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Effect of steel slag and ceramic residues on the physical and mechanical properties of concrete

David Olivert Chapoñan Mondragón[1)], Leonardo Gálvez Irigoin[1)], Sócrates Pedro Muñoz Pérez*[2)], Néstor Raúl Salinas Vásquez[1)], Juan Martín García Chumacero[1)], Elver Sánchez Diaz[1)], Carlos Eduardo Ramos Brast[3)] and Edwin Adolfo Diaz Ortiz[2)]

[1)]Professional School of Civil Engineering, Faculty of Engineering and Architecture, Universidad Señor de Sipan, Chiclayo, Peru
[2)]Professional School of Civil Engineering, Faculty of Civil and Environmental Engineering, National University Toribio Rodriguez de Mendoza of Amazonas, Chachapoyas, Peru
[3)]Professional School of Civil Engineering, Faculty of Engineering and Architecture, Universidad San Martín de Porres, Chiclayo, Peru

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Abstract

Cement is a critical component in concrete, but it significantly impacts the environment from extraction to disposal, depleting resources and generating pollution. To address this issue, the use of steel slag (SS) and ceramic waste powder (CWP) was investigated as partial replacements for cement at 8%, 10%, 12%, and 15% by weight. Various mixtures were evaluated, including a control mix with a water-to-cement (w/c) ratio of 0.52, mixtures containing SS, and an optimal blend of SS with different proportions of CWP. Physical and mechanical properties were assessed through slump tests, temperature measurements, air content, and density evaluations. Compressive strength, flexural strength, tensile strength, and modulus of elasticity were also analyzed at 7, 14, and 28 days using standardized cylindrical and prismatic specimens. The results indicated a reduction in slump and temperature of the concrete by up to 45.87% and 9.10%, respectively, with a slight increase in density and air content when incorporating 10% SS and 15% CWP. In terms of mechanical properties, the optimal substitution of 10% SS improved compressive strength by 7.39%, modulus of elasticity by 13.06%, flexural strength by 8.22%, and tensile strength by 14.10% compared to the control mix. The hybrid mix of SS and CWP (10%:10%) showed significant enhancements: compressive strength increased by 17.12%, flexural strength by 19.25%, tensile strength by 26.28%, and modulus of elasticity by 21.21%. It was concluded that substituting 10% SS and 10% CWP by weight of cement enhances the mechanical properties of concrete, promoting efficiency and sustainability in environmentally friendly construction. This hybrid concrete can be effectively used in pavements, sports floors, sidewalks, and curbs.

Keywords: Concrete, Physical and mechanical properties, Steel slag, Ceramic powder, Environment

1. Introduction

The construction industry is constantly evolving, searching for new and environmentally friendly materials. Among these materials is steel slag concrete [1], which provides benefits such as higher compressive strength and setting time control [2]. However, the production of steel slag generates large amounts of waste, about 100 million tons annually in China [3], the reuse of this waste becomes a crucial challenge [4], as steel slag contains cement-like components [5], and can be used as an aggregate or cementitious material in construction [6]. Unfortunately, only 40% of steel slag is currently reused, while the rest ends up in landfills [7]. It should be noted that there are several types of slag, electric arc furnace slag [8-10], steel slag [11, 12], ladle furnace slag [13], powdery ladle furnace slag [14].

At the same time, the ceramics industry produces ceramic waste powder, another abundant by-product with a potential for reuse in construction [15], it is estimated that the global generation of ceramic waste powder exceeds 22 billion tons per year [16]. The incorporation of ceramic waste powder as a partial substitute for cement in the production of concrete is presented as a sustainable alternative to reduce the amount of waste generated [17] and the environmental impact associated with the production of traditional cement [18].

In countries such as Peru, the use of cement has experienced significant growth [19], due to the fact that construction has been consuming raw materials that are becoming extinct over time [20], also, the massive accumulation of construction and demolition waste aggravates [21], increases the urgency of finding sustainable solutions for waste management in construction [22], so it is important to reuse demolition materials for the preservation of natural resources and reduction of environmental pollution [23], which is a major problem because there is no proper management and contaminate the soil [24-26].

Several studies have evaluated the physical properties of fresh concrete using alternative materials such as SS and CWP; such is the case of Bhargav and Kansal [27] who did not observe significant changes in slump when varying the percentages of CWP, likewise,

*Corresponding author.
Email address: socrates.munoz@untrm.edu.pe
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the addition of SS does not significantly affect the slump of concrete [28], while Altamirano and Zapata [29], noted a 15% decrease in slump when incorporating CWP in the concrete mix, regarding temperature, they indicated that by incorporating 10% CWP, the temperature decreases by 1.74%; on the other hand, Gallardo and Pariona [30], argue that by adding both steel fiber and CWP, the decrease can reach up to 10%.

Guerrero's study [31] found that the density of the material decreases by 2.65% when using 15% CWP; however, Altamirano and Zapata [29] disagree, since in their research they observed a density reduction of 1.4% when using 20% CWP. In addition, Aguilar and Blanco [28], a state that the air content increases by 2% when using 10% SS in the concrete mix.

According to various research studies, the incorporation of SS in the concrete mix has a positive impact on compressive strength. It has been observed that strength increases in the range of 4 to 15% when substituting part of the cement with SS. These substitutions range from 5 to 25% of the total cement content in the mix [27, 28, 30, 32-37]. In contrast, Taher et al. [38], found that the addition of 10% CWP reduced the compressive strength by 15%. However, other studies report improvements in compression of up to 14.98% with cement substitutions by CWP between 10 and 15% [27, 35, 37, 39], in addition, the combined effect of SS and CWP was evaluated, increasing the compressive strength by 6%, when substituting 21.4% of cement by SS and 10.7% by CWP.

In modulus of elasticity Pan et al. [35], found an increase of 5.42% in the modulus of elasticity by substituting 10% cement for SS. Altamirano and Zapata [29], reported a 3.49% improvement in the modulus of elasticity with 10% CWP.

Palod et al. [40], observed 4 and 6% improvements in flexure at 90 days with 10 and 20% SS substitutions, respectively. Pan et al. [35], found a 5.42% increase in flexure when substituting 10% cement for SS. Bhargav and Kansal [27], reported a 14.98% increase in flexural deflection with 15% CWP. Gallardo and Pariona [30], observed a 10.81% increase in flexural strength with 20% CWP.

Zhuo et al. [34], reported a 13.63% increase in the tensile strength of concrete when substituting 5% cement for SS. Palod et al. [40], observed 4% and 6% improvements in tensile strength at 90 days with 10 and 20% SS substitutions, respectively. Pan et al. [35], found a 6.45% increase in tensile strength when substituting 10% cement for SS. Gallardo and Pariona [30], reported an increase of 8.19% in tensile strength with 20% CWP; because more research is required to determine the effects of the joint addition of SS and CWP in concrete and with different substitution proportions, the present study was carried out to contribute to the joint investigation of the mentioned variables.

2. Materials and methods

2.1 Materials

2.1.1 Aggregates, cement and water

Manufactured aggregate from a quarry in the Lambayeque department of Peru was used. The fine aggregate passed through a No. 4 sieve, while the coarse aggregate had a nominal size of 19 mm. Both aggregates comply with the requirements of ASTM C136 [41]. The physical properties of the aggregates are detailed in Table 1, and their particle size distribution is shown in Figure 1. Type I Portland cement, commonly used in commercial applications, was employed, with a density of 3.15 g/cm³. The water used for preparing the concrete mixtures was in accordance with ASTM C1602 [42].

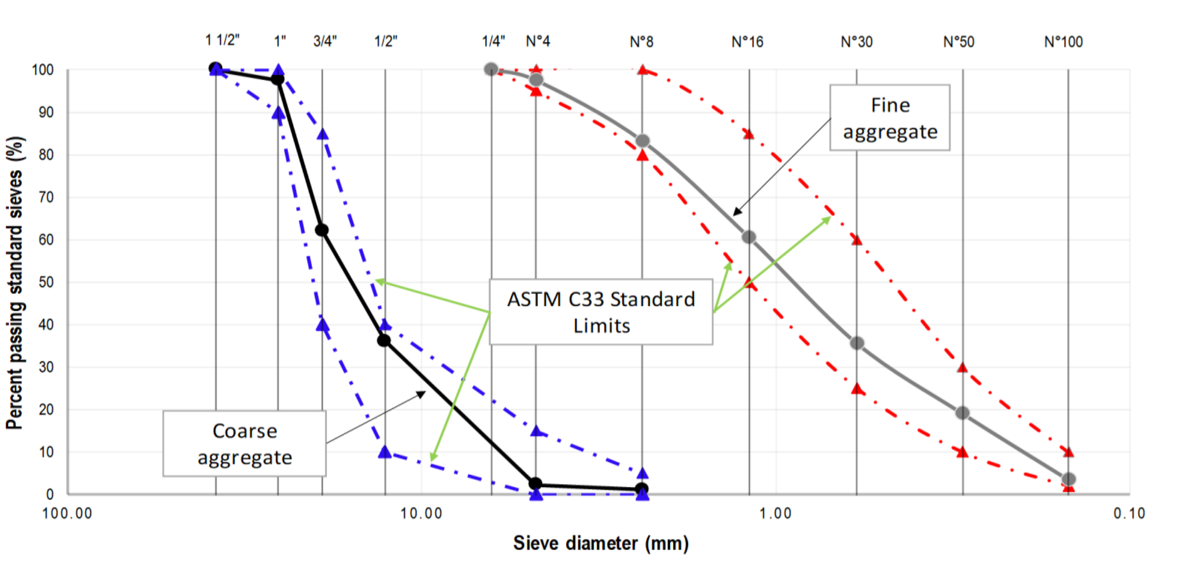

Figure 1 Aggregate particle size

Table 1 Characteristics of aggregates

Characteristics	Fine aggregate	Coarse aggregate	ASTM Standard
Fineness modulus	2.76	-	ASTM C136 [41]
Loose dry unit weight (kg/m^3)	1462	1540	ASTM C29 [43]
Compacted dry unit weight (kg/m^3)	1602	1638	ASTM C29 [43]
Specific gravity	2.66	2.40	ASTM C128 [44]
Absorption capacity (%)	0.88	0.97	ASTM C127 [45]
Natural moisture content (%)	1.06	0.88	ASTM C566 [46]

2.1.2 Steel slag

Steel slag (SS) is an industrial by-product obtained from the steel smelting process. The material used in this study was provided by SIDERPERU, located in the Ancash department of Peru. A total of 150 kg was acquired, which results from the melting and separation of impurities during steel production, as shown in Figure 2. Table 2 presents its physical properties. To determine its chemical composition, an X-ray fluorescence (XRF) analysis was conducted. This technique detects chemical elements with atomic numbers (Z) equal to or greater than 13 (aluminum) by measuring the characteristic X-rays emitted by the atoms. The detailed results are shown in Table 3, with the corresponding diagram in Figure 3. To utilize the slag as a cement substitute, it was ground for 10 minutes using an abrasion machine, followed by sieving through a No. 200 mesh, resulting in a particle size of 74 µm.

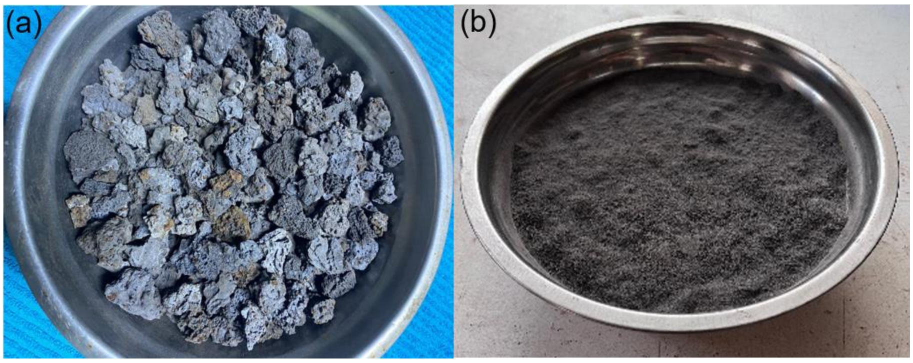

Figure 2 (a) steel slag supplied by SIDERPERU, (b) pulverized steel slag

Table 2 Physical characterization of SS

Description	Result
Specific gravity	3.29
Absorption (%)	1.95

Table 3 Chemical characterization of SS

Components	Concentration (% mass)
Al	6.183
Si	3.900
S	0.528
Cl	0.041
K	0.493
Ca	1.941
Ti	0.084
V	0.008
Cr	0.004
Mn	0.055
Fe	1.722
Ni	0.011
Cu	0.029
Zn	1.534
As	0.013
Sr	0.009
Y	0.007
Zr	0.008
Total	16.570

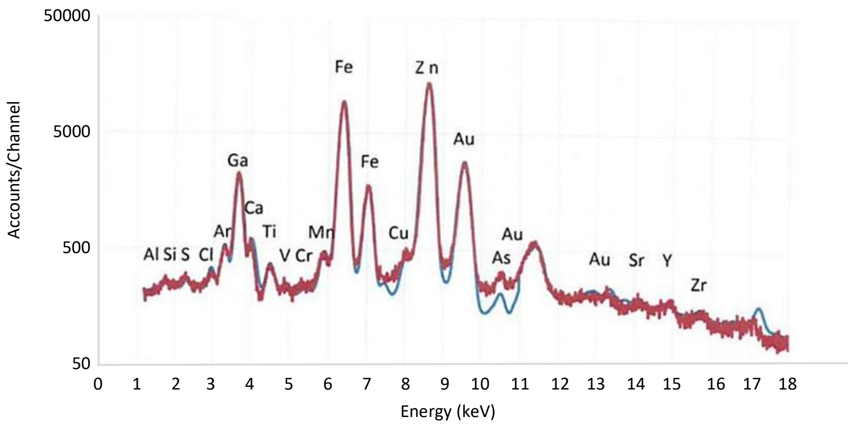

Figure 3 XRF Spectra of steel slag (SS) in Semi-Logarithmic Scale

2.1.3 Ceramic waste

Palm ceramic waste refers to the material generated during the production, installation, or demolition of ceramic products used in construction. A total of 150 kg of this material was provided by CASSINELLI, as shown in Figure 4. It was sourced from one of their sites in the Lambayeque region, where it originated from ceramic production activities. The material was subsequently washed, dried, and crushed using an abrasion machine. Finally, the ceramic waste powder was passed through a No. 200 sieve, resulting in a particle size of 74 µm. An X-ray fluorescence (XRF) test was also performed to determine its chemical composition. Table 4 presents the physical characterization, Table 5 details the chemical composition, and Figure 5 illustrates the composition diagram.

Table 4 Physical characterization of CWP

Description	Result
Specific gravity	2.36
Absorption (%)	12
Loose bulk density (kN/m^3)	14.21

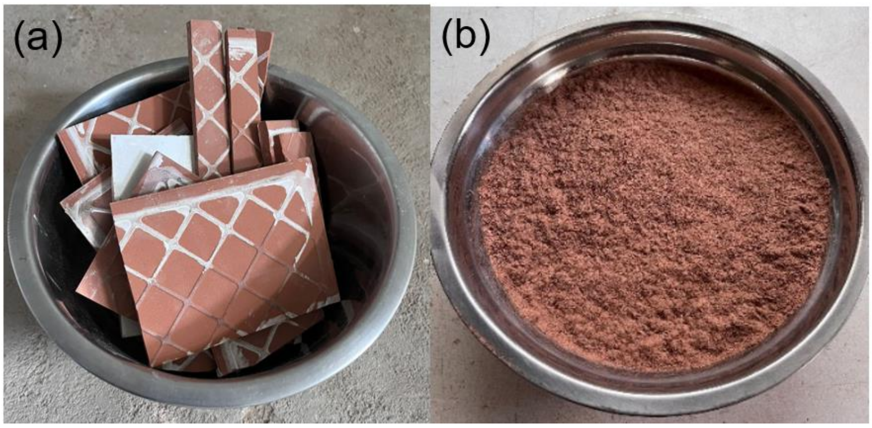

Figure 4 (a) Ceramic wastes obtained from CASSINELLI, (b) pulverized ceramic for incorporation into concrete.

Table 5 Chemical characterization of CWP

Components	Concentration (% mass)
Al	1.266
Si	0.636
Cl	0.016
K_2	0.232
Ca	0.291
Ti	0.004
V	0.009
Mn	0.001
Fe	0.007
Cu	0.006
Zn	0.007
Sr	0.005
Total	2.480

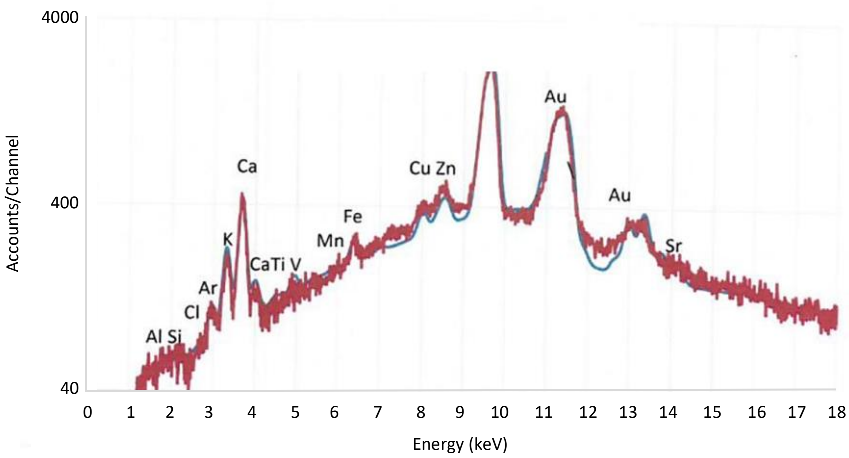

Figure 5 XRF Spectra of Ceramic Waste Powder (CWP) in Semi-Logarithmic Scale

2.2 Methods

The concrete samples were prepared using the following procedure:

First, the physical characteristics of the steel slag (SS) and ceramic waste powder (CWP) were evaluated.

Next, the mix design proportions for the control concrete, as well as for substitutions of 8%, 10%, 12%, and 15% of SS and CWP relative to the weight of cement, were established according to the ACI 211.1 methodology. The water-to-binder ratio (w/c) was 0.515, and no superplasticizer was used. The labels for each mix design are shown in Table 6, and the quantities per cubic meter are provided in Table 7.

Each mix was prepared in an 11-cubic-foot capacity mixer, with a mixing time of approximately 5 to 6 minutes, during which care was taken to prevent segregation of the mixture. Fresh concrete samples were subjected to several tests, including slump, temperature, density, and air content measurements, to assess the effects of SS and CWP.

The fresh concrete was placed in cylindrical and prismatic molds of standard dimensions. After 24 hours of setting, the specimens were demolded and immersed in potable water for curing. A total of 162 cylindrical and 81 prismatic specimens were produced, making a total of 243 concrete specimens. The mechanical properties of the hardened concrete, such as compressive strength, flexural strength, tensile strength, and modulus of elasticity, were evaluated at 7, 14, and 28 days of curing to determine the optimum percentage of SS replacement.

Finally, after determining the optimum percentage of SS, the samples with CWP substitution were evaluated. The entire process is detailed in Figure 6.

Table 6 Sample labels

ID Mix	Description
T1	Concrete control
T2	Concrete with 8% SS substitution
T3	Concrete with 10% SS substitution
T4	Concrete with 12% SS substitution
T5	Concrete with 15% SS substitution
T6	Concrete with optimum% of SS replacement and 8% of CWP
T7	Concrete with optimum% of SS replacement and 10% of CWP
T8	Concrete with optimum% of SS replacement and 12% of CWP
T9	Concrete with optimum% of SS replacement and 15% CWP

Table 7 Proportion of materials used

ID Mix	Ratio w/c	Cement (kg/m³)	Coarse aggregate (kg/m³)	Fine aggregate (kg/m³)	Water (L/m³)	SS (kg/m³)	CWP (kg/m³)
T1	0.515	375	1104	564	193	Control	Control
T2	0.515	345	1104	564	193	30	0
T3	0.515	337.5	1104	564	193	37.5	0
T4	0.515	330	1104	564	193	45	0
T5	0.515	318.75	1104	564	193	56.25	0
T6	0.515	307.5	1104	564	193	37.5	30
T7	0.515	300	1104	564	193	37.5	37.5
T8	0.515	292.5	1104	564	193	37.5	45
T9	0.515	281.25	1104	564	193	37.5	56.25

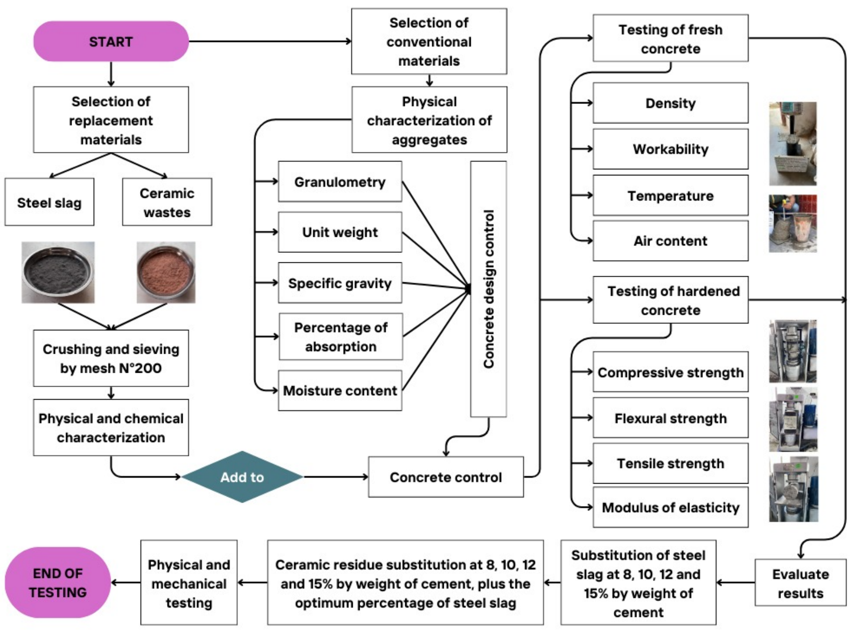

Figure 6 Process flow of the study

3. Results and discussions

3.1. Physical properties of SS concrete and SS+CWP concrete

The slump test is a physical test performed on fresh concrete to measure its workability. In this study, the effect of SS and CWP on this property was evaluated in comparison to the control concrete. The ASTM C143 [47], standard was used to determine the slump of the concrete, providing specific instructions to perform the test and obtain an accurate measurement.

Additionally, other tests were conducted following ASTM C138 [48] to assess the density of fresh concrete, an important parameter that influences the material's strength and durability. The temperature of the fresh concrete was also measured according to ASTM C1064 [49], and the entrapped air content was evaluated using ASTM C173 [50].

3.1.1 Workability and temperature

As shown in Figure 7 (a), as SS was added to the mix, the slump value decreased by up to 31.19%, corresponding to treatment T5 compared to T1. Treatment T1 had a slump of 3.6 inches, which falls within the range of plastic concrete. However, both treatments T4 and T5 had a slump of less than 3 inches, classifying them as stiff or dry concretes. Additionally, treatment T9 experienced a slump decrease of 45.9% compared to T1. This is due to the higher absorption capacity of the added materials compared to natural aggregate.

Treatment T1 exhibited a temperature of 29.3 °C, as shown in Figure 7 (a). When SS was incorporated into the concrete mix, negligible temperature variations were observed. However, even small differences in temperature could affect the concrete's properties and behavior in different environments. According to Figure 7 (b), the largest temperature decrease was recorded in treatment T9, with a reduction of up to 9.10% compared to T1. Nevertheless, the temperature variation is not considered significant.

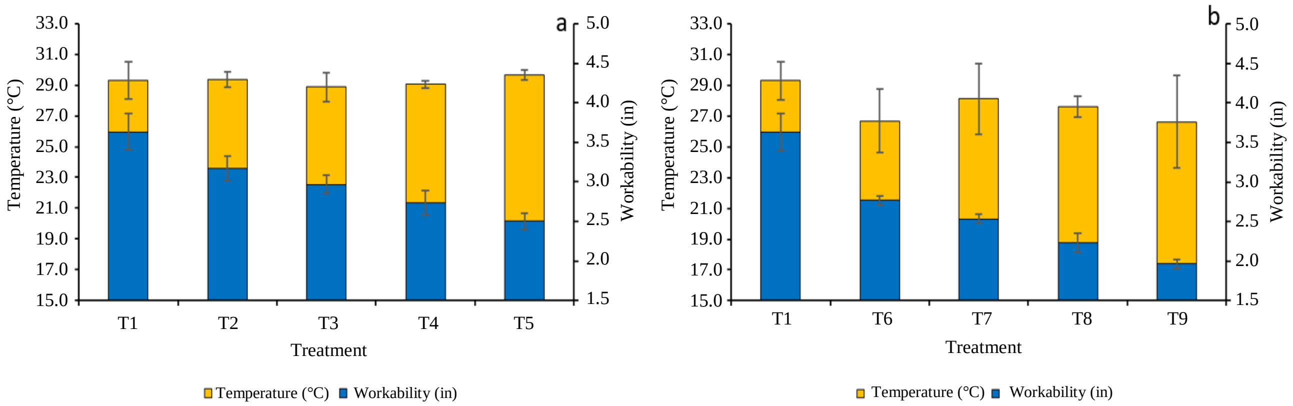

Figure 7 Physical properties of concrete, temperature and workability of concrete with (a) SS; (b) with SS and CWP.

3.1.2 Density and air content

Figure 8 (a) shows that treatment T1 had a density of 2368 kg/m³. Treatments T2, T4, and T5 exhibited slight decreases of 0.07%, 0.14%, and 0.22%, respectively, compared to T1, while T3 showed a slight increase of 0.06%. In Figure 8 (b), treatments T6, T7, T8, and T9 increased their density by 0.14%, 0.25%, 0.37%, and 0.32%, respectively, compared to T1, due to the incorporation of SS, which has a higher density than cement, influencing the concrete's properties and strength.

Regarding air content, as shown in Figure 8 (a), it decreases as SS is incorporated into the mix. However, it increases by up to 17.39% compared to treatment T1 when the substitution percentages of SS and CWP were 10% and 15%, respectively, as shown in Figure 8 (b). This increase in air content is directly related to the physical properties of SS compared to cement. SS has a higher density and is less porous than ceramic waste, and when incorporated into the mix, it occupies part of the space that would otherwise be filled with entrapped air.

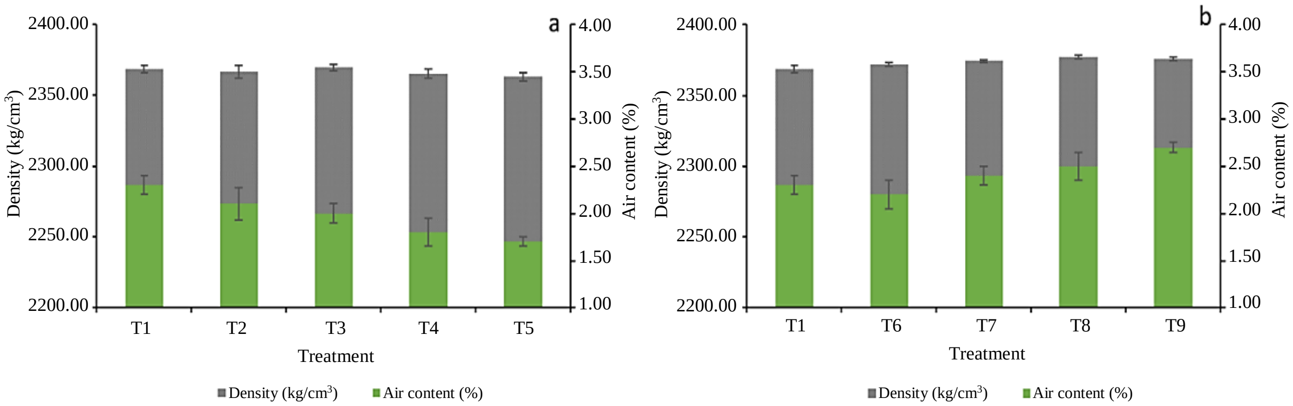

Figure 8 Physical properties of concrete, density and air content of concrete with (a) SS; (b) with SS and CWP.

3.2. Mechanical properties of SS concrete and SS+CWP concrete

3.2.1 Compressive strength

As shown in Figure 9, treatment T1 initially exhibited a compressive strength of 20.58 MPa after 28 days of curing. With the incorporation of SS, treatment T3 achieved the highest strength, showing an improvement of 7.39% compared to T1. The hybrid mixture of SS and CWP (10%:10%), represented by treatment T7, experienced a strength increase of 17.12% over T1. The compressive strength showed a p-value of less than 0.05, specifically $p = 7.01e\text{-}11 < 0.05$, indicating significant differences between the mixtures evaluated. Treatment T7 demonstrated a significant difference from the other mixes, maximizing compressive strength with an average of 24.10 MPa. This behavior is influenced by the use of hybrid materials, as SS and CWP possess beneficial characteristics, such as the high silica content of SS.

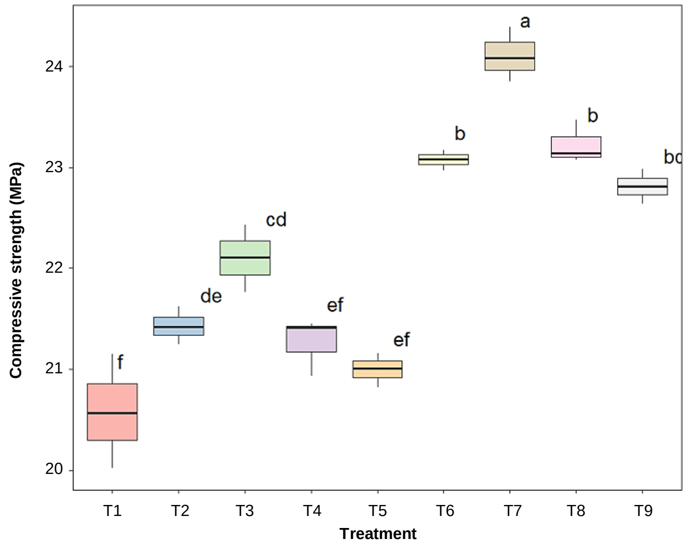

Figure 9 Results of SS, SS+CWP on the 28-day compressive strength of concrete.

3.2.2 Modulus of elasticity

According to Figure 10, treatment T1 initially exhibited an elastic modulus of 18.88 GPa after 28 days of curing. With the incorporation of SS, treatment T3 achieved the highest value, showing an increase of 13.06% compared to T1. The hybrid mixture of SS + CWP (10%:10%), represented by treatment T7, experienced an increase, reaching a peak of 21.21% above T1. Additionally, the data shows that the modulus of elasticity has a p-value of less than 0.05 ($p = 2.86e\text{-}13 < 0.05$), indicating significant differences between the mixtures. The post hoc test revealed that there were no significant differences between mixtures T6 and T7. Treatment T7 exhibited the highest modulus of elasticity, with an average value of 22.88 GPa.

This behavior correlates with the observed increase in compressive strength, as both SS and CWP contribute to enhancing the material's rigidity. The incorporation of these materials likely improves the bond between the cement matrix and the aggregates, reducing microcracks under load and allowing the concrete to better resist deformation stresses. The high silica content in SS, along with the pozzolanic activity of CWP, likely contribute to this improvement, resulting in a more resilient and durable material.

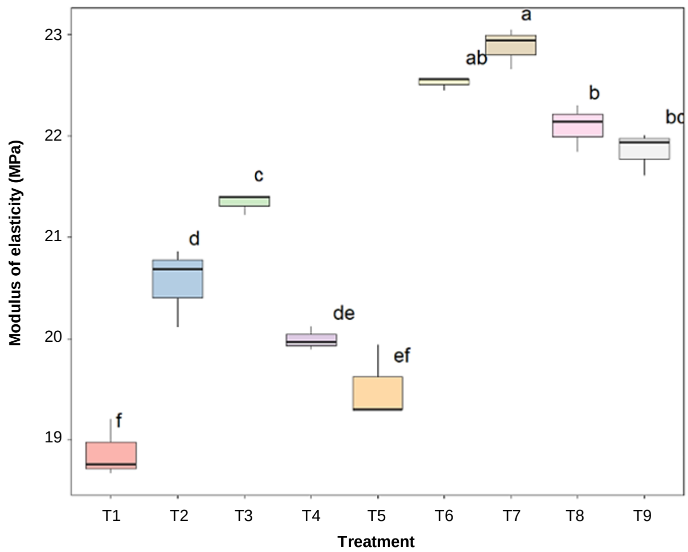

Figure 10 Results of SS, SS+CWP on the 28-day modulus of elasticity of concrete.

3.2.3 Flexural strength

Figure 11, treatment T1 initially exhibited a strength of 4.77 MPa after 28 days of curing. With the incorporation of steel slag (SS), treatment T3 demonstrated the highest strength, showing an improvement of 8.22% compared to T1. Furthermore, when ceramic waste powder (CWP) was combined with 10% SS, treatment T7 experienced a notable increase in strength, reaching a peak of 19.25% above T1. The flexural strength data showed a p-value of less than 0.05 ($p = 2.81e\text{-}05 < 0.05$), indicating significant differences between the mixtures. Mixtures T6, T7, T8, and T9 all exhibited high flexural strength and did not show significant differences among themselves. Treatment T7 achieved the highest flexural strength, with an average of 5.69 MPa.

The observed increase in flexural strength can be attributed to the enhanced bonding and structural integrity provided by the hybrid use of SS and CWP. SS contributes to the improvement due to its high density and high silica content, which enhances the matrix's overall strength. CWP, with its pozzolanic properties, reacts with the cement to form additional cementitious compounds that further increase the material's ability to resist bending stresses. Together, these materials improve the load-bearing capacity and overall durability of the concrete, leading to superior flexural strength.

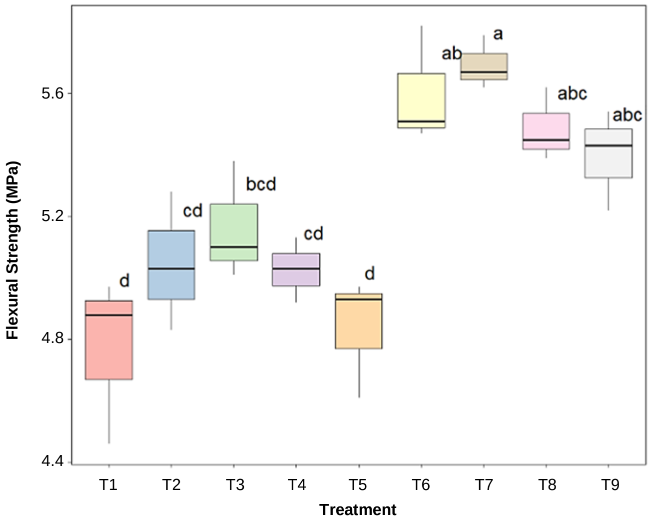

Figure 11 Results of SS, SS+CWP on the flexural strength of concrete at 28 days.

3.2.4 Tensile strength

In Figure 12, treatment T1 initially exhibited a tensile strength of 2.04 MPa after 28 days of curing. With the incorporation of steel slag, treatment T3 demonstrated the highest strength, showing an improvement of 14.10% compared to T1. Further incorporation of ceramic waste powder along with 10% SS in treatment T7 resulted in an exceptional increase in tensile strength, reaching a peak of 26.28% above T1. The p-value was less than 0.05 ($p = 0.00016 < 0.05$), indicating significant differences between the mixtures. Regarding treatments T3, T6, T7, T8, and T9, there were no significant differences among them. However, treatment T7 achieved the highest tensile strength, with an average of 2.58 MPa.

The notable increase in tensile strength can be attributed to the combined effects of SS and CWP. SS enhances the tensile strength due to its high density and mineral content, which contribute to improved bonding within the concrete matrix. CWP, with its pozzolanic properties, reacts with the cement to form additional cementitious compounds, which strengthen the matrix and improve its ability to resist tensile forces. Together, these materials enhance the overall structural integrity of the concrete, resulting in higher tensile strength.

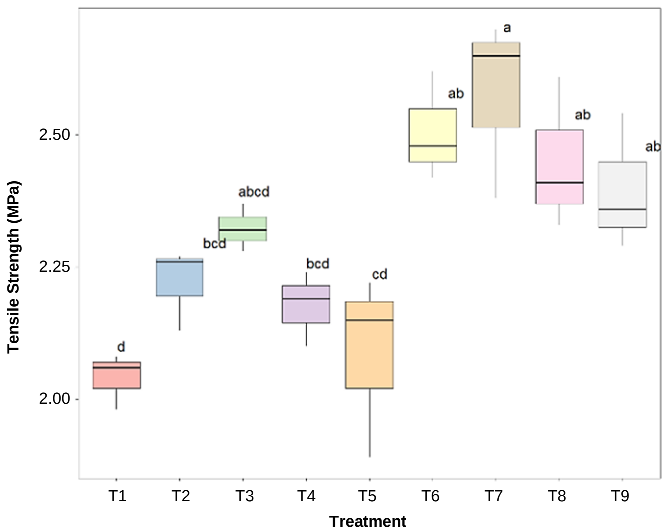

Figure 12 Results of SS, SS+CWP on the tensile strength of concrete at 28 days.

4. Discussions

4.1 Physical properties

The results are related to those obtained by the research of Aguilar and Blanco [28] who point out that the substitution of cement for SS decreases the workability of concrete, while Li et al. [37] and Bhargav and Kansal [27], state that the incorporation of CWP for cement also makes concrete less workable. Altamirano and Zapata [29] specifies that the temperature of concrete with 10% CWP and 10% up to 1.74%; in the case of Gallardo and Pariona [30], they point out that the temperature decreases up to 10% when incorporating steel fiber and CWP. It is interesting to note that the data obtained disagree with the statements of Guerrero [31], who claims that the density of concrete with CWP tends to decrease up to 2.65% when replacing 15% CWP. For its part, Altamirano and Zapata [29], on the other hand, identified a 1.4% decrease in concrete density when incorporating 20% CWP. These discrepancies highlight the importance of considering different factors and contexts when interpreting the results. On the other hand, ceramic residue powder tends to increase the air content because it is less dense than cement and when mixed it creates additional spaces for the air to be trapped, while Aguilar and Blanco [28], indicate that concrete with the incorporation of 10% SS obtains a 2% increase in the air content in the mix.

4.2 Mechanical properties

The results obtained coincide with the findings of Hussain et al. [33], who state that 10% SS improves compressive strength by 13%; similarly, Pan et al. [35], reported that 10% SS increases strength by 6.94%. On the other hand, the results obtained by Palod et al. [40], since the strength showed a 4% improvement at 90 days of curing with the addition of 10% SS. Zhuo et al. [34], found that 5% SS increased compressive strength by 4.1%, while Sha et al. [32], found that 15% SS substitution increased strength by 7.4%. Several authors [27, 29, 31, 37] report that replacing cement with CWP in a percentage close to 10% increases the compressive strength. However, Taher et al. [38], found that replacing 10% of cement with CWP reduces the compressive strength. Gu et al. [39], incorporated SS and CWP at 10.7% each material with respect to cement and determined that the compressive strength increases by 6%.

In the study by Pan et al. [35], it was observed that replacing 10% cement with SS increases the modulus of elasticity by 5.42%. Other researchers, Altamirano and Zapata [29], who found that the incorporation of 10% CWP increases the modulus of elasticity by 3.49%.

Aguilar and Blanco [28], who carried out a national study found similar results, and concluded that the incorporation of 10% SS improves flexural strength by 3%. Most studies [27, 29, 30, 39], how that the replacement of cement by CWP in a percentage close to 10%, between 6 and 20%, increases the flexural strength of concrete.

This is in agreement with the results obtained by Pan et al. [35], who reported that 10% SS improves the tensile strength by 6.45%, while it differs with the results obtained by Zhuo et al. [34], who established that the incorporation of 5% SS increases the tensile strength by 13.63%. Most studies show that the replacement of cement by CWP in a percentage close to 10% increases the tensile strength of concrete [27, 29]. However, Gallardo and Pariona [30] found that a 20% replacement of CWP also improves the tensile strength to a lesser extent.

5. Conclusions

The study provides valuable insights into the effects of incorporating steel slag (SS) and ceramic waste powder (CWP) in concrete. Key findings include:

- The substitution of SS and CWP affects the concrete's physical properties. While the density of the mixture increases due to the nature of the substitute materials, CWP, being less dense, creates voids that influence air content. This results in decreased workability and mixture temperature.
- SS and CWP significantly enhance mechanical properties. The concrete's compressive, tensile, and flexural strength, as well as its modulus of elasticity, improve by 10.83% to 26.28%.
- The optimal levels of substitution are 10% for both SS and CWP, replacing a total of 20% of cement. This substitution yields beneficial effects on the concrete's properties.
- This hybrid concrete is suitable for high-performance structural components, pavements, and durable construction elements, supporting sustainable construction practices by recycling industrial by-products.
- It is recommended to study the durability of concrete with SS and CWP under environmental stresses such as humidity, temperature variations and chemical exposure. Evaluate the behavior of this hybrid concrete in real structural applications and under dynamic loads for future research.

6. References

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