

BINDURA UNIVERSITY OF SCIENCE EDUCATION

DEPARTMENT OF NATURAL RESOURCES

**CARBON SEQUESTRATION POTENTIAL OF TAILINGS DAMS: A CASE STUDY
OF FREDA REBECCA GOLD MINE.**



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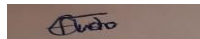
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DEDICATION

I dedicate this dissertation to my mother, whose unwavering love, encouragement and support kept me grounded and motivated throughout this academic journey. I also dedicate it to the entire Gusho family for always believing in me. I am forever grateful.

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ABSTRACT

Mine tailings are increasingly recognised as potential substrates for mineral carbonation, but they may also contain environmentally important heavy metals. This study assessed the carbon sequestration potential of the tailings storage facility at Freda Rebecca Gold Mine, Zimbabwe, using tailings deposited between 2022 and 2026. Twenty surface samples were collected, with four samples representing each deposition year. Acid-reactive mass loss was assessed using a hydrochloric acid fizz procedure, thermal mass loss was measured after heating samples to 800 °C, and selected heavy metals (Pb, Cu, Cd, As and Zn) were determined after acid digestion. Acid-reactive mass loss attributed to carbonate presence decreased from a mean of 4.2% in the 2022 and 2023 deposits to 2.9% in 2026. Thermal mass loss decreased from 7.7% in 2022 to 5.4% in 2026. The annual mean concentrations of Pb, Cu, Cd and Zn were 0.3061–0.5575, 0.6167–0.9984, 0.0054–0.0420 and 0.4307–0.5348 mg/L, respectively, while the annual As means reported in the dataset ranged from 0.0024 to 0.0230 mg/L. The older deposits therefore showed higher acid-reactive mass loss and thermal mass loss than the more recent deposits. These patterns are consistent with increasing weathering and possible mineral carbonation with longer exposure, although atmospheric CO₂ uptake was not measured directly and carbonate mineral identity was not confirmed mineralogically. The heavy-metal results demonstrate that potentially toxic elements remain present and require monitoring. The study concludes that the Freda Rebecca tailings storage facility has measurable indicators consistent with passive carbon storage potential, while further work is required to quantify actual CO₂ uptake and confirm the mineralogical mechanisms involved.

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LIST OF ACRONYMS /ABBREVIATIONS

Cd	Cadmium
Zn	Zinc
Cu	Copper
Pb	Lead
As	Arsenic
NET	Negative Emission Technologies
CCS	Carbon Capture and Storage
DAC	Direct Air Capture
BECCS	Bioenergy with carbon capture and storage
TSF / TSFs	Tailings storage facility / facilities

CHAPTER 1: INTRODUCTION

1.1 Background of the Study

The mining sector is important to Zimbabwe because it contributes mineral production, employment, infrastructure development and foreign-currency earnings (Nyamadzawo, et al. 2022). Mining activities also generate large quantities of waste materials that are commonly stored in tailings storage facilities. Climate change, however, remains a major environmental concern because of increasing atmospheric concentrations of greenhouse gases, particularly carbon dioxide (CO₂) (Maphosa, et al., 2025). Human activities such as fossil-fuel combustion, industrial production and mining contribute to greenhouse-gas emissions and associated environmental change (Friedlingstein et al., 2022). Consequently, negative-emission technologies that remove CO₂ from the atmosphere and store it in durable forms have received increasing attention.

Mineral carbonation is one of the most promising NET options due to its long-term permanence and ecological safety (Kandji et al., 2023). Mineral carbonation is the chemical reaction between CO₂ and reactive calcium- and magnesium-rich minerals to form stable carbonate minerals such as calcite, magnesite and dolomite. Mineral carbonation provides carbon storage with minimal leakage risk and requires less long-term monitoring and storage infrastructure as opposed to other methods of carbon capture. Mineral carbonation can occur naturally through weathering reactions and/or can be promoted through engineered mineral carbonation processes, as described by Power et al. (2020).

Furthermore, considering that mine tailings are finely milled during mineral processing, their reactive surface area and potential weathering rate increase, which is why they are increasingly becoming important for the study of carbon sequestration (Chitakira et al., 2024). Silicate minerals in the tailings from ultramafic and mafic mines and some gold mines have the potential to react with atmospheric CO₂. In Australia, tailings from the Mount Keith Nickel Mine were reported to passively capture between 15 and 25 kg of CO₂ per tonne of tailings each year, by natural mineral carbonation (Harrison et al., 2023). A similar study was conducted in Tanzania by Kweka and Mtei (2020) where carbonation reactions were favoured by tropical climatic conditions to achieve sequestration rates of 30 to 60 kg CO₂/tonne/year.

Mine tailings may also contain elevated concentrations of potentially toxic metals. Pb, Cd, As, Cu and Zn are commonly associated with mining wastes, and their environmental behaviour depends on factors such as pH, mineralogy and redox conditions. Carbonate formation can potentially influence metal retention through precipitation or adsorption; however, such stabilisation cannot be demonstrated from total acid-digested concentrations alone. In this study, heavy-metal concentrations are therefore interpreted as indicators of occurrence and distribution rather than direct measures of mobility or bioavailability.

Freda Rebecca Gold Mine has generated substantial quantities of tailings over many years. The tailings storage facility therefore represents an anthropogenic surface where weathering and mineral reactions may occur. However, the extent of carbon storage associated with these processes has not been quantified locally, and empirical information linking carbonate-related indicators with heavy-metal occurrence in Zimbabwean gold mine tailings remains limited. Addressing this knowledge gap can assist policymakers, environmental regulators and mining companies in considering carbon management alongside conventional tailings rehabilitation.

1.2 Problem Statement

In Zimbabwe, mining generates large quantities of tailings that are commonly stored in tailings storage facilities. These facilities can present environmental risks, including heavy-metal contamination, acid mine drainage, dust emissions and land degradation (Hudson Edwards et al., 2024). At the same time, international research has shown that some mine tailings can undergo natural mineral carbonation, potentially converting atmospheric CO₂ into stable carbonate minerals.

Recent studies have demonstrated that mineral carbonation can occur in mine tailings and may provide a pathway for relatively permanent carbon storage (Wilson et al., 2021; Oskierski et al., 2022). Carbonate formation may also influence the retention of some metals under favourable geochemical conditions. Despite this potential, limited empirical work has quantified carbon-related indicators in Zimbabwean gold mine tailings or compared these indicators with heavy-metal concentrations.

With many years of mining operations at Freda Rebecca Gold Mine, a large mass of tailings has been generated. However, the extent to which these tailings contain accumulated carbonate and

other carbon-related material is not well documented. In addition, limited data are available on the distribution of Pb, Cu, Cd, As and Zn across deposition years and on their possible association with carbonate-related processes.

The current study therefore assesses carbon-related indicators in the Freda Rebecca tailings storage facility by comparing deposition years. The emphasis is on measured acid-reactive mass loss, thermal mass loss and acid-digested heavy-metal concentrations. Because the study does not directly measure CO₂ flux, mineralogical phases or metal mobility, conclusions about atmospheric CO₂ sequestration and heavy-metal stabilisation are presented as evidence-based interpretations rather than direct measurements.

1.3 Justification of the Study

The significance of this study can be seen through growing global awareness of climate change mitigation and sustainable mining practices. The conventional understanding of mine tailings is that they are environmental burdens as they are associated with pollution, heavy metal contamination and ecosystem deterioration. Recent global studies, however, have indicated that tailings materials could be an important carbon sink through mineral carbonation. However, very little research has been conducted on the carbon sequestration potential of mine waste in Zimbabwe.

The study generates empirical data on acid-reactive mass loss, thermal mass loss and the occurrence of selected heavy metals in tailings deposited between 2022 and 2026. These results contribute to understanding whether older tailings show patterns consistent with progressive weathering and carbonate accumulation. The heavy-metal results also provide baseline information that can support environmental monitoring and pollution management at the study site.

The study has practical relevance for mine rehabilitation and environmental management because carbon-related processes can potentially be considered alongside erosion control, revegetation and pollution prevention. However, any carbon-credit or climate-finance application would require direct measurement and verification of CO₂ uptake, which was beyond the scope of this study.

1.4 Research Aim

To assess the carbon sequestration potential of the tailings storage facility at Freda Rebecca Gold Mine by comparing carbonate-related indicators, thermal mass loss and selected heavy-metal concentrations across tailings deposited in different years.

1.5 Research Objectives

1. To determine the concentration and distribution of selected heavy metals (lead (Pb), copper (Cu), cadmium (Cd), arsenic (As), and zinc (Zn)) within the tailings samples collected from different deposition years.
2. To quantify acid-reactive mass loss attributed to carbonate presence and thermal mass loss at 800 °C in tailings materials as indicators relevant to carbon sequestration potential.
3. To compare the patterns of thermal mass loss, acid-reactive mass loss attributed to carbonate presence and selected heavy-metal concentrations across tailings deposition years.

CHAPTER 2: LITERATURE REVIEW

2.1 Climate change and carbon dioxide emissions

One of the greatest environmental issues facing the world today is climate change. This is primarily attributed to the rise of greenhouse gases such as carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O), in the atmosphere. Atmospheric CO₂ levels have increased rapidly since the industrial revolution due to human activities such as fossil fuel combustion, industrial processes, deforestation or mining (Intergovernmental Panel on Climate Change [IPCC], 2021). The rise of GHGs has resulted in rising global temperatures, changes in precipitation, an increase in droughts and floods, melting ice and biodiversity loss (Power et al., 2020).

The mining industry releases GHGs directly and indirectly as a result of mineral extraction, mineral processing, transport and energy use. The tailings storage facilities can also contribute to environmental degradation through dust emissions and land disturbance, and via contamination of adjacent ecosystems. With the growing concerns about climate change, attention has turned to the search for technologies that can reduce the amount of CO₂ in the air.

As one of the critical strategies to combat climate change, carbon sequestration involves the removal of atmospheric carbon dioxide and its storage in stable forms (Chitakira et al., 2024). There are several proposed methods of carbon sequestration: geologic sequestration, biological sequestration and mineral carbonation. Of these, mineral carbonation has become of particular interest due to its low leakage risk and its permanent carbon storage.

2.2 Carbon Sequestration

Carbon sequestration is the process of capturing and storing atmospheric carbon dioxide to reduce greenhouse gas concentrations and slow climate change. Carbon sequestration can be a natural process or an engineered technology. Natural sequestration takes place via biological and geological mechanisms, such as through the activity of photosynthesis, accumulation of soil carbon and weathering of rock. Engineered sequestration techniques are carbon capture and storage (CCS), direct air capture (DAC), bioenergy with carbon capture and storage (BECCS) and mineral carbonation.

The primary objective of carbon sequestration is to reduce CO₂ levels in the atmosphere and limit global warming. Friedlingstein et al. (2022) indicated that achieving global climate targets in the framework of the Paris Agreement requires not only greenhouse gas emission reductions but also the active removal of CO₂ from the atmosphere. Therefore, negative emission technologies play an increasingly important role in climate mitigation policies.

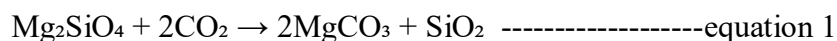
Of the various sequestration methods, mineral carbonation is considered particularly attractive because it converts CO₂ into stable carbonate minerals that can be stored for geological periods of time (Zhang et al., 2023). In contrast, mineral carbonation forms chemically stable species with potentially lower environmental impacts, circumventing the need for long-term monitoring that is required for geological storage systems because of leakage risks.

2.3 Mineral Carbonation

Mineral carbonation is the process whereby carbon dioxide reacts with magnesium- and calcium-abundant minerals to create stable carbonate minerals such as calcite (CaCO₃), magnesite (MgCO₃) and dolomite (CaMg(CO₃)₂). It can occur naturally through weathering or be accelerated using engineered systems.

The carbonation process typically begins with the reaction of carbon dioxide with water to form carbonic acid, which then reacts with silicate minerals (Kandji et al., 2023). The overall process leads to the precipitation of stable carbonate minerals. The common minerals in the carbonation process are olivine, serpentine, pyroxene and brucite. The common rocks associated with these minerals are ultramafic and mafic rocks that are associated with mining activity.

The carbonation reaction can be expressed as in equation 1:



This reaction shows how magnesium silicate minerals can be converted into magnesium carbonate by reaction with carbon dioxide.

Mineral carbonation offers a number of advantages over other carbon sequestration technologies. First, the carbon is securely locked in the solid mineral form reducing the risk of release to the atmosphere. Second, it could use industrial waste material, such as mine tailings, and reduce the environmental costs associated with disposal of these materials (Hamilton et al., 2022). Third,

mineral carbonation can occur passively in the atmosphere without the requirement of complicated infrastructure.

However, the carbonation process in nature can often be slow because its rate which is influenced by mineral composition, particle size, temperature, concentrations of carbon dioxide and moisture. Researchers have therefore investigated ways to increase carbonation rates, such as mineral grinding, chemical activation, heat treatment and biological processes (Oskierski et al., 2022).

2.4 Mine Tailings and Tailings Dams

Finely milled waste materials, produced after the valuable minerals have been removed from the ore by mineral processing, are called mine tailings. Typical constituents of the tailings include crushed rock particles, remaining chemicals, water and trace metals. These materials are typically contained in specially designed facilities known as tailings storage facilities (TSFs) or tailings dams.

Tailings dams are among the biggest waste storage systems connected with mining activities. Though they are used to contain waste, tailings dams often bring environmental problems such as acid mine drainage, heavy metal contamination, dust emissions, water pollution and degradation of land. Poorly operated tailings dams can fail as well, leading to an environmental disaster.

Despite these environmental worries, recent studies have shown that mine tailings may offer opportunities for carbon sequestration via mineral carbonation processes (Chitakira et al., 2024). Tailings materials are particularly suitable for carbonation, since they are finely crushed during ore processing, and the reactive surface area is high. In addition, some tailings have a high amount of reactive magnesium and calcium minerals that react with atmospheric carbon dioxide.

2.5 Carbon Sequestration in Mine Tailings

The study of carbon sequestration in the mine tailings has increased significantly over the last 20 years. Natural weathering and the formation of carbonate minerals provide a mechanism for tailings materials to absorb atmospheric carbon dioxide, as demonstrated in several studies.

Due to the high content of magnesium in the ultramafic mine tailings, they have good potential for carbon sequestration, as reported by Power et al., 2020. Nickel tailings were found to be able to naturally create carbonate crusts that can store a significant amount of atmospheric CO₂ in Canada. Similarly, research at the Mount Keith Nickel Mine in Australia found sequestration rates from 15 to 25 kg CO₂ per tonne of tailings per year (Harrison et al., 2023).

Similarly, in Tanzania, Kweka and Mtei (2020) noted that the carbonation rate is higher in the tropics because of the relatively high temperatures and available moisture during a certain season. According to the report, the nickel tailings of the Kabanga Belt were able to sequester 30 to 60 kg CO₂ per tonne per year. In Morocco, Benzaazoua et al. (2019) also observed that the phosphate mine tailings possessed excellent carbonation properties due to their high Ca and Mg content.

The amount of carbon sequestration in the mine tailings is influenced by various factors such as mineral composition, pH, particle size, moisture availability, temperature, and duration of exposure (Daitsh et al., 2021). The carbonation potential of tailings is typically higher for tailings with a high content of reactive silicate minerals (such as olivine and/or serpentine) than for those in which quartz is the predominant mineral. However, over time, inorganic carbon can be accumulated in even gold mine tailings as a result of atmospheric weathering and carbonate precipitation (Nyamunda et al., 2024).

2.6 Carbonate Minerals in Tailings Dams

In tailings dams, carbonate minerals can be created through the reaction of atmospheric carbon dioxide and reactive minerals in the tailings. The carbon dioxide dissolves in pore water, forming carbonic acid which reacts with calcium and magnesium containing minerals. This process results in the precipitation of carbonate minerals, which are able to sequester carbon in stable solid forms (Raza et al., 2023).

Environmental factors such as moisture, temperature, pH and oxygen influence the formation of carbonate minerals. Moisture availability is particularly important since carbonation reactions occur in an aqueous environment. The carbonation rate in tailings dams might, however, be affected by seasonal rainfall and humidity (Power et al., 2020).

Age of tailings deposition might also affect the formation of carbonate. Under atmospheric conditions, some of the older tailings have been exposed to the atmosphere for a longer period, allowing increased weathering and carbonate precipitation. Therefore, the carbonate contents of the different tailings layers can vary as a function of exposure time and the environment.

Carbonate formation not only supports carbon sequestration, but can also influence the geochemical stability of heavy metals in the tailings material. Carbonate minerals are able to immobilize the metals via the precipitation and adsorption processes to reduce their mobility in the environment (Maphosa et al., 2025).

2.7 Heavy Metals in Mine Tailings

Heavy metals are metals with high atomic number and density which can be harmful at elevated concentrations. Mining is a major source of heavy metal contamination as ores can have trace amounts of metals that are concentrated in the waste after ore extraction.

Lead (Pb), cadmium (Cd), arsenic (As), copper (Cu) and zinc (Zn) are common heavy metals associated with gold mine tailings. Leaching, erosion and wind dispersion are possible sources of soil, water and vegetation pollution by these metals. Heavy metal pollution poses threats to the environment, crop yields and human health (Zhang et al., 2023).

Lead (Pb) is a dangerous metal that is linked to neurological problems, developmental disorders and kidney damage in humans. Cadmium (Cd) is a highly toxic metal that can be stored in biological tissues. Arsenic (As) is recognized as a carcinogenic element that can pollute groundwater and agricultural soils. Copper (Cu) and zinc (Zn) are micronutrients that are needed in small amounts but toxic in larger amounts.

Mineral composition, carbonate formation, pH and oxidation-reduction conditions affect the environmental behavior of heavy metals contained in the tailings dams. Generally, an increase in acidity increases the solubility and mobility of metals, while an increase in alkalinity can promote the precipitation and immobilization of metals (Li et al., 2022).

2.8 Total Carbon and Thermal Mass Loss

Total carbon is conceptually important when evaluating carbon storage because it includes organic and inorganic carbon fractions. Inorganic carbon in mineralised tailings may occur as

carbonate minerals, whereas organic carbon can accumulate through vegetation establishment, microbial activity and organic-matter inputs. Accurate carbon accounting therefore requires analytical methods that distinguish these fractions (Alakangas et al., 2022; Fonteneau et al., 2021).

Thermal mass loss during heating can provide information about volatile components in a sample, but mass loss at 800 °C is not equivalent to total carbon because it may include moisture, organic matter, structural water, carbonate decomposition and other thermally labile phases. Consequently, the thermal results in this study are reported as thermal mass loss rather than as a direct measurement of total carbon. Direct total organic carbon (TOC) and total inorganic carbon (TIC) measurements would be required for carbon accounting.

Combining thermal mass-loss measurements with carbonate-related tests and heavy-metal concentrations can nevertheless provide a preliminary comparison of deposition years. For robust carbon accounting, future studies should use elemental or dedicated TOC/TIC analytical methods and mineralogical analyses to identify the carbon-bearing phases responsible for carbon storage.

2.9 Relationship between Thermal Mass Loss, Carbonate-related indicators and Heavy Metals

Understanding the relationship between carbon-related measurements and heavy metals is important when assessing the environmental behavior of mine tailings. Carbonate minerals can influence metal retention through precipitation and adsorption, but the strength of this effect depends on pH, mineralogy, moisture and the chemical form of the metal (Li et al., 2022; Maphosa et al., 2025).

In this study, acid-digested metal concentrations represent the amount of each selected element released into the analytical digest. They do not directly measure metal mobility, leachability or bioavailability. Therefore, a pattern in which carbonate-related indicators and measured metal concentrations vary with deposition age should be interpreted as a descriptive association rather than proof that carbonate formation immobilized the metals.

Direct assessment of metal stabilisation would require additional approaches such as sequential extraction, leaching tests, pore-water analysis or mineralogical/speciation analysis. These methods were outside the scope of the present study.

2.10 Factors influencing Carbon Sequestration in Tailings Dams

There are a number of factors which influence the carbon sequestration potential in tailings dams. These include the mineral composition, particle size, climate, moisture supply, pH and tailings age. The mineralogical composition is one of the most important factors, as the carbonation process requires calcium- and magnesium-bearing minerals that are reactive. Generally, the higher carbonation potential is found in tailings containing more silicate minerals (Hamilton et al., 2022).

The particle size also affects the rate of carbonation as smaller particles have larger surface areas, which can increase weathering reaction rates. Hence, the tailings from mines are suitable for carbonation, since they are finely milled during ore processing. Carbonation reactions can be influenced by climatic conditions like temperature and rainfall which control the availability of moisture and the weathering rate. Tropical climates might increase carbonation because of increased chemical weathering.

Tailings age also plays a role as older tailings will have been exposed to atmospheric CO₂ and environmental weathering processes for longer periods of time. As a result, the amount of carbonate accumulated can be greater in the older deposits.

2.11 Carbon Sequestration and Sustainable Mine Rehabilitation

Sustainable mine rehabilitation is the process of rehabilitating mined areas in a manner that is more sustainable and less harmful to the environment. The traditional mine rehabilitation approaches primarily focus on erosion control, revegetation and pollution reduction. However, with the increasing interest in the mitigation of climate change, carbon management strategies have been added to the mine rehabilitation programs (Kweka and Mtei, 2020).

Carbon sequestration could potentially provide several environmental benefits for tailings rehabilitation, such as greenhouse gas mitigation, heavy metal stabilisation and soil formation. The establishment of vegetation on tailings dams can also increase carbon storage by organic matter production and root-mediated weathering (Moyo et al., 2025).

Carbon-smart mine rehabilitation may also generate economic opportunities via carbon credit schemes and climate finance mechanisms. Some possibilities exist for mining companies to benefit from carbon offset programs if tailings carbonation can be measured and verified.

2.13 Conceptual Framework

The conceptual framework links deposition age to carbon-related indicators and heavy-metal occurrence through environmental and geochemical conditions. Deposition age is treated as the independent variable. Thermal mass loss and acid-reactive mass loss attributed to carbonate presence, together with measured concentrations of Pb, Cu, Cd, As and Zn, are the dependent variables. pH, moisture availability and tailings mineralogy are considered mediating conditions because they can influence weathering, carbonate formation and metal behavior. The expected pattern is that longer exposure may favor weathering and carbonate accumulation, while changes in geochemical conditions may influence measured metal concentrations and their potential retention.

The framework is therefore interpreted as a set of expected relationships rather than a causal model. The study tests these expectations through comparison of deposition-year groups and descriptive interpretation of the laboratory results.

Table 2.13.1 Conceptual framework table

Independent Variable	Mediating Conditions	Environmental Processes	Dependent Variable/Indicators	Expected Outcome
Deposition Age (2022- 2026)	Ph	Weathering	Acid-reactive mass loss	Older tailings may show greater evidence of carbonate related carbon accumulation, while heavy metal patterns may vary with geochemical conditions
	Moisture availability	Carbonate formation	Thermal mass loss	

	Tailings mineralogy	CO2 incorporation	Pb	
			Cu	
			Cd	
			As	
			Zn	

CHAPTER 3: METHODOLOGY

3.1 Description of the Study Area

The study was conducted at Freda Rebecca Gold Mine, located in Bindura District of Mashonaland Central Province, Zimbabwe. The mine is situated at approximately 17°17'47" S and 31°18'31" E (WGS84), about 2.4 km from Bindura town (Mindat, 2026). The geographical position places the study site within the Bindura mining area of northern Zimbabwe. The Freda Rebecca gold deposit is associated with the geological formations of the Bindura area, including the Rebecca diorite and Bindura granodiorite, which form part of the geological setting of the mineralised zone (Klemm & Krautner, 2000).

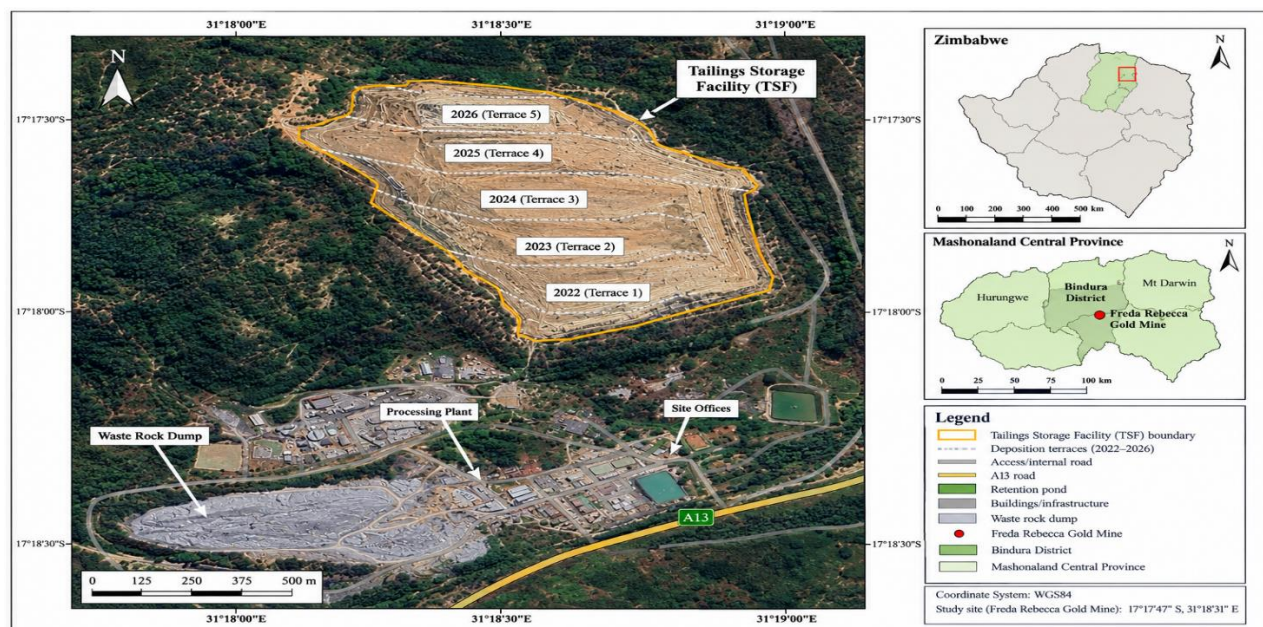


Figure 3.1: Location of Freda Rebecca Gold Mine, Bindura District, Mashonaland Central Province, Zimbabwe.

The climatic conditions of Bindura are characterised by distinct seasonal variation, with rainfall concentrated mainly during the wet season. District-level information indicates an average annual rainfall range of approximately 600–1000 mm, with effective rainfall for agricultural activities generally beginning towards the end of November (Food and Nutrition Council of Zimbabwe, 2023). The rainfall information in the district profile is based on data from the Zimbabwe Meteorological Department. Peer-reviewed research using meteorological records from the Bindura Railway station also confirms the availability of long-term precipitation data for the area and identifies substantial temporal variability in rainfall (Mavhura et al., 2021).

These climatic conditions are relevant to the study because seasonal rainfall and associated moisture availability can influence the physical and chemical processes occurring within exposed mine tailings. In particular, water availability may affect mineral weathering, dissolution and precipitation reactions and consequently influence the formation or accumulation of carbonate minerals and the mobility or redistribution of heavy metals within tailings materials. Research conducted on mine tailings in the Bindura area similarly identifies the importance of the local wet-summer and dry-winter climate in relation to processes occurring on mine waste substrates (Sardans et al., 2020).

The specific study site comprised a tailings storage facility at Freda Rebecca Gold Mine. The facility contains tailings deposited during different periods, providing an opportunity to examine changes associated with the age of deposited tailings. For this study, deposition terraces representing the years 2022 to 2026 were selected. The terraces provided the sampling units for assessing the relationship between tailings deposition age, carbonate accumulation and the distribution of heavy metals. Thus, the study area was defined not only by its geographical location at Freda Rebecca Gold Mine but also by the different deposition-age terraces within the selected tailings storage facility.

3.2 Research Design

The study used a quantitative, cross-sectional comparative observational design involving field sampling and laboratory analysis of tailings from five deposition-year terraces. Deposition year was observed rather than manipulated and therefore represents the independent variable. The dependent variables were acid-reactive mass loss, thermal mass loss at 800 °C and acid-digested concentrations of Pb, Cu, Cd, As and Zn. Four field samples were collected from each deposition

year ($n = 4$ per year), giving 20 field samples in total. The study was descriptive and comparative; no causal experiment was conducted and no inferential relationship test was used.

Table 3.3.1: Distribution of Tailings Samples

Tailings Level	Deposition Year	Number of Samples
Level 1	2022	4
Level 2	2023	4
Level 3	2024	4
Level 4	2025	4
Level 5	2026	4

The sampling design provided four spatially distributed grab samples from each deposition-year zone, resulting in 20 field samples. The design enabled comparison of acid-reactive mass loss, thermal mass loss and selected heavy-metal concentrations among tailings deposited between 2022 and 2026. Since sampling was restricted to accessible near-surface material, the results represent the sampled portions of the respective deposition-year zones and do not represent the complete vertical tailings profile.

3.4 Data/Sample Collection Procedure

Tailings samples were collected from the Freda Rebecca Gold Mine tailings storage facility on 23 April 2026. A stratified purposive sampling design was used to obtain samples representing different tailings deposition years. The tailings storage facility was stratified into five depositional age classes based on company deposition records, namely 2022, 2023, 2024, 2025 and 2026.

The spatial extent of each deposition-year zone was delineated using GPS coordinates obtained from the mine survey department and processed in QGIS. A 50 m $\times$ 50 m grid was overlaid separately on each deposition-year zone. Four sampling points were selected within each zone

using a systematic grid approach, with the centroid of every second grid cell selected as a sampling location. This resulted in 20 sampling points, comprising four sampling points for each deposition year.

At each selected sampling point, stones, surface litter and other visible foreign materials were removed before sampling to minimise contamination. An individual grab sample of tailings material was collected from the accessible near-surface portion of the tailings at each designated sampling point. The samples were not composited because maintaining individual samples allowed each observation to be linked to its specific deposition year and sampling location.

Sampling was restricted to the accessible near-surface tailings material at each selected point. No excavation or coring was undertaken to obtain samples from deeper layers, and an exact sampling depth was not recorded during field collection. Consequently, the samples represent near-surface tailings at the selected locations and cannot be used to characterise the complete vertical profile of the tailings storage facility.

Each sample was placed in a clean, labelled container indicating the deposition year and sample number. The 20 samples were transported to the laboratory using procedures intended to minimise contamination, material loss and mixing between samples. The four samples from each deposition-year zone were retained as individual samples throughout sample preparation and laboratory analysis.

3.5 Sample Preparation

Following field collection, all 20 tailings samples were prepared using the same laboratory procedure before analysis. Clean 250 mL glass beakers and other laboratory equipment were used during sample preparation. The equipment was cleaned with distilled water and allowed to dry before use to minimise cross-contamination between samples.

Each tailings sample was oven-dried at 105 °C for 24 hours to remove moisture. After drying, the samples were allowed to cool to room temperature. The dried tailings were gently disaggregated to break down loose aggregates and then thoroughly homogenised to obtain a uniform sample material for subsequent analyses.

The homogenised samples were passed through a 2 mm sieve to obtain a consistent particle-size fraction and to remove coarse stones and other relatively large particles that were not

representative of the analytical tailings fraction. The material passing through the sieve was thoroughly mixed and transferred into clean, dry and airtight containers.

Each prepared sample was labelled according to its deposition year and sample number, maintaining the identity established during field collection. The samples were stored in airtight containers under dry laboratory conditions until analysis. The same drying temperature and duration, disaggregation, homogenisation, 2 mm sieving and storage procedures were applied to all 20 field samples.

The prepared samples were subsequently used for determination of thermal mass loss at 800 °C, acid-reactive mass loss attributed to carbonate presence and acid digestion for determination of selected heavy metals.



Figure 3.5.1 Laboratory sample preparation

3.6 Determination of Thermal Mass loss at 800 °C

Thermal mass loss was determined on 3 June 2026 by heating approximately 10 g of each prepared tailings sample in a muffle furnace from ambient temperature to 800 °C at a heating rate of 10 °C per minute. The initial and final masses were recorded and percentage mass loss was calculated as: $\text{thermal mass loss (\%)} = [(\text{initial mass} - \text{final mass}) / \text{initial mass}] \times 100$. Because the method used a muffle furnace rather than a thermogravimetric analyzer and because mass loss at 800 °C can include moisture, organic matter, structural water and carbonate decomposition, these results are reported as thermal mass loss and not as direct total carbon measurements. The available laboratory record does not specify an instrument model, crucible material or controlled-gas atmosphere; therefore, no such details are assumed in this dissertation.

3.7 Determination of Acid-reactive Mass Loss Attributed to Carbonate Presence

Acid-reactive mass loss was assessed using a hydrochloric acid fizz procedure. Exactly 1.000 g of prepared tailings was placed in a clean 250 mL beaker and 2–3 drops of 10% hydrochloric acid were added to the sample surface. Effervescence was observed qualitatively as evidence of acid-reactive carbonate-bearing material. The beaker and sample were then allowed to stabilize and were reweighed. The difference between initial and final mass was recorded as acid-reactive mass loss. Each field sample was tested in quadruplicate. Because the addition of a small volume of acid can cause retained solution, incomplete reaction or dissolution of non-carbonate phases, this procedure is treated as a semi-quantitative indicator of acid-reactive material rather than a definitive carbonate concentration measurement.

The same nominal acid concentration and number of drops were used for all samples, and the analytical balance was checked before weighing. The replicate values are reported individually in Table 4.2.1 and summarized using yearly means and standard deviations. A recognised TIC or carbonate-mineral analytical method such as acid digestion with CO₂ quantification, calcimetry or mineralogical analysis would be required to validate the absolute carbonate concentrations.

3.8 Acid Digestion Procedure

To extract selected heavy metals from the tailings, an acid mixture of nitric acid (HNO₃) and hydrochloric acid (HCl) in a 1:3 ratio was prepared. One gram of each tailings sample was treated with the acid mixture and digested using a Kjeldahl digestion apparatus. The acid treatment was intended to release metal-bearing phases into solution for subsequent measurement. The available dissertation record does not document the exact acid volumes, digestion temperature, digestion duration, final digest volume, filtration/dilution factors or the instrument used for metal measurement. Consequently, the reported results are retained in the units supplied by the laboratory record (mg/L) and are not converted to mg/kg of tailings.

The acid mixture oxidizes and complexes metal-bearing phases, releasing metal ions into solution. The digestion was monitored to minimize overheating, evaporation and loss of sample. Each digestion used 1 g of tailings sample. After digestion, the laboratory digest was prepared for instrumental determination of the selected metals according to the laboratory procedure available at the time of analysis. Because the analytical instrument and dilution details were not recorded in the dissertation dataset, they are identified as methodological limitations rather than

being inferred. The digestion process was closely monitored to ensure full digestion of the samples as well as to prevent loss of sample due to overheating and evaporation.

3.9 Quality Assurance and Quality Control

Quality assurance and quality control included cleaning laboratory equipment, use of distilled water, careful measurement of sample masses, consistent treatment of all samples, replicate analysis and clear sample labelling. However, the available laboratory record does not document method blanks, certified reference materials, matrix spikes, calibration-standard details, limits of detection or quantification, or spike recoveries. These omissions are acknowledged as limitations of the analytical dataset and should be addressed in future work. For carbonate-related and thermal mass-loss measurements, the four field samples per deposition year provide replication at the sampling level, while the quadruplicate acid-reactivity tests provide analytical repeatability.

3.10 Ethical Considerations

Prior to fieldwork, permission to undertake sampling at Freda Rebecca Gold Mine was obtained from relevant authorities. Sampling was conducted in a manner that minimized disturbance to the tailings storage facility and the surrounding environment.

Acid digestion and sample handling procedures were conducted safely in the laboratory to ensure protection of staff from harmful chemicals. Gloves and laboratory coats were worn when preparing and digesting the samples. The research results were recorded and reported accurately and were not manipulated or falsified.

3.11 Limitations of the Study

The study was limited to one mining site and five deposition-year terraces, so the findings cannot be assumed to represent all Zimbabwean tailings storage facilities. Sampling was restricted to surface material, and the available field records did not provide an exact sampling depth or formal spatial sampling design; vertical profiles were therefore not assessed. The analytical methods also imposed important limitations: thermal mass loss at 800 °C is not equivalent to total carbon, the HCl fizz procedure is semi-quantitative for carbonate-related material, and the acid-digestion dataset does not provide direct measurements of metal mobility or speciation. In addition, details such as digestion temperature, duration, final digest volume, dilution factors,

analytical instrument, detection limits and certified reference materials were not available in the dissertation record. These limitations mean that the study demonstrates comparative patterns consistent with carbon-related weathering processes rather than providing a direct annual CO₂ sequestration rate or definitive proof of metal immobilization.

CHAPTER 4: RESULTS

4.0 Introduction

The chapter presents the laboratory results for tailings samples collected from deposition years 2022–2026 at Freda Rebecca Gold Mine. The results cover acid-digested concentrations of Pb, Cd, Cu, As and Zn, acid-reactive mass loss attributed to carbonate presence, and thermal mass loss after heating to 800 °C. The results are presented descriptively because the study did not include a validated direct CO₂ uptake measurement, mineralogical identification of carbonate phases or direct measurements of metal mobility.

4.1 Heavy Metal Concentrations in Tailings Samples

Pb, Cu, Cd, Zn and As were detected in the laboratory results for the deposition-year groups. Annual mean concentrations varied among the years. Each annual mean represents four field samples (n = 4), but replicate-level heavy-metal values and analytical uncertainty were not retained in the presented tables; therefore, the metal results are interpreted descriptively.

Table 4.1.1: Mean lead (Pb) concentrations in tailings samples (mg/L)

YEAR	MEAN(MG/L)
2022	0.3288
2023	0.3061
2024	0.4658
2025	0.3484
2026	0.5575

Table 4.1.2: Mean cadmium (Cd) concentrations in tailings samples (mg/L)

YEAR	MEAN (MG/L)
2022	0.0117
2023	0.0164
2024	0.0420
2025	0.0088
2026	0.0054

Table 4.1.3: Mean zinc (Zn) concentrations in tailings samples (mg/L)

YEAR	MEAN(MG/L)
2022	0.5348
2023	0.5238
2024	0.5109
2025	0.4307
2026	0.4620

Table 4.1.4: Mean copper (Cu) concentrations in tailings samples (mg/L)

YEAR	MEAN(MG/L)
2022	0.7349
2023	0.8311
2024	0.6167
2025	0.9984
2026	0.8337

Table 4.1.5: Mean arsenic (As) concentrations in tailings samples (mg/L)

YEAR	MEAN (MG/L)
2022	0.0024
2023	0.0063
2024	0.0230
2025	0.0100
2026	0.0103

METAL	MINIMUM CONCENTRATION (MG/L)	MAXIMUM CONCENTRATION (MG/L)	RELATIVE OCCURRENCE
PB	0.0690	0.8927	Moderate to High
CU	0.0879	1.2672	High
CD	0.0034	0.1223	Low
ZN	0.1137	0.6298	Moderate
AS	0.1365	0.4571	Moderate

Heavy-metal results were obtained on 27 May 2026. Among the reported annual means, copper had the highest values, ranging from 0.6167 mg/L in 2024 to 0.9984 mg/L in 2025. Lead annual means ranged from 0.3061 mg/L in 2023 to 0.5575 mg/L in 2026. Zinc annual means were relatively similar across the deposition years, ranging from 0.4307 to 0.5348 mg/L, while cadmium means ranged from 0.0054 to 0.0420 mg/L. The annual arsenic means reported in Table 4.1.5 ranged from 0.0024 to 0.0230 mg/L. These results demonstrate the occurrence of selected metals in the tailings and support continued environmental monitoring.

The available annual means show variation among deposition years, but the dataset does not contain sufficient replicate-level information to calculate standard deviations for the heavy metals or to determine whether the differences are statistically significant. In particular, the conflicting minimum and maximum arsenic values previously reported in the dissertation were removed because they could not be reconciled with Table 4.1.5 from the available dataset.

The results should not be interpreted as evidence that older deposits have lower metal mobility or that carbonate formation stabilized the metals, because mobility, leachability and speciation were not directly measured. The observed differences in acid-digested concentrations may reflect differences in tailings composition, deposition history, weathering or other geochemical processes.

4.2 Acid-reactive Mass Loss Attributed to Carbonate Presence

Acid-reactive material was detected in all deposition-year groups. The mean mass loss attributed to acid-reactive carbonate-bearing material was highest in the 2022 and 2023 deposits (4.2% each) and decreased to 3.0% in 2024 and 2025 and 2.9% in 2026. Visible effervescence was stronger in the older deposits. These results indicate the presence of acid-reactive carbonate-bearing material, but they do not by themselves identify the carbonate mineral species or directly quantify atmospheric CO₂ uptake.

Table 4.2.1: Acid-reactive mass loss attributed to carbonate presence

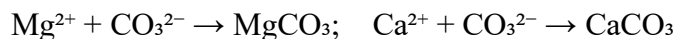
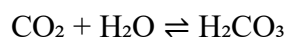
Year	Sample ID	Initial Weight (g)	Final Weight (g)	Weight Loss (g)	Acid-reactive mass loss (%)
2022	2022 -1	1.000	0.958	0.042	4.2
	2022 -2	1.000	0.959	0.041	4.1
	2022 -3	1.000	0.957	0.043	4.3
	2022 -4	1.000	0.958	0.042	4.2
2023	2023 -1	1.000	0.958	0.042	4.2
	2023 -2	1.000	0.959	0.041	4.1
	2023 -3	1.000	0.958	0.042	4.2
	2023-4	1.000	0.957	0.043	4.3
2024	2024 -1	1.000	0.970	0.030	3
	2024 -2	1.000	0.971	0.029	2.9
	2024 -3	1.000	0.969	0.031	3.1
	2024 -4	1.000	0.970	0.030	3
2025	2025 -1	1.000	0.970	0.030	3
	2025 -2	1.000	0.969	0.031	3.1
	2025 -3	1.000	0.971	0.029	2.9
	2025 -4	1.000	0.970	0.030	3
2026	2026 -1	1.000	0.971	0.029	2.9
	2026 -2	1.000	0.970	0.030	3

	2026 -3	1.000	0.972	0.028	2.8
	2026 -4	1.000	0.971	0.029	2.9

4.3 Analysis of Acid-reactive Mass Loss

Samples from 2022 and 2023 exhibited stronger bubbling than samples from 2024 to 2026. The yearly means were $4.2 \pm 0.08\%$ for 2022, $4.2 \pm 0.08\%$ for 2023, $3.0 \pm 0.08\%$ for 2024, $3.0 \pm 0.08\%$ for 2025 and $2.9 \pm 0.08\%$ for 2026 (mean $\pm$ SD, n = 4). The small standard deviations show that the four analytical measurements within each year were closely grouped, although the HCl fizz method remains semi-quantitative. The higher acid-reactive mass loss in older deposits is consistent with longer exposure and possible accumulation of carbonate-bearing material, but direct atmospheric CO₂ sequestration was not measured.

The relevant aqueous carbonation reactions can be represented separately as follows:



4.4 Thermal Mass Loss at 800 °C

Table 4.4.1: Thermal mass loss at 800 °C

Year	Sample ID	Initial Weight (g)	Final Weight (g)	Weight Loss (g)	Thermal mass loss at 800 °C (%)
2022	2022 -1	10.00	9.23	0.77	7.7
	2022 -2	10.00	9.24	0.76	7.6
	2022 -3	10.00	9.22	0.78	7.8
	2022 -4	10.00	9.23	0.77	7.7
2023	2023 -1	10.00	9.26	0.74	7.4
	2023 -2	10.00	9.25	0.75	7.5
	2023 -3	10.00	9.27	0.73	7.3
	2023 -4	10.00	9.26	0.74	7.4

2024	2024 -1	10.00	9.42	0.58	5.8
	2024 -2	10.00	9.41	0.59	5.9
	2024 -3	10.00	9.43	0.57	5.7
	2024 -4	10.00	9.42	0.58	5.8
2025	2025 -1	10.00	9.43	0.59	5.9
	2025 -2	10.00	9.42	0.57	5.7
	2025 -3	10.00	9.44	0.58	5.8
	2025 -4	10.00	9.43	0.57	5.7
2026	2026 -1	10.00	9.46	0.54	5.4
	2026 -2	10.00	9.45	0.55	5.5
	2026 -3	10.00	9.47	0.53	5.3
	2026 -4	10.00	9.46	0.54	5.4

4.5 Analysis of Thermal Mass Loss

Thermal mass loss after heating to 800 °C varied among deposition years. Mean values were $7.70 \pm 0.08\%$ for 2022, $7.40 \pm 0.08\%$ for 2023, $5.80 \pm 0.08\%$ for 2024, $5.78 \pm 0.10\%$ for 2025 and $5.40 \pm 0.08\%$ for 2026 (mean $\pm$ SD, n = 4). The 2022 deposit therefore had 2.30 percentage points more thermal mass loss than the 2026 deposit. The results show a clear deposition-year pattern, but the mass loss cannot be interpreted as total carbon because several components can decompose or volatilize during heating to 800 °C.

The higher thermal mass loss in older deposits may be consistent with greater accumulation or transformation of thermally labile material during longer environmental exposure. However, because TOC and TIC were not measured separately, the results do not quantify the amount of carbon sequestered. The thermal measurements are therefore used as comparative indicators rather than as direct carbon-stock estimates.

CHAPTER 5: DISCUSSION

5.0 Introduction

This chapter discusses the findings from Chapter 4 in relation to the objectives of the research, and the literature on total carbon, carbonate formation and heavy metal behavior in mine tailings. Results from carbonate accumulation, heavy metal concentrations and the effect of tailings age are combined to assess the carbon sequestration potential of the tailings dams at Freda Rebecca Gold Mine.

5.1 Thermal Mass Loss at 800 °C

Thermal mass loss decreased from $7.70 \pm 0.08\%$ in the 2022 deposits to $5.40 \pm 0.08\%$ in the 2026 deposits. This pattern shows a clear difference among deposition years, but it should not be described as a decline in total carbon because the method did not isolate carbon from other thermally labile components. Longer exposure may alter moisture retention, organic inputs, mineral hydration and carbonate abundance, all of which can influence thermal mass loss. Direct TOC and TIC measurements would be needed to determine which carbon fractions account for the observed differences. The 2022–2026 pattern is therefore useful as a comparative indicator of differences among the deposition-year terraces, but it is not a direct carbon-sequestration rate. The findings are consistent with the broader literature showing that tailings weathering can change with exposure time and environmental conditions (Power et al., 2020; Daitsh et al., 2021).

5.2 Acid-reactive Mass Loss Attributed to Carbonate Presence

The acid-reactive mass-loss results showed higher mean values in the older deposits: $4.2 \pm 0.08\%$ in both 2022 and 2023, compared with $3.0 \pm 0.08\%$ in 2024 and 2025 and $2.9 \pm 0.08\%$ in 2026. This pattern is consistent with the possibility that longer exposure to atmospheric CO_2 , water and mineral weathering promotes formation or accumulation of carbonate-bearing phases. However, because the HCl fizz procedure was not validated against a quantitative carbonate or TIC method, the results should be interpreted as evidence of acid-reactive carbonate-bearing material rather than definitive carbonate concentrations.

During natural weathering, atmospheric CO_2 can dissolve in water and form carbonic acid, which participates in mineral dissolution and carbonate precipitation. Where reactive Ca- and Mg-

bearing phases are present, these reactions can produce stable carbonate minerals and thereby provide a potential mechanism for inorganic carbon storage (Power et al., 2020; Raza et al., 2023).

The higher acid-reactive mass loss in older deposits is consistent with longer exposure times, but the present study cannot distinguish whether the difference resulted from new carbonate formation, inherited carbonate minerals, differences in tailings mineralogy or other acid-reactive phases. Mineralogical analysis would be required to confirm the mechanism.

5.3 Heavy Metal Concentrations in Tailings Samples

The selected heavy metals showed variation among deposition years. Copper had the highest annual mean values, while cadmium had the lowest. Lead means were highest in 2026, copper in 2025, cadmium in 2024, zinc in 2022 and arsenic in 2024. These differences may reflect variation in tailings composition and deposition history. Because the analysis measured acid-digested concentrations rather than mobile or bioavailable fractions, the results do not demonstrate metal stabilisation or reduced mobility. Nevertheless, the presence of Pb, Cd and As warrants continued environmental monitoring because of their potential toxicity.

5.4 Relationship between Thermal Mass loss and Acid-reactive Mass Loss

The yearly means show a parallel pattern in which acid-reactive mass loss and thermal mass loss are generally higher in the older deposits. This descriptive co-variation is consistent with the possibility that carbonate-related weathering contributes to the thermal response of the tailings. However, thermal mass loss is not equivalent to total carbon, and the acid-reactive procedure is not a validated quantitative carbonate method. No inferential correlation was calculated because the study was designed for descriptive comparison and only five deposition-year means were available.

Table 5.4.1: Thermal mass loss and acid-reactive mass loss attributed to carbonate presence

Year	Total Carbon (%)	Carbonate concentrations (%)
2022	7.7	4.2
2023	7.4	4.2
2024	5.8	3.0

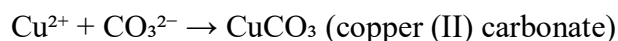
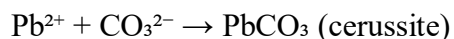
2025	5.7	3.0
2026	5.4	2.9

The observed patterns therefore support the interpretation that weathering and carbonate-related processes may contribute to differences among the deposition years, but they do not establish the amount of atmospheric CO₂ stored in the tailings. Direct CO₂ uptake measurements and TOC/TIC analyses would be required for quantitative carbon-sequestration assessment.

5.5 Description ass between Carbonate-related indicators and Heavy Metals

A descriptive comparison shows that the deposition years with higher acid-reactive mass loss also tend to have different heavy-metal concentration patterns. This may indicate that weathering and mineral transformation influence both carbonate-related reactions and metal occurrence. However, the study did not measure pH, metal mobility, leachability, speciation or carbonate mineral identity. Therefore, a stabilisation mechanism cannot be demonstrated from the present data. Carbonate minerals can theoretically retain some metals through precipitation or adsorption, but this remains a hypothesis requiring direct testing at the study site.

Examples of possible metal-carbonate precipitation reactions include:



5.6 Carbonate-related indicators and Tailings Age

Older tailings deposits showed higher acid-reactive mass loss attributed to carbonate-bearing material than the recent 2025 and 2026 deposits. This temporal pattern is consistent with the interpretation that exposure time can influence weathering and carbonate accumulation. However, the study did not measure the rate of carbonate formation directly, so age should be interpreted as an observed grouping variable rather than proof of a causal time-dependent reaction rate.

The 2022 deposits had the highest acid-reactive mass loss, while the 2026 deposits had the lowest. Similar age-related patterns have been reported in studies of mine wastes where

prolonged exposure permits weathering and carbonate formation (Power et al., 2020; Hamilton et al., 2022). The relevance of these findings to Freda Rebecca depends on the mineralogical composition of its gold tailings, which was not determined in the present study.

Recent deposits also showed some of the higher measured concentrations of selected metals, but this does not demonstrate higher metal mobility. Differences may reflect variation in the material deposited, mineral processing conditions or weathering history. A depth-resolved and replicated geochemical study would be needed to distinguish these mechanisms.

5.7 Climate Change Mitigation Implications

The detection of acid-reactive carbonate-bearing material in all deposition-year groups provides evidence that the tailings contain material capable of reacting with acid and is consistent with the possibility of carbonate minerals. This supports further investigation of passive mineral carbonation at Freda Rebecca. However, the study did not directly measure atmospheric CO₂ uptake, carbonate mineral identity or a carbonation rate; therefore, the term “carbon sequestration potential” is used as an indication for further investigation rather than as a quantified sequestration rate.

If confirmed by mineralogical and CO₂-flux measurements, passive carbonation could provide an additional environmental service within tailings rehabilitation. Such an approach should complement, rather than replace, conventional measures for erosion control, dust suppression, water management and heavy-metal risk reduction.

5.8 Environmental Implications of Heavy Metals

Although acid-reactive carbonate-bearing material was detected, selected heavy metals remained present in the tailings. Lead, cadmium and arsenic are of particular environmental concern because of their potential toxicity. Possible exposure pathways include leaching, groundwater interaction, dust dispersion and surface erosion. Because metal mobility was not measured, the present study cannot quantify these risks or demonstrate that carbonate formation has reduced them.

The results are broadly consistent with international studies showing that mine wastes can undergo natural carbonation under favorable mineralogical and environmental conditions (Oskierski et al., 2022; Daitsh et al., 2021). However, direct comparison of carbonation capacity

between Freda Rebecca gold tailings and ultramafic wastes is not justified from the present measurements because mineralogical composition and CO₂ uptake rates were not measured at Freda Rebecca.

CONCLUSIONS AND RECOMMENDATIONS

6.0 Conclusions

The study found clear deposition-year differences in acid-reactive mass loss attributed to carbonate-bearing material and in thermal mass loss at 800 °C. Acid-reactive mass loss was highest in the 2022 and 2023 deposits (4.2%) and lowest in the 2026 deposits (2.9%), while thermal mass loss declined from 7.7% in 2022 to 5.4% in 2026. These patterns are consistent with longer exposure influencing weathering and carbonate-related processes, but they do not constitute a direct measurement of atmospheric CO₂ sequestration. Selected heavy metals were detected in the tailings, with copper generally showing the highest annual means among the analyzed metals. Because metal mobility and carbonate mineral identity were not measured, carbonate-induced metal stabilisation should be regarded as a possible mechanism rather than a demonstrated effect. The findings nevertheless show that the Freda Rebecca tailings storage facility warrants further investigation as a potential site of passive mineral carbonation while requiring continued management of potentially toxic metals.

6.1 Recommendations

Carbon-related monitoring should be incorporated into tailings rehabilitation programs, but quantitative carbon claims should be based on validated TOC/TIC methods, mineralogical confirmation and direct CO₂ uptake measurements. Freda Rebecca Gold Mine should continue progressive rehabilitation and environmental management measures that control erosion, dust and water interactions while allowing scientifically monitored weathering where appropriate. Any decision to optimize exposure for carbonation should be balanced against tailings stability, dust generation and contamination risks.

Long-term monitoring should measure TOC, TIC, carbonate mineral abundance, pH, moisture and selected heavy metals at repeated time intervals. Where possible, field CO₂ flux or net CO₂ uptake should be measured so that sequestration can be expressed as mass of CO₂ per tonne of

tailings per year. Quality assurance should include method blanks, calibration standards, certified reference materials, analytical duplicates and reporting of detection limits and recovery data.

Future investigations should include X-ray diffraction (XRD), scanning electron microscopy with energy-dispersive spectroscopy (SEM-EDS) or equivalent mineralogical methods to identify carbonate phases. Sequential extraction and/or standardized leaching tests should be used to evaluate metal mobility and determine whether carbonate formation is associated with reduced leachability. These measurements would provide stronger evidence for any proposed relationship between carbon storage and metal stabilisation.

6.2 Areas for Further Research

Future research should specifically: (1) measure annual or seasonal CO₂ uptake per tonne of tailings using direct field or laboratory flux methods; (2) separate TOC and TIC; (3) confirm carbonate mineral phases using XRD and SEM-EDS; (4) sample multiple depths to establish vertical carbon and metal profiles; (5) conduct leaching, sequential extraction or speciation tests for metal mobility; and (6) replicate the study across multiple Zimbabwean mines to determine how mineralogy, climate, tailings age and rehabilitation status influence carbonation potential.

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