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LinkedIn Revista Ingeniería de Construcción

Vol. 39
Special Issue 2024
DOI: 10.7764/RIC.00133.21

Use of Artificial fine aggregates from copper tailings in mortar: Mechanical Performance

Desempeño mecánico de mezclas de mortero fabricadas con áridos finos artificiales hechas con relaves de cobre

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Fecha de Recepción: 30/09/2024
Fecha de Aceptación: 25/11/2024
Fecha de Publicación: 30/12/2024
PAG: 1-9

Abstract

The construction and mining industries are among the most impactful on the environment. A significant issue in the mining industry is the generation of mine tailings, with copper tailings being among the most voluminous. One potential way to utilize them is as a replacement for fine aggregates, although they are extremely fine. Through an alkaline activation process, it is possible to agglomerate them and use them in mortar mixtures. This research used copper tailings to produce an artificial fine aggregate (AFA) through an alkaline agglomeration process and assessed its impact on mortar mixtures. The results demonstrate that it is feasible to manufacture an artificial fine aggregate by alkaline agglomeration using the proposed methodology. Also, it is shown that replacement levels up to 45% show improvements in the mechanical performance of the mortar mixes. Additionally, a decrease in the density of the mixtures was observed.

Keywords: Artificial fine aggregate; copper tailings; alkaline activated materials (AAMs); mortar; mechanical performance.

Resumen

Las industrias de la construcción y la minería se encuentran entre las que más impactan el medio ambiente. Un problema importante en la industria minera es la generación de relaves mineros, siendo los relaves de cobre uno de los más masivos. Una posible forma de utilizarlos es como reemplazo de los agregados finos, aunque son extremadamente finos. Mediante un proceso de activación alcalina es posible aglomerarlos y utilizarlos en mezclas de mortero. Esta investigación utilizó relaves de cobre para producir un agregado fino artificial (AFA) mediante un proceso de aglomeración alcalina y evaluó su impacto en las mezclas de mortero. Los resultados demuestran que es factible fabricar un agregado fino artificial mediante aglomeración alcalina utilizando la metodología propuesta. Asimismo, se demuestra que niveles de reemplazo de hasta el 45% presentan mejoras en el desempeño mecánico de las mezclas de mortero. Además, se observó una disminución en la densidad de las mezclas.

Keywords: Agregado fino artificial; relaves de cobre; materiales alcalinos activados (MAA); mortero; desempeño mecánico.

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Special Issue 2024
DOI: 10.7764/RIC.00133.21

1. Introduction

The construction industry represents a significant portion of natural resource consumption (Monteiro et al., 2017), and its constant growth poses a major threat to environmental balance. One of the key issues in the development of this industry is the use of natural resources, which are neither infinite nor widely available (Saberian et al., 2022). Among the most used materials, natural aggregates are well-known for their availability in almost any location. However, particularly in the case of fine aggregates, there is a trend toward depletion of this material, reduced availability of high-quality aggregates (Almadani et al., 2022), and the rise of a black market consequently (Navarrete and Vargas, 2024). Another relevant issue is the transportation of these materials, as long distances must often be covered from sources of quality materials (Nguyen et al., 2018).

On the other hand, the mining industry continuously generates waste in large quantities. Copper mining is one of the most massive on a global scale. Approximately 200 tons of copper tailings are generated for every ton of copper extracted (Schlesinger et al., 2011). This represents, in countries like Chile, around 600 million cubic meters of new tailings annually (Vargas et al., 2020). These wastes are typically stored in tailings dams, where they are deposited and can produce significant environmental impacts (Thomas et al., 2013). Moreover, these storage sites are often located near the mining operations themselves.

Previous studies have attempted to increase the use of this by-product to minimize its impact on both the mining industry and the construction industry. Various applications in construction have been studied for copper tailings: as a replacement for cement, for block manufacturing, and as a replacement for fine aggregates. Its use as a supplementary cementitious material has shown that, at replacement levels below 20%, there is an increase in the mechanical strength of the mixes (Vargas and Lopez, 2018); however, the environmental benefits of its use must be studied in greater depth (Vargas et al., 2020). In the case of block manufacturing, potential applications have been described as a replacement for traditional bricks, with mechanical strengths around 15 MPa (Ahmari and Zhang, 2012), though its use has not been widespread. Finally, the use of copper tailings as a replacement for fine aggregates has been investigated, showing contradictory results regarding its effect on mechanical strength. A major issue with this approach is that the particle size of copper tailings is generally smaller than what is considered suitable for use as fine aggregate, with d90 values below 120 microns (and d50 easily below 50 microns) due to the copper extraction optimization processes employed by mining companies (Onuaguluchi and Eren, 2013).

One option to generate larger-sized aggregate, agglomerate particles, and maximize the use of tailings is to employ some form of alkali activation process. Alkali-activated materials (AAMs) are produced in highly basic solutions, in the presence of potassium, sodium, or calcium (Patel et al., 2018). For their production, the base material must contain reactive aluminosilicates, or this material can be supplied from a co-activator that provides these elements. Co-activators can include cement, rice husk ash, or fly ash (Bui et al., 2012). Depending on the characteristics of the base material, strengths of up to 30 MPa can be achieved.

This technology has been used for block formation, as well as in soil improvement processes, stabilization/solidification (S/S), and cold pelletization of other types of waste, such as slags or clays (Madani et al., 2020). However, in the case of cold pelletization, the particle size obtained is typically suitable for replacing coarse aggregates (Ren et al., 2021). Nevertheless, strategies can be developed for agglomeration that do not result in such large particle sizes, allowing for their use as fine aggregate (sizes greater than 75 microns and less than 4.75 mm).

The use of these artificial aggregates can help avoid significant impacts related to the extraction and transportation of the natural aggregates currently in use, which must be transported to mining operations—major consumers of construction materials.

The objective of this study is to test the use of an artificial fine aggregate (AFA) made from copper tailings, using an agglomeration process that produces suitable sizes. This aggregate will be tested in mortar mixtures, evaluating both the mechanical strength measured as compressive strength and the changes in density caused by its use, at various levels of natural aggregate replacement.

2. Materials and Methods

2.1 Materials Characterization

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For the production of the aggregate, a copper tailing (CT) was used. The tailing was collected from an ongoing mine operation in Calama, Chile and was first passed through a No. 30 sieve (600 µm) to eliminate any external content. Due to the typical high crystallinity and low reactivity of tailings, a fly ash was used as a co-activator for the copper tailings. A class F fly ash (FA) was collected from a coal power plant located in Valparaiso, Chile. FA is a product of a process that does not use flue gas desulfurization to reduce sulfur dioxide emissions, therefore, its composition presents low SO3 and CaO contents (Navarrete et al., 2021). For the alkaline activation, Sodium Hydroxide PanReac AppliChem (NaOH) in solution was used at 5M and 10M.

For the mortar mixes, a normal-weight siliceous aggregate was used as natural aggregate and a pozzolanic blended cement (IPC) was used as binder. IPC is the most used cement in Chile, and its composition is similar to ASTM Type IP cement, with an estimated content of natural pozzolans of 35% by mass (approx. 39% by volume).

2.1.1 Particle Size Distribution (PSD)

(Figure 1) shows the particle size distribution (PSD) of CT and FA, which were measured using a laser diffractometer Malvern Mastersizer 2000. The CT and FA were dispersed in isopropanol with a refractive index of 1.250 and 1.458 respectively. Each measurement was carried out six times for 10 s at 2000 RPM.

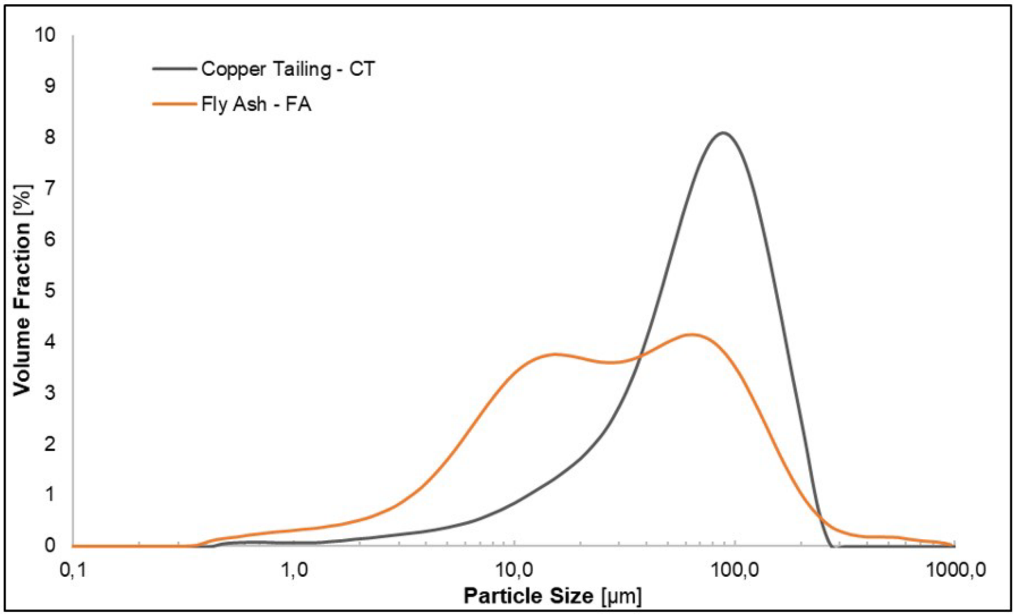

Figure 1. PSD of CT and FA. Volume fraction.

2.1.2 Chemical Composition (XRF)

The chemical composition of all the cementitious materials, shown in (Table 1), was determined by X-ray fluorescence (XRF) using a Bruker S8 Tiger spectrometer. Specific gravity and loss on ignition (LOI) are also reported.

2.2 Production of the artificial fine aggregate (AFA)

The artificial fine aggregate (AFA) was produced at room temperature using 10% mass FA as a co-activator. A dry pre-mix of CT and FAs was performed until a homogeneous mix was obtained. 200 grams of mix were produced each time, and a solution of sodium hydroxide 5M or 10M was mixed with the binder in a proportion of 20:3 by mass (Figure 2a). The materials were manually mixed until homogenization was achieved (Figure 2b) and an agglomeration of the particles was obtained by vibration in a table. Immediately after this process, aggregates were stored at 60° in an oven for curing for 7 days to increase the gain of strength and completed 28 days of curing at room temperature before usage. AFA can be seen in (Figure 2c). (Table 2) shows the physical characterization of the aggregates. The aggregates were sieved and the fraction between 0.3mm and 4.75mm was used for this study (defined as fine aggregate).

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Table 1. Oxide composition, specific gravity, and loss on ignition of materials.

	IPC	CT	FA
CaO (%)	65.8	1.34	1.61
SiO_2 (%)	19.3	63.4	59.79
Al_2O_3 (%)	4.5	16.6	21.85
SO_3 (%)	2.34	0.35	0.806
Fe_2O_3 (%)	3.04	5.708	6.785
MgO (%)	1.11	1.78	1.69
Other minor oxides (%)	3.91	7.31	4.73
Loss on ignition (%)	2.71	3.42	2.74
Specific gravity	3.14	3.13	2.41

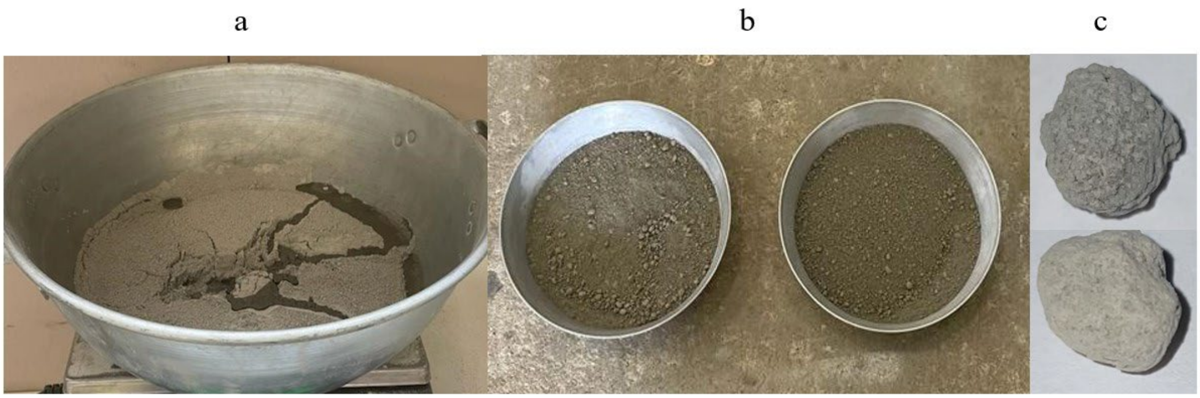

Figure 2. Production of the artificial fine aggregate. (a) Mixed materials. (b) Artificial aggregate once mixed with water and vibrated. (c) Artificial fine aggregate.

Table 2. Physical characterization of artificial and natural fine aggregate.

	5M solution AFA	10M solution AFA	Natural aggregate (NA)
Bulk density – loose (kg/m^3)	1070	1150	1510
Bulk density – loose (kg/m^3)	1240	1330	1740
Real density – SSS (kg/m^3)	2290	2430	2660
Real density – dry (kg/m^3)	2130	2280	2600
Water absorption (%)	7.6	6.6	2.1

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2.3 Mechanical performance

The effect of the use of the artificial fine aggregate was experimentally evaluated on the compression strength of mortar mixes, according to ASTM C109 (ASTM, 2020). The mixture proportions are listed in (Table 3). For each type of aggregate (produced with 5M and 10M solutions) 4 replacement levels were used (15%, 30%, 45% and 60% by volume) plus a control sample. 6 5x5x5 cm cubic specimens were cast for each mix to measure mechanical performance at 7 and 28 days. Water-to-binder ratio was fixed at 0.5 by mass and the proportion of paste-to-aggregates is also 0.5 by mass. Due to the difference between the density of the natural and artificial aggregates, increasing replacement levels generate differences in the ratio between paste and aggregates by volume. Also, due to the absorption of aggregates, water content must be corrected for each type of mix. In addition, the density of the samples is reported.

Table 3. Mixture proportions of the mortar mixes used in this study.

	IPC (kg/m^3)	NA (kg/m^3)	AFA (kg/m^3)	Water (kg/m^3)
MP	463,07	1359,61	0	261,12
$M_{15}C_{5M}$	442,83	1155,67	136,44	257,79
$M_{30}C_{5M}$	422,59	951,73	272,88	254,45
$M_{45}C_{5M}$	402,35	747,79	409,31	251,11
$M_{60}C_{5M}$	382,11	543,84	545,75	247,78
$M_{15}C_{10M}$	446,51	1155,67	148,23	258,88
$M_{30}C_{10M}$	429,95	951,73	296,45	256,63
$M_{45}C_{10M}$	413,39	747,79	444,68	254,39
$M_{60}C_{10M}$	396,83	543,84	592,90	252,15

3. Results and Discussion

The compressive strength at 7 days is shown in (Figure 3). In general, the samples using aggregates prepared with 5M and 10M solutions exhibit an improvement in mechanical strength at this age. This can be explained by the absorption of the aggregates, which, although accounted for in the design, may momentarily lower the w/c ratio, thus increasing the strength. On the other hand, variations in workability induced by the artificial aggregates may lead to better levels of mix compaction, resulting in enhanced mechanical strength at early ages. Another explanation is that during the handling and preparation of the samples, some tailings particles disintegrate into smaller sizes, acting as nucleation points due to their particle size, thereby increasing cement reactivity. However, as time progresses, this effect may be counteracted by the electrostatic interaction between finer particles detached from the AFA, as observed in other studies (Adiguzel et al., 2022) on the direct use of tailings as fine particulate material.

At 28 days, the strength gain effect is mostly reduced (Figure 4), and the strengths are more similar to those obtained by the control sample MP. In general, the mechanical strength of the specimens shows a slight increase with replacement levels up to 30% for both types of aggregates, followed by a general decrease in mechanical strength. This is due to the weaker nature of artificial aggregates compared to natural aggregates. Additionally, at this age, the potential effects of water release or nucleation from disintegrated material are minimized. When compared with other studies where fine aggregate was replaced with unbonded tailings (Thomas et al., 2013), a similar behavior is observed in the mixes, with strength gains up to replacement levels of 20-30%, followed by a decrease in mechanical strength

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DOI: 10.7764/RIC.00133.21

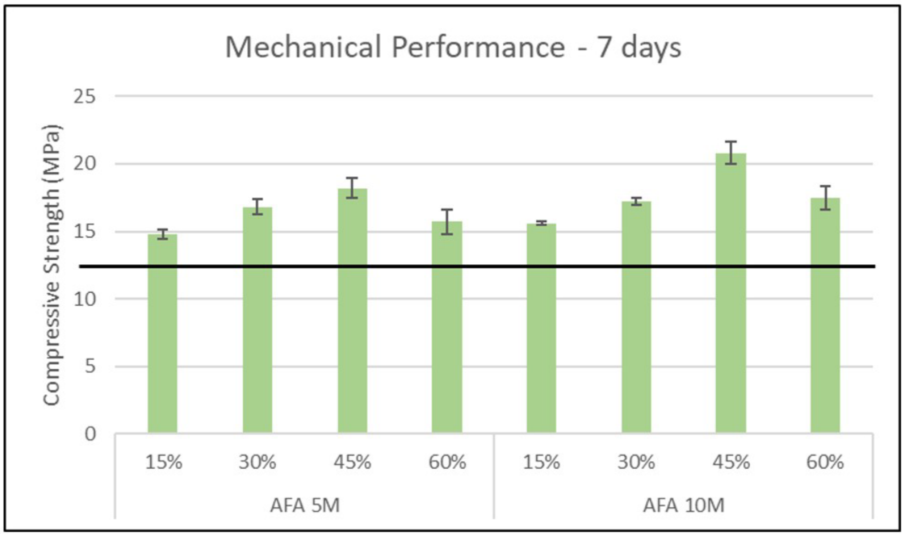

Figure 3. Mechanical performance as the compressive strength of mortar mixes at 7 days. The line represents the mechanical performance of the control mix at 7 days.

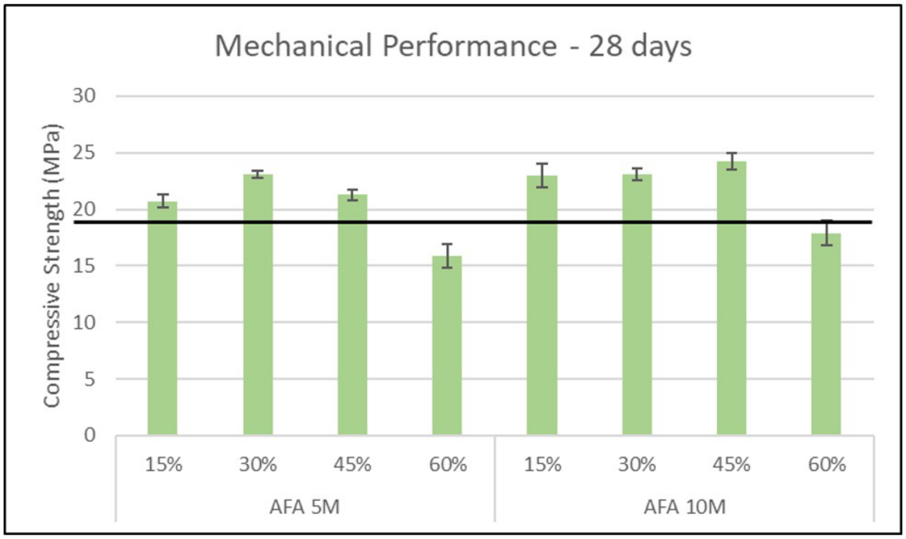

Figure 4. Mechanical performance as the compressive strength of mortar mixes at 28 days. The line represents the mechanical performance of the control mix at 28 days.

Another possible explanation for the increase in mechanical strength, particularly in mixtures with higher molar concentrations (10M), is the fact that despite the aggregates being more compact and having higher density, part of the solution and material used for alkali activation is not fully utilized in the aggregate production. Being available within or on the surface of the aggregate, it can contribute to an alkali activation reaction with the paste around the aggregate, creating a more compact structure and thereby increasing mechanical strength (Swathi and Vidjeapriya, 2023), although this effect is localized around the aggregate.

Although a difference is observed between the two types of aggregates, statistical analysis of both sample groups indicates that the difference is not significant, showing that while both types of aggregates induce variations in their properties, these are not significant enough to alter the behavior of the mortar mixes produced with them.

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Regarding the density of the mortar samples observed at 7 and 28 days (Figure 5), a sustained decrease in density is observed as the replacement level increases. This is consistent with what has been reported in other studies and is clearly related to the lower density observed in the aggregates. The decrease is consistent across both types of aggregates and over the sample age, which can be attributed to water loss (when analyzed with respect to age) and the higher density observed in the artificial fine aggregates (AFA) produced with higher molar concentrations of alkali activator.

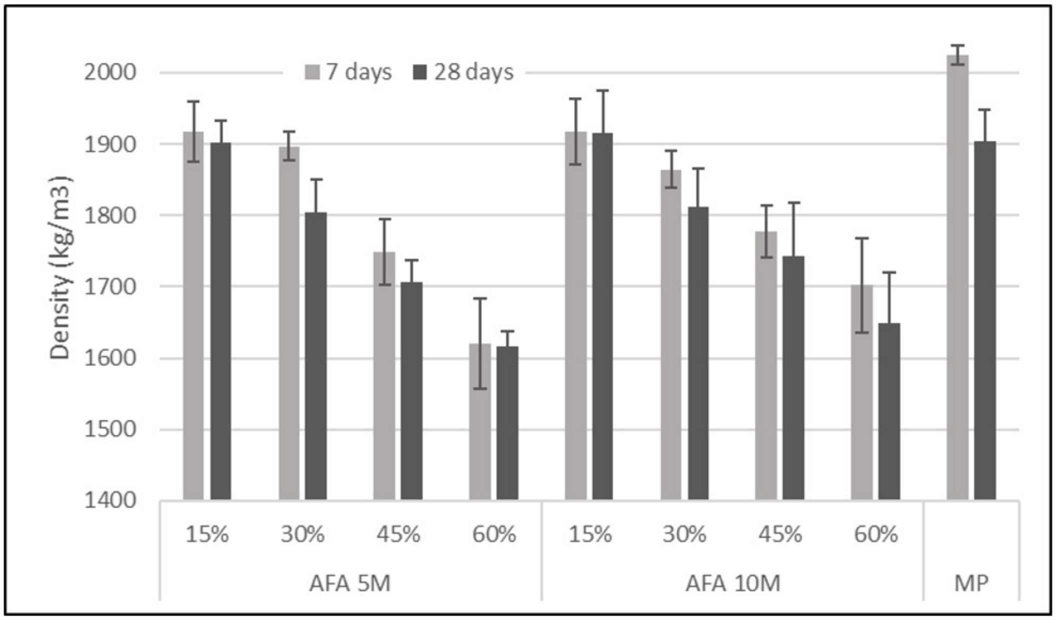

Figure 5. Density of mortar samples at 7 and 28 days.

4. Conclusions

The use of artificial aggregates derived from mining industry waste is a plausible alternative and an important way to reduce the environmental impacts of both the construction and mining industries. Although the use of copper tailings as a replacement for cement or fine aggregate has been studied, the particle size of the tailings presents a limitation for widespread use in engineering applications, such as their use as aggregate replacement. In this study, an artificial fine aggregate made from tailings through an alkali activation agglomeration method was used in mortar mixes, comparing two molar concentrations of the alkali activator. Based on the results, the main conclusions are as follows:

1. It is feasible to use tailings as raw material for the production of artificial fine aggregates through the alkali activation process, yielding an aggregate with lower density than natural aggregate and higher absorption.
2. However, at 7 days, higher mechanical strengths were observed in mixtures with artificial fine aggregate (AFA) compared to the base mixture (MP). This can be attributed to changes in workability and the disintegration of aggregate particles.
3. At 28 days, the increase in mechanical performance is reduced. Despite this, still it is observed an increase in mechanical performance at lower replacement levels, up to 29%. For replacement levels above 45%, a decrease in the mechanical strength of the specimens was noted, up to 15% for samples with AFA made with 5M alkaline activator concentration.
4. The density of the mortar specimens decreased as the replacement level increased. This is consistent with the lower density of the AFA compared to natural aggregates.

The use of these aggregates can reduce the environmental impact of construction activities at mining operations by decreasing the reliance on natural aggregates and minimizing transportation-related impacts. Additionally, the accumulation of copper tailings can be mitigated by utilizing them as a base material for aggregate production.

Although the results are promising, more detailed analyses of the production method for artificial aggregates (including production variables and mix design) and of the replacement of natural aggregates in different types of mixtures (concrete or other types of cement and mix designs) are

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necessary to deepen the understanding of the use of tailings to produce these alternative materials. Also, other mechanical performance variables such as elastic modulus, Young´s modulus or fracture mechanisms can be studied in the future.

5. Acknowledgment

This project was supported by project Fondecyt Iniciacion 11230537. The testing performed in this study was mainly conducted at the Construction Materials Laboratories at the Universidad Austral de Chile. The authors acknowledge the assistance provided by Alejandro Silva at these facilities.

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