REPORT NO. M10617

Evaluating the Potential of Mine Waste for Construction Solutions

Results of research carried out as MRIWA Project M10617

at The University of Western Australia

by

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Project Context and Scope

This report was produced as part of a Cooperative Education for Enterprise Development (CEED) Industry Placement project undertaken by the named author while enrolled as a student at The University of Western Australia, with support from the Minerals Research Institute of Western Australia (MRIWA). The work comprised a structured review of peer-reviewed literature, publicly available data sources, and documented case studies relevant to the repurposing of mine tailings for construction applications within Western Australia.

The project constitutes a desktop-based scoping and synthesis study intended to inform early-stage understanding of the technical potential for valorising iron ore and gold tailings in construction materials, including concrete and bricks. The analysis draws on existing published datasets, statistical analyses reported in the literature, and qualitative assessment of material behaviour relative to relevant Australian Standards. Comparative trends in mechanical performance, workability, and microstructural characteristics were assessed using only secondary data.

No site-specific tailings sampling, geochemical or mineralogical characterisation, original laboratory experimentation, durability testing, leaching assessment, life-cycle analysis, cost modelling, or techno-economic evaluation was undertaken as part of this project. Where statistical analyses were performed, these were based exclusively on digitised data extracted from published studies and were used to identify indicative trends rather than to derive definitive performance metrics.

Accordingly, the findings, comparisons, and interpretations presented in this report are indicative in nature and should not be construed as assessments of site-specific technical feasibility, regulatory compliance, economic viability, or commercial readiness. The outcomes are intended to support MRIWA's research prioritisation by identifying potential application pathways, key knowledge gaps, and areas requiring further targeted experimentation and validation. Any progression toward pilot-scale trials or commercial deployment would necessitate comprehensive site-specific characterisation, durability and environmental testing, and a detailed feasibility assessment.

Executive Summary

Western Australia has an expansive mining sector, which generates substantial volumes of waste every year, presenting considerable environmental and economic challenges. The repurposing of this mine waste, particularly tailings, into construction materials could be one viable approach to combat waste accumulation while simultaneously providing valuable resources. The potential for the construction of bricks and concrete by using tailings aids in the transition towards a circular economy while simultaneously making a positive contribution to Western Australia's environmental and economic scene.

This project aims to assess the feasibility and benefits of repurposing tailings, specifically iron ore and gold tailings, through literature and case studies. Data analysis of available studies provided a foundation of current developments and identified potential gaps in knowledge or technology. It was found that an optimal replacement level of tailings exists when used as concrete aggregate for enhanced compressive strength, however, a negative relationship exists between replacement percentage and concrete workability. The addition of tailings in cement showed a minor negative relationship with compressive strength of concrete, and the results of utilisation in bricks were varied. ANOVA tests reveal statistical significance between both the percentage of tailings and curing time on compressive strength in almost all studies. Results were validated using SEM images to investigate changes in microstructure of the produced materials.

As a result of this review, the basis and opportunities for further research and implementation can be established, allowing for the optimal revaluation of mine waste in Western Australia. Recommendations for further research include additional experimentation in terms of long-term durability studies and leaching effects, as well as small-scale testing using tailings from Western Australian specific mine sites. Life-cycle assessment, cost analysis and market research are also vital next steps to assess the feasibility of implementation.

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Terms, Abbreviations and Acronyms

ANOVA: Analysis of Variance

DEMIRS: Department of Mines, Industry Regulation and Safety

IOT: Iron ore tailings

MRIWA: Minerals Research Institute of Western Australia

PSD: Particle size distribution

SCM: Supplementary cementitious material

SEM: Scanning electron microscopy

UHPC: Ultra high-performance concrete

WA: Western Australia

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1. Introduction

Globally, mine waste is one of the most significant waste streams, with tailings a major contributor estimated 13 billion tonnes per year (Franks et al., 2021). A steady growth of metal ore mining in Australia (Figure 1), contributes to a continuous accumulation of mine waste, and a growing environmental issue. As ore grades decline and demand for metals grows, the quantity of tailings produced is expected to continue to increase in the coming decades (Calvo et al., 2016). Given the significant contribution mining makes to Western Australia's economy, the ability to repurpose mining waste could yield both environmental and economic benefits to the state.

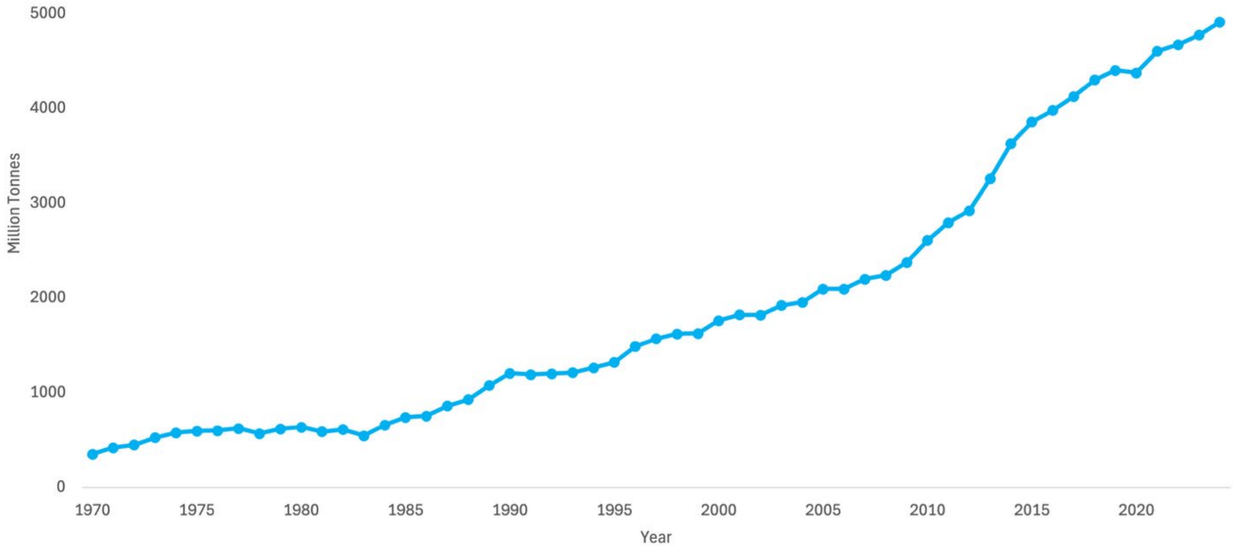


Figure 1: *Extraction of metal ores in Australia since 1970*

Note. This figure shows the year-on-year tonnage of metal ores produced in Australia since 1970. Adapted from "Global Material Flows Database" by the UN Environment Programme, n.d.

Tailings, a byproduct of mining that poses environmental challenges, can be upcycled into construction materials, including bricks and concrete, or downcycled for backfilling and road construction. Understanding the viability of these approaches can address environmental issues and reduce waste accumulation in the mining industry, as well as encourage resource efficiency in the construction industry, contributing towards a circular economy. This project focuses on reviewing existing research on both iron ore and gold tailings for use in concrete and bricks.

Several challenges must be addressed to utilise mining waste in this manner. Assessment of the quality and durability of materials produced from tailings for compliance with regulatory and safety standards, including Australian Standards. The differing chemical and mineralogical compositions of tailings poses a challenge in implementing a standard approach of repurposing and must be accurately analysed for each mine site to ensure relevant standards will be met. Due to the remoteness of mining operations across Western Australia (WA), the logistical cost of repurposing may be significant, and should be considered for feasibility.

The Minerals Research Institute of Western Australia (MRIWA), a statutory body established by the WA Government, has a significant stake in the project's outcomes, given their research priority into alternative uses for tailings and waste with the aim to deliver environmental and socioeconomic benefits to the state. This project will serve as a valuable contribution to shaping MRIWA's strategy and future direction.

Repurposing of mine waste is gaining traction worldwide, with an increasing number of researchers performing primarily small-scale laboratory testing, as evident from the number of yearly publications on the topic in Figure 3. Interpretation and analysis of this research is a vital first step in assessing feasibility for implementation in WA, by evaluating consistency in material properties and reliability of data. Analysis will aid in assessing the possibility of repurposing mining byproducts, drawing parallels in results, identifying successful implementation and challenges in this process, and providing a base for planning further research.

1.1. Minerals research/industry challenge and background

The mining industry in WA generates substantial quantities of waste materials, including tailings, overburden and waste rock. Tailings are the byproduct of mining that remains after valuable minerals have been extracted and processed, typically deposited as a slurry with a high-water content into a tailings dam (Wills & Napier-Munn, 2006). These byproducts pose significant environmental risks, including soil and water contamination from acid mine drainage and heavy metal leaching, and potential land degradation (Cacciuttolo et al., 2023). Heavy metal contamination in soil and water from tailings can have a carcinogenic effect on humans if ingested (Cortes-Ramirez et al., 2025).

The effects of seepage from tailings on groundwater, surface water and vegetation or structural integrity issues pose potential environmental issues (Department of Water and Environmental Regulation, 2000). In 2023, reports at Newmont Corporation's Telfer mine in WA were made of cracking and seepage in the tailings storage facility, forcing suspended processing by the company to prevent failure and environmental harm (Szabo, 2024). Contamination of land from lead and copper tailings in Northampton required the remediation of over 17,000 cubic meters of impacted soil (Department of Planning, Land and Heritage, n.d.). The contamination and stability concerns tailings pose, which have been realised across various WA sites, highlight the potential benefits that repurposing can present to reduce associated environmental and safety risks.

The Western Australian Government's Department of Mines, Petroleum and Exploration (DMPE) has developed a code of practice to guide the mining industry in the storage and management of tailings to meet legislative and environmental obligations (DMPE, 2013). This code primarily focuses on safe storage with limited guidance on value added from repurposing.

The idea of repurposing mine waste into construction materials is gaining traction worldwide as a sustainable alternative. The Web of Science database shows the increasing trend in publications on "tailings" and "construction materials", as observed in Figure 3. Preliminary research and case studies have primarily focused on applications for cemented paste backfill and geopolymer materials. The use for construction materials, including concrete and bricks has been widely tested, but there are gaps in the assessment of long-term durability as well as compliance with construction and environmental standards (Zetola et al, 2024).

Practical implementation of this research has been limited, particularly in Australia, with some small-scale investigations underway. Colliecrete is one such company looking into the use of industrial waste in Collie, WA for geopolymers (Colliecrete, n.d.). Minimal validation has been conducted to confirm the compliance of experimental results with relevant Australian Standards. Regulatory compliance should be verified through specific testing to ensure the strength and durability properties of the tailings-based materials meet the requirements specified in applicable standards, including AS3600 Concrete Structures (Standards Australia, 2018) and AS4455 Masonry Units, Pavers, Flags and Segmental Retaining Wall Units (Standards Australia, 2008) for concrete and bricks respectively. This compliance as well as understanding of practical feasibility, are of high importance for future implementation in WA and hence guide the need for this project.

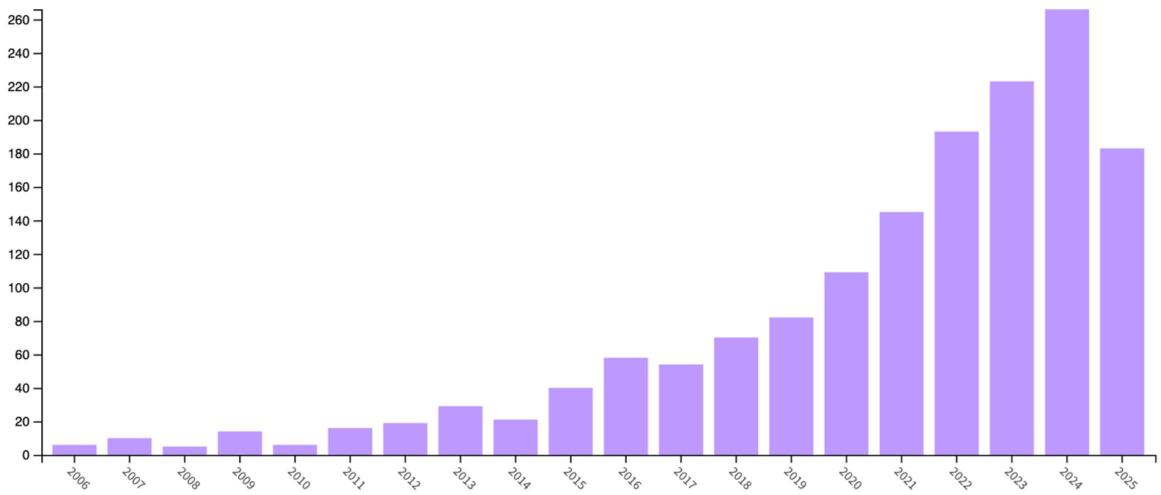


Figure 2: *Number of publications relating to "tailings" and "construction materials" per year available through Web of Science (Clarivate, n.d.).*

Note. This figure shows the yearly number of publications relating to "tailings" and "construction materials" on Web of Science database. From "Web of Science" by Clarivate, n.d., *Web of Science Database*. (https://www.webofscience.com/).

1.2. Objectives of the research

The project has focused on the identification and review of existing research into the utilisation of iron ore and gold tailings for construction products, including concrete and bricks, and by doing so detecting where knowledge gaps lie, which is vital for MRIWA's strategic planning. Analysis of the literature and case studies will help in assessing the feasibility and benefits of repurposing mining byproducts.

The intent of the literature review was to assess the feasibility of upcycling tailings in terms of quality, strength and compliance with the relevant Australian Standards. Data analysis and comparison between studies contribute to ensuring the reliability of the assessment.

Identifying the feasibility of repurposing mine waste into construction materials could benefit WA. Financially, the ability to recycle otherwise unutilised materials might generate an additional income stream for the state. Environmentally, reducing the accumulation of mine waste could reduce the potential of water and soil contamination through acid mine drainage and heavy metal leaching (Cacciuttolo et al., 2023). Benefits may extend to the construction industry in terms of sustainable development of materials, with concrete one of the most used building materials, estimated to have an annual production of 4 billion tonnes (Palcis, 2023).

1.3. Scope

The scope of the project involved the investigation of repurposing of both iron ore and gold tailings to potentially have the most considerable impact from the significant amounts of accumulated waste. These specific types of tailings were chosen due to their availability and extensive production in WA. Australia-wide, these two minerals produce the most substantial amount of mine waste (as illustrated in Figure 2), hence potentially providing the most significant environmental and economic benefits if repurposed.

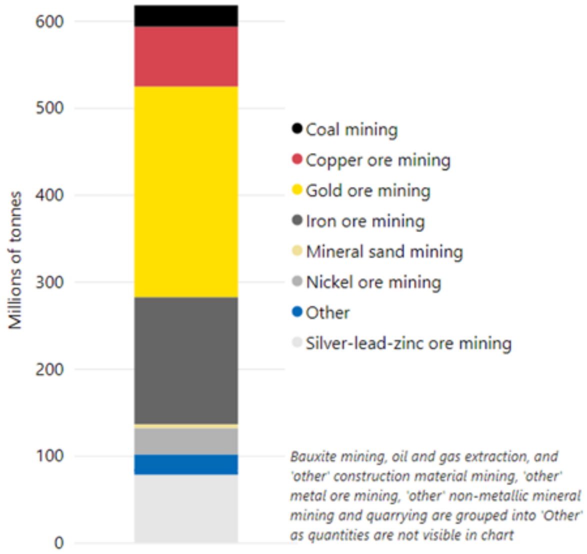


Figure 3: *Estimated mining waste by commodity in Australia 2020-2021 (Department of Climate Change, Energy, the Environment and Water (DCCEEW), 2022).*

Note. This figure shows the estimated tonnage of mining waste produced in Australia from 2020-2021. From "National Waste Report 2022," by DCCEEW, 2022, *Australian Government*, Figure 12, p.17 (https://www.dcceew.gov.au/sites/ default/files/documents/national-waste-report-2022.pdf).

The construction materials in focus were concrete and bricks, due to their extent of use for construction in WA. Concrete production is a notoriously significant carbon dioxide emitter, estimated to account for approximately 8% of the global total carbon emissions (Palcis, 2023), therefore, substituting with tailings may prove beneficial to reducing WA's carbon footprint. With the extensive use of these materials in WA's construction sector, the production using tailings byproducts may be in high demand. The scope of analysis included changes in mechanical properties of the produced materials, including compressive strength and workability, and comparison to relevant Australian Standards. Feasibility in terms of economics and logistics has been excluded from the scope, however, it should be considered in future research.

2. Methodology

Initial background research into literature on mine waste utilisation for construction materials provided a base of understanding in extensively researched areas. The Geological Survey of Western Australia's Mindex database (DEMIRS, n.d.) was used to understand the basic mineral composition of mines within WA that produce tailings. These reviews informed the decision to focus the project on iron ore and gold tailings due to their volume and prevalence in WA, and the extensive literature available on repurposing.
For each of these tailings, a review of literature was conducted, followed by data analysis and evaluation of scanning electron microscopy (SEM) images. The presentation of project findings allows recommendations to be made on the feasibility of using these tailings for construction materials, and identification of knowledge gaps, to provide a contribution to MRIWA's future strategy.

Case studies on the recycling of iron ore tailings (IOT) into construction materials (concrete or bricks) was investigated initially, then replicated for gold tailings. Relevant literature was compiled from references and citations in preliminary background readings, as well as through Web of Science, filtering for "iron ore tailings", "iron ore waste", "concrete", "bricks", "construction materials", etc. Importance was put on the number of citations of each paper to filter by credibility and quality, with the date of publication indicating whether findings and/or applications may have progressed substantially since. Peer-reviewed literature was also prioritised. These case studies included investigations into strength and material properties and their suitability for viable construction materials and implementation reports.

The graphical data produced in these papers were digitised with the aid of PlotDigitizer freeware (Rohatgi, 2025) to allow for analysis and comparisons to be drawn. While PlotDigitizer is a helpful tool to obtain data points from graphs, it cannot provide the exact results as collected in the experimental procedure, therefore, it was used to identify overall trends and similarities, without focusing on the exact quantities. Factorial design of experiments, specifically through analysis of variance (ANOVA) was used to investigate the effects of multiple variables, such as percentage of tailings replacement and curing time on the compressive strength of the produced materials, thereby determining whether the observed variations can be attributed to random change or underlying effects. The workability of produced concrete was investigated by comparing data on the change of slump with different tailings replacement percentages. Comparing data across a range of sources was intended to provide insight into the most examined methods while also recognising other important developments.

The acquired data was compared with relevant thresholds for strength provided within Australian Standards. These include AS3600 Concrete Structures (Standards Australia, 2018) and AS4455 Masonry Units, Pavers, Flags and Segmental Retaining Wall Units (Standards Australia, 2008).

Changes in the microstructure of the materials were analysed by taking SEM images of the produced materials from the literature and measuring the particle size and percentage pore area using ImageJ freeware (ImageJ.JS, n.d.) to validate the changes in strength observed due to the replacement with tailings.

3. Results and Findings

3.1 Use as Concrete Aggregate

The variation in tailings properties between mine sites has a much greater impact on chemical composition than physical properties, so utilisation as aggregate in concrete may be a simple alternative, with numerous studies existing. Tailings generally contain mostly ‘silt’, with a maximum particle size less than 1mm (Adiguzel et al., 2022), making them an effective replacement for fine aggregate. Tailings greater than 4.75mm in size can be used as coarse aggregates, however studies on this are far more limited. Finer tailings particles (less than 250 μm) have been tested as an inert filler to fill intergranular voids between cement particles, reducing porosity and increasing compressive strength (Moosberg-Bustnes et al., 2004). The use of tailings as replacement for aggregate has proven potential by researchers, with limited pre-processing required and aggregate contributing up to 80% of the concrete mix, making it one of the most feasible alternatives (Shetty et al., 2014).

For concrete, most testing has focused on the change in mechanical properties resulting from the addition of tailings as aggregate and variation with curing time. The general consensus from various literature is that tailings have the potential to enhance strength of concrete up to a certain extent of tailings replacement for fine aggregate, and once this threshold has been reached, compressive strength declines (Shettima et al., 2018; Tian et al., 2016; Protasio et al., 2021; Chinnappa and Karra, 2019; Krishna et al., 2024; Jayasimha et al., 2022; Shettima et al., 2018; Ince, 2019; Preethi et al., 2017; Adeyeye et al., 2025; Widojoko et al., 2014; Song et al., 2024). Optimal substitution of tailings for strength enhancement ranges from 10% to 35%, potentially attributed to the differing mineral composition of the tailings (Shettima et al., 2016). The enhancement is due to optimisation of pore structure by filling of smaller sized tailings particles (Amjad et al., 2025).

3.2 Use as Supplementary Cementitious Material (SCM) in Concrete

Various literature has explored the potential use of tailings as replacement for cement in concrete due to its self-cementing nature (Kuranchie et al., 2013). Replacement of Portland cement with tailings has potential to also reduce associated carbon emissions and the negative environmental impacts of concrete production processes. Materials with a combined SiO_2, Al_2O_3, and Fe_2O_3 content greater than 75% can be considered for use as a supplementary cementitious material but must show pozzolanic activity (Adiguzel et al., 2022). Tailings, including both iron-ore and gold tailings, generally contain a high percentage of silica (SiO_2), as shown in Figure 4, a percentage that is increasing as processing methods develop and leave less excess iron and valuable minerals in the waste (Amjad et al., 2025), providing a suitable chemical makeup for such use. However, most tailings show low pozzolanic activity, making them unsuitable without effective activation (Jankovic, 2017). Therefore, a large focus area across the literature was dedicated to mechanical and chemical activation techniques to improve cementitious properties of tailings. This process may face technological and economic challenges, impacting the feasibility of repurposing in this way. With a lower utilisation rate potential, more research is committed to methods such as using tailings as fine aggregate (Zhang et al., 2021).

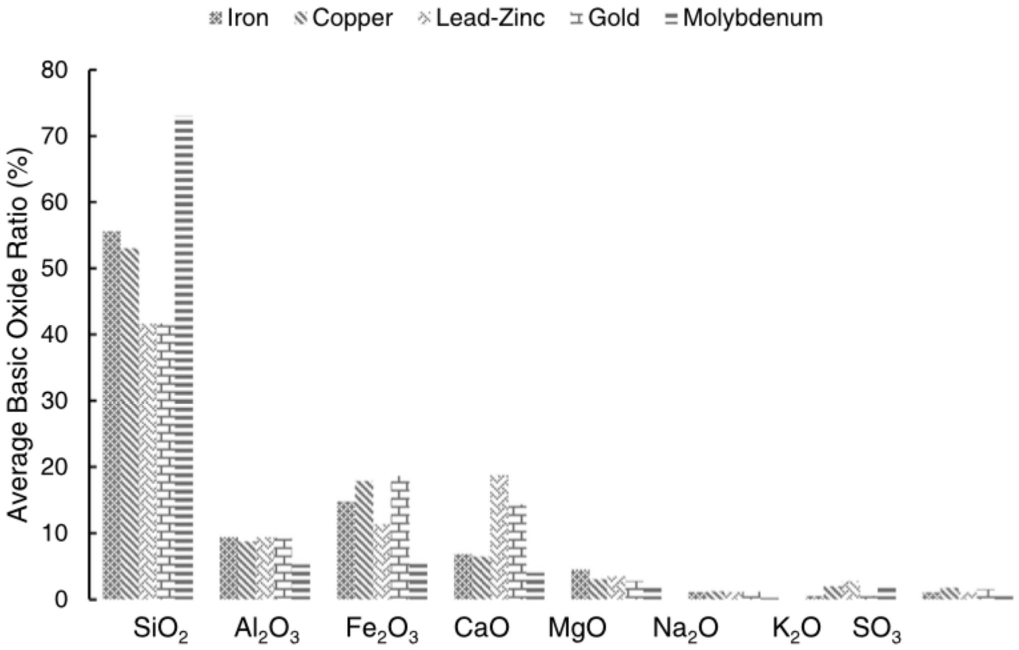


Figure 4: *Average basic oxide ratios for different metal mine tailings (Adiguzel et al., 2022).*

Note. This figure shows the average basic oxide ratios for different types of metal mine tailings. From "Utilization of Tailings in Concrete Products: A Review" by Adiguzel et al., 2022, Figure 2, p.2 (https://doi.org/10.1016/j.conbuildmat.2022.129574).

3.3 Use in Bricks

Literature available on the use of tailings in bricks is generally more limited. Bricks are typically made from materials high in silica and alumina (Vasic et al., 2014), of similar chemical composition to that of tailings in Figure 4. The influence of tailings on the mechanical properties of bricks is largely dependent on the chemical and mineralogical composition of the tailings, which is largely unknown and varies between mine sites, making employing a blanket repurposing approach more challenging (Silva et al., 2025).

4 Discussion

The following section covers the impact of tailings on the mechanical properties of the produced materials by use case, with a review of the literature covering both iron ore and gold tailings.

4.1 Use as Concrete Aggregate

4.1.1 Influence of Tailings Replacement Percentage

The studied literature indicated that replacement up to a certain percentage of tailings showed improvement in the compressive strength properties of concrete (Shettima et al., 2018; Tian et al., 2016; Protasio et al., 2021; Kuranchie et al., 2015; Chinnappa and Karra, 2019; Krishna et al., 2024; Jayasimha et al., 2022; Shettima et al., 2018; Ince, 2019; Preethi et al., 2017; Adeyeye et al., 2025; Widojoko et al., 2014; Song et al., 2024). The optimum percentage varied between 10-35%, with replacement up to 60% having comparable results to the reference sample in almost all literature. Figures 5 and 6 illustrate these optimum mixes, showing the results of numerous levels of tailings replacement from the literature on compressive strength of concrete at 28 days of curing, for iron ore and gold ore tailings respectively. These laboratory results are compared to AS3600 strength requirements. A minimum strength of 20MPa concrete can be used for residential and light-traffic applications such as driveways and pavements, with concrete of strength 50MPa used for industrial applications (Cement Concrete & Aggregates Australia, 2020). As indicated in the figures, almost all samples met the minimum strength requirement, and thus are deemed potentially suitable for use in Australia based on compressive strength.

Figure 5: *Influence of percentage of iron ore tailings replacement for fine aggregate on compressive strength of concrete and AS3600 limits.*

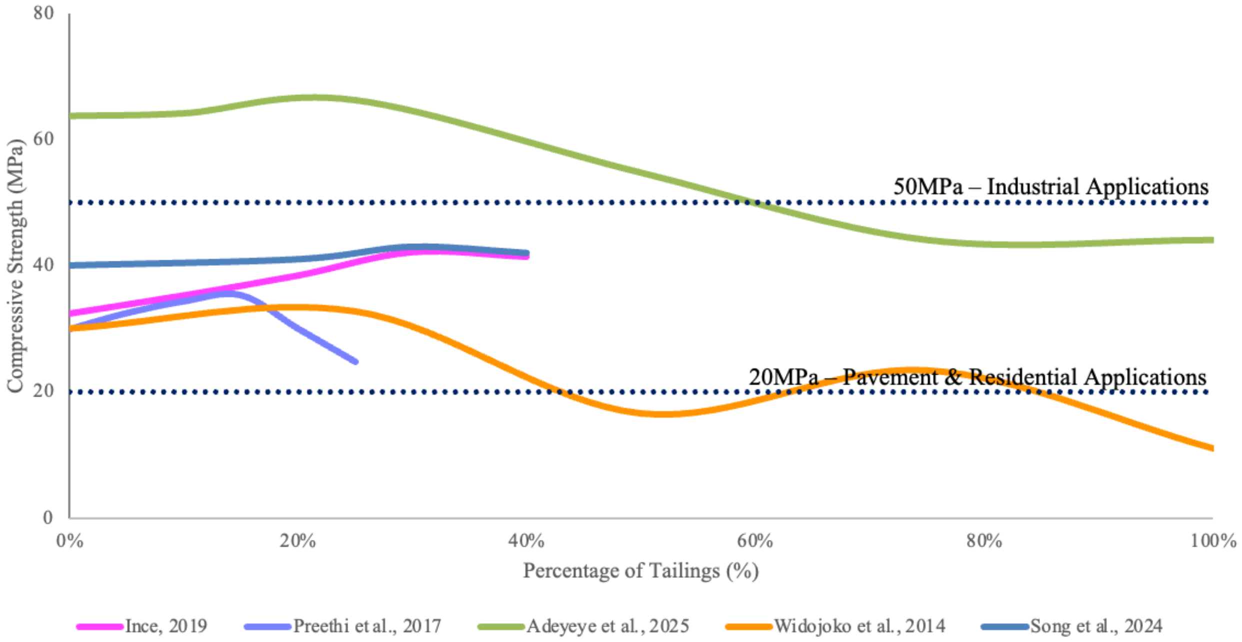


Figure 6: *Influence of percentage of gold tailings replacement for fine aggregate on compressive strength of concrete and AS3600 limits.*

The enhancement of compressive strength is largely due to the physical composition of tailings, specifically their particle size, hence why both iron ore and gold tailings behaved similarly. The particle size distributions (PSD) of the sampled tailings from the literature are provided in Figure 7, with solid and dashed lines representing iron ore and gold tailings respectively. Generally, gold tailings were slightly finer due to additional processing for ore retrieval, with most samples falling within the natural aggregate range as specified by AS2758.1 (Standards Australia, 2014) or slightly finer. The fineness of the tailings compared to natural aggregate, enables it to act as filler material within the concrete. This micro-filling effect optimises pore structure and improves matrix packing, enhancing compressive strength properties of the concrete material. The rough and angular texture of tailings can also improve the bond between the cement and aggregate interface, contributing to the higher strength results (Shettima et al., 2016). However, the decrease in strength beyond the optimum replacement may be attributed to the high-water demand for the hydration process, creating more pores within the concrete and weakening the hardened structure (Shettima et al., 2018).

Figure 7: *PSD of tailings used as fine aggregate in concrete and AS2758.1 specifications.*

To complement the literature review, a two-way ANOVA analysis was performed on the compressive strength values reported by the different studies. This was to investigate whether tailings percentage and curing time had a statistically significant effect on the strength of the material within each study. The significance level was taken as 0.05 (Weiss, 2005). Table 1 summarises whether each factor was significant for the reviewed studies, with detailed ANOVA results provided in Appendix A.

Across the 15 studies analysed, of which three produced ultra-high-performance concrete (UHPC), tailings percentage was significant in 12 cases, indicating the inclusion level of tailings generally shows a measurable effect on compressive strength. The statistical results align with the trends seen in the literature, with a higher proportion of tailings typically leading to a reduction in compressive strength after the optimum percentage, reflecting changes in porosity. In a small number of cases, the effect of tailings percentage was not statistically significant, possibly attributed to differences in tailings minerology, mix design, or the limited range of replacement levels tested.

The potential for up to full utilisation of tailings as fine aggregate due to the dependence on physical properties, which is more consistent between sites, makes a blanket approach to repurposing applicable. Hence, implementation is more feasible with pre-processing being either negligible or relatively simple.

Table 1: Significance of tailings percentage and curing time on compressive strength of concrete with aggregate replacement from literature.

Study	Research Area	Tailings Percentage	Curing Time
Kuranchie et al., 2015	Iron Ore	Yes	Yes
Shettima et al., 2016	Iron Ore	No	Yes
Zhao et al., 2013 (UHPC)	Iron Ore	Yes	Yes
Zhang et al., 2020 (UHPC)	Iron Ore	Yes	Yes
Tian et al., 2016	Iron Ore	Yes	Yes
Chinnappa and Karra, 2019	Iron Ore	Yes	Yes
Jayasimha et al., 2022	Iron Ore	Yes	Yes
Shettima et al., 2018	Iron Ore	Yes	Yes
Protasio et al., 2020	Iron Ore	No	No
Ahmed et al., 2021 (UHPC)	Gold	Yes	Yes
Ince, 2019	Gold	Yes	Yes
Preethi et al., 2017	Gold	Yes	Yes
Adeyeye et al., 2025	Gold	Yes	Yes
Widojoko et al., 2014	Gold	Yes	Yes
Song et al., 2024	Gold	No	Yes

4.1.2 Influence of Curing Time

Curing time is crucial for achieving maximum compressive strength in concrete, as it allows for adequate hydration and hardening. Most literature analysed the strength of concrete at multiple stages of the curing process, typically 1, 3, 7, 14, 28 or 56 days (Figure 8) and found a significant correlation between compressive strength and curing time in all but one case. The p-value was of an order of magnitude ranging from -4 to -12, indicating the curing time has a significant positive impact on the strength of tailings-based concrete, and does not hinder normal strength development processes. Maximum strength was generally achieved between 28 to 90 days, reinforcing the understanding that longer hydration periods improve microstructural development and mechanical performance, as with traditional concrete. Even in studies where tailings percentage was not influential this factor remained significant, indicating curing time can be used to partially mitigate strength losses at higher substitution levels.

Protasio et al. (2020) was the only study showing no statistical significance in curing time, which may be attributed to the testing at only 28 and 90 days of curing. Typically, the strength increases are most rapid in early stages, up to 28 days, when the cement hydration process is most active, with limited strengthening occurring past 28 days (Al-Jabari, 2022). This trend is observed across all the literature.

Figure 8: *Influence of curing time on compressive strength of concrete using tailings as aggregate.*

4.1.3 Impact of Tailings on Workability

The replacement of tailings for fine aggregate has shown to impact the workability of the produced concrete. It was generally agreed by all literature used in this study that the inclusion of tailings exhibits a negative linear relationship with workability, as indicated by the slump value. Figure 9 shows the percentage change in slump measured by various researchers with the addition of tailings as fine aggregate. This relationship may be attributed to the fine texture, higher water absorption and non-uniformity of tailings, which reduces lubrication between aggregate particles and cement paste, making the concrete stiffer and less workable (Shettima et al., 2016; Ahmed et al., 2021). The Australian Standards specify no requirements for slump values, so if the intended application of concrete can still be met, this is not an issue. Low slump concrete is generally used in road construction and foundations.

Figure 9: *Influence of percentage of IOT replacement for aggregate on slump of concrete.*

4.1.4 SEM Analysis

The SEM images produced in various literature have revealed the impact of tailings replacement on pore area. Analysis of the percentage void area of SEM images produced by Liu et al. (2022) and Song et al. (2024) showed a decrease in pore area to the optimum percentage of tailings replacement for compressive strength, followed by a further increase in pore area to full replacement, shown in Figure 10. Zhao et al. (2013) observed a similar trend between pore area and compressive strength, with the highest strength values corresponding to the lowest void space. This reinforces the findings in Section 4.1.1, where the maximum compressive strength corresponds to the lowest porosity. At this optimum strength, the tailings act as a micro-filler within the concrete matrix, filling void space, hence observing the lowest percentage of pore area. After the optimum percentage, the higher water requirements increase porosity to a level equivalent, or greater than, the reference sample.

Figure 10: *Influence of tailings replacement on pore percentage found in SEM images.*

Liu et al. (2022) investigated the microstructure at 0%, 40% and 100% replacement with IOT, with the highest compressive strength achieved at 40% replacement, and SEM images shown in Figure 11. Analysis with ImageJ software showed a percentage of void area of 3.0%, 1.8% and 6.7% at these replacement percentages respectively. The microstructure of normal concrete was relatively loose, with compactness improving and void space decreasing at 40% replacement due to micro-filling with the finer tailings. At full replacement, it is evident that porosity increases, with several micro-pores and cracks observed, corresponding to a decrease in compressive strength. In terms of durability, highly porous material generally leads to reduced durability, as it increases water absorption which can make concrete more susceptible to damage from freeze-thaw cycles and salt crystallisation (Netinger Grubeša et al., 2020).

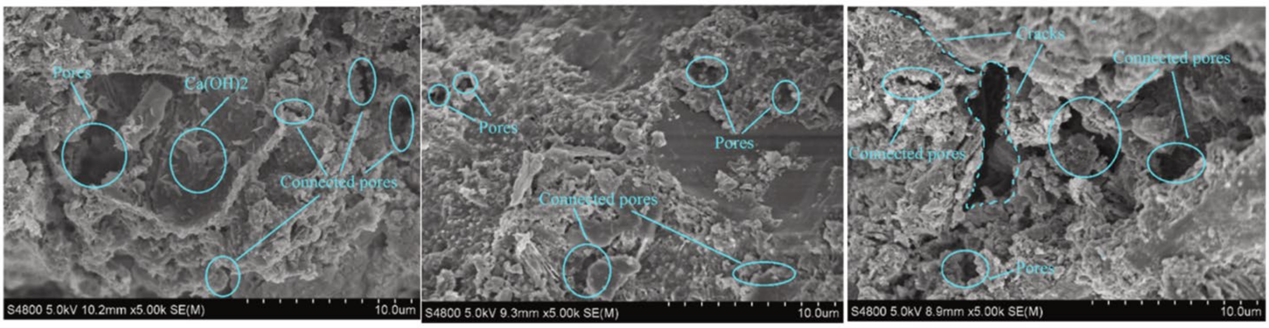


Figure 11: *SEM micrographs of hardened concrete with IOT at (a) 0%, (b) 40% and (c) 100% replacement for fine aggregate (Liu et al., 2022).*

Note. This figure shows the SEM micrographs of hardened concrete. From “Effect of iron ore tailings industrial by-product as eco-friendly aggregate on mechanical properties, pore structure, and sulfate attack and dry-wet cycles of concrete" by K. Liu et al., 2022, 17(e01472), Figure 20. (https://doi.org/10.1016/j.cscm.2022.e01472).

4.2 Use as Supplementary Cementitious Material (SCM) in Concrete

4.2.1 Influence of Tailings Replacement Percentage

The review showed replacement of cementitious materials with tailings had an adverse effect on compressive strength of the produced concrete in almost all investigated literature (Protasio et al., 2021; Zhang et al., 2023; Cheng et al., 2016; Ince, 2019; Wang et al., 2020; Celik et al., 2006; Sigvardsen et al., 2018). Up to 30% decrease in strength was observed in the samples with 40% tailings replacement. The same trend was observed for both iron ore and gold tailing samples. Replacement levels above 40% were rarely explored due to the requirement for some Portland cement to act as a binding material. The influence of tailings percentage on compressive strength at 28 days of curing can be visualised in Figure 12 and 13 for iron ore and gold tailings respectively.

Figure 12: *Influence of percentage of iron ore tailings replacement for cementitious material on compressive strength of concrete and AS3600 limits.*

Figure 13: *Influence of percentage of gold tailings replacement for cementitious material on compressive strength of concrete and AS3600 limits.*

The decrease in strength is due to the substitution of cement, an active material, with an inert material, as tailings exhibit low pozzolanic activity, thus limiting the reaction that forms cementitious compounds (Protasio et al., 2020). Mechanical or chemical activation techniques can be used to increase pozzolanic activity, however, these require significant pre-processing of the tailings, making it costly and potentially unfeasible. While a reduction in strength is evident, it is not extreme, and all samples containing tailings still exhibit strengths complying with Australian Standards, making it suitable for use in Australia. Hence, tailings may be suitable at replacement levels of up to 40% for cementitious materials.

The PSD (Figure 14) for tailings used as SCM showed a range of sizes between studies, however, it was generally an order of magnitude lower than that of tailings used as fine aggregate. Solid lines represent iron ore tailings and dashed lines represent gold tailings. This may be due to the enhancement in pozzolanic activity achieved with greater surface area from smaller particles.

Figure 14: PSD of tailings used as SCM in concrete.

ANOVA results are summarised in Table 2, investigating the effect of tailings percentage and curing time on compressive strength for a 5% significance level, with detailed ANOVA results provided in Appendix A. In all studies, the percentage of tailings used as SCM within concrete was found to have a statistically significant impact on compressive strength, meaning the decrease in strength is influenced by the inclusion of a larger proportion of tailings.

Table 2: Significance of tailings percentage and curing time on compressive strength of concrete as SCM from literature.

Study	Research Area	Tailings Percentage	Curing Time
Protasio et al., 2021	Iron Ore	Yes	Yes
Zhang et al., 2023	Iron Ore	Yes	Yes
Cheng et al., 2016	Iron Ore	Yes	Yes
Wang et al., 2020	Gold	Yes	Yes
Ince, 2019	Gold	Yes	Yes
Celik et al., 2006	Gold	Yes	Yes
Sigvardsen et al., 2018	Gold	Yes	Yes

4.2.2 Influence of Curing Time

As per the results in Table 2, the curing time of concrete is significant in all cases, indicating the strength-enhancing properties of concrete are not impeded by the partial replacement of cement with tailings. As expected, the most considerable portion of strength enhancement occurs within the first 28 days of curing and observes a similar trend to that when used as fine aggregate (Figure 15). After 28 days, minimal improvement in compressive strength is realised.

Figure 15: *Influence of curing time on compressive strength of concrete using tailings as SCM.*

4.2.3 SEM Analysis

Lyu et al. (2020) compared the effects of mechanical activation on the microstructure of the tailings. The raw tailings (Figure 16) displayed an irregular shape with a smooth surface. After mechanical activation, several small spherical shaped particles were produced, with refinement increasing the surface area of the tailings. Increased surface area leads to more complete cementitious compound formation as it provides more points of contact for the pozzolan to react with $Ca(OH)_2$, increasing pozzolanic activity (Bumanis, 2020). Hence, mechanical activation may be effective in increasing the compressive strength of tailings concrete, but further testing is needed.

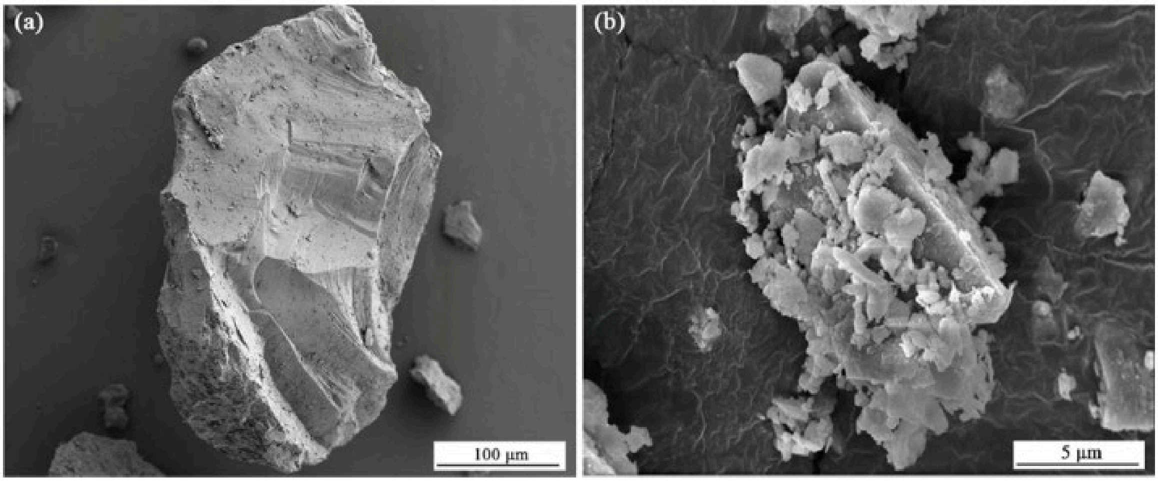


Figure 16: *SEM micrographs of (a) raw and (b) mechanically activated tailings (Lyu et al., 2020).*

Note. This figure shows the SEM micrographs of raw and mechanically activated tailings. From “Hydration kinetics and properties of cement blended with mechanically activated gold mine tailings” by X. Lyu et al., 2020, 683(17457), Figure 2. (https://doi.org/10.1016/j.tca.2019.178457)

4.3. Use in Bricks

4.3.1 Influence of Tailings Replacement Percentage

Limited studies have been conducted on the use of tailings in bricks, despite their high percentage of silica and moderate amounts of alumina, which are two commonly occurring compounds in bricks. Avizovas et al. (2022) found that brick specimens high in silicon and aluminium oxides had better physical and mechanical properties. However, generally, the tailings tested by the researchers had a widely varying content of these minerals, ranging from 18-68%. These differing compositions may explain much of the diverse range of results produced by different researchers (Figures 17 and 18) (Beulah et al., 2021; Chen et al., 2011; Kumar et al., 2017; Yang et al., 2014; Behera et al., 2019; Roy et al., 2007; Wei et al., 2021; Hasan et al., 2021). The influence of chemical composition on the strength of bricks, which is largely unknown and varied between sites, has a significant effect on feasibility.

As per AS4455.1, the minimum strength required for masonry is 3MPa, which is achieved in almost all studies (Beulah et al., 2021; Chen et al., 2011; Kumar et al., 2017; Yang et al., 2014; Behera et al., 2019; Wei et al., 2021; Hasan et al., 2021) except for that conducted by Roy et al. (2007). However, for specific applications a larger strength is required, such as for use in retaining walls a minimum strength of 10MPa must be achieved. It is vital for site-specific testing to be conducted to validate the achieved masonry strength, with specific tailing compositions.

Figure 17: *Influence of percentage of iron ore tailings replacement on compressive strength of bricks and AS4455.1 minimum strength limits.*

Figure 18: *Influence of percentage of gold tailings replacement on compressive strength of bricks and AS4455.1 minimum strength limits.*

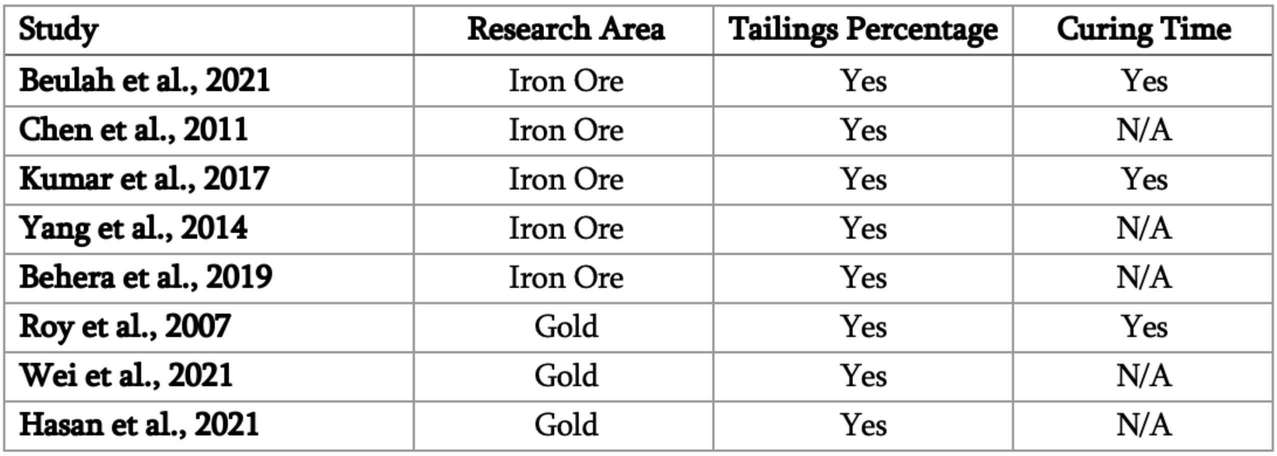
Particle size is known to also have an impact on the compressive strength (Ikechukwu & Shabangu, 2021). The PSD of tailings (Figure 19) indicates a range in the size of particles used to construct bricks, typically from silt to sand. Smaller sized particles tend to be favourable for their cementitious properties (Hasan et al., 2021), however, a correlation between PSD and compressive strength is difficult to decipher from the literature.

Figure 19: *PSD of tailings used within bricks.*

Table 3 summarises the significance of tailings percentage and curing time across the reviewed studies, at a 5% significance level, with detailed ANOVA results provided in Appendix A. All studies showed a significant correlation between the percentage of tailings and the compressive strength of the produced bricks. However, due to the variation in results between literature, it is hard to determine how the two are correlated, with further research required to confirm this relationship.

A blanket approach for use of tailings in bricks is more difficult, with the chemical composition required to be tested and validated regularly. Ultimately, for repurposing of tailings as bricks to move forward, more research is required, and site-specific testing is necessary due to differing chemical properties, which may be an extensive and costly process.

Table 3: Significance of tailings percentage and curing time on compressive strength of bricks from literature.



Study	Research Area	Tailings Percentage	Curing Time
Beulah et al., 2021	Iron Ore	Yes	Yes
Chen et al., 2011	Iron Ore	Yes	N/A
Kumar et al., 2017	Iron Ore	Yes	Yes
Yang et al., 2014	Iron Ore	Yes	N/A
Behera et al., 2019	Iron Ore	Yes	N/A
Roy et al., 2007	Gold	Yes	Yes
Wei et al., 2021	Gold	Yes	N/A
Hasan et al., 2021	Gold	Yes	N/A

4.3.2 Influence of Curing Time

The influence of curing time on the produced bricks was not tested by all research investigations used in the current study, as shown in Figure 20. As per the results in Table 2, for the three papers that reported strength at different curing times, all were significant on the strength of the produced material. In contrast to the influence of curing time on concrete, the results for bricks showed a more linear relationship, with a longer curing time beneficial in enhancing the compressive strength by achieving optimal hardness and reducing cracking and shrinkage.

Figure 20: *Influence of curing time on compressive strength of brick samples.*

4.3.3 SEM Analysis

Kumar et al., (2019) investigated the microstructure of bricks produced with various levels of IOT shown in Figure 20. At 20% tailings content, corresponding to the highest compressive strength, the particles appear relatively smooth and of similar size. At 30% and 40% addition of tailings, the microstructure shows more irregularity and roughness of particles. Roughness may increase mechanical interlocking, improving compressive strength, however, excessive roughness can create a weaker bond between the mortar and aggregate, increasing porosity at the interfacial transition zones and creating local weaknesses (Chang et al., 2022). At these higher tailings contents, particularly 40%, a larger range of particle sizes is observed, with several smaller particles and larger clumps visible.

Examining the changes in microstructure of the bricks allows further understanding on the role of tailings within construction material. This can form the basis for optimisation of composition, while assessing mechanical performance and durability impacts. As with concrete, high porosity has a negative impact on durability, so SEM analysis provides insight to the potential durability issues at greater content of tailings within bricks, even if limited literature has investigated this.

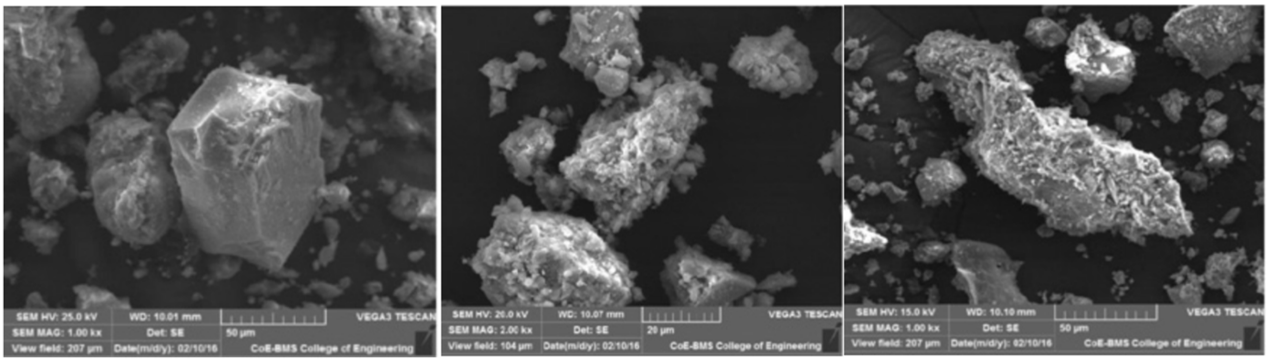


Figure 21: *SEM micrographs of (a) 20% (b) 30% and (c) 40% IOT bricks (Kumar et al., 2017).*

Note. This figure shows the SEM micrographs of raw and mechanically activated tailings. From "Utilization of iron ore tailings for the production of flyash-GGBS-based geopolymer bricks" by R. Kumar et al., 2017, 16(3), Figure 8. (https://doi.org/10.1142/S0219686717500172)

4.4. Effect of Sulfate on Durability

Sulfate, commonly found in mine tailings from oxidised sulphide minerals like pyrite (Lindsay et al., 2015) can corrode and reduce the durability of reinforced concrete (Klein et al., 2022). Most studies on sulfate attack assess strength loss after several dry-wet or freeze-thaw cycles, with Liu et al. (2022) finding the compressive strength loss of IOT concrete at 20% and 40% replacement, was less than that of the reference concrete when subject to dry-wet cycles. Xu et al. (2021) studied the effect of sulfate in concrete subject to freeze-dry cycles, with increased IOT content resulting in a greater compressive strength loss. Given WA's high temperatures, climate-specific investigation is needed to confirm the effect of sulfate under these conditions.

Over 90 days of sulfuric acid exposure, tailings-based concrete shows greater mass loss than reference samples (Shettima et al., 2016; Jayasimha et al., 2022). Shettima et al. (2016) recorded double the mass loss at 100% tailings replacement for fine aggregate (Figure 22), attributed to the fineness of IOT, disrupting the aluminosilicate framework and weakening bonds. A greater mass loss is typically due to expansion and deterioration of the concrete structure, which also impacts strength and durability. These studies are not representative of real-world conditions, as concrete structures are rarely fully immersed, overestimating the effect of sulfuric acid exposure. The lack of realistic studies represents a knowledge gap on the effect of sulfate on tailings-based concrete.

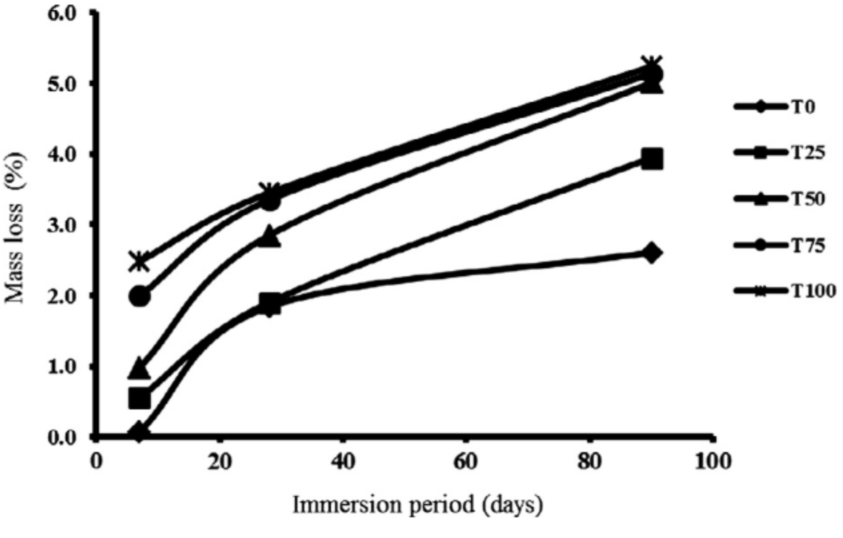


Figure 22: *Mass loss of concrete immersed in sulphuric acid solution (Shettima et al., 2016).*

Note. This figure shows the mass loss of concrete immersed in sulphuric acid solution. From "Evaluation of iron ore tailings as replacement for fine aggregate in concrete" by A. Shettima et al., 2016, 16(3), Figure 13. (http://dx.doi.org/10.1016/j.conbuildmat.2016.05.095).

5 Conclusions

This project explored the potential of repurposing iron ore and gold tailings into construction materials, namely bricks and concrete. Literature and case study reviews aided in understanding current developments, optimal formulations and alternative approaches to utilising tailings into such products. As a result, benefits and challenges were identified, including areas requiring further research, and directions for future work.

This review has shown that a potential exists for repurposing of iron ore and gold tailings into construction materials, namely concrete and bricks, in terms of mechanical properties. The results of various studies on the impact of these tailings on compressive strength when used in concrete is largely consistent. However, the use in bricks provided variable results which should be explored further. For WA, this has shown upcycling of tailings into concrete may be feasible in terms of reaching relevant strength standards for the produced materials, however, further research is required to assess economic and logistical feasibility.

Repurposing tailings as fine aggregate in concrete shows the greatest potential for both compressive strength and large-scale implementation. The ability for utilisation of up to 100% tailings with comparable strength to control specimens, and the significant volume that fine aggregate contributes to concrete structures makes extensive scales of implementation possible. The strength dependence on physical composition in terms of particle size, increases ease of implementation, with tailings generally of similar PSD, without the need for significant pre-processing. Given the trade-off between tailings percentage and workability, the optimal formulation will need to be determined for the intended use case of the concrete. If concrete is intended for foundations or road construction, complete substitution of tailings may be appropriate.

Potential for use as SCM within concrete without significant hindering of strength has been determined through this literature review. A strength reduction up to 30% was observed at 40% tailings content, with almost all samples performing to within AS3600 guidelines. Given the positive environmental potential of supplementing Portland cement with alternative sources in terms of carbon emissions, this option should be further explored even with its sub-optimal effects on strength.

The analysis has provided limited insight into the potential for the use of tailings in bricks, due to the variation in strength results. However, it is evident that the chemical composition of tailings has an impact on the compressive strength properties of the bricks produced. Since knowledge on the mineralogy of tailings is largely unknown, and varies significantly between sites, a blanket approach to repurposing is harder to achieve. On a small site-scale, implementation may be possible with the right tailings, but at a large statewide scale, this may be harder to achieve. Further research is required to validate the impact of tailings on the mechanical properties of bricks, particularly at WA-specific sites.

Results of ANOVA statistical testing have revealed significance in both the percentage of tailings replacement and curing time on the compressive strength of materials made with repurposed tailings across most literature. Analysis of microstructural changes through SEM images of both concrete and bricks, with differing percentages of tailings, validated the changes observed in compressive strength in terms of changing porosity, particle roughness and bonding characteristics. Overall, the potential exists for repurposing of tailings into construction materials in WA, but further research is required to assess durability, site-specific tailing behaviours and logistical feasibility.

6 Recommendations for further work

Future Experimental Work

Limited studies have been performed on the durability of materials constructed from tailings. Further experimental work is required to validate the performance of these materials. Some beneficial tests include permeability, chemical resistance, freeze-thaw and thermal tests, carbonation resistance, reinforcement corrosion tests and mechanical strength retention over time. These tests will provide insight into the performance of the produced materials in real-world scenarios. Studies into other types of tailings may also be beneficial.

Tailings can be comprised of toxic metals, which may be released into the environment over time. The produced construction materials must be assessed for their leaching characteristics to ensure they are safe to use. Limited studies have been performed in this area with Adiguzel et al (2022) finding the use of tailings in concrete generally reduces the heavy metal content values due to the denser microstructure and reduced porosity of concrete with tailings, when used as fine aggregate. Further experimental work is required to assess whether the produced material acts as a stable matrix or if the harmful substances can still leach. Evaluating leaching is essential to ensure regulatory compliance and address environmental and safety concerns.

Once experimentation has been performed to understand durability and leaching characteristics, site-specific testing can be used to validate the performance of specific WA tailings with the findings of the literature review. This is a first step for implementation in WA, ensuring that the properties of tailings in the state perform as expected. Experimentation will allow optimisation of mix proportions and confirm compliance wixth regulatory and safety standards.

Following small-scale site-specific experimentation, pilot projects should be performed to assess the feasibility in operation before full-scale use. This will help confirm mechanical properties, durability and environmental safety can be achieved on site and identify any practical issues. In doing so, risks associated with implementation can be reduced, ensuring the process from moving the tailings from waste dumps to the production of materials can be accomplished.

Life Cycle and Cost Analysis

Life-cycle assessment is required to evaluate the economic and environmental impacts of repurposing tailings into construction material over its entire lifetime. This would involve assessing any pre-possessing requirements, transportation, and production costs, comparing with conventional construction materials to understand the feasibility of implementation logistically. Minimal studies have been performed on cost analysis; however, results are subject largely to the geographical location of tailings and country specific costing. WA specific cost-benefit analysis and life cycle assessment would be required to understand potential for industry adoption, due to the remote location of most iron ore and gold tailings. Supply chain logistics in mapping the proximity of tailings sources to construction markets is vital to establish both cost and environmental performance at a large scale.

Market Research

Future research must also consider the market feasibility of tailings upcycling, with the successful adoption dependent significantly on the endorsement of mining companies and the acceptance by the construction industry. Comprehensive market research is required to identify potential early adopters and to understand social and economic factors influencing uptake. Industry perception and consumer acceptance must be evaluated to understand the willingness of contractors, developers and end-users to adopt materials containing mining byproducts.

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Appendix 1

Kuranchie et al., 2015

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*
Curing Time	495.4	5	99.1	41.1	0.0004597
Tailings Percentage	63.0	1	63.0	26.2	0.0037239
Error	12.0	5	2.4		
Total	570.5	11			

Shettima et al., 2016

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*
Curing Time	227.0	2	113.5	80.5	5.013E-06
Tailings Percentage	21.3	4	5.3	3.8	0.0516489
Error	11.3	8	1.4		
Total	259.7	14			

Zhao et al., 2013 (UHPC)

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*
Curing Time	9588.3	3	3196.1	212.4	1.6572E-12
Tailings Percentage	616.8	5	123.4	8.2	0.00066603
Error	225.7	15	15.0		
Total	10430.8	23			

Zhang et al., 2020 (UHPC)

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*
Curing Time	1045.3	1	1045.3	107.4	0.00014403
Tailings Percentage	401.0	5	80.2	8.2	0.01855833
Error	48.7	5	9.7		
Total	1495.0	11			

Tian et al., 2016

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*
Curing Time	1016.9	2	508.5	2116.6	2.83522E-09
Tailings Percentage	3.5	3	1.2	4.8	0.048502798
Error	1.4	6	0.2		
Total	1021.8	11			

Chinnappa and Karra, 2019

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*
Curing Time	11605.7	3	3868.6	3152.9	3.2159E-21
Tailings Percentage	171.7	5	34.3	28.0	4.2146E-07
Error	18.4	15	1.2		
Total	11795.8	23			

Jayasimha et al., 2022

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*
Curing Time	1234.9	2	617.5	715.8	1.6056E-11
Tailings Percentage	66.5	5	13.3	15.4	0.00020175
Error	8.6	10	0.9		
Total	1310.1	17			

Shettima et al., 2018

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*
Curing Time	277.1	2	138.6	1353.9	7.5285E-11
Tailings Percentage	29.7	4	7.4	72.5	2.541E-06
Error	0.8	8	0.1		
Total	307.6	14			

Protasio et al., 2020

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*
Curing Time	10.9	1	10.9	5.2	0.10794166
Tailings Percentage	48.4	3	16.1	7.6	0.06436836
Error	6.3	3	2.1		
Total	65.5	7			

Ahmed et al., 2021 (UHPC)

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*
Curing Time	11527.3	2	5763.7	431.8	1.9655E-10
Tailings Percentage	503.4	5	100.7	7.5	0.00355826
Error	133.5	10	13.3		
Total	12164.2	17			

Ince, 2019

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*
Curing Time	49.1	1	49.1	213.6	0.00069464

Tailings Percentage	49.8	3	16.6	72.2	0.00269784
Error	0.7	3	0.2		
Total	99.5	7			

Preethi et al., 2017

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*
Curing Time	393.6	2	196.8	128.9	7.2657E-08
Tailings Percentage	164.7	5	32.9	21.6	4.6281E-05
Error	15.3	10	1.5		
Total	573.6	17			

Adeyeye et al., 2025

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*
Curing Time	3445.3	3	1148.4	33.0	7.4982E-07
Tailings Percentage	1307.5	5	261.5	7.5	0.00103075
Error	521.5	15	34.8		
Total	5274.2	23			

Widojoko et al., 2014

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*
Curing Time	131.0	2	65.5	30.7	0.00017736
Tailings Percentage	782.1	4	195.5	91.5	1.0272E-06
Error	17.1	8	2.1		
Total	930.2	14			

Song et al., 2024

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*
Curing Time	248.7	2	124.3	190.3	3.7368E-06
Tailings Percentage	2.6	3	0.9	1.3	0.35679975
Error	3.9	6	0.7		
Total	255.2	11			

Protasio et al., 2021

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*
Curing Time	4043.7	4	1010.9	50.7	2.0254E-07
Tailings Percentage	1010.0	3	336.7	16.9	0.00013231
Error	239.3	12	19.9		

Total	5293.0	19			

Zhang et al., 2023

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*
Curing Time	280.1	2	140.0	56.7	0.00012695
Tailings Percentage	116.8	3	38.9	15.8	0.00299172
Error	14.8	6	2.5		
Total	411.7	11			

Cheng et al., 2016

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*
Curing Time	1332.2	2	666.1	850.5	4.80074E-10
Tailings Percentage	255.3	4	63.8	81.5	1.61453E-06
Error	6.3	8	0.8		
Total	1593.7	14			

Wang et al., 2020

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*
Curing Time	1737.6	1	1737.6	261.2	0.00051519
Tailings Percentage	194.0	3	64.7	9.7	0.04696719
Error	19.9	3	6.7		
Total	1951.5	7			

Ince, 2019

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*
Curing Time	35.7	1	35.7	115.1	0.00173139
Tailings Percentage	10.2	3	3.4	11.0	0.03984358
Error	0.9	3	0.3		
Total	46.9	7			

Celik et al., 2006

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*
Curing Time	1329.5	3	443.2	284.5	7.4192E-07
Tailings Percentage	189.2	2	94.6	60.7	0.00010427
Error	9.3	6	1.6		
Total	1528.0	11			

Sigvardsen et al., 2018

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*
Curing Time	134.5	2	67.3	27.2	0.00468548
Tailings Percentage	109.2	2	54.6	22.1	0.00689599
Error	9.9	4	2.5		
Total	253.6	8			

Beulah et al., 2021

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*
Curing Time	156.4	1	156.4	158.0	0.00023067
Tailings Percentage	141.6	4	35.4	35.7	0.00218238
Error	4.0	4	1.0		
Total	301.9	9			

Chen et al., 2011

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*
Between Groups	478.95	1	478.9	176.0	1.1332E-05
Within Groups	16.3	6	2.7		
Total	495.3	7			

Kumar et al., 2017

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*
Curing Time	47.9	2	24.0	140.3	0.00019765
Tailings Percentage	29.6	2	14.8	86.6	0.00050976
Error	0.7	4	0.2		
Total	78.2	8			

Yang et al., 2014

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*
Between Groups	1028.6	1	1028.6	136.0	2.6668E-06
Within Groups	60.5	8	7.6		
Total	1089.1	9			

Behera et al., 2019

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*

Between Groups	777.4	1	777.4	44.7	0.00015543
Within Groups	139.3	8	17.4		
Total	916.6	9			

Roy et al., 2007

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*
Curing Time	8.7	3	2.9	8.5	0.0026907
Tailings Percentage	53.1	4	13.3	38.8	9.0213E-07
Error	4.1	12	0.3		
Total	65.9	19			

Wei et al., 2021

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*
Between Groups	311.6	1	311.6	12.5	0.00769252
Within Groups	199.7	8	24.9		
Total	511.3	9			

Hasan et al., 2021

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*
Between Groups	1125.8	1	1125.8	132.0	2.611E-05
Within Groups	51.2	6	8.5		
Total	1176.9	7			