanellopoulos, 2021; Adiguzel, Tuylu & Eker, 2022; Kahabi et al., 2022). Furthermore, it was observed in this study that the higher the replacement ratio of the Gold mine tailings, the higher the dosage of superplasticizer will be required to maintain the target slump of the concrete.

Combined FM values were calculated using the ratios of each fine aggregate used in the concrete mix designs and are presented in Table 4-3. It can be seen that the combined FM values when used in all replacement ratios in this study, had FM values falling between 2.84 and 3. These FM values indicate that the concrete made using these fine aggregates would produce concrete that is adequately workable and cohesive when looking at the FM values on their own however, the FM value should be used in conjunction with the PSD, the slump test, the compressive strength and OPI to determine if the material is suitable to be used in concrete mixes.

Table 4-3: Combined FM values of fine aggregate combinations used in this study

Replacement Ratio	Proportion			Combined FM values
	Gold mine tailings	Philippi dune sand	Greywacke crusher sand	
0	0%	50%	50%	3.00
20	10%	40%	50%	2.96
40	20%	30%	50%	2.92
60	30%	20%	50%	2.88
80	40%	10%	50%	2.84

It can be seen from Table 4-3 that the FM value decreases with an increase in the amount of Gold mine tailings in the mix which is expected as this material contains a much larger proportion of finer particles when compared to the Philippi dune sand and the Greywacke crusher sand. The fine dune sand used in the study by Al-Harthy (2007) had FM values of between 0.45 and 0.88 and was still successfully used as a replacement for fine aggregates at low ratios of replacement. The FM value is an indication of the compatibility of the fine aggregate to be used in a concrete mix but cannot be used alone to determine if a material is a suitable fine aggregate to be used in a concrete mix.

4.2.2 Particle relative density

The particle relative density of the Gold mine tailings was found to be 2.86 which is in line with the literature. Various studies have indicated that the relative density of Gold mine tailings falls between 2.7 and 4.9 (Vermeulen, 2001; Sibanda, 2019; Maruthupandian, Chaliasou & Kanellopoulos, 2021). These relatively high values are attributed to the packing capabilities and subsequently lower void ratios of the fine-grained material (Adiguzel, Tuylu & Eker, 2022). The relative densities for the Philippi dune sand and 5-mm Greywacke crusher sand used in this study were found to be 2.32 and 2.79, respectively.

The relatively high relative density of the Greywacke crusher sand can be attributed to the presence of larger particles and a good grading of smaller particles which fills the voids between the particles by means of the filling effect (Adiguzel, Tuylu & Eker, 2022). Combined relative densities were calculated based on the percentage of each fine aggregate and used in the concrete mix design calculations as presented in Section 3.3 of this dissertation.

Table 4-4: Relative density of the fine aggregates used in this study

Material	Particle relative density
Gold mine tailings	2.86
Philippi dune sand	2.32
5 mm Greywacke crusher sand	2.79

4.3 Fresh concrete properties

The slump test is an indication of the workability and cohesiveness of the concrete mixture (Padmanaban, Nithila & Reshma Jahaan, 2019). It was found generally that an increase in the amount of Gold mine tailings in the concrete mixture resulted in a decrease in slump and therefore higher dosages of superplasticizer were required to maintain the workability of the concrete mixtures. An initial dosage of 10 mℓ of superplasticizer was added to each concrete mixture and the slump was checked, then additional dosages of superplasticizer were added to the mixes in 5 mℓ increments until the required slump was achieved. For both mixes, it was found that the same dosage of superplasticizer could be used for fine aggregate replacement ratios of 0%, 20%, and 40% without significantly affecting the slump of the concrete however, from a replacement ratio of 60% of Philippi dune sand with Gold mine tailings, the superplasticizer requirement increased exponentially in both mixes. A collapsed slump was noted in the 0% replacement for both mixes and can be attributed to a high initial dosage of superplasticizer. The measured slumps and dosage of admixture are presented in Table 4-5.

Table 4-5: Admixture dosages and slumps achieved

Mix	**Dosage of superplasticizer (mℓ)**	**Slump achieved (mm)**	**Mass superplasticizer (kg)**	**Admixture to binder ratio**	**Comments**
Mix A: 0% Replacement	30	Collapse	0.03	0.79%	At 20 mℓ no slump was achieved, at 30 mℓ the slump collapsed. This could be due to the improper dispersion of the admixture and dosages should have been added using 5 mℓ increments instead of 10 mℓ increments.
Mix A: 20% Replacement	30	120	0.03	0.79%	
Mix A: 40% Replacement	30	87	0.03	0.79%	A higher dosage of superplasticizer compared to the 20% ratio of replacement, was not used as the 87 mm fell within the allowable range and the slump increased significantly from 27 mm to 87mm when a dosage of 25 mℓ and 30 mℓ was used, respectively.
Mix A: 60% Replacement	80	140	0.09	2.10%	
Mix A: 80% Replacement	85	Collapse	0.08	2.23%	The mixture was very sticky and non-cohesive.
Mix B: 0% Replacement	10	Collapse	0.01	0.35%	A lower dosage of superplasticizer should have been used to avoid slump collapse in this reference mix.
Mix B: 20% Replacement	8	75	0.01	0.28%	
Mix B: 60% Replacement	28	110	0.03	0.98%	

Mix B generally required less superplasticizer than Mix B to achieve the target slump of 75 mm – 125 mm. At the 0% replacement, a 30 mℓ dose of superplasticizer was used in Mix A compared to a 10 mℓ of superplasticizer in Mix B with both resulting in a collapsed slump. At a 20% replacement, a 30 mℓ dose of superplasticizer in Mix A resulted in a 120 mm slump compared to an 8 mℓ dose of superplasticizer in Mix B which resulted in a 75 mm slump. At a 60% replacement an 80 mℓ dose of superplasticizer in Mix A resulted in a 140 mm slump and a 28 mℓ dose of superplasticizer in Mix B resulted in a 110 mm slump.

The lower superplasticizer requirement in Mix B is attributed to the higher w:b ratio and these results were expected as the amount of water used for both mixes remained constant while the amount of cement decreased in Mix B. This change in the w:b was recalculated intentionally to mitigate the compressive strength results observed through the testing of Mix A as described in Section 3.4 of this dissertation.

When looking at the 0%, 20%, and 40% replacements of Mix A where the dosage of superplasticizer remained at 30 mℓ, it can be seen that the slump decreased as the ratio of Gold mine tailings increased. Additional superplasticizer was not added at the 40% replacement as the 87 mm slump still fell within the acceptable range of 75 mm – 125 mm. Furthermore, in Mix B a superplasticizer dosage of 10 mℓ and 8 mℓ were used for the 0% and 20% replacements, respectively. The lowered dosage of superplasticizer was chosen due to the collapsed slump at the 0% replacement. From this mix, with a 2 mℓ decrease in superplasticizer, the collapsed slump reduced to a slump of 75 mm. These slump values reiterate the literature that an increase in the quantity of mine tailings results in an increase in water demand and a reduced slump due to the increased surface area of the finer particles (Otieno & Ndoro, 2020; Maruthupandian, Chaliasou & Kanellopoulos, 2021; Adiguzel, Tuylu & Eker, 2022; Méndez et al., 2022).

When looking at Mix A, the superplasticizer was initially added to the concrete mixture in dosages of 10 mℓ such that when 20 mℓ was used in the 0% replacement of Philippi dune sand with Gold mine tailings, no slump was measured and when increasing the dosage to 30 mℓ a collapsed slump was achieved. This dosage was then reduced to 5 mℓ increments for the rest of the experimental programme. Furthermore, the collapsed slump that was noted at the 80% replacement of fine aggregate in Mix A can be attributed to the lack of cohesiveness between the particles once the finer particles have surpassed the ratio at which it contributes to the filler effect (Maruthupandian, Chaliasou & Kanellopoulos, 2021; Adiguzel, Tuylu & Eker, 2022). This can be reiterated by the sticky and harsh nature of the concrete that was observed at higher replacement ratios of Philippi dune sand with Gold mine tailings as depicted in Figure 4-3. The collapsed slump at the 0% replacement ratio of Mix B was a result of the initial 10 mℓ dosage of superplasticizer used as this increased w:b resulted in a much lower superplasticizer requirement as compared to Mix A.

In both mixes, the superplasticizer requirement for the 60% replacement ratio of Philippi dune sand with Gold mine tailings was significantly higher than lower ratios of replacement, such that 80 mℓ was used in Mix A and 28 mℓ was used in Mix B. This exponential increase in superplasticizer was expected due to the increased water requirement of the finer particles in the Gold mine tailings (Padmanaban, Nithila & Reshma Jahaan, 2019; Otieno & Ndoro, 2020; Maruthupandian, Chaliasou & Kanellopoulos, 2021; Adiguzel, Tuylu & Eker, 2022). The results highlight that at lower ratios of replacement, the finer particles act as a filler material, after which it interferes with the aggregate and cement paste interface (Maruthupandian, Chaliasou & Kanellopoulos, 2021; Adiguzel, Tuylu & Eker, 2022). The exponential increase in the demand for superplasticizer in the mixes with replacement ratios higher than 60% proves that the water requirement of the concrete mixes is only significantly affected at higher ratios of replacement. The exponential increase in superplasticizer requirements for replacement ratios higher than 40% used was still within the limit as per the Chryso guidelines however, the use of the superplasticizer became a possible contributing factor to the results in Mix A.

Figure 4-3: Visual representation of the sticky and non-cohesive concrete observed at higher replacement ratios

4.4 Concrete compressive strength

This section summarises the experimental results obtained from the compressive strength test results of the concrete made with Gold mine tailings as a partial replacement for the Philippi dune sand used in this study. The average compressive strength results are given for Mix A and Mix B and critically discussed. With regards to the ratios of replacement it is important to note that the 20%, 40%, 60% and 80% ratios of replacement translate to 10%, 20%, 30% and 40% respectively as 50% of the fine aggregate was accounted for by the Greywacke crusher sand and only the Philippi dune sand was being replaced in this study.

Figure 4-4 shows the compressive strength test results for Mix A on the 50 mm and 100 mm cubes for all replacement ratios. The average compressive strength results of 43.9 MPa, 43.5 MPa, 41.6 MPa, and 43.4 MPa were recorded for 20%, 40%, 60%, and 80% replacement ratios of fine aggregate with Gold mine tailings on the 100 mm cubes at 28-days of curing, respectively.

It was found that the 50 mm concrete cubes had higher compressive strengths than the 100 mm cubes tested at the same curing age. According to the literature, generally, an increase in cube size results in a decrease in compressive strength. This decrease in compressive strength occurs due to the stress distribution on smaller specimens being more uniformly distributed as compared to larger specimens and the possibility of a larger number of microcracks forming on larger specimens during the curing process where failure can be initiated during the compressive strength test. Furthermore, heterogeneity of the concrete also plays a role where the distribution of concrete constituents is more uniform in smaller specimens as opposed to larger specimens resulting in weaker points being created in larger specimens (Yi, Yang & Choi, 2006; Talaat et al., 2021).

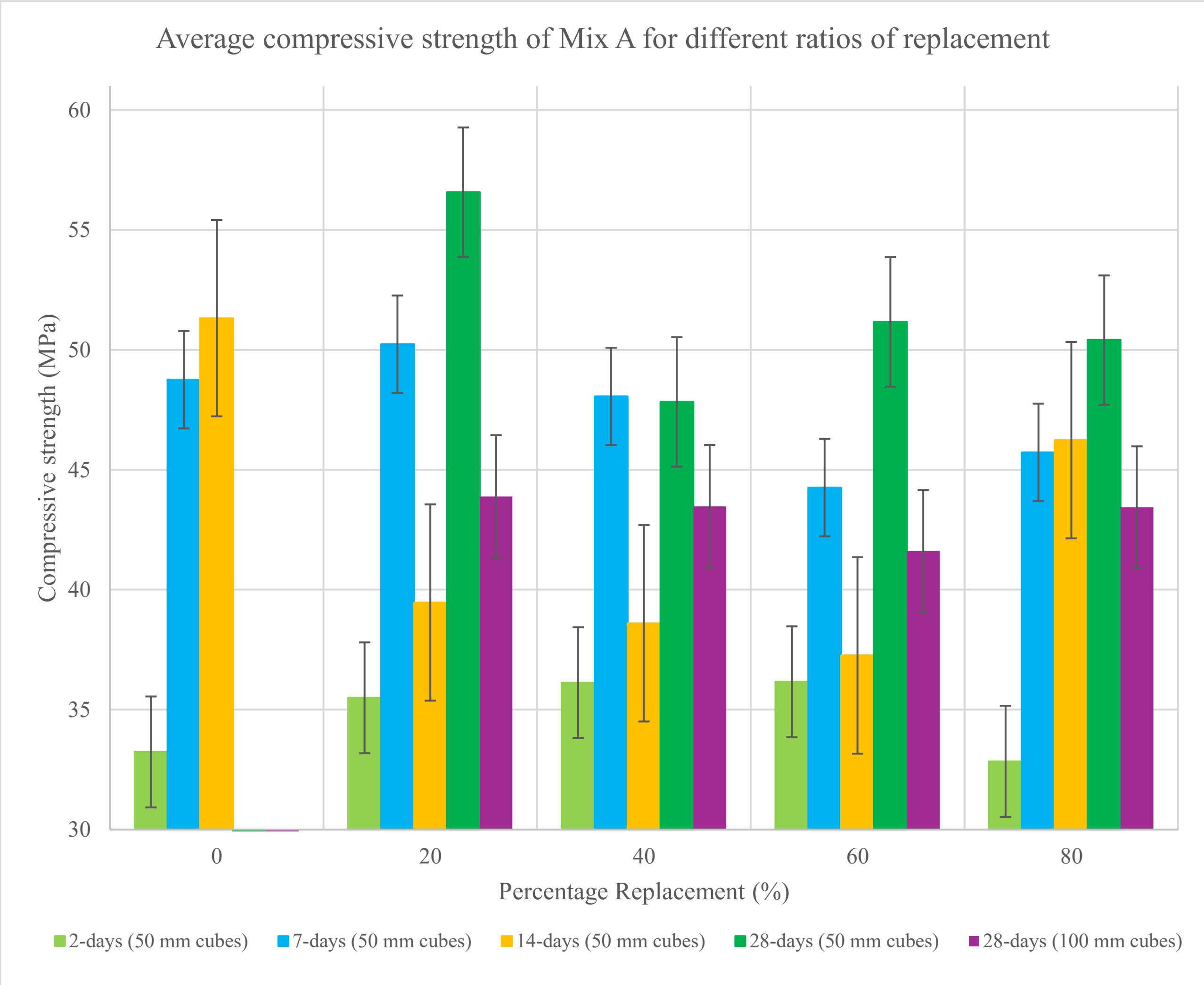


Figure 4-4: Average compressive strength results for Mix A at different curing ages

In Mix A, the 0% replacement was tested at 2-day, 7-day and 14-day curing ages as the initial experimental programme was a comparative study and did not consider the 28-day strengths. However, the 28-day strength was later added to the experimental programme following the results obtained at 14-days for the 20%, 40% and 60% replacement of fine aggregate with Gold mine tailings which showed a decrease in compressive strength, to determine whether the concrete would continue to lose compressive strength after 14-days. It was found that in the 0% and 80% replacement, the concrete continued to increase in compressive strength with the curing age. This is in line with the literature that states that the compressive strength of conventional concrete will continue to increase with time at a decreasing rate and reach about 90% of the compressive strength at 14-days of curing (Boshoff, Combrinck & van Zijl, 2021; Converge.io, 2022; theconstructor.org, 2024).

The compressive strength development of each concrete mix can be illustrated by the gradients of a line graph between the testing ages where a steeper gradient indicates a faster rate of compressive strength development as compared to a softer gradient which indicates a slower rate of compressive strength development. This compressive strength development trend can be compared between different ratios of replacement by comparing the gradients of the graphs and not looking at the actual values of compressive strength. The compressive strength development of all mixes is indicated by Figure 4-5.

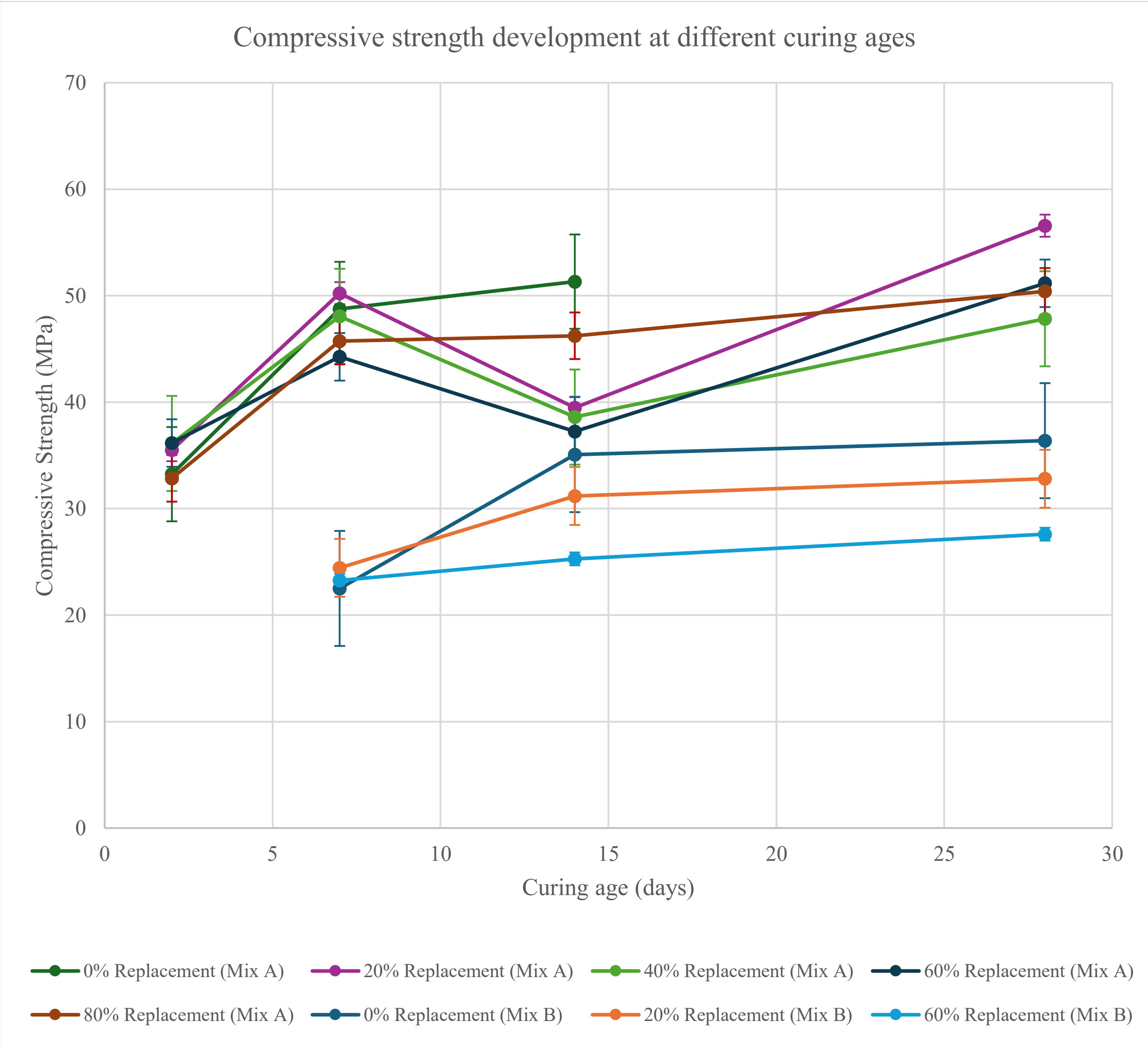


Figure 4-5: Compressive strength development of all mixes

For the concrete mixes that had 20%, 40%, or 60% of Gold mine tailings as a substitute for fine aggregate, it was found that the compressive strengths of Mix A had a decreased compressive strength at 14-days, followed by an increase in compressive strength at 28-days of curing. The literature suggests that the compressive strength of the concrete containing mine tailings can be retarded and show lower early-age compressive strengths due to the possible presence of heavy metals and organic impurities (Bonser & Alexander, 2021; Brouard, 2021; Adiguzel, Tuylu & Eker, 2022). Furthermore, the use of superplasticizers in high dosages can also retard the strength development of concrete mixtures (Brouard, 2021). Typically, the effect an admixture has on the retarding of concrete mixtures is dependent on the composition of the admixture. For example, admixtures containing polysaccharides do not have linear retarding effects and typical dosages range between 0.1% - 0.6%. Admixtures containing phosphates on the other hand have a more linear effect on the retarding of concrete mixtures with typical dosages ranging between 0.1% - 3.0% (Brouard, 2021). The Chryso Premia 550 superplasticizer used in this experiment is formulated using polycarboxylate ethers (PCEs) which has a non-linear effect on the retarding of concrete and a maximum dosage of 3% (Chryso, 2015).

The retarding of strength development between 14 and 28-days can generally be seen in Figure 4-5, which is indicated by smaller gradients on the graphs between 14 and 28-days as the ratio of replacement increases. A retarded strength development has been noted in some studies using mine tailings as a replacement for fine aggregate in concrete however, the compressive strength of the samples all continued to show that the compressive strength follows the same general trend as would in conventional concrete such that the compressive strength continues to increase with time, even though the early age strength development might be lower than that of conventional concrete.

The dosage of superplasticizer was 30 mℓ for the 0%, 20% and 40% ratios of replacement and 80 mℓ and 85 mℓ for the 60% and 80% replacement ratios, respectively which is in line with the Chryso 550 guidelines of a maximum of 3% of the binder weight (Chryso, 2015). However, the decrease in compressive strength at 14-days, followed by an increase in compressive strength at 28-days, is inexplicable by the literature. This result introduced the inclusion of Mix B in the experimental programme to verify or dispute the trend observed in Mix A.

Furthermore, when looking at the 2-day, 7-day and 28-day results of Mix A, it was found that at 2-days, the compressive strength increased for ratios of replacement of 20%, 40% and 60% and decreased at 80% when compared to the 0% replacement. At 7-days, the compressive strength was found to increase at a replacement ratio of 20% and decreased at ratios of replacement of 40%, 60% and 80% when compared to the 0% replacement ratio. The initial experimental programme was a comparative study which included up to 14-day strength testing which resulted in an inadequate number of samples being produced for the 0% replacement compressive strength test at 28-days which was later added to the study. The choice to include the 28-day compressive strength followed an observation of abnormal strength development trends between 7 and 14 days. The 28-day compressive strength of Mix A was therefore done at 20%, 60% and 80% ratios of replacement of fine aggregate with Gold mine tailings and it was found that the compressive strength decreased as the ratio of replacement increased.

The increase in compressive strength at low ratios of replacement, followed by a decrease in compressive strength with higher replacements of fine aggregate with Gold mine tailings can be explained by the filler effect. At lower ratios of replacement, the fine particles of the Gold mine tailings move into the pores created by the larger particles of the concrete mix and fill the voids, thus reducing the permeability of the concrete and increasing its mechanical resistance (Adiguzel, Tuylu & Eker, 2022). The same trend was observed in the literature for replacement ratios up to 40% of fine aggregate with materials containing finer particles than the conventional fine aggregate used in each reference mix (Otieno & Ndoro, 2020; Adiguzel, Tuylu & Eker, 2022; Li et al., 2023). In these studies, the increase in compressive strength was followed by decreasing compressive strengths as the ratio of replacement increased which is explained further by the filler effect such that the finer particles fill in the voids of the concrete matrix to such an extent that these particles fill gaps between the cement-paste and the aggregate and interfere with the adhesion of the aggregate to the cement paste making the mix less cohesive (Maruthupandian, Chaliasou & Kanellopoulos, 2021; Adiguzel, Tuylu & Eker, 2022).

Following these trends, the development of Mix B was included in the experimental programme to determine if the compressive strength would continue to decrease beyond 14-days with the replacement of fine aggregate with Gold mine tailings. Mix B indicated a more linear trend between the ratios of replacement that follows the literature on the strength development of concrete which stipulates that the compressive strength of the concrete will continue to increase at a decreasing rate with the age of the concrete (Converge.io, 2022; theconstructor.org, 2024). The compressive strength test results for Mix B are presented in Figure 4-6.

For Mix B, three (3) ratios of replacement were chosen due to the limited amount of homogenous Gold mine tailings that were available at the time of the experimental programme. The ratios of replacement chosen were 0%, 20% and 60%. It can be seen from Figure 4-6 that an increase in the replacement of fine aggregate with Gold mine tailings resulted in a decrease in compressive strength. A decrease in compressive strength was already experienced at a ratio of replacement of 20% (which translates to 10%) and a further reduction in compressive strength was experienced at a ratio of 60% for all testing ages.

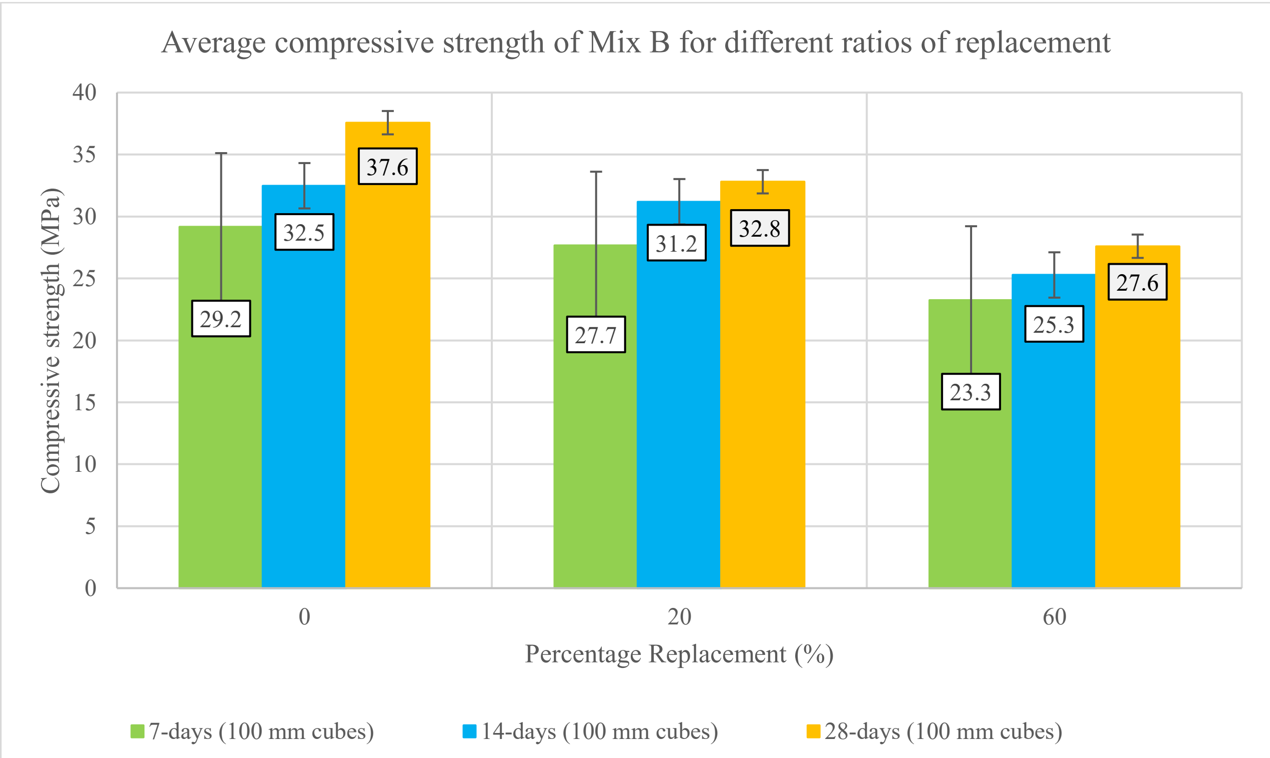


Figure 4-6: Average compressive strength results for Mix B at different curing ages

The compressive strength of Mix B was assessed in terms of the percentage of the compressive strength of the 0% replacement of fine aggregate with Gold mine tailings at the different ages for the 20% and 60% ratio of replacement. It was found that the 20% replacement achieved 95%, 89% and 90% of the compressive strength when compared to the 0% replacement at 7, 14 and 28-days, respectively. The 60% replacement achieved 80%, 72% and 76% of the compressive strength of the 0% replacement at 7, 14 and 28-days, respectively.

The literature suggests that at low ratios of replacement of fine aggregate with mine tailings, the compressive strength of the concrete should increase because of the filler effect (Maruthupandian, Chaliasou & Kanellopoulos, 2021; Adiguzel, Tuylu & Eker, 2022). However, a decrease in strength was already noted at a ratio of replacement of 20%, achieving 90% of the strength of the 0% replacement at 28-days. Furthermore, an even greater loss in compressive strength was noted on the 60% replacement of fine aggregate with Gold mine tailings achieving 76% of the compressive strength of the 0% replacement at 28-days. A similar trend found in the literature was observed in this study such that an increase in the amount of tailings resulted in a greater loss in compressive strength. This is different from the literature which shows that at low ratios of replacement, various studies noted an increase in compressive strength (Otieno & Ndoro, 2020; Maruthupandian, Chaliasou & Kanellopoulos, 2021; Adiguzel, Tuylu & Eker, 2022; Li et al., 2023).

The increase in compressive strength at low ratios of replacement has been found in literature where finer particles have been used as a replacement for conventional aggregate up to a replacement between 20% - 40% in experiments using fines, fine dune sand, ceramic powder and copper slag and steel slag as replacements for conventional fine aggregate in concrete (Katz & Baum, 2006; Al-Harthy et al., 2007; Chitra, 2015; Padmanaban, Nithila & Reshma Jahaan, 2019). These experiments considered the effect of the physical properties of finer, more angular particles on the compressive strength of concrete. When looking at the physical properties of tailings which are crystalline, porous and angular in shape and are primarily comprised of quartz which is considered a hard natural aggregate the effects on the compressive strength of the concrete should theoretically follow the same trend (Maruthupandian, Chaliasou & Kanellopoulos, 2021). The common observation between the materials tested in the different studies is that the replacement material comprised smaller particles than the fine aggregate that was being replaced. The studies noted that with higher replacement ratios, the concrete's water demand increases, the slump decreases, and the compressive strength initially increases and then decreases at higher replacement ratios. However, the loss of compressive strength suggests that the particle size of the tailings is not the most prominent factor contributing to the results.

The literature on concrete using mine tailings suggests a number of reasons that a loss in compressive strength may be experienced when replacing the fine aggregate in concrete with materials containing finer particles. The first reason is the filler effect which, at higher replacement ratios, results in an interference of the cement paste-aggregate and reduces the cohesion of the concrete constituents (Maruthupandian, Chaliasou & Kanellopoulos, 2021; Adiguzel, Tuylu & Eker, 2022). However, the filler effect causes the compressive strength to increase at low ratios of replacement which was not noted in Mix B.

When looking at the results of Mix B, it can be concluded that the mine tailings, even though it comprised primarily of particle sizes between 0.30 mm – 0.60 mm, which are smaller than the Philippi dune sand used in this study containing 7.1% of particles ranging between 1.18 mm - 2.36 mm, the compressive strength decreased at ratios of replacement as low as 20%. This suggests that the chemical composition of these Gold mine tailings and the ways in which it reacts with the constituents of concrete need to be further investigated to determine the cause of the loss in compressive strength.

When looking at the average compressive strength results of Mix B, between 7 and 14-days, the strength development of the concrete decreased as the amount of Gold mine tailings increased. This is indicated by more gentle gradients of the higher replacement ratios between 7 and 14-days on the graphs in Figure 4-6. Furthermore, between 14 and 28-days, the strength development increases as the amount of mine tailings increases. This is indicated by more steeper gradients of the higher replacement ratios between 14 and 28-days on the graphs in Figure 4-6. From this, it can be noted that the higher the replacement ratio of fine aggregate with Gold mine tailings, the more the compressive strength development is retarded which, from the literature can be attributed to the possibility of heavy metals and organic impurities such as chemicals used in the extraction process present in the Gold mine tailings or an excess amount of superplasticizer being used in the concrete mix (Brouard, 2021; Maruthupandian, Chaliasou & Kanellopoulos, 2021; Adiguzel, Tuylu & Eker, 2022).

When looking at the replacement ratios of 0% and 20% in Mix B, it is important to note that a higher dosage of superplasticizer was used in the 0% replacement (10 mℓ) than the 20% replacement (8 mℓ). This disputes that the superplasticizer was the reason for the retarding of compressive strength development in the concrete samples. It is therefore recommended that in future studies, the chemical composition of the mine tailings as well as the reactivity within the concrete matrix be studied further to determine the chemical contributions to the loss in compressive strength.

4.5 Oxygen Permeability Index (OPI) test results

This section summarises the experimental results of the OPI test which was conducted on 100 mm samples for all replacement ratios of Mix A and was used to compare the different mixes in terms of the gas permeation potential of the concrete, which illustrates the porosity and hence the quality of the concrete. The OPI results are calculated as the negative log of the samples' Darcy coefficient of permeability (Alexander, 2018). Despite having different replacement ratios of Gold mine tailings, all mixes showed an excellent quality of concrete, as seen in Figure 4-7.

Lower OPI values indicate higher permeability within the concrete mix which can be translated to a higher void content (Kahabi et al., 2022). The results found in this study showed that the permeability of the different ratios of replacement are comparable, and all fall within the excellent quality of concrete category as the difference between the OPI values is negligible. The negligeable differences in OPI values indicated that regardless of the level of replacement, the Gold mine tailings had good resistance to the permeability of oxygen (Ikotun, Adeyeye & Otieno, 2024). The highest OPI value indicating the lowest permeability was noted for the reference mix and measured at 10.85, and then a decrease in the OPI value was noted at the 20% replacement ratio, followed by gradual increases from 20% replacement ratios, up to 80% replacement ratios.

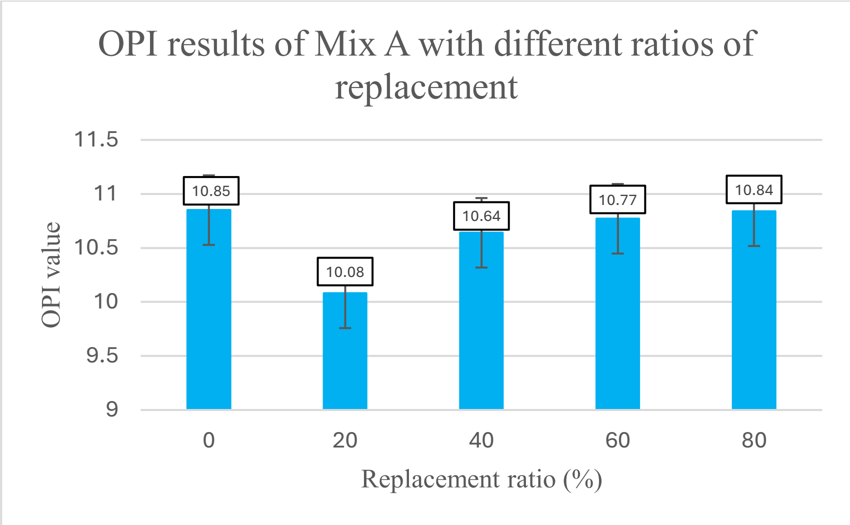


Figure 4-7: OPI at different replacement ratios of Mix A

The decrease in OPI at very low levels of replacement of fine aggregate such as at the 20% replacement can be attributed to the smaller particle sizes of the Gold mine tailings as compared to the fine aggregate that is being replaced. Studies using replacements of fine aggregate with materials with finer particles have noted the following contributing factors to the decrease in OPI at lower levels (Immelman, 2013):

- The inclusion of the Gold mine tailings at low replacement levels may disrupt the gradation of the fine aggregate, reducing the packing and compaction capabilities of the fine aggregate which leads to an increase in the voids content and subsequently increases the oxygen permeability of the concrete. This initial disruption in the packing capabilities of the Gold mine tailings within the concrete matrix is counteracted at higher levels due to the incorporation of the Gold mine tailings which has a better gradation on its own as compared to being incorporated in the mix, thus balancing the gradation of the concrete mix better than at low ratios of replacement.
- The more angular particle shape of the Gold mine tailings affects the ability of the material to fill in the micro voids in the concrete, thus increasing the porosity and subsequently increasing the oxygen permeability of the concrete.

OPI testing was not conducted on Mix B for this study, as this mix was designed as an additional component of this study to validate the compressive strength of Mix A and due to the limited amount of Gold tailings available. It is possible that the compressive strength results obtained on Mix A affected the OPI values of the samples and it is recommended that in further studies the OPI values be re-evaluated.

The literature states that the durability of the concrete using mine tailings as a replacement for fine aggregate was mostly found to be a function of the porosity and microstructure of the concrete (Gou, Zhou & Then, 2019; Otieno & Ndoro, 2020; Maruthupandian, Chaliasou & Kanellopoulos, 2021; Adiguzel, Tuylu & Eker, 2022).

Generally, an increase in mine tailings that are derived from hard rock should result in increased densities with higher replacement ratios and where there is a higher content of SiO2, Al2O3, and Fe2O3, result in a greater amount of hydrates being formed from hydration reactions which will result in a denser matrix with fewer pores (Gou, Zhou & Then, 2019; Otieno & Ndoro, 2020; Maruthupandian, Chaliasou & Kanellopoulos, 2021; Adiguzel, Tuylu & Eker, 2022).

Gold mine tailings are made up of quartz which is considered to be a hard material, and comprises of 68% - 90% of silicates which can participate in hydration reactions, meaning that the OPI value should increase as the ratio of replacement increases (Sibanda, 2019; Adiguzel, Tuylu & Eker, 2022; Méndez et al., 2022). This is true from the replacement of 20% to 80% in this study however, the OPI of the 0% replacement is still the highest at a value of 10.85.

4.6 Chapter summary

The fine aggregates used in this study did not fall within the guidelines for fine aggregates as set out by SANS 1083 guidelines when evaluated as individual fine aggregate materials. However, the grading of these fine aggregates was improved when used in combination with one another. In general, the Gold mine tailings and the Philippi dune sand contained higher percentages of finer particles than set out by the guidelines but was improved with the incorporation of the Greywacke crusher sand which contained higher ratios of larger particles and included particles larger than 1.18 mm accounting for 66.8% of its mass, whereas the Gold mine tailings did not contain any particles larger than 1.18 mm and the Philippi dune sand only contained particles larger than 1.18 mm accounting for 0.6% of its mass.

The Gold mine tailings predominantly contained particle sizes smaller than 0.6 mm, with only 1% of its mass containing particle sizes larger than 0.6 mm. The Philippi dune sand had a lightly similar gradation with most of its particle sizes measuring smaller than 0.6 mm however, the Philippi dune sand contained 22.7% of particles ranging from 0.6 mm to 1.18 mm and 0.6% being larger than 1.18 mm, but smaller than 2.36 mm. The Greywacke crusher sand had the highest percentage of fines (particles smaller than 0.075 mm) which accounted for 1% of its mass. Furthermore, the Greywacke crusher sand was the only fine aggregate used in this study containing particles larger than 2.36 mm which accounted for 49.4% of the mass of the aggregate.

The PSD of the blended fine aggregates fit more in line with the SANS 1083 guidelines however, it was found that for all the ratios of replacement, the blended aggregates did not contain enough particles in the 0.075 mm – 0.3 mm range.

The FM values obtained from the sieve analysis were 1.7, 2.1, and 3.9 for the Gold mine tailings, Philippi dune sand and Greywacke crusher sand, respectively. The FM values for the Gold mine tailings and the Philippi dune sand were in line with SANS 1083 guidelines which recommends an FM value of 1.2 – 3.5 for fine aggregates to be used in concrete, whereas the Greywacke crusher sand did not. The non-compliance of the Greywacke crusher sand is attributed to the high percentage of larger particles however, the blend of aggregates helped in creating fine aggregates with more compliant FM values which ranged from 2.84 – 3.00 and decreased as the amount of Gold mine tailings increased.

The relative density results of 2.86, 2.32 and 2.79 were obtained for the Gold mine tailings, Philippi dune sand and Greywacke crusher sand, respectively. Combined relative densities were calculated based on the ratio of each fine aggregate and used in the concrete mix designs. The relative density of the Philippi dune sand was 2.32 which is lower than the relative densities of the Gold mine tailings and the Greywacke crusher sand. This lower RD value can be attributed to the uniformity of particle sizes in the Philippi dune sand which reduces the action of the filler effect experienced by aggregates with a larger variance in particle size (Maruthupandian, Chaliasou & Kanellopoulos, 2021; Adiguzel, Tuylu & Eker, 2022).

When assessing the physical characteristics of the Gold mine tailings, it was expected that the concrete would perform similarly to the findings in the literature relating to using aggregates which are comprised of particle sizes similar to the Gold mine tailings or other tailings. The common observation between the materials tested in the different studies is that the replacement material comprised smaller particles than the fine aggregate that was being replaced. The studies noted that with higher replacement ratios, the concrete's water demand increases, the slump decreases, and the compressive strength initially increases and then decreases at higher replacement ratios.

The slump values and dosage of the superplasticizer required varied between the mixes, and the sensitivity of the superplasticizer resulted in a collapsed slump in some of the cases notably at 0% replacement ratios for both Mix A and Mix B which is attributed to a high initial dosage of superplasticizer being chosen and was amended in the subsequent mixes. Furthermore, a collapsed slump was experienced in the 80% replacement of concrete Mix A where a dosage of 5 mℓ less had almost no slump. This collapsed slump at the 80% replacement ratio also produced a concrete mix that was harsh and sticky, indicating that the high fines content in the concrete mix interfered with the cohesiveness of the concrete (Maruthupandian, Chaliasou & Kanellopoulos, 2021; Adiguzel, Tuylu & Eker, 2022). In general, the amount of superplasticizer required to achieve a desirable slump drastically increased at replacement ratios of 60% and higher.

The compressive strength tests were done on Mix A at 2, 7, 14, and 28-day testing ages on 50 mm cubes and 28-day testing ages on 100 mm cubes, and Mix B was tested at 7, 14, and 28-day testing ages on 100 mm cubes. Mix A was calculated based on a 0.45 w:b ratio and Mix B on a 0.6 w:b ratio. Mix A had varying results between the replacement ratios, but Mix B showed a more linear trend, the higher the replacement ratio of the Philippi dune sand with Gold mine tailings, the lower the compressive strength.

The OPI values were calculated for Mix A on all the ratios of replacement and yielded values between 10.08 and 10.85 indicating that all concrete mixes tested in this study could be classed as excellent in terms of quality when testing the gas permeation potential of the concrete mixes.

5. Conclusion and recommendations

5.1 Broad Conclusion

This study investigated the impact of using Gold mine tailings from the Witwatersrand region as a replacement for fine aggregate in concrete mixes. The study was done using different replacement ratios of fine aggregate with Gold mine tailings and tested in terms of the slump in the fresh state and the compressive strength and OPI in the hardened state. Gold mine tailings were chosen as a potential replacement for fine aggregate in concrete due to the abundance of Gold mine tailings in South Africa. The study's significance is to find alternative uses for mine tailings to reduce the amount of solid waste being stored in TSFs and by using it in concrete, it will alleviate the pressures on the construction industry to supply natural aggregates.

The aim of this study was to test the viability of using Gold mine tailings as a substitute for fine aggregate in concrete mixes through laboratory testing. It was found that using Gold mine tailings as a replacement for fine aggregate in concrete mixes generally resulted in reduced workability in the fresh state and a reduction in compressive strength in the hardened state making this replacement unviable. The OPI results were not significantly affected by the replacement. Furthermore, an increased amount of superplasticizer is required to maintain the workability of the concrete which makes the concrete more costly to produce.

The objectives of this study included performing a detailed literature review on the replacement of fine aggregates in concrete mixes with Gold mine tailings on the compressive strength and durability of the hardened concrete which included literature on mining wastes in the South African context with a specific focus on Gold mine tailings, a brief summary of the different constituents of concrete and ways in which mine tailings can be recycled by replacing the fine aggregate in concrete mixes, and previously done studies on replacing fine aggregate with different mine tailings and finer materials in concrete mixes because through the literature, a common trend was noted in that mine tailings generally contain finer particles than conventional fine aggregate.

The common trend between the studies presented in this literature review was that the use of finer particles in concrete when compared to the material being replaced was that the hardened concrete experienced an increase in compressive strength at low ratios of replacement, followed by a decrease in compressive strength as the ratio of replacement increased which is due to the filler effect of the aggregate. The filler effect is where the finer particles increase the packing capabilities of the different concrete constituents by filling in voids of the concrete matrix and reduces the void content of the concrete. Furthermore, at higher ratios of replacement, the finer particles fill the voids between the cement and aggregate and interfere with the cement-mortar interface, thus reducing the cohesiveness of the concrete mix. A similar trend was expected with the Gold mine tailings as this material contained larger fractions of finer particles when compared to the Philippi dune sand which was being replaced.

The next objective was sourcing the Gold mine tailings from a TSF in the Witwatersrand region and using it to determine the PSD and relative density of the material and comparing it to the other fine aggregates used in this study which was 5-mm Greywacke crusher sand and Philippi dune sand, to use these materials in concrete mix designs and determine the influence of using the Gold mine tailings as a replacement for the Philippi dune sand on the concrete by testing the slump, compressive strength and OPI of the different mixes which was achieved through laboratory testing.

These aims and objectives bring us to the study questions “Can Gold mine tailings from the Witwatersrand region be used as a replacement for fine aggregates in concrete mix designs and create concrete products of adequate strength and quality?” and “What percentage of tailings can be used in concrete mixes such that adequate strength is maintained?”

Through this study, these questions can be simply answered such that Gold mine tailings from the Witwatersrand region cannot be used as a replacement for fine aggregate in concrete mixes without significantly affecting the compressive strength of the concrete and creating a less workable concrete mix which will require larger dosages of superplasticizer to maintain the workability and achieve the target slumps, and that no ratio of replacement would be acceptable in the industry. However, one common trend in the literature is that the different mine tailings, and even Gold mine tailings from different sources have resulted in varying conclusions thus, this investigation should be done more quantitatively as well as on other mine tailings as this replacement could potentially alleviate the pressures on the construction industry and the mining industry.

When looking at the fresh and hardened properties of the concrete mixes in this study, it is important to note that the 20%, 40%, 60% and 80% ratios of replacement translate to 10%, 20%, 30% and 40% respectively as 50% of the fine aggregate was accounted for by the Greywacke crusher sand and only the Philippi dune sand was being replaced in this study.

5.2 Physical properties of fine aggregates

The PSD of each fine aggregate was assessed in terms of the grading envelope provided by SANS 1083 guidelines for fine aggregates to be used in concrete. It was found that none of the fine aggregates used in this study fell within the suggested grading envelope on their own however, all the blended fine aggregates fitted in the SANS 1083 grading envelope guideline.

The Gold mine tailings contained particles predominantly in the 0.3 mm – 0.6 mm range, similar to the Philippi dune sand. The particle sizes of the Gold mine tailings were expected from the literature which states that the Gold mine tailings generally ranges between 0.001 mm – 0.65 mm in size. The Greywacke crusher sand contained particles larger than 1.18 mm accounting for 66.8% of its total mass, in comparison with the Philippi dune sand and Gold mine tailings which contained less than 1.0% of its mass accounting for particles larger than 1.18 mm. These PSDs made the Gold mine tailings a more suitable substitution for the Philippi dune sand in the concrete mix design.

Particle sizes measuring less than 0.075 mm accounted for less than 1% of the total aggregate masses for all of the fine aggregates used in this study, which is less than the suggested fines contents as per ASTM C33 and SANS 1083 guidelines.

The FM of each fine aggregate was found to be 1.7, 2.1, and 3.9 for the Gold mine tailings, Philippi dune sand, and Greywacke crusher sand, respectively. Only the Greywacke crusher sand does not fall within the 1.2 – 3.5 range of FM specified by SANS 1083. Furthermore, the FM values of the blended aggregates were found to be between 2.84 – 3.00 and decreased as the ratio of Gold mine tailings increased. These blended aggregates had FM values that were within the acceptable range as per SANS 1083 guidelines.

The relative densities of the fine aggregates were found to be 2.86, 2.32, and 2.79 for the Gold mine tailings, Philippi dune sand and Greywacke crusher sand, respectively. The lower packing capability of the Philippi dune sand makes the material less dense as compared to the Gold mine tailings and Greywacke crusher sand used in this study.

Furthermore, the Gold mine tailings had a relative density of 2.86 which is in line with the expected relative density of mine tailings used in the literature, generally between 2.70 and 4.29. These relatively high values are attributed to the packing capabilities and subsequently lower void ratios of the fine-grained material. The higher relative density of the Greywacke crusher sand can be attributed to the presence of larger particles and a good grading of smaller particles which fills the voids between the particles by means of the filling effect.

The investigation of the physical properties of the fine aggregates achieved the objective of characterizing the Gold mine tailings as a fine aggregate in comparison to the conventional fine aggregates used in this study. From the PSD, the Gold mine tailings was similar to the Philippi dune sand with a larger proportion of finer particles and an FM of 1.7 which is still within the SANS 1083 guidelines. Furthermore, the relative density of the Gold mine tailings was similar to the Greywacke crusher sand and in line with the literature yielding a value of 2.86. In theory, when looking at the physical properties of the Gold mine tailings only, it should make a good fine aggregate when used in the correct proportions.

The physical characteristics of the fine aggregates used in this study were then used to achieve the objective of designing concrete mixes which could be tested in terms of fresh and hardened properties to determine the viability of the replacement of fine aggregate with Gold mine tailings in concrete mixes.

5.3 Fresh concrete properties

The fresh properties of the concrete were determined by means of the slump test. The slump of each concrete mix was measured during the mixing phase of the experimental procedure. The target slump was set to be 100 mm, and superplasticizer was added to the mixes as needed to achieve this target slump. The slump test indicated that generally an increase in Gold mine tailings resulted in a decrease in the workability of the concrete. The reduction in slump indicated lower workability as the amount of Gold mine tailings increased and a higher dosage of superplasticizer was required to maintain the workability of the concrete.

For both mixes it was found that the same dosage of superplasticizer could be used for replacement ratios up to 40% and still achieve a slump within the allowable range of 75 mm – 125 mm however, as the ratio of Gold mine tailings increased, the slump decreased. At higher replacement ratios the amount of superplasticizer required to maintain the workability of the concrete increased exponentially.

A collapsed slump was noted at the 0% replacement for both mixes and at the 80% replacement for the 0.45 mix. The collapsed slump at the 0% replacement can be attributed to a high initial dosage of superplasticizer being chosen and at the 80% replacement, can be attributed to the fine particles interfering with the cement-aggregate interface by lodging between the particles in the concrete mix which was indicated by a harsh and sticky concrete mixture.

The superplasticizer requirement was significantly lower in the 0.60 mix when compared to the 0.45 mix which indicated that the lower w:b ratio in combination with an increased amount of Gold mine tailings required more superplasticizer to maintain the workability of the concrete. This trend reiterates the literature in that a higher amount of mine tailings results in an increased water demand and decreased slump due to an increase in surface area of the finer particles.

Relating to the aim of this study, the reduced slump and increased requirement for superplasticizer with an increase in mine tailings makes the substitution of fine aggregate with Gold mine tailings unsuitable at ratios higher than 40% of the Philippi dune sand. Superplasticizer is a costly admixture that should only be added to concrete mixtures in controlled amounts as it can increase air entrainment of the concrete, cause bleeding and retard early age strength development of the concrete when added in larger amounts.

The increase in superplasticizer dosage with increased ratios of replacement of fine aggregate with Gold mine tailings should be considered when determining the economic implications of this replacement. Furthermore, where quick setting times of concrete is required, such as in the cases where there is a risk of environmental influence on the setting of the concrete, the retardation of early-age strength could potentially make the use of Gold mine tailings as a replacement for fine aggregate in concrete unsuitable in practice.

At this point of the research investigation, the Gold mine tailings made a suitable fine aggregate, and in terms of the fresh properties of the concrete, this substitution was only significantly affected at replacement ratios higher than 40%. In terms of the physical and fresh properties, Gold mine tailings was a suitable replacement for the Philippi dune sand in this study, at low ratios of replacement up to 40% addressing the primary and secondary questions of this study however, the compressive strength of the concrete made using Gold mine tailings is the distinguishing point of the viability of this replacement.

5.4 Hardened concrete properties

The hardened properties of the concrete were investigated by means of the compressive strength test and OPI which were done in accordance with SANS 5863-2006 and SANS 3001-C03-1:2015 guidelines.

The compressive strength testing was done on two (2) different mixes which used a 0.45 and 0.6 w:b. In the 0.45 concrete mix, variable compressive strengths were recorded. Furthermore, the second concrete mix showed a more linear trend in that the compressive strength of the concrete decreased as the ratio of replacement increased. The results from the compressive strength of the 0.45 mix lead to the conclusion that more quantitative compressive strength testing should be done to generate more concise results.

The compressive strength testing was done on the 0.45 mix on 50 mm cubes at 2, 7, 14 and 28-days, with additional compressive strength tests being done on 100 mm cubes at 28-days. The results showed that the compressive strength of the concrete for the 20%, 40% and 60% ratios of replacement decreased at 14-days and then increased at 28-days for all mixes. This trend does not fall in line with the strength development of concrete such that the compressive strength of concrete should continue to increase with time. The trend of a decrease in compressive strength, followed by an increase in compressive strength is inexplicable by the literature. A retarded strength development has been noted in some studies using mine tailings as a replacement for fine aggregate in concrete however, the literature does not explain the reduction in compressive strength at 14-days. The retarding of strength development in concrete using mine tailings as a replacement for fine aggregate is a result of the possible presence of heavy metals and organic impurities and high dosages of superplasticizer.

This finding led to the inclusion of the second concrete mix to either verify or dispute the findings of the first mix. The second mix had a w:b of 0.60 and compressive strength testing was conducted on 100 mm cubes at 7, 14 and 28-days using replacement ratios of 0%, 20% and 60%. The 0.60 mix showed a more linear trend in that the compressive strength of the concrete decreased as the amount of Gold mine tailings increased and this decrease in compressive strength started at replacement ratios as low as 20% (which translates to 10% of the total fine aggregate in the concrete mix).

When looking at the compressive strength test results for the 0.45 mix at 28-days, it was found that generally the compressive strength of the 50 mm cubes was higher than that of the 100 mm cubes. This is explained by the literature which states that the compressive strength of concrete samples varies with specimen sizes in a non-linear manner but generally, an increase in specimen size results in a decrease in compressive strength due to the uniformity of stress distribution and the heterogeneity of concrete constituents which reduces when the size of the specimen increases. This highlights the importance of assessing compressive strength development trends as opposed to actual compressive strength values in this study. It is therefore recommended that future studies focus on these trends of compressive strength when using different specimen sizes and shapes. The use of the 50 mm cubes in this study as opposed to 100 mm cubes as per SANS 5860 and SANS 5861-1 guidelines was chosen due to the constraint in available tailings material for this experiment and allowed for an adequate number of samples to be produced to compare the compressive strength of the sample at different ratios of replacement.

It was expected from the literature that at lower replacement ratios of fine aggregate with Gold mine tailings (up to about 40% replacement of fine aggregate) the compressive strength of the concrete would increase prior to it decreasing as the ratio of replacement increased. This has been noted in some studies and is explained by means of the filler effect such that the inclusion of the smaller particles of the Gold mine tailings fills the voids between the constituents of the concrete mix and increases the mechanical resistance of the concrete by reducing the number of pores and the size of the pores created in the concrete matrix. Furthermore, these studies have noted that once the filler effect has reached the full potential of assisting in the mechanical resistance of the concrete, a high amount of finer particles between the constituents of the concrete results in an interference of the aggregate-paste interface and lessens the cohesion between the particles, making the concrete less cohesive and subsequently reducing the compressive strength and mechanical resistance of the concrete.

The linear trend observed in the 0.60 mix helped draw more conclusive results in this study. It was found that the compressive strength decreased as the ratio of Gold mine tailings increased and the decrease in compressive strength occurred at all ratios of replacement including the 20% replacement of fine aggregate with Gold mine tailings (which translates to 10%). A further reduction in compressive strength was experienced in the 60% replacement of fine aggregate with Gold mine tailings. This strength reduction was true for all ratios of replacement at all testing ages (which included 7, 14 and 28-day compressive strengths).

To determine the viability of using Gold mine tailings as a partial replacement for fine aggregate in concrete mixes, the compressive strength test results of the 0.60 mix was assessed in terms of a ratio of the 0% replacement at each testing age. It was found that 90% and 76% of the compressive strength was achieved at 28-days for the 20% and 60% ratios of replacement, respectively. The trend observed in this mix follows the literature in that an increase in the amount of tailings used in the concrete mix resulted in a greater loss in compressive strength however, at low ratios of replacement, the literature noted an increase in compressive strength which was not true in this concrete mix.

Through investigation of the strength loss at low ratios of replacement, the literature discussed the interference of the aggregate-paste interface of the concrete however, if this were the only contributing factor to the loss of strength, the results would have shown an increase in compressive strength at low ratios of replacement. Hence, other contributing factors to the loss of compressive strength should be considered, which includes the strength of the aggregate used and the heavy metals and organic impurities that may be present in the mine tailings. Gold mine tailings is primarily made up of Quartz, which is considered a hard rock, thus leaving only the chemical components of the mine tailings as a contributing factor to the loss of compressive strength in this study.

Another contributing factor to retarded compressive strength development in concrete is the use of superplasticizer, which if used incorrectly can increase air entrainment, cause bleeding and reduce the early age strength of the concrete. The 0.60 mix was therefore investigated in terms of the strength development by checking the gradients of the compressive strength graphs between the different testing ages. It was found that between 7 and 14-days, the rate at which the compressive strength increases, decreased with an increase in the amount of Gold mine tailings in the mix and increased between 14 and 28-days as the ratio of replacement increased. This trend of compressive strength development indicates that the higher the replacement ratio of fine aggregate with Gold mine tailings, the more the compressive strength development is retarded which can be attributed to the possibility of heavy metals and organic impurities an excess amount of superplasticizer being used in the concrete mix. Furthermore, the effect of the superplasticizer on the compressive strength development was disputed when looking at the difference between the 0% and 20% replacement of the 0.60 mix wherein a higher dose of superplasticizer was used in the 0% replacement of fine aggregate with Gold mine tailings when compared to the 20% replacement. Between the two (2) mixes, it was still noted that the 20% replacement had a lower rate of compressive strength development between 7 and 14-days and a higher rate of compressive strength development between 14 and 28-days.

By eliminating the PSD and superplasticizer impact on the concrete compressive strength loss, the literature leaves only the presence of organic impurities and heavy metals in mine tailings as the possible cause of the compressive strength loss noted in this study.

The OPI was done on 2 (two) 100 mm concrete cubes for all ratios of replacement of the first mix and it was found that the permeability of the different concrete mixes was comparable and all yielded results indicating excellent quality of concrete ranging from 10.08 – 10.85. The highest OPI value was noted at the 0% replacement which did not line up with the trend of the increasing ratios of replacement, which gradually increased as the ratio of replacement increased. This increasing trend was expected due to the increased packing capabilities and increased relative density of the Gold mine tailings when compared to the Philippi dune sand which was being replaced. Furthermore, the OPI testing was not done on the second mix due to the limited amount of Gold mine tailings available at the time of casting, and the abnormal compressive strength trends noted in the first mix indicated that this mix may not yield reliable results and conducting the testing on the second mix would have been beneficial to verifying these OPI results.

The compressive strength and OPI testing lines up with the aim of this study in that the compressive strength tests indicate that Gold mine tailings are an unviable option for replacement of fine aggregates in concrete mixes, but the OPI values indicate that it is a viable alternative. Concrete performance is measured against its compressive strength, thus making the compressive strength of the concrete the most important factor when determining the viability of using an alternative, in conjunction with the physical and fresh properties of the concrete. Although the physical properties of the Gold tailings, the fresh properties of concrete made with low ratios of replacement of fine aggregate with Gold mine tailings and the OPI values for all ratios of replacement indicate that this replacement is possible without significantly affecting the quality of the concrete, the compressive strength results indicate that it is an unviable option, with strength loss being noted at ratios of replacement as low as 20%.

Relating back to the secondary study question "What percentage of tailings can be used in concrete mixes such that adequate strength is maintained?" the compressive strength test results indicate that no replacement of fine aggregate with Gold mine tailings will achieve the target compressive strength however, at low replacement ratios, it is possible to achieve most of the compressive strength that would be achieved without the Gold mine tailings. The applicability of the low ratios of replacement is dependent on the construction requirements of the concrete and where possible, literature suggests that the use of blended fine aggregates incorporating mine tailings be used to achieve successful incorporation of mine tailings in concrete mixes.

5.5 Recommendations for further work

This study was limited to Gold mine tailings from a single source, with limited material available. For this method to be put into practice, similar studies need to be conducted on Gold mine tailings from different sources and include other durability tests that were not included in this study. Furthermore, studies should include larger sample sizes to reduce the impact of abnormal compressive strength development as noted in Mix A of this study. Both the compressive strength and OPI tests should be conducted on other Gold mine tailings to help identify the similarities and the differences between the Gold tailings, as well as on other mine tailings to determine which tailings can be used in concrete mixes without adversely affecting the compressive strength of the concrete.

Literature suggested that mine tailings can be used at low ratios of replacement and for mine tailings to be used in this manner, research needs to be done on different mine tailings to develop guidelines to introduce this fine aggregate replacement into the construction industry. Successful implementation, even at low ratios of replacement has the potential to reduce pressures on the construction industry, as well as TSFs and this replacement can be achieved through blended fine aggregates.

The loss in compressive strength makes the utilization of Gold mine tailings unsuitable as a substitute for fine aggregate in the industry however, the literature indicates promising results for some other mine tailings including Kimberlite, Lead-Zinc and even Gold mine tailings from other sources. Furthermore, the literature also suggests other uses for Gold mine tailings such as in the use of masonry concrete, as backfill in mine goaf areas, and in the production of ceramics. The alternative uses for mine tailings both as a replacement for fine aggregate and other uses should be investigated to address the key issues identified in this study with regards to conventional mine waste disposal and the demand for natural raw aggregates, to achieve aims of sustainable development by providing alternative methods of mine waste disposal without adversely affecting the rate at which development can occur.

One common trend in the literature for alternative uses for mine tailings is the use of mine tailings as a supplementary cementitious material (SCM). It is therefore suggested that mine tailings be investigated as a replacement for SCMs as it may be possible that mine tailings is a more suitable substitute for SCMs as opposed to fine aggregate in concrete based on the oxide content of the mine tailings.

Mine tailings from different mining operations are non-homogenous in nature and have different physical and chemical properties making it important for tailings to be tested in terms of the mine type and method of extraction prior to using it as a replacement in concrete. Furthermore, the chemical constituents of mine tailings sometimes contain toxic chemicals and heavy metals which can contribute to AMD and be detrimental to human health and the environment. For this reason, the chemical composition and long-term effects of the concrete need to be studied from an environmental and health perspective prior to application.

Mine tailings are generally crystalline in nature and the aluminates and silicates in the material may not be available for reactions. Furthermore, the constituents of the mine tailings can neutralise the pH of the concrete depending on the reactions that occur. This reiterates that the chemical reactivity of the mine tailings should therefore be assessed both as a material on its own and within a concrete matrix. The long-term durability of the concrete needs to be tested to ensure that the chemical constituents of the mine tailings do not cause delayed reactions within the concrete matrix and deteriorate the quality of the concrete over time.

Further research includes the development of practical and legislative guidelines to ensure that the repurposing of mine tailings is done in a safe and ethical manner that is sustainable and easy to achieve. The guidelines should stipulate the methods in which the mine tailings should be stored and incorporated into concrete mixes as well as testing that needs to be done on the materials as have been developed for concrete. Furthermore, research will aid in identifying the potential issues that may arise from this method of concrete production and should be documented and incorporated into the guidelines to mitigate the adverse effects of using mine tailings in this way.

For use in the industry, technological advancements will have to be investigated to ensure that this method of using mine tailings in concrete is achievable and will include transportation and storing of mine tailings from TSFs or mining operations to aggregate suppliers. Furthermore, it may be found that the testing of the mine tailings or the processing of the mine tailings in this way may require additional equipment which will need to be investigated to put this method into practice.

Any method adopted by the industry needs to be economically viable to be accepted and it is therefore important that the start-up and maintenance costs, as well as the economic benefits from repurposing mine tailings be investigated.

Finally, the tests conducted in this study should be re-investigated in terms of long-term effects on the compressive strength and durability properties of the concrete which should include the chemical composition of these mine tailings as a material and as a constituent of concrete. This will need to be done to ensure that these mine tailings do not have an adverse impacts on human health and the environment and that the quality of the concrete does not deteriorate over time.

6. References

Adiguzel, D., Tuylu, S. & Eker, H. 2022. Utilization of tailings in concrete products: A review. *Construction and Building Materials*. 360:1–8. DOI: 10.1016/j.conbuildmat.2022.129574.

Alexander, M.G. 2018. *Durability Index Testing Procedure Manual*. Cape Town.

Al-Harthy, A.S., Halim, M.A., Taha, R. & Al-Jabri, K.S. 2007. The properties of concrete made with fine dune sand. *Construction and Building Materials*. 21(8):1803–1808. DOI: 10.1016/j.conbuildmat.2006.05.053.

Benzaazoua, M. & Taha, Y. 2020. *Towards a Sustainable Management of Mine Wastes*. Quebec.

Bhanbhro, R. 2017. *Mechanical Behavior of Tailings: Laboratory Tests from a Swedish Tailings Dam*. Luleå, Sweden. DOI: 10.13140/RG.2.2.29809.68969.

Bonser, R. & Alexander, M.G. 2021. Fulton's concrete technology. In *Fulton's Concrete Technology*. 10th ed. V. 10. M.G. Alexander, Ed. Midrand: Cement and Concrete . 91–148.

Boshoff, B., Combrinck, R. & van Zijl, G. 2021. Strength and physical properties of hardened concrete. In *Fulton's Concrete Technology*. 10th ed. M. Alexandar, Ed. Midrand: Cement & Concrete SA. 233–246.

Brouard, B. 2021. Fulton's concrete technology. In *Fulton's concrete technology*. 10th ed. M.G. Alexander, Ed. Midrand: Cement and Concrete SA. 161–187.

Cement and Concrete SA. 2015. *Admixtures for concrete*. Midrand.

Chitra, R. 2015. Replacement of Cement and Fine Aggregate by Ceramic Powder and Copper Slag in Concrete. *Indian Journal of Science and Technology*. 8(32):1–7. DOI: 10.17485/ijst/2015/v8i32/87540.

Chryso. 2015. *chryso-fluid-premia-550-tds_8864_5518*. Available: chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://za.chryso.com/p/8864/3/5518/en [2024, July 09].

Converge.io. 2022. *Concrete Cube Test - Explained By Converge*. Available: https://www.converge.io/blog/concrete-cube-test [2024, October 17].

Gou, M., Zhou, L. & Then, N.W.Y. 2019. Utilization of tailings in cement and concrete: A review. *Science and Engineering of Composite Materials*. 26(1):449–464. DOI: 10.1515/secm-2019-0029.

HSA Silica Fume. 2024. *Properties of cement compounds and silica content in cement* . Available: https://microsilica-fume.com/properties-cement-compounds-silica-content-cement.html#:~:text=Silica%20(Si02)%20imparts%20strength%20to,its%20setting%20time%20is%20prolonged. [2024, August 03].

Ikotun, J.O., Adeyeye, R.A. & Otieno, M. 2024. Experimental Investigation on the Effect of Gold Tailings as a Partial Replacement for Sand in Concrete. *Sustainability*. 16(17):7762. DOI: 10.3390/su16177762.

Immelman, D.W. 2013. *The influence of percentage replacement on the aggregate and concrete properties from commercially produced coarse recycled concrete aggregate*. Stellenbosch. Available: https://scholar.sun.ac.za/bitstreams/b0845c05-94cb-4be1-b6b4-c6ac109316a4/download [2025, June 03].

JXSCmachine. 2024. *Tailings Recycling: A Sustainable Solution*. Available: https://www.jxscmachine.com/new/tailings-recycling-sustainable-solution/#:~:text=Tailings%20recycling%20refers%20to%20recovering,extract%20any%20remaining%20valuable%20minerals. [2024, May 18].

Kahabi, N.S., Beushausen, H., Prof, E. & Alexander, M. 2022. *The effect on the durability properties of concrete of partial replacement of natural fine aggregates with recycled concrete fine aggregates*. Cape Town .

Katz, A. & Baum, H. 2006. Effect of High Levels of Fines Content on Concrete Properties. *ACI Materials Journal*. 106(6):474–482.

Kneen, M.A., Ojelede, M.E. & Annegarn, H.J. 2015. Housing and population sprawl near tailings storage facilities in the Witwatersrand: 1952 to current. *South African Journal of Science*. 111(11/12):1–9. DOI: 10.17159/sajs.2015/20140186.

Li, R.;, Yin, Z.;, Lin, H., Li, R., Yin, Z. & Lin, H. 2023. *Research Status and Prospects for the Utilization of Lead–Zinc Tailings as Building Materials*. Multidisciplinary Digital Publishing Institute. DOI: 10.3390/BUILDINGS13010150.

Lindsley, R. 2024. *Climate Change: Atmospheric Carbon Dioxide*. Available: Climate Change: Atmospheric Carbon Dioxide [2024, July 21].

Lords Builders Merchants. 2021. *Differences Between Cement, Concrete and Mortar - Builders Merchants Guides & Building Products Blog – Lords Life*. Available: https://lordsbm.co.uk/blog/post/cement-concrete-mortar [2024, July 07].

Malatse, M. & Ndlovu, S. 2015. The viability of using the Witwatersrand gold mine tailings for brickmaking. *Journal of the Southern African Institute of Mining and Metallurgy*. 115(4):321–327.

Maruthupandian, S., Chaliasou, N.A. & Kanellopoulos, A. 2021. Recycling Mine Tailings for a Sustainable Future Built Environment. In *Energy and Sustainable Futures*. 1st ed. V. 1. I. Mporas, A. Al-Habaibeh, V. Vukovic, P. Kourtessis, A. Asthana, & J. Senior, Eds. 163–169. DOI: 10.1007/978-3-030-63916-7_21.

Méndez, D., Guzmán-Martínez, F., Acosta, M., Collahuazo, L., Ibarra, D., Lalangui, L. & Jiménez-Oyola, S. 2022. Use of Tailings as a Substitute for Sand in Concrete Blocks Production: Gravimetric Mining Wastes as a Case Study. *Sustainability (Switzerland)*. 14(23):1–14. DOI: 10.3390/su142316285.

Minerals Council South Africa. 2024. *Where Gold is currently mined* . Available: https://www.miningforschools.co.za/lets-explore/gold/where-gold-is-currently-mined [2024, August 04].

miningweekly.com. 2023. *As gold demand rises, South Africa has opportunity to recover 30Moz of gold from dumps*. Available: https://www.miningweekly.com/article/as-gold-demand-rises-south-africa-has-opportunity-to-recover-30moz-of-gold-from-dumps-2023-07-18#:~:text=%E2%80%9CIn%20South%20Africa%2C%20we',presentation%2C%20covered%20by%20Mining%20Weekly. [2025, June 02].

Oelofse, S.H.H., Hobbs, P.J., Rascher, J. & Cobbing, J.E. 2010. OELOFSE_2010. *RêSource*. 12(2):51–55. Available: chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://researchspace.csir.co.za/server/api/core/bitstreams/bf8dd9c0-625b-4820-bc95-be7510aa256f/content [2025, June 02].

Otieno, M. & Ndoro, E. 2020. Utilization of kimberlite tailings as aggregates in concrete - Strength and selected durability properties. *MRS Advances*. 5(25):1259–1266. DOI: 10.1557/adv.2020.153.

Padmanaban, I., Nithila, S. & Reshma Jahaan, K. 2019. Replacement of fine aggregate by using construction demolition waste steel powder in concrete. In *Materials Today: Proceedings*. V. 26. Elsevier Ltd. 1551–1556. DOI: 10.1016/j.matpr.2020.02.318.

PPC. 2016. *Material Safety Data Sheet for cement MSDS*. Sandton, South Africa.

Roxburgh, J. 2021. Fulton's concrete technology. In *Fulton's concrete technology*. 10th ed. M. Alexander, Ed. Midrand: Cement and Concrete. 149–160.

sgu.se. 2024. *Chapter 12:Tailings Storage Facility*. Available: https://www.sgu.se/en/itp308/knowledge-platform/chapter-12-tailings-storage-facility/ [2024, October 24].

Sibanda, L.K. 2019. *Re-purposing of mine waste: an alternative management approach to Gold tailings in South Africa*. Cape Town, South Africa.

Talaat, A., Emad, A., Tarek, A., Masbouba, M., Essam, A. & Kohail, M. 2021. Factors affecting the results of concrete compression testing: A review. *Ain Shams Engineering Journal*. 12(1):205–221. DOI: 10.1016/j.asej.2020.07.015.

theconstructor.org. 2024. *Strength of Concrete -Cube Test [PDF], Procedure, Results*. Available: https://theconstructor.org/concrete/compressive-strength-concrete-cube-test/1561/ [2024, October 17].

Vermeulen, N.J. 2001. *The composition and state of Gold tailings*. Pretoria.

Worldometer. 2024. *World Population by Year*. Available: https://www.worldometers.info/world-population/world-population-by-year/ [2024, July 20].

Yi, S.T., Yang, E.I. & Choi, J.C. 2006. Effect of specimen sizes, specimen shapes, and placement directions on compressive strength of concrete. *Nuclear Engineering and Design*. 236(2):115–127. DOI: 10.1016/j.nucengdes.2005.08.004.

Zhao, W., Mao, K., Ma, R., Guo, L. & Feng, Z. 2019. Influence of mixing process of high performance concrete. In *IOP Conference Series: Materials Science and Engineering*. V. 563. Institute of Physics Publishing. DOI: 10.1088/1757-899X/563/2/022036.

Appendix A: Results

Table A-1: PSD and FM calculations of Philippi dune sand

Sieve opening (mm)	Mass retained (g)	Mass retained (%)	Cum. retained (%)	Cum. passing (%)
4.75	0.00	0.00	0.00	100.00
2.36	0.00	0.00	0.00	100.00
1.18	3.00	0.60	0.60	99.40
0.6	136.00	27.10	27.69	72.31
0.3	269.00	53.60	81.29	18.71
0.15	88.70	17.67	98.96	1.04
0.075	5.00	1.00	99.96	0.04
PAN	0.20	0.04	100.00	0.00
Total mass	501.9			

Table A-2: PSD and FM calculations of 5-mm Greywacke crusher sand

Sieve opening (mm)	Mass retained (g)	Mass retained (%)	Cum. retained (%)	Cum. passing (%)
4.75	65.00	13.12	13.12	86.88
2.36	179.70	36.28	49.40	50.60
1.18	86.30	17.42	66.83	33.17
0.6	52.00	10.50	77.33	22.67
0.3	52.00	10.50	87.83	12.17
0.15	48.30	9.75	97.58	2.42
0.075	7.00	1.41	98.99	1.01
PAN	5.00	1.01	100.00	0.00
Total mass	495.3			

Table A-3: PSD and FM calculations of Gold mine tailings

Sieve opening (mm)	Mass retained (g)	Mass retained (%)	Cum. retained (%)	Cum. passing (%)
4.75	0.00	0.00	0.00	100.00
2.36	0.00	0.00	0.00	100.00
1.18	0.00	0.00	0.00	100.00
0.6	5.00	1.00	1.00	99.00
0.3	341.67	68.33	69.33	30.67
0.15	135.00	27.00	96.33	3.67
0.075	16.67	3.33	99.67	0.33
PAN	1.67	0.33		
Total mass	500			

Table A-4: Relative density calculations of Philippi dune sand

Relative density of Philippi dune sand					
	Weights (kg)				**kg/m³**
Test	**Jar**	**Material**	**Material + Water**	**Water**	**Density**
1	0.560	0.500	1.360	1.080	2.27
2	0.560	0.500	1.365	1.080	2.33
3	0.560	0.500	1.368	1.080	2.36
				Average	2.32

Table A-5: Relative density calculations of 5-mm Greywacke crusher sand

Relative density of Greywacke crusher sand					
	Weights (kg)				**kg/m³**
Test	**Jar**	**Material**	**Material + Water**	**Water**	**Density**
1	0.560	0.500	1.400	1.080	2.78
2	0.560	0.500	1.392	1.080	2.66
3	0.560	0.500	1.410	1.080	2.94
				Average	2.79

Table A-6: Relative density calculations of Gold mine tailings

Relative density of Gold mine tailings					
	Weights (kg)				kg/m³
Test	**Jar**	**Material**	**Material + Water**	**Water**	**Density**
1	0.560	0.500	1.400	1.080	2.78
2	0.560	0.500	1.400	1.080	2.78
3	0.560	0.500	1.415	1.080	3.03
				Average	2.86

Table A-7: Average compressive strength results of Mix A 50 mm and 100 mm cubes at different curing ages

Curing Age		Average Compressive Strength (MPa)				
	Replacement level	0%	20%	40%	60%	80%
	Cube Size (mm)					
2-days	50	33.2	35.5	36.1	36.2	32.9
7-days	50	48.8	50.2	48.1	44.3	45.7
14-days	50	51.3	39.5	38.6	37.3	46.2
28-days	50	-	56.6	47.8	51.2	50.4
28-days	100	-	43.9	43.5	41.6	43.4

Table A-8: Average compressive strength results of Mix B 100 mm cubes at different curing ages

Curing Age		Average Compressive Strength (MPa)		
	Replacement Level	0%	20%	60%
	Cube Size (mm)			
7-days	100	29.2	27.7	23.3
14-days	100	32.5	31.2	25.3
28-days	100	37.6	32.8	27.6

Table A-9: Compressive strength results of Mix A (50 mm cubes)

Replacement percentage of dune sand with Gold Tailings (Mix A - 50 mm cubes)					
		2-day strength (MPa)	**7-day strength (MPa)**	**14-day strength (MPa)**	**28-day strength (MPa)**
0% replacement	**1**	34.1	44.3	54.1	
	2	22.3	49.3	51.1	
	3	32.4	52.7	48.8	
	Ave	29.6	48.8	51.3	
20% replacement	**1**	35.6	49.5	40.0	57.1
	2	35.4	50.8	41.2	55.1
	3	35.4	50.4	37.2	57.6
	Ave	35.5	50.2	39.5	56.6
40% replacement	**1**	32.8	46.5	53.8	52.4
	2	38.7	50.2	38.4	44.4
	3	36.9	47.5	38.8	46.7
	Ave	36.1	48.1	43.7	47.8
60% replacement	**1**	36.4	44.1	38.9	46.7
	2	34.8	46.5	36.6	52.1
	3	37.3	42.2	36.2	54.7
	Ave	36.2	44.3	37.3	51.2
80% replacement	**1**	31.9	44.3	37.0	51.8
	2	33.3	46.5	44.9	50.0
	3	33.3	46.4	47.5	49.4
	Ave	32.8	45.7	43.2	50.4

Table A-10: Compressive strength results of Mix A (100 mm cubes)

Replacement percentage of dune sand with Gold Tailings (Mix A - 50 mm cubes)		
		28-day strength (MPa)
20% replacement	**1**	46.2
	2	41.5
	Ave	43.9
40% replacement	**1**	42.1
	2	44.8
	Ave	43.5
60% replacement	**1**	39.8
	2	43.4
	Ave	41.6
80% replacement	**1**	45.1
	2	41.8
	Ave	43.4

Table A-11: Compressive strength results of Mix B (100 mm cubes)

Replacement percentage of dune sand with Gold Tailings (Mix A - 50 mm cubes)				
		7-day strength (MPa)	**14-day strength (MPa)**	**28-day strength (MPa)**
0% replacement	**1**	27.4	33.7	35.5
	2	9.2	39.0	36.1
	3	31.0	32.5	37.6
	Ave	22.5	35.1	36.4
20% replacement	**1**	18.0	29.7	33.4
	2	27.3	33.4	32.8
	3	28.1	30.4	32.2
	Ave	24.4	31.2	32.8
60% replacement	**1**	23.9	25.3	26.3
	2	23.2	25.3	28.0
	3	22.7	25.2	28.4
	Ave	23.3	25.3	27.6