Proceedings of the 11th World Congress on New Technologies (NewTech'25)
Paris, France - August, 2025
Paper No. ICCEIA 136
DOI: 10.11159/icceia25.136

Design of a Prefabricated Concrete Element Using Tailings Material from the Mining Extraction Area of the Portovelo Canton.

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Abstract – The cantons of Zaruma and Portovelo, located in the province of El Oro, are key mining areas in Ecuador, with mining being one of their main economic activities. However, this industry is controversial due to the waste it generates, known as mining tailings. To minimize the environmental impact caused by these byproducts, this research focuses on developing a precast element incorporating tailings material as one of its components. A physical, chemical, and mineralogical characterization of the material was conducted, and three mix designs were formulated, replacing 20%, 30%, and 40% of the fine aggregate with tailings material. The element underwent compression tests to determine its strength, revealing that the mixture containing 30% tailings was the most suitable for use. Based on this dosage, pavers were manufactured for residential streets and parking areas, meeting the required strength standard of 300 kg/cm². Compression tests confirmed a final strength of 313.4 kg/cm². The results indicate that using tailings material as a fine aggregate substitute is a viable alternative for manufacturing concrete elements.

***Keywords*:** Zaruma, Portovelo, mining, tailings, paver, precast, aggregate.

1. Introduction

Mining is one of the most economically rewarding activities in countries where it is practiced. In 2016, mining accounted for 1.20% of the global GDP [1]. Due to its economic benefits, it is evident that mining has been and continues to be an essential activity for humanity. However, the lack of advanced technology in mining processes and inadequate waste management have led to serious consequences, negatively affecting human health, soil quality, air, and water [2].

The cantons of Zaruma and Portovelo in the province of El Oro exemplify both the advantages and disadvantages of mining. In this province, around 50% of the population depends on mineral extraction, yet, as in other parts of the world, there is a lack of control over waste disposal. Statistically, nearly 3,000 tons per day of tailings (**environmental liabilities**) are deposited in the sub-basins of the Puyango-Tumbes water system, causing significant pollution in the Calera and Amarillo rivers [3].

The concept of sustainability is increasingly integrated into human activities. According to Khaldoun et al., in recent years, efforts have been made to implement new environmental regulations aimed at reducing the polluting effects of mining tailings [4]. The construction sector is one of the most promising industries for applying recycling methods to mining waste. Several studies have been conducted in this regard. For example, *Reuse of mining waste as aggregates in fly ash-based geopolymers* has demonstrated the feasibility of using mining waste as a substitute for fine aggregate [5]. Thus, the interest in developing and implementing new techniques and processes that promote sustainability has been growing, aiming to reduce the use of natural resources and environmental impact through recycling, reuse, and other sustainable practices [6].

Considering the possibility of incorporating mining waste as a substitute for conventional aggregates and to promote environmental change, this study proposes the design of a precast concrete element, based on physical and mechanical regulatory requirements, using tailings material from the Zaruma-Portovelo mining extraction area as one of its components. To achieve this objective, a practical-experimental methodology was employed to determine the optimal mix design for producing pavers intended for parking lots and/or residential streets (with a required strength of 300 kg/cm²).

The materials underwent aggregate characterization tests, and additional chemical-mineralogical analyses were performed on the tailings material. The results revealed that the material exhibits cement-like properties, as it contains 62.3%

silica and 12.4% alumina. Additionally, sulfate content was less than 1%, consisting of calcium sulfate (gypsum), a common component of Portland cement, which eliminated the need for any removal process. Furthermore, traces of gold and silver were identified.

Various mix designs were developed, replacing fine aggregate with 20%, 30%, and 40% tailings material. Initially, replacement levels of 50% and 60% were also tested but were discarded due to insufficient workability and inadequate slump values. Nine test specimens were prepared for each mix design, including a control sample. These were subjected to compression tests at 7, 14, and 28 days. The results determined that the optimal mix contained 30% tailings replacement, which was then used for manufacturing the final product: the paver.

The results confirm that tailings material can be effectively used as an aggregate in concrete mixtures for paver production. This presents benefits not only for mining companies but also for the local communities near extraction sites and the environment. Utilizing tailings in precast elements helps reduce the amount of waste left exposed to the atmosphere and water sources, thereby lowering pollution levels and contributing to a more sustainable construction industry.

2. Theoretical Framework

The following section present the most relevant topics related to the research, providing a better understanding of the subject.

2.1. Mining in the Zaruma-Portovelo Mining District

Mining is the second most important economic activity in the province of El Oro. According to the Mining Regulation and Concession Agency, the Zaruma-Portovelo district is one of the most significant mining areas in Ecuador. In 2017, gold production in the province of El Oro accounted for 45.45% of the country's total gold output [7]. However, studies conducted in the area indicate significant environmental risks. Sánchez reports that 71 regulated processing plants operate in the district, but due to a lack of adequate technology and infrastructure for treating and disposing of mining waste, these facilities pose environmental hazards [3].

2.2. Mining Waste (tailings)

The waste generated from mining extraction processes is classified into three categories: solid waste, processing and metallurgy waste, and wastewater. The second category includes tailings, which are the primary focus of this research. According to Sánchez, approximately 3,000 tons of tailings are produced daily in the Zaruma-Portovelo mining district [3].

Lottermoser defines "tailings" as the residue from milling and concentration processes that extract valuable metals, minerals, fossil fuels, or coal from mined resources [8]. Tailings are composed of gangue, which is the waste material left after most valuable minerals have been extracted. This material has no economic value and is typically discarded. In the Zaruma-Portovelo mining district, around 1,560 m³ of mining waste is discharged daily into the communal tailings storage facility known as "El Tablón" [9].

2.3. Environmental Effects of Mining Waste

According to Orimoloye and Ololade, global studies on mining pollution from 1990 to 2018 have directly linked gold extraction to environmental degradation [10]. Throughout the Zaruma-Portovelo mining district, tailings of unknown origin have been found, indicating that waste is being discarded without proper regulation [3].

Fernández highlights another significant issue caused by tailings accumulation: the contamination of water bodies near processing plants. This leads to increased water turbidity and higher concentrations of potentially harmful elements. A surface water quality analysis in the district revealed cyanide levels exceeding 0.1 mg/L and copper (Cu) levels above 1.00 mg/L near processing plants. Additionally, sediment samples from the Amarillo and Calera rivers showed high levels of cadmium, arsenic, copper, lead, and zinc—exceeding the maximum limits established by environmental regulations [11].

2.4. Treatment of Tailings Material

After the mining process is completed, mined land and waste repositories must undergo rehabilitation. This is an essential part of mine planning, development, and closure, aimed at reducing the interaction of these residues with other reactants that could cause severe pollution. Some remediation strategies include selective management and isolation, disposal and mixing with other materials, the addition of organic waste, and bacterial inhibition.

In this context, Flores et al. proposed two treatments—differential flotation and gravity concentration—as remediation measures for these environmental liabilities. Their objective was to reduce the concentration of heavy metals in tailings material [12]. The Zaruma-Portovelo district faces similar issues, leading Rodríguez et al., to suggest the application of a reactive layer generating iron oxyhydrosulfates (Fe), which would limit the oxidation of waste. Their study showed an increase in iron and sulfur, a favorable outcome as it contributed to the reduction of arsenic, copper, lead, and zinc in the tailings material [13].

Determining the composition of tailings material is crucial since it serves as a fundamental step in understanding its mineralogy and chemical structure. With well-characterized material, it becomes possible to replicate methodologies that allow for its treatment and reuse as an environmental solution.

2.5. Chemical and Mineralogical Tests

The tailings material, for its use, must undergo chemical-mineralogical tests to better understand its properties; among them are: Fire Assay, Inductively Coupled Plasma Spectrometry (ICP-OES), X-ray Fluorescence (XRF), and X-ray Diffraction (XRD).

Fire Assay allows for determining the presence and concentration of gold and silver in mineral samples through the fusion of reactive agents and fluxes. On the other hand, the ICP-OES equipment, which consists of an inductively coupled plasma (ICP) and an optical emission spectrometer (OES), enables the detection and quantification of various elements by analyzing the atomic emission spectra of characteristic lines generated by this instrument.

The analysis of major and trace elements in geological materials through X-ray Fluorescence is based on the unique behavior of atoms reacting to bursts of electrons and X-rays, which allows for the identification of elements present in the samples. The relative simplicity and low cost of sample preparation, in addition to the stability and ease of operation of X-ray spectrometers, make this test one of the most widely used in geological analysis [14].

The X-ray Diffraction (XRD) test allows for characterizing materials with crystallographic structures and identifying minerals in the samples. It is based on optical interferences produced by monochromatic radiation [15].

3. Methodology

This section presents the most relevant points regarding the procedures carried out to fulfil the research objective.

3.1. Study Area

It focuses on the province of El Oro, in southwestern Ecuador; specifically, in the Zaruma-Portovelo mining sector (Figure 1), one of the most representative in the country, in terms of mining.

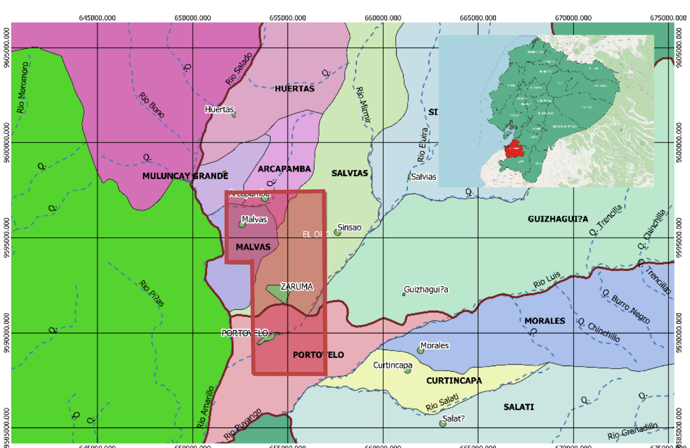

Fig. 1: Zaruma-Portovelo Mining District.

The sector has several mining companies that boost the local economy. Among them, four processing plants were visited; with Empresa Minera Reina de Fátima (EMIREIFA) being of greatest interest for the research, given that it was the only one that had a space for the disposal of waste from its mining processes (Figure 2).

Fig. 2: Tailings material deposit, EMIREIFA company.

3.2. Materials and Equipment

The materials used correspond to the aggregates necessary for the production of concrete elements: 19mm crushed gravel and coarse sand; additionally, tailings material is used as a fine aggregate.

Additionally, GU-type cement and an accelerating/plasticizing additive were used to aid the curing process of the specimen's increased strength and improve workability due to the uncertainty of the tailings material's behavior within the mixture.

Regarding the equipment used, they are detailed in the standardized documents for each test: granulometry, density an absorption, unit weight, organic impurities and moisture content.

3.3. Characterization test of aggregates

The materials are subjected to various characterization tests, thus allowing to determine their characteristics and quality, data necessary for the design of the concrete mix. The tests carried out were: Granulometry, Density and absorption, Unit weight and percentage of voids, Organic impurities, and Moisture content, following the established NTE INEN standards.

Due to the size of the particles present in the tailings material (passing the No. 4 sieve), it was subjected to tests intended for fine aggregates.

3.4. Chemical-Mineralogical Characterization Tests of Tailings Material

The tailings material was subjected to chemical-mineralogical tests, which allowed for a better understanding of its properties. Four tests were performed: Plasma Spectrometry (ICP-OES), Fire Assay, X-ray fluorescence (XRF), and X-ray diffraction (XRD). For the execution of the tests, the tailings material was previously sieved, so that the samples consisted only of particles passing the No. 200 sieve.

3.5. Proportioning/Mix design

The concrete mix is designed using the ACI 211 method, which allows obtaining an approximation of the necessary proportions of the components for 1m3 of concrete.

Once the characteristics of the components to be used were known, the mix design was carried out. Initially, a base proportioning was performed, which contained only gravel and sand as aggregates. From this, the fine aggregate was replaced by tailings material in percentages of 30%, 40%, 50%, and 60%. This incorporation in the proportioning design was done before the water correction since this material also contains a percentage of moisture.

It is worth noting that the percentages mentioned above were modified, since, at the time of making the specimens, workability problems arose in the proportioning with more than 50% tailings material as a replacement for the fine aggregate, for which the percentages were adjusted to 20%, 30%, and 40%.

3.6. Preparation of Test Elements

To verify the compressive strength, test elements were prepared, cylindrical specimens of 10cm in diameter by 20 cm in height with a volume of 1.57 dm3. Three specimens were prepared for each breaking date. The test elements were prepared following the NTE INEN 3124 standard: Concrete. Preparation and curing of test specimens in the laboratory.

3.7. Resistance Test

The prepared specimens were tested for compression at 7, 14, and 28 days, applying the NTE INEN 1573 standard: Hydraulic cement concrete. Determination of compressive strength of hydraulic cement concrete cylindrical specimens.

3.8. Physical and Mechanical Characterization of Pavers

The product validation focused specifically on its mechanical properties; for this, the *NTE INEN 3040 standard was applied: Concrete Pavers. Requirements and Test Methods.* This standard includes six tests to be developed on the pavers; however, for the present research, only two were applied: Climatic resistance and Compressive strength, with the latter being of greater interest.

4. Results and Discussion

4.1. Chemical Test of Tailings Material

Given that the tailings material is of interest for the research, it is imperative to mention the results obtained, especially in its chemical-mineralogical characterization, since, given the chemicals used in mining extraction processes, its components can contaminate and harm the concrete mix.

Once the material was subjected to fire and plasma spectrometry (ICP-OES) tests, the presence of chemical elements such as Arsenic (As) 456.10mg/L, Zinc (Zn) 159.60mg/L, Copper (Cu) 347.30mg/L and Mercury (Hg) 119.10mg/L, were determined in very high quantities compared to what is regulated in terms of limits for human consumption water, so if this material is left in unsuitable places, it could end up in channels that contaminate rivers. Furthermore, the material used still has concentrations of Silver (Ag) 6.69mg/L and Gold (Au) 0.29mg/L.

Thanks to the X-ray fluorescence test, it was possible to determine the presence of chemical compounds such as: Silicon Oxide (SiO2), Aluminum Oxide (Al2O3), and Iron Oxide (Fe2O3); in proportions of 62.3%, 12.4%, and 5.5%, respectively. In quantities less than 3%, the following were detected: Calcium Oxide (CaO), Sulfur (S), Potassium Oxide (K2O), Titanium Oxide (TiO2), Phosphorus Oxide (P2O5) and Manganese Oxide (MnO). The composition of the tailings material shows similarity to that of cement, which explains the cementitious reactions generated in the mixture, such as the low workability in percentages greater than 40% or the low slump obtained in the Abrams Cone test.

The X-ray diffraction (XRD) test showed the mineralogical composition of the tailings material; it is mostly composed of Quartz and Muscovite, with a proportion of 40.2% in both cases. The presence of sulfates in the material is less than 1% and corresponds to Calcium Sulfate, commonly called gypsum. As is known, sulfates are harmful compounds for the integrity of concrete; however, it is known that cement has gypsum as one of its components with percentages between 4% and 5%, this allows for reduce the hardening speed and provides greater workability; therefore, it is considered that the sulfate present in the analyzed tailings material is not harmful; therefore, it was not considered necessary to employ a sulfate removal process in it.

4.2. Proportions/Mix design

From the application of the ACI 211 method, the values shown in Table 1 were determined, which correspond to the control proportioning. These served as a basis for the proportioning that includes replacements with tailings material.

Table 1: Base Proportioning (without including tailings material)

Materials	Real Volume dm3	Proportions Kg		% of water	Water in weight kg	Promotions	
		Weight	Weight corrected for coarse in fines			Weight corrected by water	Unitarian
Cement	147.12	442.83	442.83			442.83	1
Water	197.5	197.50	197.50		20.12	177.38	0.40
Sand	322.65	848.58	1130.74	1.88	21.26	1151.99	2.60
Gravel	332.73	878.40	596.25	-0.19	-1.13	595.11	1.34

When the fine aggregate was replaced by tailings material, the unit proportions presented in Table 2 were obtained, where the replacement percentages 20%, 30%, and 40% are represented by 20R, 30R, and 40R respectively.

Table 2: Unit dosages (cement, sand, gravel, and tailings material)

Code	Proportions
C	1 : 2.60 : 1.34 : 0.00
20R	1 : 2.08 : 1.46 : 0.39
30R	1: 1.83 : 1.54 : 0.59
40R	1 : 1.44 : 1.55 : 0.73

4.3. Compressive Strength at 28 Days in Test Specimens

The resistance that the specimens had to achieve at 28 days corresponds to 99% of the total required resistance, which for the present investigation was 300kg/cm2; that is, they had to resist 297 kg/cm2; the resistances achieved by the control specimens (C) and those with material replacement (20R, 30R and 40R) were: C=300.37kg/cm², 20R=280.60kg/cm², 30R=314.16kg/cm² and 40R=287.56 kg/cm². Based on the results obtained, it can be mentioned that the control proportioning meets the required resistance and allows the proportioning used to be validated, a relevant result, since it was the basis for the proportioning with fine aggregate replacement.

The specimens with a replacement percentage of 20% did not meet the required resistance, assuming that the replacement made did not compensate for the amount of coarse sand that was eliminated, since the tailings material only contained particles passing the No. 4 sieve, its properties in this proportion did not allow for a balance. For their part, those specimens with a 30% replacement with tailings material not only met the required resistance but exceeded it and the values obtained in the control specimens; it can be said that considering the characteristics of the tailings material that make it a hard material, with cementitious properties, allowed for compensation and increased its resistance. Finally, regarding the proportioning with a 40% replacement, it did not meet the required resistance, it is inferred that this could be because the tailings material contains fine particles, which could produce excess fine material in the mixture, likewise, a greater amount of the material reduced the workability of the mixture, preventing a correct distribution of the aggregates, which could cause segregation of the same and, as a consequence, a reduction in its resistance.

From all the above, it was established that the optimal proportioning is that with 30% tailings material as a replacement for the fine aggregate. Figure 3 shows a detail of the performance of the different proportioning at the 3 breaking days 7, 14, and 28 days.

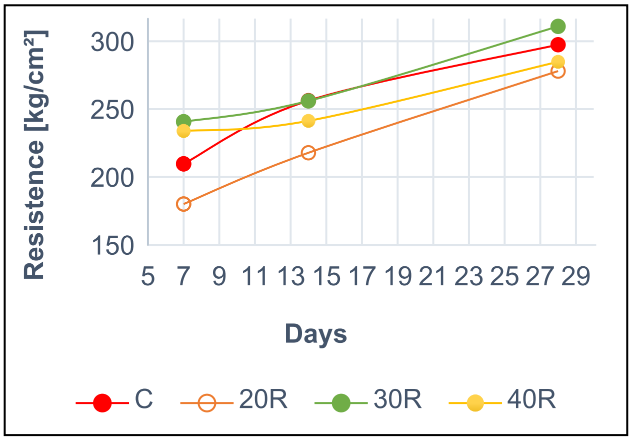

Fig. 3: Strength of the concrete mixes prepared at the three breaking dates.

The graph allows for better visualization of the resistances obtained; it is notable how the 30R proportioning shows a better performance than the rest of the proportioning and, on the other hand, the 20R proportioning had the lowest resistances; furthermore, the 30R proportioning, at 7 and 28 days, exceeds the resistances obtained with the control mix (C proportioning), denoting that a concrete mix that includes tailings material in the appropriate proportion will generate a more resistant concrete; it is estimated that the highest concrete resistance at 28 days can be obtained with a percentage of tailings material between 30% and 32%.

The replacement of tailings material in proportions greater than the optimum (30%), provides the mix with a high content of Silica and Alumina, generating a negative effect, by reducing the strength of the mix.

4.4. Compressive Strength in Pavers

For the test, it was required to obtain cores from each of the selected pavers. Three units were considered, whose resistances subjected to compression were: 312.26 km/cm2, 314.44 km/cm2, and 365.96 km/cm2. The results of the three tested cores were above the required resistance value at 28 days (297 kg/cm2 = 99% of 300 kg/cm2). The average resistance value was calculated considering the first two values that are closer to each other, obtaining an average value of 313.35 kg/cm2 equivalent to 104.45% of the required value. As can be seen, the third specimen presents a considerably high resistance, 365.96 kg/cm2, approximately sixty-six points above that established by the standard according to the type of paver selected; due to the deviation of the value concerning the first two values, it has not been included in the calculation of the average resistance; however, it is a precedent to take into consideration for its high resistance.

5. Conclusion

The present investigation had as its purpose to test the tailings material based on its performance under compressive strength tests, to determine the optimal proportioning for the preparation of concrete elements. It is concluded that the optimal proportioning is that which corresponds to a replacement of the fine aggregate by 30% of tailings material, since the test specimens prepared with this mixture met the resistances, reaching values higher than 300 kg/cm2 at 28 days; likewise, the pavers prepared with this proportioning reached an average resistance of 313.35 kg/cm2, exceeding what is required by the regulations. The presence of elements such as Silica (12.4%) and Aluminum (62.3%) in the tailings material gives it characteristics similar to those of cement, providing greater resistance to the mixture and at the same time determining that replacing the aggregate in values greater than 40% reduces workability, resulting in poor distribution of the aggregates, which leads to segregation and therefore low resistance; however, the fact of knowing that it has cementitious characteristics leaves a guideline for future research, where the tailings material is used as a replacement for cement.

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