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Valorization of Gold Mining Tailings Sludge from Vetas, Colombia as Partial Cement Replacement in Concrete Mixes

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Abstract: The accumulation and improper management of mining tailings represent significant environmental and public health challenges globally, due to their potential for water contamination and the presence of heavy metals. In recent years, various studies have explored the feasibility of using mining wastes, such as tailings sludge, as partial replacements for cement in concrete mixes. The literature highlights the pozzolanic properties of mining tailings attributable to their silica and alumina content, which contribute to the improved structural characteristics, chemical resistance, and enhanced durability of concrete. This research evaluates the specific potential of gold mining tailings sludge (REMI) from the municipality of Vetas, Santander, Colombia, as a sustainable substitute in cementitious materials. Characterization methodologies including X-ray fluorescence (XRF), X-ray diffraction (XRD), and scanning electron microscopy (SEM) confirmed the pozzolanic behavior of REMI due to its high content of silica- and alumina-rich amorphous phases and verified negligible contamination levels (Hg and cyanide below detectable limits). Concrete mixes with varying cement substitution levels (0% to 50%) were formulated and systematically evaluated to determine optimal substitution ranges based on criteria such as density, workability, setting time, and compressive strength. Consistent with previous studies, the results revealed an optimal replacement rate between 10% and 20%, with a particular emphasis on the 20% substitution achieving mechanical strengths comparable to traditional concrete. These findings underscore the technical viability and environmental benefits of using mining tailings sludge, contributing both to sustainable waste management and the advancement of eco-efficient concrete technologies.

Keywords: sludge concrete; cement replacement; road concrete; substitution; mechanical properties

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1. Introduction

Water pollution, one of the most common environmental impacts of mining, primarily originates from the direct discharge of tailings—waste generated during mineral processing—which introduce high levels of suspended solids and heavy metals (such as

arsenic, cadmium, lead, mercury, and chromium) into rivers, streams, and lakes [1,2]. These contaminants, associated with various human health complications, negatively affect the quality of life of communities that depend on these water resources [3–9].

Recognizing these risks, authorities have implemented regulatory measures to mitigate and prevent environmental impacts [1,2,10]. Given the need for mitigation and prevention strategies, it is essential to acknowledge the regulatory measures that have been introduced, such as Law 1658 of 2013 from the National Government of Colombia. This law establishes strict controls over the use and release of mercury—an element particularly problematic due to its high toxicity in air, water, and soil. Furthermore, Colombia's geological diversity provides significant potential for mineral extraction; according to the National Administrative Department of Statistics [11], mining contributes 3.8% to the country's economic growth, and the production of metallic minerals represents 14.12% of the total production value [12,13].

Specifically, the municipality of Vetas in the department of Santander is known for small-scale mining, where gold extraction using traditional tunnel techniques—a practice dating back to pre-Columbian times—generates large volumes of waste, mainly consisting of fine sands and sludges. These materials are commonly discharged into nearby water bodies; for example, the Vetas River, which accounts for approximately 30% of the Suratá River basin, is part of the water system that supplies the Metropolitan Aqueduct of Bucaramanga, a city with about 1.2 million inhabitants [14–19]. Although storing these wastes in piles has been an alternative, this method also leads to the creation of environmental liabilities, and it does not constitute a viable or sustainable long-term solution [12].

In this scenario, innovative solutions have emerged that propose the reuse of mining waste in the production of construction materials [6–9]. Recent studies have shown that both the sands and the sludges present in the tailings possess physical and chemical properties that make them suitable for incorporation into cementitious mixtures, thereby reducing dependence on conventional cement and mitigating the environmental impact resulting from the improper disposal of these wastes [20–24].

Taking the above into account, this study focuses on the application of mining tailings sludge (REMI)—considered environmental liabilities—as a partial substitute for cement in the design of 20 MPa concrete mixes aimed at constructing infrastructure on tertiary roads in the municipality of Vetas. This strategy not only contributes to a more sustainable management of mining waste but also promotes the development of low-impact concrete while reducing the extraction of natural resources. Thus, the present work offers new perspectives in the field of sustainable construction and low-impact mining, paving the way for innovative alternatives to address the environmental and health challenges associated with extractive activities.

2. Materials and Methods

2.1. Raw Material: Mining Tailings Sludge (REMI)

The mining tailings sludge (REMI) used in this study is obtained as a byproduct of the gold extraction process at the Elsy LTDA mine. Gold extraction at this facility is performed through underground mining by means of adits (socavones or tunnels), which allow access to the ore deposit. Once the mineral is extracted through these underground galleries, it is transported to the beneficiation plant where it undergoes milling and crushing. During the milling stage, the ore is finely ground, and a gravity separation process is employed to recover the gold. As a result of this beneficiation process, the residual material—consisting primarily of fine sands and sludge—is generated. This waste material, known as REMI, exhibits a heterogeneous particle size distribution and distinct physical

and chemical properties that make it a suitable candidate for partial cement replacement in concrete mixes.

Figure 1 provides an accurate cartographic representation of the location of the Elsy LTDA mine. The mine is situated in the municipality of Vetas, Santander, Colombia, placing it within a regional context and highlighting its proximity to significant water bodies and environmentally sensitive areas. This geographical location influences the management and handling of the tailings, underscoring the importance of exploring alternatives that minimize the environmental impact associated with their conventional disposal.

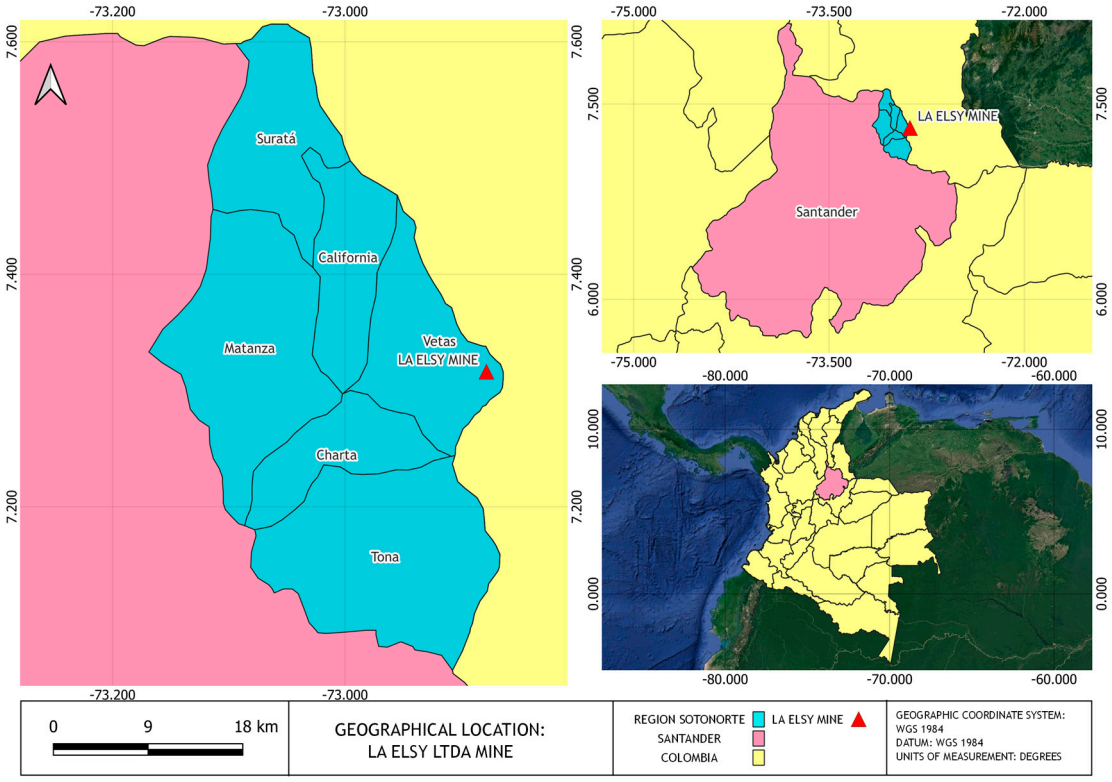


Figure 1. Geographical location of the Elsy LTDA mine.

2.1.1. Binder: Type III Portland Cement

For the formulation of concrete mixes intended for road infrastructure applications, Type III Portland Cement was selected as the binder in accordance with ASTM Type III specifications. This cement was chosen for its compliance with the quality standards set by the American Society for Testing and Materials (ASTM) and its physical characteristics, particularly the fineness of its particles, which facilitates the de-molding process. The cement's composition is characterized by a clinker content ranging from 55 to 96%, a variable presence of quartz carbonate (0–16%), and a moderate content of calcium carbonate (2–30%). These properties ensure that the cement delivers adequate structural performance in the evaluated formulations, even when partially substituted with REMI.

2.1.2. Aggregates

The aggregates used in the formulation of the concrete mixes were carefully selected to ensure the quality and strength of the final product. For the coarse aggregate, conventional gravel from the Soto Norte region (Santander) was used, which complies with the specifications for a maximum nominal size of 19 mm. This material has a moisture content between 1.6 and 2%, corresponding to an approximate absorption of 1.52%, and a compacted unit mass of 1350 kg/m^3—essential attributes that guarantee its structural performance. In contrast, the fine aggregate was obtained directly from the rock used as raw material in the

gold extraction process, resulting in a residue with a fineness modulus of 1.4. This residue is characterized by a mineralogical composition that exhibits a high concentration of silicon dioxide (74.6% SiO_2) and a significant presence of aluminum oxide (Al_2O_3).

2.2. Mix Design and Formulation

To achieve an appropriate formulation in concrete mixes—where the partial substitution of cement through the incorporation of mining tailings (REMI) is evaluated—a two-stage process was implemented: determining the mix composition using the American Concrete Institute's (ACI) absolute volume method and experimentally selecting the cement replacement percentage.

2.2.1. Mix Design Methodology

The mix design is based on the absolute volume method proposed by the ACI Committee 211.1 of the American Concrete Institute (ACI). This approach starts from a unit volume of 1 m^3, from which the volume occupied by the known components of the mix—water, cement, coarse aggregate, and fine aggregate—is subtracted in order to establish their respective proportions. In particular, the volume of fine aggregate is determined as the difference between the total volume and the sum of the volumes of water, cement, and coarse aggregate. In the present study, a concrete mix was designed that incorporates 20% mining tailings sludge (REMI) in the cementitious fraction. To achieve this, the ACI method was applied using a mix proportion of 1:2:3 (one part cement, two parts sand, and three parts gravel), where both the REMI sludge and the aggregates are maintained in their natural state, preserving their associated moisture. This strategy aims to ensure a homogeneous distribution of components while preserving the fundamental properties necessary for the proper development of the strength of the concrete.

2.2.2. Selection of the Cement Replacement Percentage with REMI

The cement replacement with REMI was evaluated by preparing concrete mixtures with substitution levels of 0%, 10%, 20%, 30%, 40%, and 50% of the cementitious material. For each formulation, the mix design was established using the absolute volume method, ensuring that 1 m^3 of concrete was produced while maintaining the predetermined ratios of aggregates. The proportions of cement, REMI, sand, and gravel were carefully adjusted to achieve consistent workability and density. In order to obtain a normal mix consistency, the water dosage was modified in accordance with NTC 110, and the density of the cementitious fraction was verified following NTC 221. Detailed mix proportions—showing the specific amounts of cement, REMI, sand, and gravel per cubic meter for each replacement level—are provided in Table 1.

Table 1. Mix proportions of cement, REMI, sand, and gravel per 1 m^3 of concrete at different replacement levels.

Sample	Binders		Sand	Gravel
	Cement	REMI		
Dose 100:0	1	0	2	3
Dose 90:10	0.9	0.1	2	3
Dose 80:20	0.8	0.2	2	3
Dose 70:30	0.7	0.3	2	3
Dose 60:40	0.6	0.4	2	3
Dose 50:50	0.5	0.5	2	3

2.3. Manufacturing and Strength Testing

To evaluate the mechanical performance of the concrete mixes modified with REMI, standardized protocols were followed for the preparation, curing, and strength tests, thereby ensuring the reproducibility and reliability of the results.

2.3.1. Sample Preparation and Curing

The samples were manufactured in accordance with NTC-454 [25], using cylindrical molds of 6 × 12 inches. In each mold, the concrete was placed in layers, with each layer being compacted by applying 25 uniform taps using stainless steel rods of 5/8 inches in diameter in order to ensure the required homogeneity and density. Once molded, the samples were subjected to standard curing according to the guidelines established in NTC-550, which allowed for the proper hydration of the cement and the progressive development of strength [26].

2.3.2. Compressive Strength Tests

The evaluation of mechanical strength was carried out through compressive tests performed at 7, 14, and 28 days of curing. For this purpose, the CT-1503/UPE Controls, DPX equipment (CONTROLS S.p.A., Milan, Italy) was used, which allowed for the application of load in a controlled manner and at a predefined rate of 0.25 MPa/s, as specified in NTC-673. These tests provided fundamental data on the evolution of strength over time, allowing the comparison of the performance of the mixes with different percentages of cement substituted with REMI.

2.4. Chemical and Mineralogical Characterization

The characterization of REMI was conducted with the objective of determining its elemental composition, identifying the mineral phases present, and evaluating its pozzolanic behavior, thus establishing a correlation between its chemical properties and its potential application as a partial substitute for cement.

2.4.1. Chemical Analysis

For the determination of the elemental composition, X-ray fluorescence (XRF) techniques and spectrophotometric methods were employed. Firstly, a spectrometer from the Bruker S8 Tiger series (Na-U) was used to quantify the main constituents of the material. Additionally, contaminant levels were evaluated. The determination of total cyanide (CN^-) was performed by subjecting the sample to acid reflux distillation for three hours, followed by volumetric titration with silver nitrate ($AgNO_3$), according to the SM 4500 CN-A2b, C, D method, with a quantification limit of 50 $mg \cdot kg^{-1}$. For the quantification of mercury (Hg), the sample was digested with concentrated nitric acid (HNO_3) and analyzed by flame atomic absorption spectrophotometry (air/acetylene/nitrous oxide), using certified standards, establishing a quantification limit of 1.5 $mg \cdot kg^{-1}$. Likewise, the contents of gold (Au) and silver (Ag) were determined.

2.4.2. Mineralogical Analysis

The identification and quantification of the mineral phases present in the REMI were carried out by XRD using a Bruker AXS D8 Advance diffractometer (Na-U) (Bruker AXS GmbH, Karlsruhe, Germany). A scan was performed over a range from 4° to 75° with a step size of 0.01° per step, and the obtained profiles were analyzed using the Rietveld method to determine both the crystalline nature and the fraction of amorphous material present in the sample. In addition, SEM was performed using a Nova NanoSEM 200 microscope (FEI Company, Eindhoven, The Netherlands) under high vacuum conditions and at a voltage of 30 kV.

3. Results and Discussion

3.1. REMI Material Characterization

3.1.1. Physical and Morphological Characterization

Figure 2 presents a comparative view of the appearance of the REMI material under two fundamental conditions. In Figure 2a, the REMI is shown directly as recovered from the storage tank in a saturated state, whereas in Figure 2b, the same material is displayed after being dried in an industrial oven (100 ± 5 °C, 24 h). This visual comparison is important for understanding how the state of the material influences its physical properties and, consequently, its behavior when incorporated into concrete mixes.

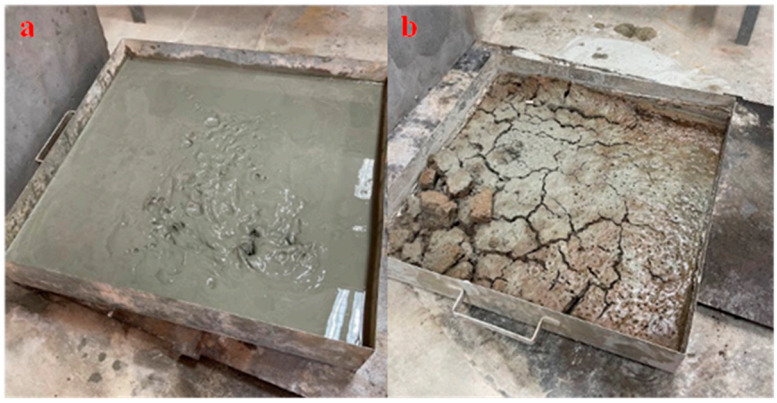


Figure 2. Appearance of REMI sludge material: (**a**) REMI material recovered from the storage tank without moisture loss; (**b**) REMI material after drying in an industrial oven.

The results demonstrate that the state of REMI significantly influences its physical properties and, consequently, its behavior when incorporated into concrete mixes. In its wet state, the material exhibits a uniform texture and notable cohesion, which favors a homogeneous distribution of the particles and contributes to the proper control of the water-to-cement ratio, a critical element for efficient cement hydration. When dried in an industrial oven, REMI undergoes a marked morphological transformation characterized by a crumbly texture, fractured aggregates, and increased surface roughness, which reduces particle cohesion but may facilitate more efficient packing within the cementitious matrix. These differences are of great importance, as they allow the modulation of the characteristics of the material through controlled physical treatment, opening the possibility of adjusting fundamental parameters in mix design. The water dosage and the selection of the cement replacement percentage directly benefit from this adaptability, which could enhance the hydration reaction and improve the mechanical performance of the concrete [27].

Figure 3 shows the particle size distribution of four sand samples extracted from the tailings (SS1, SS2, SS3, and SS4), in which the frequency curves of the particle sizes are displayed along with the uniformity coefficients (Cu) and curvature coefficients (Cc) calculated for each sample.

The analysis in Figure 3 covers a size range of approximately 0.1 to 100 µm, which classifies the material as very fine, placing it at the boundary between very fine sand and silt. On average, a Cu value of 2.9 was obtained, which indicates moderate variability in particle sizes that favors adequate packing and, consequently, a reduction in the porosity of the mix. Likewise, the average Cc value of 0.87 indicates a relatively concentrated and symmetrical distribution around the mid-point. Although in geotechnical applications optimal Cc values are usually considered to be between 1 and 3, for the design of cementitious mixes, a material with such fine and relatively uniform granulometry can be effectively integrated, especially when combined with other aggregates or when the dosage is adjusted. Recent studies [17,23] have demonstrated that, although mining tailings exhibit finer particle sizes

than conventional sands, their incorporation into concrete mixes is feasible and can even enhance the cohesion of the cementitious matrix, provided that precise adjustments are made in the dosage and the proportion of fines is adequately controlled [17]. These results underscore the technical viability of using mining tailings as fine aggregate, which not only improves the mechanical properties of the concrete but also contributes to sustainability by reducing the extraction of natural aggregates and promoting the responsible management of industrial waste [28].

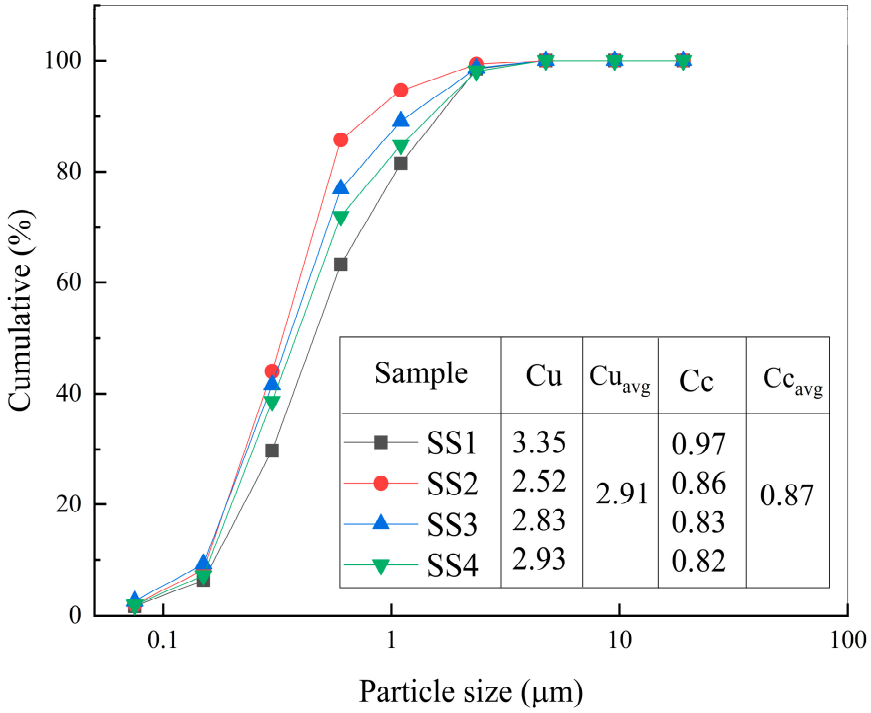


Figure 3. Granulometric distribution of SS1, SS2, SS3, and SS4.

3.1.2. Chemical and Mineralogical Characterization

The XRD analysis allowed for the identification and quantification of the mineral phases present in the REMI material, as shown in Table 2. According to the results obtained, quartz represents the predominant crystalline phase with 28.49%, followed by orthoclase with 9.54%. Among the clay-like phases and other minerals, two fractions of dickite (7.85% and 1.38%), muscovite (5.27%), and alunite (3.02%) were identified, in addition to a minor presence of pyrite (1.39%). The amorphous fraction constitutes 43.06% of the total, which suggests a high potential for pozzolanic reactivity [29].

Table 2. Percentage amounts of crystalline phases identified by XRD.

Crystalline Phases Identified by XRD			
Sample	Tailings Slurry Mine: La Elsy LTDA		
	Name	Formula	Quantity
Crystalline	Quartz	SiO_2	28.49%
	Orthoclase	$(K_{0.931}Na_{0.055}Ca_{0.009}Ba_{0.005})$ $(Al_{0.97}SI_{3.03}O_8)$	9.54%
	Dickite	$Al_2Si_2O_5$ $(OH)_4$ $(HCONH_2)$	7.85%
	Muscovite	$(K_{0.99}Na_{0.02})$ $(Al_{1.42}Mg_{0.33}Fe_{0.24}Ti_{0.04})$ $((Si_{3.45}Al_{0.55})$ $O_{10})$ $(OH)_2$	5.27%
	Alunira	$(K_{0.805}Na_{0.132}(H_2O)_{0.063})$ $Al_3(SO_4)_2(OH)_6$	3.02%
	Pyrite	$FeS_{1.92}$	1.39%
	Dickite	$Al_2Si_2O_5$ $(OH)_4$	1.38%
	Amorphous		43.06%

The significant presence of quartz, although inert, can serve as a filler and improve the microstructure of the concrete [30]. Orthoclase, in turn, indicates the presence of feldspars, which is typical in mining tailings and may influence the physical properties of the material. The detection of clay minerals, such as dickite and muscovite, is particularly relevant because these compounds can develop pozzolanic reactivity in an alkaline environment, thereby favoring the hydration and densification of the cementitious matrix [31,32]. Similarly, the low content of pyrite minimizes the risk of generating adverse reactions or contamination in the concrete [33]. The high percentage of amorphous phase (43.06%) is an important indicator, as these non-crystallized components generally exhibit greater chemical reactivity, which supports the hypothesis that REMI can function as a partial substitute for cement [12,34].

Table 3 presents the results of the elemental analysis of REMI, in which the contents of metals of interest were quantified and contaminant levels were evaluated. Specifically, it was found that the material contains 2.55 g of gold per ton and 32.11 g of silver per ton. These values indicate the presence of precious metals in moderate amounts, which could provide added value in terms of recovery; however, in this study, the main focus is on its application in concrete mixes, emphasizing that these values render the material of low mining interest, thereby classifying it as waste or an environmental liability [35].

Table 3. Percentage amounts of crystalline phases identified by XRF.

Sample	Au g Ton^{-1}	Ag g Ton^{-1}	Hg mg kg^{-1}	Cyanide mg kg^{-1}
REMI	2.55	32.11	0	0

On the other hand, the levels of mercury and cyanide were below the quantification limit (<L.C.), which guarantees that the material does not pose an environmental or health risk associated with toxic contaminants. This favorable chemical profile supports the suitability of REMI for incorporation into cementitious formulations, while promoting sustainability through the reuse of mining waste. The data presented in Table 3 confirm that, despite containing metals, REMI is a non-contaminating material, making it a viable option for partially substituting cement in concrete mixes intended for road infrastructure.

Figure 4 presents the complementary results of the chemical and mineralogical characterization of REMI. Figure 4A shows the quantitative chemical composition of REMI, determined by XRF. It highlights the high proportion of silicon dioxide (50.58% SiO_2), accompanied by significant amounts of aluminum oxide (13.85% Al_2O_3) and potassium oxide (4.36% K_2O), while oxides such as Fe_2O_3, MgO, CaO, and Na_2O are present in lower proportions. This distribution suggests the coexistence of silica-rich phases, feldspars, and clay minerals, which is consistent with the XRD results [36]. The high silica content fulfills a dual function in the cementitious matrix: on one hand, it acts as an inert filler that contributes to densification, and on the other hand, it may possess pozzolanic potential if part of that content is in an amorphous state [15,37]. Similarly, the presence of Al_2O_3 and K_2O supports the existence of feldspars and clays, which also contribute to the pozzolanic reactivity and cohesion of the concrete mix [38].

Regarding the minor elements such as Ag, W, Cr, Ni, Sn, and Ga, their concentrations are in the ppm range, which suggests that although they may be relevant as trace metals, they do not reach levels that compromise the viability of the material as a partial substitute for cement [39]. Previous studies have indicated that the incorporation of mining waste with high contents of silica and metallic oxides can improve the mechanical performance of concrete, provided that the absence of toxic contaminants at critical concentrations is verified [38,40]. On the other hand, this analysis confirms that the levels of mercury (Hg) and cyanide (CN^-) are below the quantification limit, reaffirming that REMI does

not represent a significant environmental risk. This chemical composition suggests that REMI can contribute stability and homogeneity to the concrete mix, which is essential for achieving adequate mechanical performance [41,42].

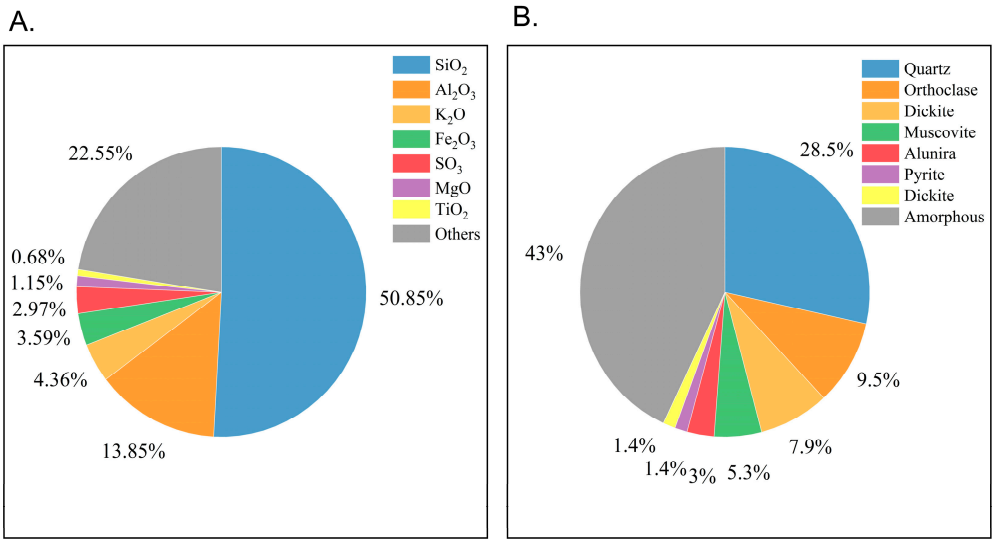
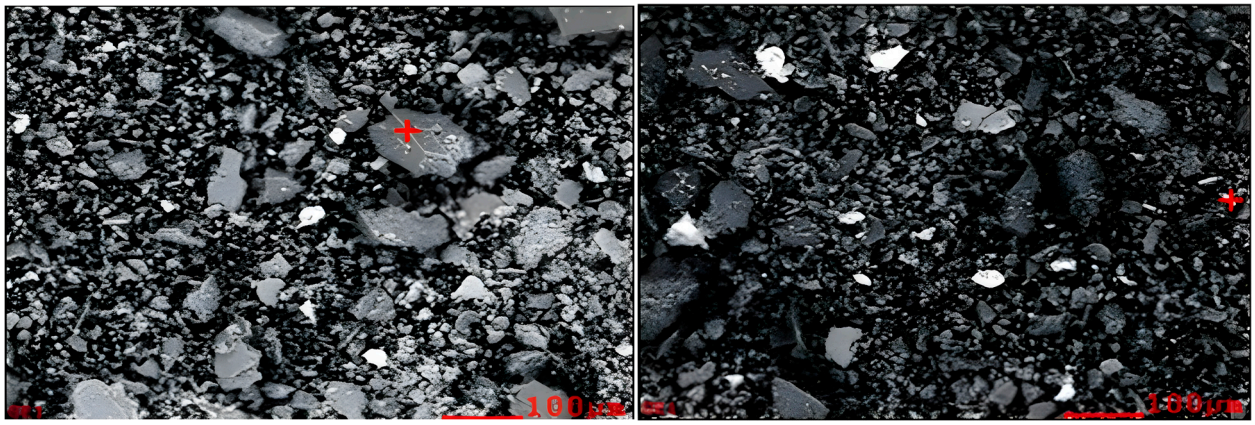


Figure 4. Elemental and crystalline composition of waste samples: (**A**) XRF analysis, (**B**) XRD characterization.

Figure 4B presents a graphical representation of the identification of mineral phases using XRD. Of particular importance is the significant amorphous fraction (43.06%), which indicates a considerable pozzolanic potential. Since amorphous components typically react in alkaline environments to form hydration products, this characteristic can contribute to the improvement of the strength and durability of the concrete [43,44].

Figure 5 presents the SEM micrographs of REMI, which reveal notable heterogeneity in the particle morphology. Angular edges, rough surfaces, and laminar structures can be observed, which is consistent with the presence of minerals such as quartz, feldspars, and clay minerals identified through XRD [45,46]. Additionally, areas where the amorphous fraction clusters are observed together, suggesting considerable pozzolanic potential.



(**a**) (**b**)

Figure 5. Scanning electron microscopy (SEM) analysis of REMI: microstructural overview and detailed observation of heavy metal particle distribution. (The red "+" symbol marks the location of metals present in the sample during elemental mapping.)

Figure 5a,b show some particles with a whitish tint, which are associated with traces of metals such as Au and Ag, in agreement with the findings reported by Ince [37]. The

REMI sample exhibits a structure that combines particles of various sizes and irregular shapes, a direct result of the gold milling and processing operations to which it has been subjected [22,47,48]. Previous studies have demonstrated that milling procedures significantly influence the morphology of the material [16]. The morphological characteristics shown in Figure 5, together with the chemical composition identified in Figure 4, support the hypothesis that REMI exhibits pozzolanic behavior in the concrete matrix, positioning it as a potential partial substitute for cement [18,49].

3.2. Evaluation of the Performance of the Modified Concrete

3.2.1. Physical Behavior of the Materials

Figure 6 presents three key parameters of physical/mechanical performance when cement is partially substituted with mining tailings sludge (REMI) at various percentages (0, 10, 20, 30, 40, and 50%). Figure 6A shows the variation in mix density (REMI/cement) as a function of the percentage of cement substituted by REMI. It can be observed that as the proportion of REMI increases from 0% to approximately 30%, the density tends to increase, reaching a maximum value close to 3.2 g/cm^3. This initial behavior can be attributed to improved particle packing: the granulometry and the presence of fines inherent to REMI may fill the voids between the cement particles, thereby increasing the overall density of the mix [50,51].

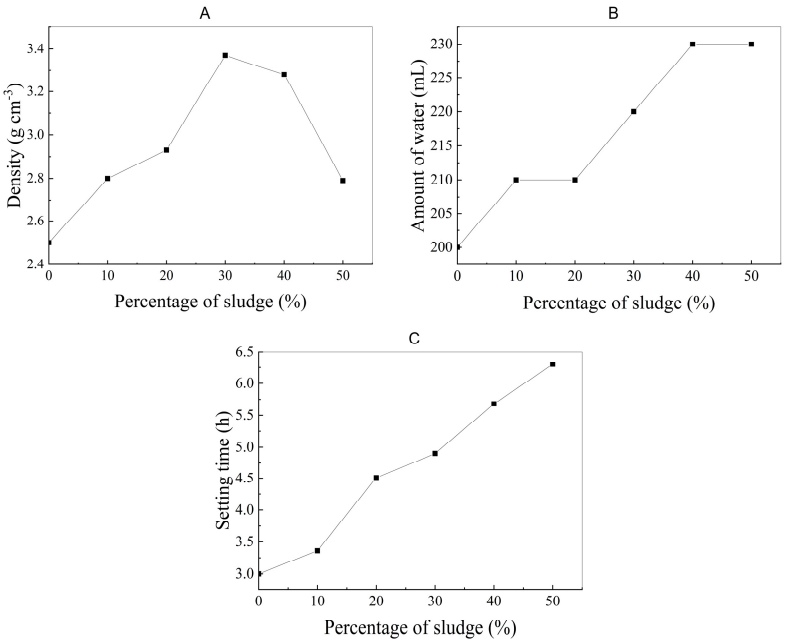


Figure 6. Physical behavior of the materials: (**A**) density variation; (**B**) normal consistency change; (**C**) setting time variation with material substitution.

However, from 30% substitution onward, the density begins to decrease, settling at approximately 2.7 g/cm^3 at 50% replacement. This decrease is related to the excess tailings material, which, by displacing a significant fraction of clinker, reduces the cohesion and possibly increases the porosity of the matrix, resulting in a less dense mix. In addition, the presence of clay minerals and the amorphous fraction of REMI may promote water retention, which also affects the final compactness of the mix [43,52].

In the context of concrete mixes used for road infrastructure, the increase in density up to around 30% substitution suggests an interval where REMI contributes benefits in particle packing without compromising the cohesion of the cementitious matrix. However, complementary studies on mechanical strength and durability usually indicate that a

substitution rate of around 20% provides a better balance between density and mechanical properties, as has been reported in previous research on the use of mining waste [53,54].

Figure 6B shows how the amount of water required to achieve normal mix consistency varies as the percentage of REMI increases. It is observed that, as the substitution level increases from 0% to 50%, the water demand progressively increases. This behavior is largely explained by the higher absorption capacity of REMI, due to its high fineness and the presence of clay minerals, which necessitates more water to achieve a homogeneous distribution of the particles. Additionally, as the proportion of tailings increases, the specific surface area of the material rises, thereby retaining a greater amount of water. The reduction in the cement fraction also means that more water is needed to compensate for the lower chemical activity and to maintain workability.

On the other hand, the curve in Figure 6B indicates that up to a 20–30% substitution level, the increase in water demand is moderate; however, beyond that range, the increase becomes more pronounced. This suggests that if the replacement exceeds approximately 30%, the final strength and durability of the concrete could be compromised due to a high water-to-cement ratio [32]. Therefore, for this work, a substitution range of 20% is proposed, as this percentage allows one to take advantage of the benefits of REMI in terms of both filler effect and pozzolanic potential without requiring an excess of water that could adversely affect the cementitious matrix [15].

Figure 6C shows how the setting time of the mix increases as cement is substituted with REMI. In the control mix, corresponding to 0% substitution, the initial set is reached in approximately 3 h, while with 50% REMI, the time extends to nearly 5 h. This increase in setting time can be attributed to several interrelated factors. First, the progressive reduction in the clinker fraction, which is the active component in hydration, decreases the rate of hardening reactions. Second, REMI possesses high fineness and, according to the XRD analysis, shows a high proportion of amorphous phase (43.06%) along with the presence of clay minerals such as dickite and muscovite (Figure 4).

These components have a notable capacity to absorb water, which delays the availability of water for cement hydration and, consequently, prolongs the setting time [18]. The behavior observed in Figure 6C suggests that, up to around 20–30% substitution, the increase in setting time is moderate, allowing workability to be maintained. However, percentages above this range lead to a considerable delay, which could compromise the early development of strength [55].

3.2.2. Mechanical Performance and Comparison with Conventional Concrete

Figure 7 presents the evolution of compressive strength at 7, 14, and 28 days for concrete mixes with different percentages of cement substituted with REMI. The control mix (0% REMI) is represented in blue, 10% in green, 20% in red, 30% in yellow, 40% in orange, and 50% in purple.

Upon analyzing Figure 7, the initially expected behavior is observed in the reference mixture (0% substitution), which exhibits significant strength development from early stages, reaching approximately 75% to 80% of the specified maximum strength at 14 days. This finding aligns with the existing technical literature regarding the typical performance of Portland cement, whose active components enable rapid mechanical strength development [18,56]. When introducing a substitution percentage of 10% with mining tailings sludge (REMI), a slight reduction in strength at 14 days is observed compared to the control mixture. However, this mixture successfully meets the expected strength of 20 MPa at 28 days. A similar but more pronounced behavior is observed in the mixture with a 20% substitution. Although this formulation shows slower strength development—as evidenced by lower values at 14 days compared to the control mixture—it nonetheless reaches the

required 20 MPa at 28 days. This reduction in the rate of strength development can be attributed to a decreased effective content of active clinker, which is primarily responsible for early strength, and to the significant presence of amorphous phases and clay minerals such as dickite and muscovite, identified through mineralogical analysis (XRD). These components possess pozzolanic properties, reacting slowly in the presence of calcium hydroxide produced during cement hydration, thus delaying early strength development but positively contributing to mechanical performance at later stages [57].

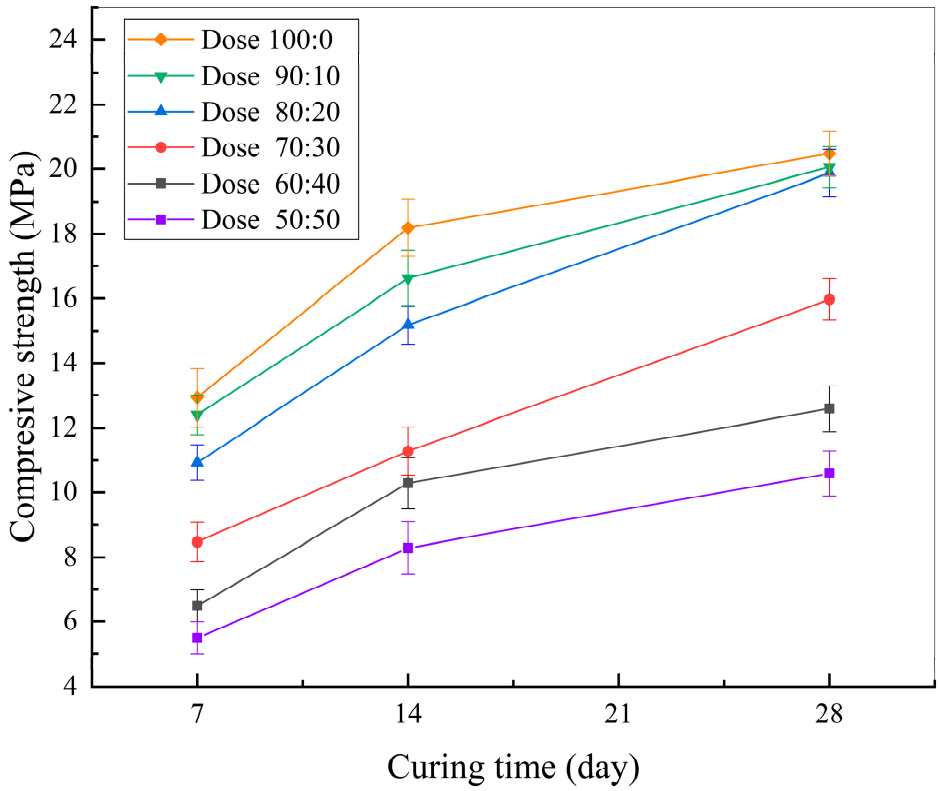


Figure 7. Compressive strength of the mix designs tested at 7, 14, and 28 days of curing time.

In contrast, mixtures with higher substitution percentages (30%, 40%, and 50%) fail to achieve the required strength (20 MPa) at 28 days, limiting their direct application in road infrastructure projects that demand higher mechanical performance. Nevertheless, these formulations show considerable potential for use in applications with lower structural requirements or non-load-bearing elements, where mechanical performance may be less critical. This alternative approach offers significant environmental and social benefits, as it enables the effective utilization of substantial environmental liabilities, such as mining tailings sludge, generated in large quantities in mining areas, which represent a significant source of pollution [58]. Moreover, these mixtures do not pose risks associated with critical contaminants such as cyanide and mercury (Hg), positioning them as a safe and environmentally favorable option for various sustainable construction applications. Finally, it is clearly established that the optimal identified condition is the mixture with 20% substitution of REMI, owing to its technical and environmental balance. This mixture provides adequate, albeit slower, development of the required strength while effectively utilizing mining waste with proven pozzolanic potential and no associated toxic risks. Thus, it emerges as an innovative and environmentally responsible strategy for the construction sector.

4. Conclusions

This study demonstrates that using mining tailings sludge (REMI) as a partial cement replacement is not only technically viable but also environmentally advantageous. By characterizing REMI through XRF, XRD, and SEM analyses, we established its high pozzolanic potential—attributed to a significant amorphous fraction and the presence of reinforcing mineral phases—which enhances the densification and overall integrity of the concrete matrix. Our experimental investigation, which compared substitution levels from 0% to 50%, indicates that a replacement level between 10% and 20%—particularly at 20%—achieves compressive strengths comparable to those of conventional concrete while effectively utilizing an otherwise hazardous waste material. This approach adds scientific value by transforming an environmental liability into a sustainable resource, thereby reducing the extraction of natural aggregates and mitigating pollution issues in mining regions. The findings also provide a robust foundation for the development of eco-efficient concrete technologies applicable to low-impact infrastructure projects. Future studies will extend these results by exploring durability under various environmental stressors, further establishing the practical relevance of REMI in industrial concrete production.

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References

1. Barcelos, D.A.; Pontes, F.V.M.; da Silva, F.A.N.G.; Castro, D.C.; dos Anjos, N.O.A.; Castilhos, Z.C. Gold mining tailing: Environmental availability of metals and human health risk assessment. *J. Hazard. Mater.* **2020**, *397*, 122721. [CrossRef] [PubMed]
2. Belle, G.; Fossey, A.; Esterhuizen, L.; Moodley, R. Contamination of groundwater by potential harmful elements from gold mine tailings and the implications to human health: A case study in Welkom and Virginia, Free State Province, South Africa. *Groundw. Sustain. Dev.* **2021**, *12*, 100507. [CrossRef]
3. Babayan, G.; Sakoyan, A.; Sahakyan, G. Drinking water quality and health risk analysis in the mining impact zone, Armenia. *Sustain. Water Resour. Manag.* **2019**, *5*, 1877–1886. [CrossRef]
4. Gombert, P.; Sracek, O.; Koukouzas, N.; Gzyl, G.; Valladares, S.T.; Frączek, R.; Klinger, C.; Bauerek, A.; Areces, J.E.Á.; Chamberlain, S.; et al. An Overview of Priority Pollutants in Selected Coal Mine Discharges in Europe. *Mine Water Environ.* **2019**, *38*, 16–23. [CrossRef]
5. Lu, J.; Lu, H.; Lei, K.; Wang, W.; Guan, Y. Trace metal element pollution of soil and water resources caused by small-scale metallic ore mining activities: A case study from a sphalerite mine in North China. *Environ. Sci. Pollut. Res.* **2019**, *26*, 24630–24644. [CrossRef] [PubMed]
6. Palmer, M.J.; Chételat, J.; Richardson, M.; Jamieson, H.E.; Galloway, J.M. Seasonal variation of arsenic and antimony in surface waters of small subarctic lakes impacted by legacy mining pollution near Yellowknife, NT, Canada. *Sci. Total Environ.* **2019**, *684*, 326–339. [CrossRef]

7. Cáceres, D.D.; Flores Jiménez, P.; Hernández, K.; Peres, F.; Maldonado, A.K.; Klarián, J.; Cáceres, D.A. Health risk due to heavy metal(Loid)s exposure through fine particulate matter and sedimented dust in people living next to a beach contaminated by mine tailings. *Rev. Int. Contam. Ambient.* **2021**, *37*, 211–226. [CrossRef]
8. Dusengemungu, L.; Mubemba, B.; Gwanama, C. Evaluation of heavy metal contamination in copper mine tailing soils of Kitwe and Mufulira, Zambia, for reclamation prospects. *Sci. Rep.* **2022**, *12*, 1–16. [CrossRef]
9. Lemos, M.G.; Valente, T.M.; Marinho Reis, A.P.; Ferreira Fonseca, R.M.; Guabiroba, F.; da Mata Filho, J.G.; Magalhães, M.F.; Delbem, I.D.; Rebelo Diório, G. Adding Value to Mine Waste through Recovery Au, Sb, and As: The Case of Auriferous Tailings in the Iron Quadrangle, Brazil. *Minerals* **2023**, *13*, 863. [CrossRef]
10. Pabón, S.E.; Benítez, R.; Sarria-Villa, R.A.; Gallo, J.A. Water contamination by heavy metals, analysis methods and removal technologies. A review. *Entre Cienc. Ing.* **2020**, *14*, 9–18. [CrossRef]
11. Cuevas, J.G.; Faz, A.; Martínez-Martínez, S.; Gabarrón, M.; Beltrá, J.C.; Martínez, J.; Acosta, J.A. Spatial distribution and pollution evaluation in dry riverbeds affected by mine tailings. *Environ. Geochem. Health* **2023**, *45*, 9157–9173. [CrossRef]
12. Departamento Administrativo Nacional de Estadística (DANE)—Colombia. *Boletín técnico Producto Interno Bruto (PIB) II Trimestre*; Departamento Administrativo Nacional de Estadística (DANE)—Colombia: Bogotá, Colombia, 2023.
13. Wolff-Carreño, E.; Pinzón-Angel, J.M.; Contreras-Moreno, R.; Bernardy, C. Geological setting, mining and reduction of mercury vapor contamination in the gold-silver district of Vetas-Calofornia (Santander, Colombia). *Episodes* **2005**, *28*, 252–256. [CrossRef] [PubMed]
14. Departamento Administrativo Nacional de Estadística (DANE)—Colombia. *Análisis Económico y Social de la Minería en Colombia: Retos y Oportunidades*; Departamento Administrativo Nacional de Estadística (DANE)—Colombia: Bogotá, Colombia, 2021.
15. Romero, A.; Silvana, F. Reuse of mining tailing as raw crude for the elaboration of aggregates of contruction for the making of bricks and tile. *Ind. Data Investig. J.* **2010**, *13*, 75–82.
16. Méndez, D.; Guzmán-Martínez, F.; Acosta, M.; Collahuazo, L.; Ibarra, D.; Lalangui, L.; Jiménez-Oyola, S. Use of Tailings as a Substitute for Sand in Concrete Blocks Production: Gravimetric Mining Wastes as a Case Study. *Sustainability* **2022**, *14*, 16285. [CrossRef]
17. Pardo, N.; Penagos, G.; Correa, M.; López, E. Development of low environmental impact mortars from alkaliny activated silical-aluminum waste from the mining sector. *Bol. Soc. Esp. Ceram. Vidr.* **2021**, *62*, 11–25. [CrossRef]
18. Gou, M.; Zhou, L.; Then, N.W.Y. Utilization of tailings in cement and concrete: A review. *Sci. Eng. Compos. Mater.* **2019**, *26*, 449–464. [CrossRef]
19. Franco de Carvalho, J.M.; Fontes, W.C.; de Azevedo, C.F.; Brigolini, G.J.; Schmidt, W.; Peixoto, R.A.F. Enhancing the eco-efficiency of concrete using engineered recycled mineral admixtures and recycled aggregates. *J. Clean. Prod.* **2020**, *257*, 120530. [CrossRef]
20. Ramos-Hernández, M.; Pérez-Rea, M.d.l.L. Characterization of mine tailings in their natural state and stabilized with cement, focused on construction Caracterización de residuos mineros en estado natural y estabilizados con cemento, enfocada a construcción. *Ing. Investig. Tecnol.* **2021**, *22*, 1–9. [CrossRef]
21. Amaral, I.B.C.; Cavalcante, L.C.D.; Fabris, J.D.; Prat, B.V.; Reis, A.B. Use of mining tailings or their sedimentation and flotation fractions in a mixture with soil to produce structural ceramics. *Sustainability* **2021**, *13*, 911. [CrossRef]
22. Solismaa, S.; Torppa, A.; Kuva, J.; Heikkilä, P.; Hyvönen, S.; Juntunen, P.; Benzaazoua, M.; Kauppila, T. Substitution of cement with granulated blast furnace slag in cemented paste backfill: Evaluation of technical and chemical properties. *Minerals* **2021**, *11*, 1068. [CrossRef]
23. Garcia-Troncoso, N.; Baykara, H.; Cornejo, M.H.; Riofrio, A.; Tinoco-Hidalgo, M.; Flores-Rada, J. Comparative mechanical properties of conventional concrete mixture and concrete incorporating mining tailings sands. *Case Stud. Constr. Mater.* **2022**, *16*, e01031. [CrossRef]
24. Romero-Perdomo, F.; Carvajalino-Umaña, J.D.; López-González, M.; Ardila, N.; González-Curbelo, M.Á. The private sector's role in Colombia to achieving the circular economy and the Sustainable Development Goals El rol del sector privado en Colombia para alcanzar la economía circular y los Objetivos de Desarrollo Sostenible. *DYNA* **2023**, *90*, 9–16. [CrossRef]
25. *NTC 454*; Standard Test Method for Sampling Freshly MIixed Concrete. Instituto Colombiano de Normas Técnicas y Certificación—ICONTEC: Bogotá, Colombia, 2022.
26. *NTC 550:2020*; Standard Test for Making and Curing of Concrete Test Specimens in the Field. Instituto Colombiano de Normas Técnicas y Certificación—ICONTEC: Bogotá, Colombia, 2020.
27. Saedi, A.; Jamshidi-Zanjani, A.; Darban, A.K. A review on different methods of activating tailings to improve their cementitious property as cemented paste and reusability. *J. Environ. Manag.* **2020**, *270*, 110881. [CrossRef]
28. Tariq, A.; Yanful, E.K. A review of binders used in cemented paste tailings for underground and surface disposal practices. *J. Environ. Manag.* **2013**, *131*, 138–149. [CrossRef] [PubMed]
29. Cordero, C.; Marchevsky, N.; Chiacchiarini, P.; Giaveno, M. Caracterización física, química y mineralógica de un antiguo relave, en busca de alternativas de reutilización. *Minería Geol.* **2022**, *38*, 70–82.

30. Casadiego Quintero, E.; Gómez Ríos, W.R.; Monroy, E.L.; Sánchez Londoño, J. Sustainable gold mining: Implications of the use of waste as an aggregate for concrete. *Inventum* **2021**, *16*, 71–77. [CrossRef]
31. Yagüe, S.; Sánchez, I.; De La Villa, R.V.; García-Giménez, R.; Zapardiel, A.; Frías, M. Coal-mining tailings as a pozzolanic material in cements industry. *Minerals* **2018**, *8*, 46. [CrossRef]
32. Liu, Y.; Jiang, Y.; Li, F.; Xue, B.; Cao, X. Pore Structure Control of Expanded Dickite and Its Application as a Clay Coating Layer on Cross-Linked Nonwoven Fabrics for Lithium-Ion Batteries. *J. Electrochem. Soc.* **2019**, *166*, A1082. [CrossRef]
33. Jamieson, H.E.; Walker, S.R.; Parsons, M.B. Mineralogical characterization of mine waste. *Appl. Geochem.* **2015**, *57*, 85–105. [CrossRef]
34. INGEOMINAS. *Geología de la Plancha 110 Pamplona*; INGEOMINAS: Bogotá, Colombia, 1977.
35. Ramírez-Morales, D.; Rodríguez-Artavia, B.; Sáenz-Vargas, W.; Sánchez-Gutiérrez, R.; Villalobos-González, W.; Mora-Barrantes, J.C. Artisanal mining for the extraction of gold through the use of mercury: State of the art of environmental impact in water, air and soil media. *Rev. Tecnol. En Marcha* **2019**, *32*, 3–11. [CrossRef]
36. Arunachalam, K.P.; Avudaiappan, S.; Maureira, N.; Da Costa Garcia Filho, F.; Monteiro, S.N.; Batista, I.D.; de Azevedo, A.R. Innovative use of copper mine tailing as an additive in cement mortar. *J. Mater. Res. Technol.* **2023**, *25*, 2261–2274. [CrossRef]
37. Ince, C. Reusing gold-mine tailings in cement mortars: Mechanical properties and socio-economic developments for the Lefke-Xeros area of Cyprus. *J. Clean. Prod.* **2019**, *238*, 117871. [CrossRef]
38. Mazhit, D.; Kaliyeva, Z.; Bazarbayev, D. Effect of glass waste on ceramics and concrete production. *Technobius* **2025**, *5*, 0075. [CrossRef]
39. Wu, C.R.; Hong, Z.Q.; Yin, Y.H.; Kou, S.C. Mechanical activated waste magnetite tailing as pozzolanic material substitute for cement in the preparation of cement products. *Constr. Build. Mater.* **2020**, *252*, 119129. [CrossRef]
40. Benkaddour, M.; Kenai, S.; Yahiaoui, W.; Bensaci, H.; Khatib, J. Rheological, mechanical and durability performance of some North African commercial binary and ternary cements. *Case Stud. Constr. Mater.* **2023**, *19*, e02689. [CrossRef]
41. Hernandez-Cordoba, O.; Castro-Herrera, F.; Paez-Melo, M. Mercury Bioaccumulation on Tadpoles of a Gold Mining Zone in Dagua River, Buenaventura, Valle del Cauca, Colombia. *Acta Biol. Colomb.* **2013**, *18*, 341–348.
42. Odero, B.J.; Mutuku, R.N.; Nyomboi, T.; Gariy, Z.A. Contribution of Surface Treatment on Physical and Mechanical Properties of Recycled Concrete Aggregates. *Adv. Civ. Eng.* **2022**, *2022*, 1–17. [CrossRef]
43. Li, L.; Lu, Y.; Ren, T.; Horton, R. Quartz contents derived from particle density measurements improve the accuracy of soil thermal conductivity estimates. *Geoderma* **2023**, *436*, 116526. [CrossRef]
44. Simonsen, A.M.T.; Solismaa, S.; Hansen, H.K.; Jensen, P.E. Evaluation of mine tailings' potential as supplementary cementitious materials based on chemical, mineralogical and physical characteristics. *Waste Manag.* **2020**, *102*, 710–721. [CrossRef]
45. Xue, G.; Yilmaz, E.; Song, W.; Cao, S. Mechanical, flexural and microstructural properties of cement-tailings matrix composites: Effects of fiber type and dosage. *Compos. Part B Eng.* **2019**, *172*, 131–142. [CrossRef]
46. Figueiredo, A.S.; Bezerra, A.C.d.S.; Costa, L.C.B.; Resende, D.M.; Kuster, L.D.; Peixoto, R.A.F. Sand Mining Tailings as Supplementary Cementitious Material. *Buildings* **2024**, *14*, 2408. [CrossRef]
47. Das, B.; Prakash, S.; Reddy, P.S.R.; Misra, V.N. An overview of utilization of slag and sludge from steel industries. *Resour. Conserv. Recycl.* **2007**, *50*, 40–57. [CrossRef]
48. Tripathi, B.; Chaudhary, S. Performance based evaluation of ISF slag as a substitute of natural sand in concrete. *J. Clean. Prod.* **2016**, *112*, 672–683. [CrossRef]
49. Fang, L.; Jiaqi, F.; Ran, T.; Yuanrui, Z. Study on strength formation and frost resistance of concrete modified by molybdenum tailings. *Case Stud. Constr. Mater.* **2022**, *17*, e01280. [CrossRef]
50. Solís, R.G.; Moreno, E.I.; Arjona, E. Resistencia de concreto con agregado de alta absorción y baja relación a/c. *Rev. Alconpat* **2012**, *2*, 21–28. [CrossRef]
51. Pyo, S.; Tafesse, M.; Kim, B.J.; Kim, H.K. Effects of quartz-based mine tailings on characteristics and leaching behavior of ultra-high performance concrete. *Constr. Build. Mater.* **2018**, *166*, 110–117. [CrossRef]
52. Argane, R.; El Adnani, M.; Benzaazoua, M.; Bouzahzah, H.; Khalil, A.; Hakkou, R.; Taha, Y. Geochemical behavior and environmental risks related to the use of abandoned base-metal tailings as construction material in the upper-Moulouya district, Morocco. *Environ. Sci. Pollut. Res.* **2016**, *23*, 598–611. [CrossRef]
53. Cao, S.; Yilmaz, E.; Song, W. Evaluation of viscosity, strength and microstructural properties of cemented tailings backfill. *Minerals* **2018**, *8*, 352. [CrossRef]
54. Li, C.; Jiang, L. Utilization of limestone powder as an activator for early-age strength improvement of slag concrete. *Constr. Build. Mater.* **2020**, *253*, 119257. [CrossRef]
55. Herrera, C. *Evaluación de Mezclas Proyectadas: Comportamiento y Durabilidad*; Universitat Politècnica de Catalunya: Barcelona, Spain, 2017.
56. Taha, Y.; Benzaazoua, M.; Edahbi, M.; Mansori, M.; Hakkou, R. Leaching and geochemical behavior of fired bricks containing coal wastes. *J. Environ. Manag.* **2018**, *209*, 227–235. [CrossRef]

57. Shamseldeen Fakhri, R.; Thanon Dawood, E. Limestone powder, calcined clay and slag as quaternary blended cement used for green concrete production. *J. Build. Eng.* **2023**, *79*, 107644. [CrossRef]
58. Chen, J.J.; Ng, P.L.; Kwan, A.K.H.; Li, L.G. Lowering cement content in mortar by adding superfine zeolite as cement replacement and optimizing mixture proportions. *J. Clean. Prod.* **2019**, *210*, 66–76. [CrossRef]

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