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Evaluation Of Concretes With Mining And Steelmaking Waste As Aggregates In Concrete Production

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Abstract:
Background*: Technological development, although essential for progress, is intrinsically linked to the exploitation of natural resources and the generation of waste, especially in sectors such as mining, steel production, and construction.*
Materials and Methods*: In this context, with the aim of promoting sustainability in construction, this research evaluated the potential of copper ore and steel industry waste as aggregates in concrete.*
Results*: The waste, sourced from the Carajás region (PA), was characterized by granulometry and X-ray diffraction (XRD), and incorporated at different levels (0%, 15%, 25%, 50%, 75%, and 100%) into concrete mixes with Portland cement CP V-ARI. Slump, water absorption, and axial compressive strength tests were conducted.*
Conclusion: *The results indicated that substitution levels of 15% and 25% resulted in lower water absorption and compressive strengths similar to or higher than the reference concrete, demonstrating the potential of these wastes as aggregates and contributing to the circular economy and reduction of natural resource consumption.*
Key Word: *Sustainability; Waste utilization; Concrete aggregates; Circular economy.*

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I. Introduction

Since the beginning, technoscientific development has provided an elevation in the quality of life for the populations that are its protagonists. Nevertheless, such progress is intrinsically intertwined with the exploitation of natural resources and the processes of manufacturing beneficiation. According to Ramos[1], anthropic activities have experienced intensification since the early days of industrialization, manifesting to this day, exemplified by the extraction and burning of fossil fuels, as well as by the transformation of environments.

Throughout the interactions and transformations mentioned, it can be said that there are both favorable and inconvenient impacts. On the positive side, there is the economic and intellectual growth of populations who gain access to the products generated by technoscientific innovations. However, on the harmful and opposing side, the socio-environmental modifications generated, particularly in the form of social caste segregations and changes to geographic spaces, sometimes become evident.

Looking at the Brazilian secondary sector, with a focus on tasks related to mining, steelmaking, and construction, one can see how these activities serve as a driving force in the national economy. However, as pointed out by Trentin[2] and Zhouri[3], despite the economic benefit generated, there is a chronic need for studies and evaluations of the environmental impacts associated with the processes carried out, along with raising awareness for decision-making, particularly regarding the final disposal of the generated waste, especially with the occurrence of accidents involving the accumulation of such waste.

Moreover, Brazil is considered the fourth largest generator of solid waste in the world, highlighting the importance of strategic actions from public, private, and civil society sectors aimed at improving waste management conditions and promoting the value of these wastes[4]. Therefore, there are practices that can be cited as encouraging the adoption of sustainable measures aimed at minimizing the extraction of natural resources and reducing environmental degradation, such as the Sustainable Development Goals (SDGs) developed by the United Nations (UN)[5] in 2020, which comprise action goals to be achieved by 2030; as well as Law 12.305/2010, which deals with the National Solid Waste Policy (PNRS).

Thus, the adoption of sustainable practices aims to minimize the extraction of natural resources and reduce environmental degradation[6], i.e., these practices encourage the maintenance of productive sectors. According to Severiano Junior[7], in the construction sector, the use of renewable resources benefits not only the execution processes of the work but also its functionality, ensuring quality of life, economy, and the harmonious use of raw materials.

In this sense, this study proposes the evaluation of the potential of mining and steelmaking waste as aggregates for concrete in civil construction. The analyses were focused on the interaction between mechanical strength results and the various concrete mixtures, incorporating variations in waste content as a replacement for natural aggregates.

II. Material And Methods

This section addresses the presentation of the starting materials and the waste, discussing the intrinsic initial characteristics of each one. Subsequently, the proposed experimental program details the applied methods.

Materials

The materials used in this research come from the Carajás Integration Region in the state of Pará, and are either available for commercialization or deposited in freely accessible stockpiles.

Binder

Portland cement CP V-ARI was used as the binder material, as specified by NBR 16697[8]. The choice of this type of cement is justified by the methodologies employed, as this material contains virtually no additives in its composition, allowing the analysis and correlation of factors and uses in the research.

Natural Aggregates

The aggregates are of natural origin and available for commercialization in the municipality of Marabá, Pará, with natural sand used as fine aggregate and crushed stone used as coarse aggregate.

For the classification of the aggregates, which will be further detailed in the methodological section, NBR 7214[9] was used for natural sand, with commercial nomenclature following IPT. The crushed stone was classified according to NBR 7211[10], adopting the commercial nomenclature from Technical Report 30 of the MME[11].

Thus, the natural sand used as fine aggregate has a predominant granulometric distribution around #50, corresponding commercially to medium-fine sand. The coarse aggregate, crushed stone, has a characteristic maximum diameter of 19 mm and is classified as Grade 1 gravel.

Water

The water used in the concrete preparation came from the water supply system of the Federal University of Southern and Southeastern Pará (UNIFESSPA), at the Institute of Geosciences and Engineering (IGE), and its potability is guaranteed by the institution itself, eliminating the need for specific testing.

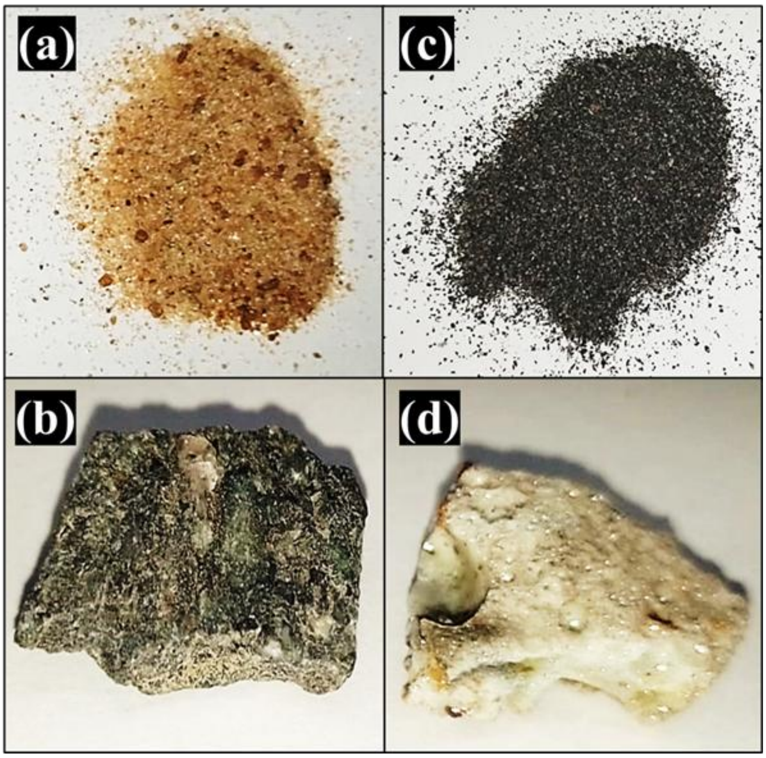
Copper Ore and Steelmaking Waste

The copper ore waste used in this research was collected at the Sossego Dam, located in the municipality of Canaã dos Carajás, in the Southeast mesoregion of Pará. The flotation tailings samples were collected at the coordinates 6° 27’ 11.377” S and 50° 4’ 55.670” W, at an elevation of 264.928 m above sea level.

The steelmaking waste, on the other hand, was collected from the only steel mill in the Northern Region of Brazil, located in the municipality of Marabá, in the state of Pará, in the Carajás Region. Specifically, the steelmaking waste collected comes from the blast furnace, which is the process of producing pig iron. The waste is rapidly cooled in a water tank, resulting in a granular and porous material; the coordinates of the blast furnace slag collection point are 5° 24' 48.762" S and 49° 4' 40.876" W.

Figure 1 shows the appearance of the waste and compares it with the natural materials, all of which were used in this research.

Figure no 1: Appearance of the aggregates used in the research



(a) Natural Sand; (b) Crushed Stone; (c) Copper Waste; (d) Blast Furnace Slag

Due to the appearance of the obtained materials, the wastes were adjusted in terms of the granulometry of the natural sand and crushed stone, with the copper waste being adjusted to the size of medium sand, and the steelmaking waste to Grade 1 gravel.

Method

After obtaining the materials, the research was conducted in three main stages: characterization of the constituent materials, determination of the dosages, and execution of technological tests on the concrete samples produced. During this process, the analysis criteria and the number of specimens for each procedure were defined.

Characterization of the Materials

In the characterization process, due to the supply, the water was considered potable and therefore suitable for concrete production. For the Portland cement (CP V-ARI), the specific mass and fineness of the material were determined physically, following the prescriptions of NBR 16605[12] and NBR 11579[13], respectively. The chemical composition of the cement used was considered in compliance with NBR 16697[8].

Regarding the materials used as aggregates, the granulometric ranges of the materials available in the region's market—namely natural sand and crushed stone—were determined using the sieving method. Subsequently, to optimize the properties of the mixture and the resulting concrete, the copper waste was adapted to the granulometric range of natural sand (fine aggregate), while the steelmaking waste was harmonized with the granulometric range of crushed stone (coarse aggregate).

Additionally, besides the granulometric compatibility, the densities of the aggregates were verified according to the prescriptions of NBR 16916[14] and NBR 16917[15] for fine and coarse aggregates, respectively. For the natural sand used, the granulometric classification followed the prescriptions described in NBR 7214[9], and the commercial nomenclature was as per the material provided by the Technological Research Institute (IPT). For the crushed stone, the granulometric classification followed the specifications in NBR 7211[10], and the commercial nomenclature was as per Technical Report 30 from the Ministry of Mines and Energy (MME)[11]. Tables 1 and 2 are presented below, illustrating the classifications described earlier.

Table no 1: Classification Limits of Fine Aggregates- Source: Adapted from NBR 7214[9]

National Standard Classification	Commercial Nomenclature	Sieve Opening for Retained Material (mm)	Percentage of Mass Retained in Sieve Range
#16	Coarse Sand	2,4 – 2,0	≤10
		2,0 – 1,2	≥90
#30	Medium-Coarse Sand	1,2 – 0,6	≥95
#50	Medium-Fine Sand	0,6 – 0,3	≥95
#100	Fine Sand	0,3 – 0,15	≥95

Table no 2: Classification Limits of Coarse Aggregates- Source: Adapted from NBR 7211[10]

Granulometric Zone	Sieve Opening for Retained Material (mm)	Percentage of Mass Retained in Sieve Range	Commercial Nomenclature	Maximum Diameter Range "d" (mm)
4,75/12,5	12,5	≤ 0 - 5	Crushed Stone 0	4,75 ≥ d ≤ 9,50
	2,36	≥ 95 -100		
9,5/25	25	≤ 0 - 5	Crushed Stone 1	9,50 > d ≤ 19
	4,75	≥ 95 -100		
19/31,5	31,5	≤ 0 - 5	Crushed Stone 2	19 > d ≤ 25
	9,50	≥ 95 -100		
25/50	50	≤ 0 - 5	Crushed Stone 3	25 > d ≤ 50
	19	≥ 95 -100		
37,5/75	75	≤ 0 - 5	Crushed Stone 4	50 > d ≤ 76
	31,5	≥ 95 -100		
-			Crushed Stone 5	76 > d ≤ 100
-			Gabion Stone	100 > d ≤ 150

The information on the granulometric ranges used for natural sand and crushed stone was previously mentioned in the presentation of the materials. However, as evidence of the chemical characterization of the aggregates used in this research, all underwent X-ray diffraction (XRD) analysis.Next, Table 3 presents the characterization processes applied to commercially available materials and waste. It also includes the nomenclature used throughout the research.

Table no 3: Characterization Process of Materials Used as Aggregates

Usage	Technical Test	Standard Reference	Material and Nomenclature	
Fine Aggregate	Granulometric Analysis	NBR 7211[10] and NBR 17054[22]	Natural Sand (NS)	Copper Ore Tailings (COTS)
	Density	NBR 16916[14]		
	X-ray Diffraction (XRD)	-		
Coarse Aggregate	Granulometric Analysis	NBR 7211[10] and NBR 17054[22]	Crushed Stone (CS)	Steel Industry Waste - Blast Furnace Slag (SIFBS)
	Density	NBR 16917[15]		
	X-ray Diffraction (XRD)	-		

Concrete Mixes with Aggregate Substitution

The selection of the mix design was based on the reproduction of a theoretical-experimental analysis, using proportional volumetric reference contents. Since the mix design stemmed from an experimental analysis assumption, the aim was to study the feasibility of incorporating waste materials into the produced composites, where the volume of materials used as aggregates was adjusted according to their densities.

Additionally, to reduce the number of chemical interactions, no additives or other materials that could interfere with the basic properties of the concrete were used. Therefore, only the binder, aggregates, and water were used to form the mixes.

The basic volumetric mix design was defined in the proportion of 1:2:3 (cement: fine aggregate: coarse aggregate), with a water/cement ratio of 0.45. The incorporation of the different waste contents was based on the relative percentages proposed for the respective materials, with the substitution percentages of natural aggregates by waste being of the same fraction.

The rationale behind choosing this proportion was its common use in small works in the Carajás region, its ease of reproduction, and its alignment with the work developed by Pinheiro[6]. It also follows the work of Muleya[16], Lam Esquenazi[17] and Premkumar, Chokkalingam, and Rajesh[18].

Moreover, it was estimated that this basic mix design complies with NBR 6118 regarding the water/cement ratio for the highest class of environmental aggressiveness, as well as for achieving at least the lowest class of mechanical strength.

The proposal included six substitution percentages for fine and coarse aggregates by waste, namely 0%, 15%, 25%, 50%, 75%, and 100%. The following Table 4 presents the nomenclature for the produced concretes, along with the incorporation levels of the aggregates.

Table no 4: Nomenclature of Concretes and Aggregate Contents

Nomenclatura	Percentual de substituição	Agregados Naturais	Rejeitos de barragem cobre e siderurgia
C0	0%	100%	0%
C15	15%	85%	15%
C25	25%	75%	25%
C50	50%	50%	50%
C75	75%	25%	75%
C100	100%	0%	100%

Thus, as exemplified in Table 4, for instance, in the C15 mix starting from C0, the volumes used were 85% natural sand and 85% crushed stone. A substitution of 15% of the relative volume of natural sand (NS) was made with copper ore tailings (COTS), and 15% of the relative volume of crushed stone (CS) was substituted with steel industry waste - blast furnace slag (SIFBS). This volumetric compensation will also be applied to the other concrete mixes and substitution percentages.

Therefore, for these mix designs, the focus was to form a curve with the maximum and minimum points of results achieved for mechanical strength, as well as to understand these results through microstructural interactions.

Technological Tests on the Concrete Samples Produced.

The methodology for technological testing adopted comprised two distinct stages. Initially, in the fresh state of the concrete, the consistency of the mixes was evaluated through the slump test using the cone mold, in accordance with the specifications established by NBR 16889[19].

In order to standardize the workability of the produced concretes, the slump was set at 2.50 cm, with a tolerance of ± 0.5 cm. In this context, the water/cement (w/c) ratio of each concrete was adjusted, assessing the influence of water incorporation to maintain the pre-defined workability range.

In the second stage, with the concretes already in the hardened state, the variety of technical tests was broader than in the initial phase. For this, test specimens were molded from the samples, in accordance with the specifications of NBR 5738[20]. Table 5, presented below, shows the tests performed, their respective normative references, and the specific ages for their execution, as well as describing the format of the test specimens to be produced.

Table no 5: Designations of Tests in the Hardened State for the Concretes

Technical Test	Standard Reference	Testing Age (Days)			Sample Format	Dimensions (cm – diameter x height)
Water Absorption by Capillarity	NBR 9779[21]	28			Cylindrical	10 x 20
Axial Compression	NBR 9779[21]	07	28	56	Cylindrical	10 x 20

Criteria for Analyzing the Results

The criteria for analyzing the results followed the number of samples taken from the produced concretes. Statistical tests, such as Analysis of Variance (ANOVA), were applied to the results, with significant variance when $P < 0.05$. When necessary, other tests were applied to check for contrasts among the samples, such as the Tukey test, a statistical test that compares all possible combinations of means. Thus, Table 6 presents the number of samples taken.

Table 6: Number of Samples for the Technical Tests

Technical Test	Testing Age (Days)			Number of Samples at Each Age	Total Number of Samples for All Mixes
Consistency with the Cone Mold	-			1	6
Water Absorption by Capillarity	28			5	30
Axial Compression	07	28	56	5	90

III. Result And Discussion

The analysis of the materials and the subsequent discussion of the results are based on the characterization of the crystallographic mineral phases of the aggregates used, employing the X-ray Diffraction (XRD) technique, and on the evaluation of the properties of the produced concretes.

The evaluated properties include the consistency of the mix in the fresh state, water absorption, and compressive strength in the hardened state.

In light of the above**,** Figures 02 and 03 present the graphs of the crystallographic peaks obtained for the materials used as fine and coarse aggregates, respectively.

Figure 2: XRD of Materials Used as Fine Aggregate

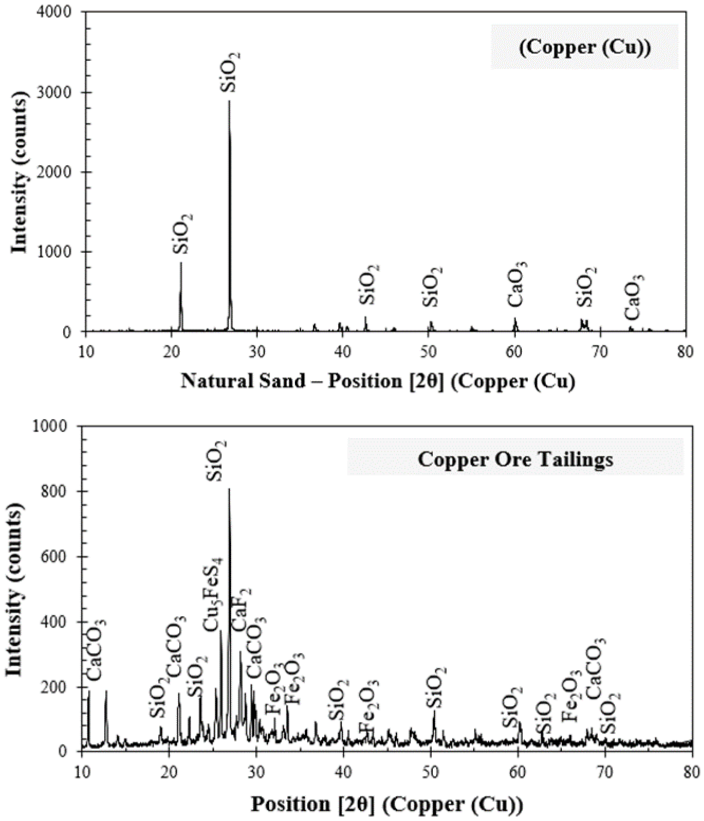
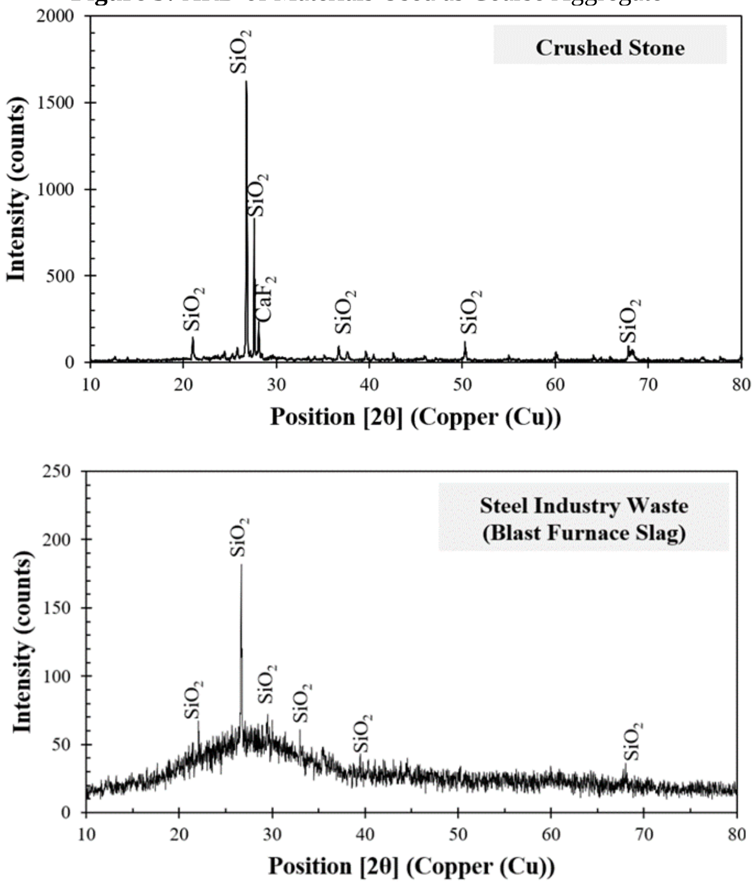


Figure 3: XRD of Materials Used as Coarse Aggregate



The analysis of the crystallographic peaks found reveals that natural sand consists solely of silicon dioxide (SiO_2). Meanwhile, the X-ray diffraction (XRD) pattern of copper ore tailings, despite showing peaks indicating the presence of other minerals, also exhibits a high concentration of SiO_2. This analysis is supported by similar results presented by Muleya[16] and Lam Esquenazi[17], who identified high quartz content in copper tailings, as well as the presence of bornite (Cu_5FeS_4), hematite (Fe_2O_3), fluorite (CaF_2), and calcite ($CaCO_3$).

Thus, it is evident that the mineralogical composition of copper ore tailings is complex, containing multiple crystalline phases. The diffractogram reveals that copper ore tailings are composed of a complex mixture of oxides (quartz, hematite), carbonates (calcite), and sulfides (bornite), along with the possible presence of fluorite. The presence of bornite confirms the material's origin as a byproduct of copper mining. The occurrence of calcite and hematite may be due to alterations in the original minerals or their presence in the host rock.

However, when compared to the studies conducted by Pinheiro[6], who analyzed tailings from the same copper dam, it is inferred that the presence of these elements may trigger reactions with cement components, either through hydration or atmospheric exposure. Such reactions may lead to the formation of expansive products, which could ultimately compromise the durability and mechanical strength of the concrete over time.

Given this, it can be concluded that natural sand is much more suitable for use as fine aggregate in concrete due to its simple composition and the absence of deleterious minerals. Copper ore tailings, on the other hand, present certain limitations due to the presence of sulfides and their complex mineralogy, which will always require prior treatment and in-depth studies to ensure the durability of the produced concrete.

Regarding the analysis of materials used as coarse aggregates, both diffractograms show significant peaks corresponding to silica (SiO_2), indicating that this mineral is a key component in both blast furnace slag and crushed stone. This finding aligns with the research of Premkumar, Chokkalingam, and Rajesh[18], who highlight that industrial waste byproducts can contribute to a more sustainable environment. The use of industrial waste in concrete not only prevents the depletion of natural resources but also helps to mitigate waste disposal issues.

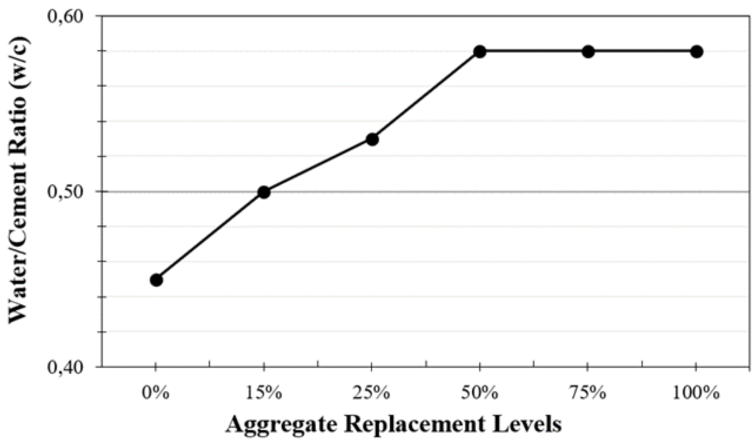
However, the way silica is presented and its crystallinity may vary when comparing the XRD patterns of crushed stone and steel slag. For crushed stone, the SiO_2 peaks are much more intense and well-defined, indicating a higher proportion of crystalline silica and/or larger crystals. In the XRD pattern of steel slag, although SiO_2 peaks are present, they are less intense and overlapped by the amorphous halo, suggesting a lower proportion of crystalline silica and/or smaller crystals. This observation is supported by Rebelo, Nascimento, and Corrêa[23], who analyzed slags from the same region as this study.

Crushed stone provides high strength and is a well-established construction material, whereas blast furnace slag offers environmental advantages and can improve concrete durability, provided that proper characterization, dosage, and quality control measures are taken. The steel slag studied here has the potential to react with Portland cement hydration products, forming compounds that refine the concrete's pore structure, making it denser and less permeable. This enhances resistance to aggressive agents such as sulfates and chlorides.

Thus, both materials can be used as coarse aggregates in concrete. The choice between them will depend on project requirements, material availability, and economic and environmental considerations.

Moving forward to the analysis after concrete production, in the fresh state, with a slump range fixed at 2.50 cm ±0.5, the necessary corrections were made to the water/cement (w/c) ratios of the produced mixes. Figure 4 illustrates this behavior in response to changes in the aggregate replacement levels.

Figure 4: Behavior as a Function of Changes in Aggregate Replacement Levels

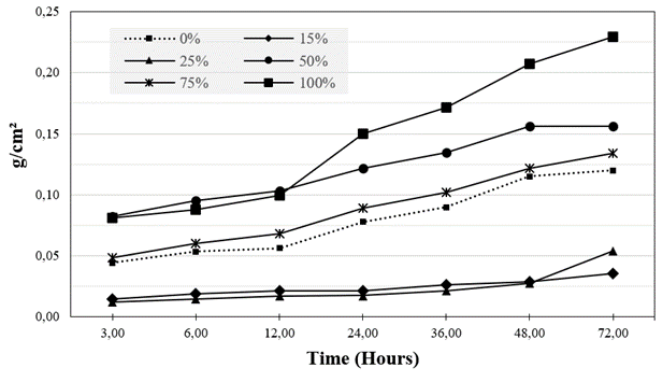


The analysis of Figure 4 suggests that the replacement of aggregates in concrete mix designs can lead to an increase in the water/cement (w/c) ratio. This finding highlights the importance of careful mix design and quality control to ensure the proper performance of the material.

It is inferred that the change in the water/cement (w/c) ratio occurs because concrete mixtures with aggregate replacements require more water to achieve the desired workability, mainly influenced by the physical characteristics of the aggregates.

Thus, to verify whether this increase in the w/c ratio would affect the porosity of the produced samples—and consequently their water absorption—Figure 5 illustrates the average behavior of the samples in terms of capillary water absorption after 72 hours.

Figure 5: Capillary Water Absorption Results After 72 Hours



The analysis of water absorption in concrete samples provides important insights into the impact of this practice, even though the initial differences are not drastic. The results demonstrate a gradual increase in water absorption over time, highlighting the influence of aggregate replacement on the microstructure of the concrete.

When comparing the samples with aggregate replacement to the reference sample (0% replacement), it is observed that the 15% and 25% replacement fractions exhibit slightly lower results. However, it is important to note that all other samples with aggregate replacement show higher water absorption levels than the reference.

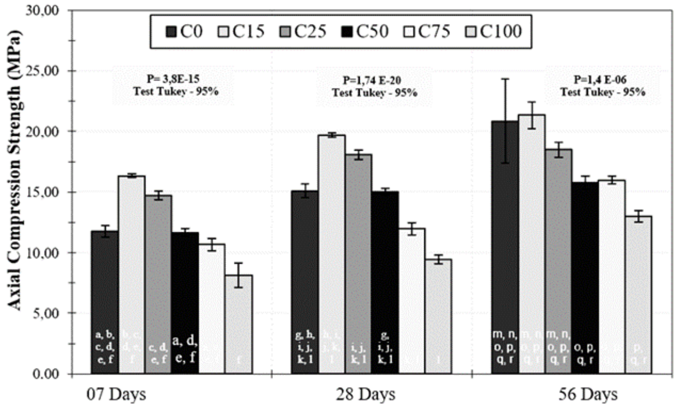
The comparison of Figures 4 and 5, concerning concrete samples with 15% and 25% aggregate replacement by tailings, reveals an interesting aspect. Despite the increased water content in the mixing stage, the porosity appears to be reduced. This observation prompts a deeper analysis, correlating the results with the crystallographic peaks shown in Figures 2 and 3, which detail the composition of the tailings used.

Given this, the possible reduction in porosity, even with the added water, suggests mechanisms that compensate for this effect, such as the formation of new chemical compounds, evidenced by the possible hydration reactions of the minerals present in the tailings. These compounds may fill the pores and microcracks in the concrete, reducing the overall porosity and, consequently, the permeability of the material. This phenomenon may have positive impacts on the durability and mechanical strength of the concrete.

As a result, Figure 6 presents the average results for axial compression strengths at 7, 28, and 56 days, with the relevant analyses to follow.

Figure 6: Average Results of Achieved Axial Compression Strengths

(Significant variance when $P<0.05$; One-Way ANOVA, Tukey test. Different letters represent statistically significant variation)



The analysis of variance (ANOVA) revealed statistically significant differences between the mean compressive strengths of the concrete groups at all evaluated ages. The Tukey test, used as a multiple comparison method, allowed for the identification of similarities between groups, even in the presence of significant differences indicated by the ANOVA. Groups with similar letters do not differ significantly from each other, suggesting the formation of clusters with similar behavior in relation to compressive strength.

Regarding the behavior of the peaks, the graphical analysis of the results suggests an asymptotic behavior for the curves of average concrete strength as a function of age. This pattern is consistent with the cement hydration process, which occurs non-linearly over time, and the results obtained corroborate existing literature on the subject, particularly the classic work by Falcão Bauer[24], which describes the non-linear growth of concrete strength as an intrinsic characteristic of the cement hydration process.

In general, the strength gain is concentrated mainly between 7 and 28 days, with a slower and more gradual increase between 28 and 56 days. This behavior aligns with products involving cementitious matrices and is also emphasized by Metha and Monteiro[25], who state that compressive strength increases significantly with age for all concrete mixes.

In this context, the influence of aggregate substitution on compressive strength varies according to the substitution level and age. At seven days, concretes with lower substitution levels (C15 and C25) show strengths similar to or slightly higher than the reference concrete (C0), while concretes with higher substitution levels (C50, C75, and C100) exhibit progressively lower strengths, with C100 showing the lowest strength.

At 28 days, the age considered the characteristic strength for concrete, the C15 and C25 samples showed good results, with average strengths higher than the others, demonstrating the technical viability of these mixes, as they statistically resemble the reference concrete (C0). These findings are also in line with the results obtained by De Paula Junior and Oliveira[26] and Arrighi[27], who produced cementitious composites with similar mineral waste incorporation and obtained satisfactory results.

At the later age of 56 days, C15 shows a peak of average strength higher than all others, but with statistical similarities to C0 and C15. Meanwhile, the other concrete mixes with substitution show lower strengths, following a downward trend with increased substitution levels.

Therefore, in terms of axial compressive strength, we can conclude that partial substitution of aggregates by copper and steel industry wastes, at lower levels, especially at 15% and 25%, can result in compressive strengths similar to or even higher than the reference concrete, particularly at 28 days.

Thus, making a parallel between all the results discussed here, we can infer that the substitution of conventional aggregates by copper and steel industry wastes, particularly around 15% and 25%, appears to be the most promising, offering a good balance between material use and mechanical performance of the concrete.

IV. Conclusion

This research investigated the potential use of mining and steelmaking waste as aggregates for concrete in the Carajás Region, revealing promising results for the development of a more sustainable civil construction industry.

The mineralogical analysis showed the presence of crystalline silica in both types of waste, as well as quartz content in copper ore waste, a finding that supports previous studies indicating the potential of industrial waste byproducts to promote environmental sustainability. This is because, in addition to avoiding the consumption of natural resources, it contributes to the minimization of problems related to the final disposal of waste.

The technological tests demonstrated that partial replacement of natural aggregates with these wastes, up to levels of 25%, can result in concrete with low water absorption and compressive strength similar to or even greater than the reference concrete, particularly at 28 days. However, it is important to emphasize that conducting additional studies is crucial to evaluate the behavior of these concretes under different environmental conditions and exposure scenarios, ensuring their durability and long-term safety.

From a sustainability perspective, the results suggest that using these wastes as aggregates in concrete can be a viable alternative for civil construction in the region, contributing to reducing the environmental impact of mining and steelmaking while promoting sustainability in the construction industry, in line with the Sustainable Development Goals (SDGs).

In conclusion, it can be stated that the partial replacement of aggregates with industrial waste, at appropriate levels, can be an environmentally sustainable and economically viable solution for civil construction, reducing the consumption of natural resources and improper waste disposal, as well as contributing to the development of materials with satisfactory mechanical performance. This practice represents an opportunity for the construction industry to promote circular economy principles and reduce environmental impact.

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