Experimental investigations on sustainable mortar containing mining tailing as partial replacement of fine aggregate

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Abstract:

Mine tailings, originating from diverse regions in central Chile (Andina, Los Bronces, El Teniente), were systematically collected and subjected to mineralogical analysis. Based on this analysis, the tailings were categorized into distinct minerals groups, including silicate, carbonate, and feldspar. Following this categorization, these mine tailings were explored as promising substitutes for fine aggregates in concrete constituents. It was found a substantial enhancement in the compressive strength of concrete when incorporating mine tailings, particularly when replacing up to 30% of the fine aggregates. This improvement can be initially attributed to the presence of heavy metals within the tailings. However, exceeding the 30% threshold for fine aggregate replacement with tailings, results in a diminishing effect on concrete compressive strength. The favourable outcomes can be attributed to the mineralogical compositions of the tailings, particularly to the SiO_2 content, which exerts a positive influence on the overall matrix mix.. This innovative approach not only augments the performance of concrete but also contributes to a noteworthy reduction in the environmental footprint associated with mining activities.

Keywords: Concrete, Copper Tailing, Replacement, Mechanical resistance, Chemical Characterisation, SEM, EDS

1 Introduction

The practice of solid waste recycling, which aims to reduce consumption of natural resources and, in turn, slow the rate of environmental deterioration is an activity which is gaining importance worldwide [1,2].

In Chile, copper ores are processed to recover their valuable minerals before being deposited in a tailing dam, with just a few examples of recovery of additional elements or reuse of this material. [6]. [7,8]. While there is no great benefit in using copper tailings as subsurface infill, experts see great promise in using tailings in construction projects as an additive or aggregate in concrete [9–12]. The efficient usage of copper tailings and improved concrete performance have both been researched via the use of copper tailings as micronized sand to alter manufactured sand (MS) in concrete preparation. According to studies conducted by Yuxing Eka et al.[13], reducing the size of the Interfacial Transition Zone (ITZ) between the aggregates and paste in the modified concrete was achieved by substituting 20% of the MS with copper tailings. The concrete's pore size distribution was improved even as its porosity grew. Copper tailings may be used as a partial replacement for fine natural aggregates at a rate of up to 60%, according to research by Saxena et al.[14] . This was especially true for water-cement ratios of 0.40, 0.45, and 0.50. Copper tailings-reinforced concrete specimens showed increased strength and durability, particularly at water-cement ratios of 0.40 and 0.45, indicating its potential use in a wide range of building applications..

There has been a substantial uptick in the extraction and use of minerals in today's contemporary mineral business. In particular, mineral tailings, a byproduct of ore processing steps including crushing and screening, have become an urgent environmental issue[15,16]. Particularly robust expansion in the copper mining industry has led to a steady increase in tailings output. In Chile, copper tailings production topped 10 million tons, according to a research on the competitiveness and growth prospects of the tailings use sector in Chile for the years 2027-2030[17](). Large amounts of land have been taken up by copper tailings deposits; the leaching of heavy metals from these tailings poses a serious environmental danger that has the potential to severely disrupt the ecological balance [18–20]. Because of this, it is crucial to look into efficient means of handling mineral tailings, such as those left over from copper production, in order to safeguard the environment and stop any possible ecological harm.

Geological aggregation of mineral tailings for use as a building material is a cost-effective strategy that has received a lot of attention[21,22]. Making geopolymer materials from metal tailings and combining them with fly ash and other ingredients[23] resulted in the successful production of geopolymer composites with good performance. When creating zinc tailings-metakaolin geopolymer composites, Wan et al. (reference?) used metakaolin as an activator to improve the composites' characteristics. Metakaolin increases the mechanical strength of the zinc tailings-metakaolin geopolymer, according to their research[24]. Multifunctional geopolymers, such as refractory geopolymers, were also studied by Jiao et al. (reference), who investigated their use with vanadium tailings and fly ash. They discovered that the geopolymer samples were very resistant to heat, with no visible structural degradation occurring at temperatures as high as 900 °C. This underlines the potential of vanadium tailings as a useful source for creating refractory geopolymers[25].

Through a uniaxial compression test, Zhang et al.[26] were able to deduce the connection between mechanical characteristics and microstructure to analyze the leaching behavior and durability of gold tailings geopolymer. Han and Zhang analyzed the tailings geopolymer's potential as a construction material by examining its fracture behavior mechanism[27]. Tungsten tailings geopolymer paste was used by Torgal et al.[28] as a surface treatment material for Ordinary Portland Cement PC concrete, and the researchers found that it provided much stronger bonding even on surfaces with minimal roughness than commercial repair materials.

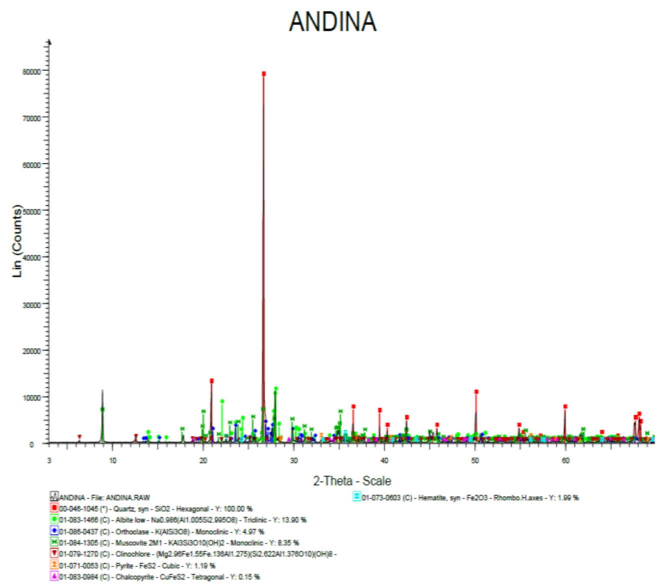
The impact of copper tailings on the mechanical properties of geopolymers remains uncertain, and further research into the topic is needed. Concurrently, numerous experts have looked at incorporating tailings into concrete as an alternative to traditional admixtures or aggregates. As example, Chen et al. [29] discovered that 35% copper tailings may be substituted to enhance the mechanical characteristics and pore structure of cement mortar. The characteristics of the concrete were improved when copper tailings were used in place of micronized sand. For best results with artificial sand aggregate gradation, Zhang et al. (reference?) recommended using copper tailings with a 20% percentage. The transition zone interface between the aggregate and binder in the concrete was enhanced due to the more refined pore size distribution[30]. Thomas et al. (reference?) looked at how changing the water-cement ratio impacted the strength and durability of copper tailings concrete. Samples of concrete made with water-cement ratios of 0.40 and 0.45 showed improved strength and durability when copper tailings were used to partly substitute natural fine aggregate[31].

As an alternative to using fine natural aggregates, this study looked at using copper tailings from the Andina, Los Bronce, and El Teniente copper mines in mortar samples. The copper tailings were mixed to make mortar to test the effect of particle size distribution on the mechanical characteristics and pore structure of cement-based materials. The tailings, substituting varied fractions of the fine aggregate (0%,10%,20%, 30% ,40% and 50%) had particular size distributions comparable to fine aggregate. Microscopic properties were analyzed using scanning electron microscopy (SEM) pictures, whereas macroscopic indicators included flexural strength, compressive strength, and water absorption. The results may help engineers decide how much copper tailing to use and what size particles they should be to substitute fine aggregate.

2 Methodology

Properties of tailings:

Different varieties of tailings, encompassing both metallic (like iron, copper, gold, lead, zinc from metal ore processing) and non-metallic (such as oil sand, quartz, phosphate, forsterite from non-metal ore processing), form are categorized based on the specific ores they originate from. However, the chemical composite of mining tails are highly variable according several factors such as types of tailings, age of tailings and method of extraction among others. The chemical compositions of different sources of mining tailings were very diverse in minerals phases, but in general $Si0_2$, AI_20_3, Fe_20_3, Ca0, Mg0 etc., according to the XRD patterns shown in Figure 1.



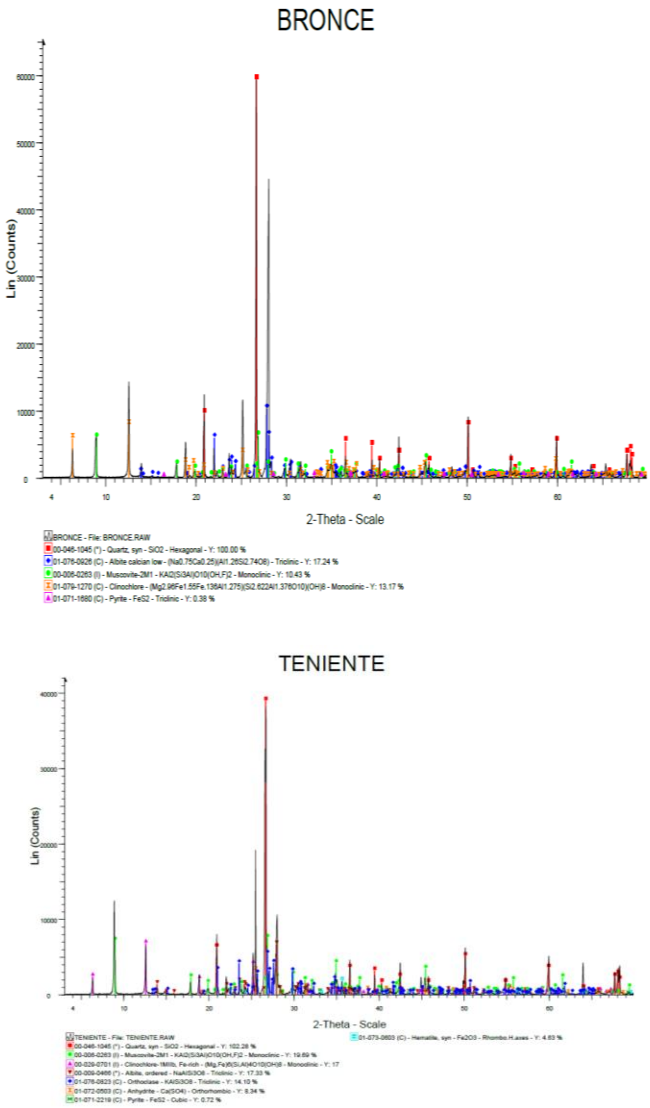
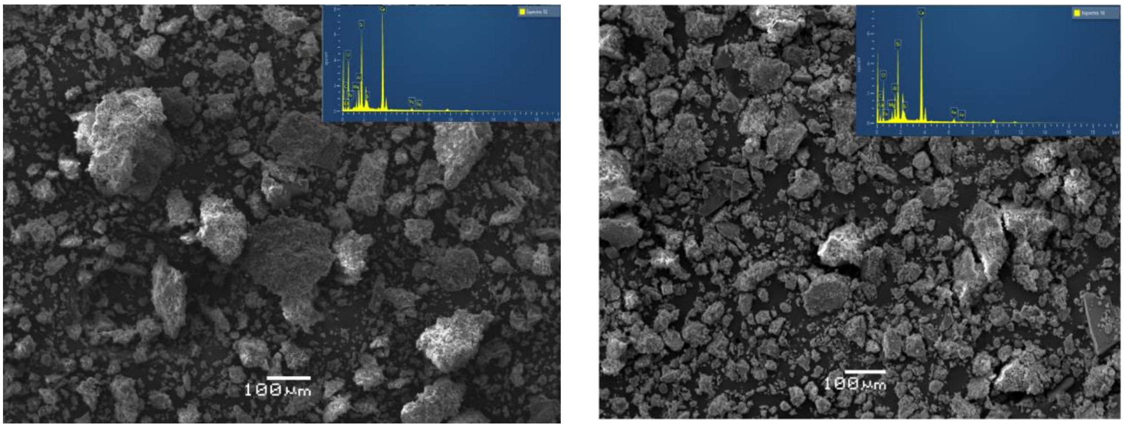


Figure 1. XRD pattern of phosphate mining tailings

The physical properties of mining tailings were not much different among different sources of tailings when comparing to chemical composite as well as in mineral phases. Based on the method of refining methods and standards, the size fractions of mining tailings are classified as “clay, sand and slit”. Mostly, the mining tails are rough and irregular surface due to the grindability of different mineral phases as well as various density and water absorption which could directly affect the particle size of the mining tails. In general, mining tails are utilized in mortar as partial of full replacement to river sand, since particle size with find diameter lesser than 1mm. The concrete with high volume replacement of mining tails could influence the dimensional stability, workability, density, strength and durability. The chemical characterisation of cement-based mortar and 30% replacement of mining tails were analysed by SEM image and EDS as shown in Figure 2.



30% replacement of Mining tails — Control Cement Mortar

Figure 2. SEM image and EDS of phosphate

Preparation of test specimens:

The raw materials utilized for the investigations are presented in Table1. The standard laboratory planetary were used to mix the raw materials. In the present research five different ratios of mining tails and river sand were used with constant water cement ratio to identify the influencing parameter in the strength of the mortar. In each ratio of mining tails and river sand, three specimens were fabricated. The cement, sand and mining tailings were mixed under dry condition for 1 min at 75rpm. Then, water with additive was added in the dry mix and planetary mixed at 75rpm and 150rpm for 2min, respectively. Once the mixing process of cement-mortar of mining tails and river sand were poured into the prismatic moulds (40 × 40 × 160 mm). The cement-based mortar of mining tails and river sand poured on the RELEM prismatic moulds were vibrated for 5s to remove the air bubbles inside. The specimens will be covered using acetate sheets and placed at 22±5 °C ambient conditions for 24 h in the laboratory prior to demoulding. The demoulded specimens were cured in the controlled atmosphere and humidity for 28 days. Totally 18 prismatic test specimens and 36 compressive test specimens were fabricated.

Table 1: Parameters of preliminary designs

Specimen ID	Mortar matrix				Addition of mining tails as fine aggregate	
	Mass cement (g)	Mass water (g)	Additive volume (cm^3)	Relation w/c	addition of mining tails (g)	addition of river sand (g)

Control					-	1350
10MT90RS					135	1215
20MT80RS	450	225	4.2	0.5	270	1080
30MT70RS					405	945
40MT60RS					540	810
50MT50RS					675	675

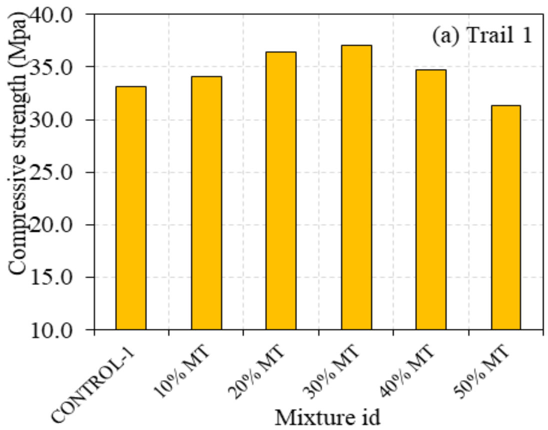
MT-Mining Tails, RS-River Sand

3 Experimental Results

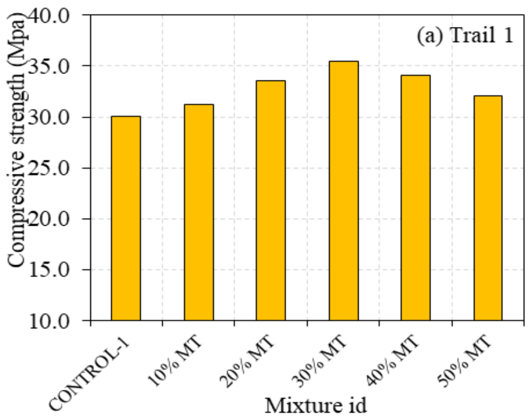
Compressive Strength

The compressive strength assessment of concrete incorporating copper tailings as fine aggregate was conducted across various mining sources (Andina mine, Los Bronces mine, El Teniente mine) with different percentages of tailings replacement. Incorporating copper tailings at different replacement levels showcased noteworthy effects on the compressive strength. Figure 3 shows the result of the compressive strength. Across all three mining sources, the incorporation of 30% mining tailings consistently displayed an increase in compressive strength compared to other substitution rates. For instance, in the Andina mine tailings, the compressive strength saw an increment from the control strength (CS) of 32.98 MPa to 37.06 MPa at a 30% replacement level. Similarly, in the Los Bronces and El Teniente sources, the 30% replacement exhibited significant enhancement in compressive strength, reaching 35.46 MPa and 34.69 MPa, respectively. It's notable that while certain substitution levels showed improvement, others demonstrated marginal fluctuations or even a reduction in compressive strength. For instance, at 0% replacement, the compressive strength notably declined across all mining sources, indicating a diminishing effect on strength beyond certain substitution thresholds. This consistent trend suggests an optimal percentage of tailings replacement, around 30%, that consistently augments the compressive strength of concrete across diverse mining sources.

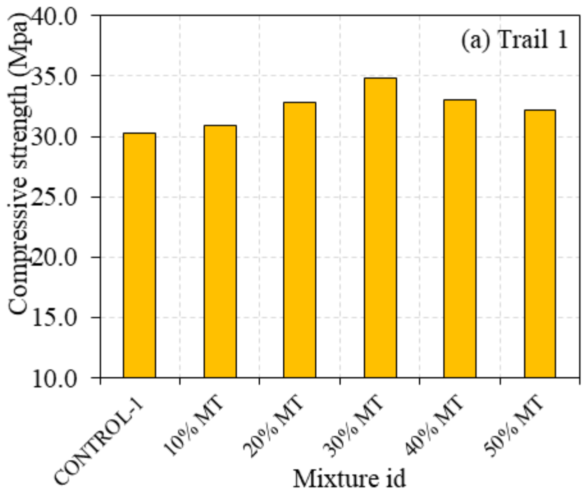
Figure 3: Compressive Strength Testing



(a) Andina



(b) Los Bronces



(c) El Teniente

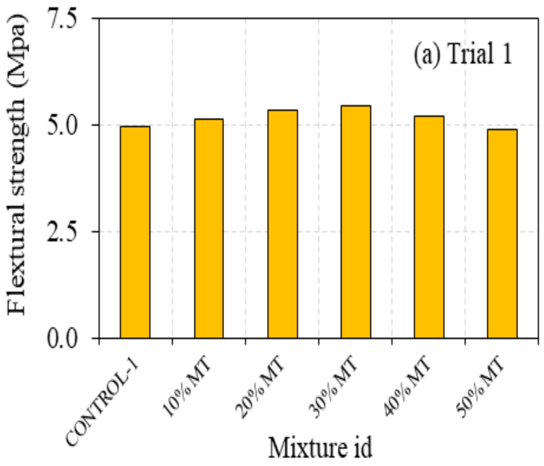
Figure 3: Compressive Strength results at 28 days

These findings underscore the significance of tailings as a partial replacement for fine aggregates, indicating their potential to positively influence concrete's mechanical properties while also addressing environmental concerns associated with mining activities.

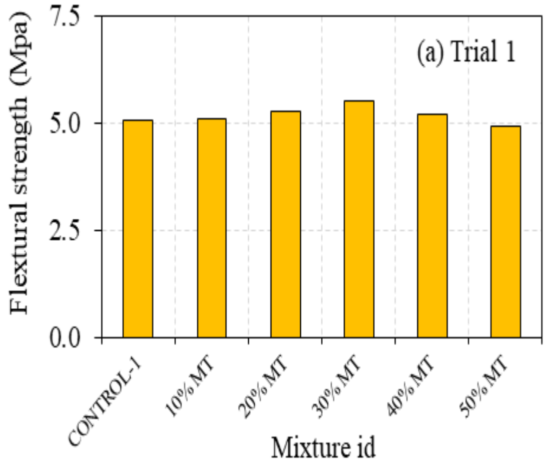
Flexural Strength

The flexural strength within concrete containing copper tailings as fine aggregates presents insightful outcomes shown in Figure 4. The flexural strength generally exhibited an increasing trend up to a certain replacement percentage before experiencing fluctuations or slight reductions. For instance, in the Andina mine source, the flexural strength increased steadily up to 30% tailings replacement, reaching a peak of 5.46 MPa, showcasing an improvement from the control strength (CS) of 4.97 MPa. However, beyond this replacement percentage, the flexural strength witnessed a marginal decline at 40% and 50% replacements. Similar patterns were observed in the Los Bronces and El Teniente sources, where the flexural strength demonstrated enhancement up to 30% replacement, achieving strengths of 5.54 MPa and 5.28 MPa, respectively, before showing minor decreases at higher substitution rates.

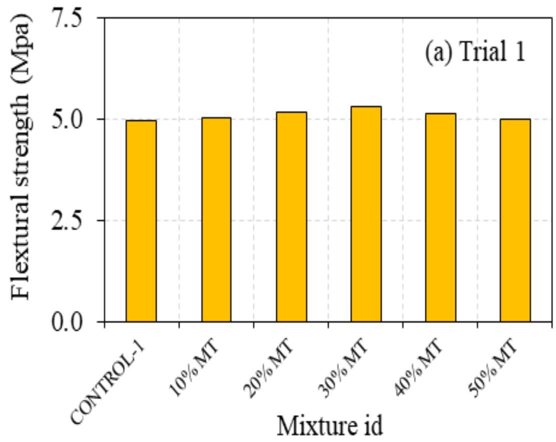
Figure 4: Testing of Flexural Strength



(a) Andean



(b) Bronze



(c)Teniente

Figure 5: Flexural Strength results at 28 days

The findings indicate an optimal percentage of copper tailings substitution (around 30%) that consistently enhances the flexural strength of concrete across diverse mining sources. Beyond this threshold, higher substitution percentages tend to have a diminishing effect on the flexural strength. These observations emphasize the critical influence of tailings content on flexural strength, reinforcing the potential of tailings as a beneficial additive for concrete, while highlighting the importance of controlled substitution levels for optimal mechanical performance.

4 SEM and EDS discussion

By using Scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDS) the microstructural features within these concrete specimens can be unraveled. SEM aids in visualizing the surface morphology and internal structure, providing information about the particle distribution, shape, and interfacial characteristics between the tailings and the cementitious matrix. EDS complements SEM by identifying and mapping the elemental composition, highlighting the presence and distribution of key elements like copper, silicon, aluminum, and other minerals present in the tailings. Moreover, transmission electron microscopy (TEM) can delve deeper into the fine details of these materials, revealing the crystallographic structures, possible interfaces, and nanoscale features within the concrete. This analysis aids in understanding the bonding mechanisms between the copper tailings and the cement matrix, shedding light on how these materials interact at a microscopic level and potentially influence the concrete's mechanical properties. Microstructural analysis of these concrete compositions provides valuable data crucial for optimizing their formulations, understanding their performance, and potentially tailoring them for specific applications in construction and infrastructure development. Understanding the microstructural nuances aids in harnessing the advantages of incorporating mine tailings as aggregates while ensuring the concrete's durability, strength, and long-term stability.

Conclusions

The integration of mine tailings, specifically copper tailings, as substitutes for fine aggregates in concrete compositions from diverse mining sources has revealed significant insights into the material's performance and potential applications. Comprehensive analysis and testing elucidated distinct patterns in compressive and flexural strength, shedding light on the optimal percentages of tailings replacement that positively influence concrete properties.

The findings suggest that a 30% replacement of river sand with copper tailings consistently enhances both compressive and flexural strength across various mining regions, including Andina mine, Los Bronces mine, and El Teniente mine. At this replacement level, concrete exhibited noteworthy improvements in both mechanical parameters, showcasing increased strength compared to conventional concrete mixes.

However, beyond the 30% threshold, the enhancement in strength showed marginal fluctuations or declines, indicating a diminishing effect on mechanical properties. This underscores the critical importance of controlled substitution levels in tailings incorporation for optimal mechanical performance of concrete.

Regarding the area where copper tailings demonstrated the most promising results, the comprehensive evaluation indicates that across the tested tailings, the optimal percentage of copper tailings replacement for enhanced mechanical properties lies around 30%. This suggests a consistent influence of copper tailings on concrete performance across diverse mining sources, emphasizing its potential as a valuable additive for enhancing concrete's mechanical strength while mitigating environmental concerns associated with mining activities.

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Guidelines and Regulations: All testing was performed in accordance with the relevant ASTM standards. The methods and procedures used were compliant with the guidelines and regulations outlined in the ASTM standard to ensure accurate and reliable results. **Data Availability**: The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Competing interests: The authors declare no competing interests.

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