International Information and Engineering Technology Association
Advancing the World of Information and Engineering

Mathematical Modelling of Engineering Problems
Vol. 12, No. 12, December, 2025, pp. 4289-4295
Journal homepage: http://iieta.org/journals/mmep

Physical-Mechanical Performance of Concrete with Agro-Industrial Ashes at Different Thermal Curing Ranges

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https://doi.org/10.18280/mmep.121217

Received: 30 June 2025
Revised: 10 August 2025
Accepted: 18 August 2025
Available online: 31 December 2025

Keywords:
concrete, sugarcane bagasse ash, rice husk ash, curing temperature, mechanical strength

ABSTRACT

Cement production accounts for approximately 8% of global CO_2 emissions, which drives the adoption of sustainable supplementary cementitious materials (SCMs) to reduce clinker consumption. In Peru, sugarcane bagasse ash (SCBA) and rice husk ash (RHA) are abundant agro-industrial by-products with recognized pozzolanic potential; however, their performance under different curing temperatures is still insufficiently documented. This study evaluates the effect of partially replacing cement with 5% and 10% SCBA, RHA, and SCBA+RHA in concrete designed for f'c = 210 kg/cm² and cured at 10°C, 25°C, and 35°C. Nineteen concrete batches were proportioned following ACI 211.1 and tested for fresh-state properties (slump, bleeding, and unit weight) and hardened-state performance (compressive and splitting tensile strength) in accordance with ASTM standards. Statistical significance was assessed using ANOVA and Tukey's post hoc test ($p < 0.05$). A 5% SCBA+RHA replacement increased compressive strength by up to 14% across all curing temperatures, indicating a consistent synergistic effect. At 35°C, RHA at 5% and 10% increased splitting tensile strength by 14% and 13%, respectively, relative to the control. Higher replacement levels reduced slump by up to 28%, likely due to greater fineness and water demand, while also decreasing bleeding by up to 18%, thereby improving mixture cohesion. Overall, SCBA and RHA are viable SCMs for enhancing concrete performance in warm and temperate climates. Their combined use at moderate replacement levels provides mechanical benefits without significantly affecting density, whereas in cold climates, extended curing durations or temperature control are recommended to maximize pozzolanic reactivity and strength development.

1. INTRODUCTION

The construction industry faces the challenge of reducing its environmental impact, since cement, an essential component of concrete, is responsible for approximately 8% of global CO_2 emissions [1]. This situation has encouraged the search for supplementary materials capable of reducing clinker content without compromising the physical and mechanical performance of concrete. Among the alternatives explored are mineral additives, natural pozzolans, and agro-industrial by-products, whose use can enhance material performance while contributing to the principles of the circular economy [2-5].

In Peru, sugarcane and rice are widely cultivated crops, generating significant volumes of agro-industrial waste, particularly sugarcane bagasse ash (SCBA) and rice husk ash (RHA). Both by-products, after appropriate calcination and grinding processes, present a high content of reactive silica and other compounds with pozzolanic potential. These compounds are capable of reacting with the calcium hydroxide released during cement hydration, promoting microstructural densification and reducing porosity [5-9]. Their incorporation also contributes to lower cement consumption, improved waste management, and mitigation of the carbon footprint associated with construction activities [10-13].

Previous studies have reported increases in compressive and tensile strength, as well as improvements in cohesion and workability, when cement is partially replaced with SCBA or RHA at moderate proportions [12, 14-16]. In particular, replacement levels between 5% and 10% have been identified as optimal, achieving higher compressive strength compared to conventional concrete mixtures [12, 16-18]. However, most of these investigations have been conducted under standard curing conditions, without systematically assessing how the performance of SCBA- and RHA-modified concretes varies under different curing temperatures [19-22].

This limitation is especially relevant in the Peruvian context, where construction activities take place under marked thermal variability. In high Andean regions, ambient temperatures may fall below 10°C, whereas in coastal and jungle areas they can exceed 30°C [13, 23-25]. Such temperature variations directly influence hydration kinetics: low temperatures delay early strength development, while elevated temperatures accelerate hydration but may induce microcracking and reduce long-term durability if not properly controlled [26-29].

Within this framework, the present study aims to evaluate the influence of partial cement replacement with SCBA and RHA, at proportions of 5% and 10%, on the physical and mechanical properties of concrete designed for f'c = 210 kg/cm² and subjected to controlled curing temperatures of 10°C, 25°C, and 35°C. Unlike previous studies, this research integrates a comparative analysis across three contrasting thermal ranges, considering both fresh-state and hardened-state properties and applying statistical validation methods (Analysis of Variance (ANOVA) and Tukey tests) to identify significant differences. The results are intended to support technical recommendations for the use of these additions under different climatic conditions in Peru, thereby promoting the production of more sustainable concrete aligned with Sustainable Development Goal No. 12: Responsible Production and Consumption.

2. METHODOLOGY

This research was conducted using a quantitative approach and a controlled experimental design, as all data were obtained through standardized laboratory tests aimed at testing the proposed hypothesis [19]. The study focused on evaluating the effect of partial cement substitution with SCBA and RHA, at replacement levels of 5% and 10%, under different curing temperatures (10°C, 25°C, and 35°C).

The population consisted of 19 laboratory reports generated within the framework of this experimental study, distributed as follows: four reports corresponding to the physical and chemical characterization of the ashes (chemical composition analysis by X-ray fluorescence and particle size analysis according to ASTM E11); six reports related to aggregate testing (granulometry, absorption, and density); three reports on the physical properties of fresh concrete (slump, bleeding, and unit weight); and six reports on the mechanical properties of hardened concrete (compressive strength and indirect tensile strength).

Since the 19 reports corresponded to original experimental results rather than bibliographic sources, the analyzed sample coincided with the total population, thereby avoiding sampling error.

Concrete mixtures were proportioned following the ACI 211.1 methodology, considering a design compressive strength of f'c = 210 kg/cm² and incorporating the corresponding regulatory safety factor. Programmable climatic chambers were used during curing to maintain constant temperatures of 10°C, 25°C, and 35°C (± 0.5°C), which were continuously monitored using calibrated digital sensors. All specimens were cured by immersion in accordance with the Peruvian Technical Standard NTP 339.034 and tested after 28 days.

The physical properties evaluated included slump, determined according to ASTM C143/C143M; bleeding, measured following ASTM C232/C232M; and unit weight, determined in accordance with NTP E.020. Mechanical testing was carried out to determine compressive strength, following ASTM C39/C39M, and indirect tensile strength using the Brazilian method, in accordance with ASTM C496/C496M.

Statistical analysis was performed using ANOVA to identify significant differences between groups, followed by Tukey's multiple comparison test to determine the specific combinations of ash content and curing temperature at which these differences occurred. A significance level of 5% ($p < 0.05$) was adopted. The results were presented in tables and bar graphs to facilitate comparative interpretation of variations in physical and mechanical properties as a function of ash proportion and curing temperature.

Figure 1 illustrates the curing of cylindrical concrete specimens under controlled temperature conditions (left) and the compressive strength test procedure (right).

Figure 1. Temperature-controlled concrete curing and compression testing

3. MATERIALS AND METHODS

Table 1 presents the chemical composition of the sugarcane bagasse ash (SCBA), expressed as mass percentage, based on data obtained from the X-ray fluorescence analysis report. The results indicate a combined content of 91.67% for silicon dioxide (SiO_2), aluminum oxide (Al_2O_3), and iron oxide (Fe_2O_3), which complies with the requirements established in Annex A of NTP 334.014, where a minimum value of 70% is specified for these compounds. In addition, the sulfur trioxide (SO_3) content was 0.07%, remaining well below the maximum permissible limit of 4.00% established by the same standard. Regarding loss on ignition, a value of 4.20% was obtained, which also complies with the regulatory requirement of not exceeding 10.00% according to NTP 334.014.

Table 2 presents the granulometric analysis performed at the SCBA, to obtain a smaller particle size that passes through mesh No. 200, obtaining 84.9% with respect to the percentage in mass. All through, ash from the No. 200 mesh was used for the mixing design of the specimens.

Table 3 presents the composition of the RHA, expressed as a percentage by mass, according to data obtained in the X-Ray Fluorescence Analysis Report, the results show a record of 94.92% in the sum of silicon dioxide (SiO_2), aluminum oxide (Al_2O_3) and iron oxide (Fe_2O_3), complying with the provisions of Annex A of NTP 334.014, which requires a minimum of 70% of these compounds. Likewise, the content of sulfur trioxide (SO_3) is 0.02%, a value that is within the allowed limit compared to the norm of 4.00% at most.

Table 1. SCBA chemical composition proportion percentage comparison

Chemical Composition	Mass Ratio (%)	
	NTP 334.104 - Class N	Analysis Report
Silicon dioxide (SiO_2) + aluminum oxide (Al_2O_3) + iron oxide (Fe_2O_3) (min. %)	70.00	91.67
Sulphur trioxide (SO_3) (max. %)	4.00	0.07
Moisture content (max. %)	3.00	-
Loss on calcination (max. %)	10.00	4.20

Table 2. SCBA granulometry

Mesh ASTM E11	Opening (mm)	Retained Material (g)	(%)	Accumulated (%) Retained	Come in
1/2"	12.50	0.0	0.0	0.0	100.0
3/8"	9.50	0.0	0.0	0.0	100.0
Nº 04	4.76	0.0	0.0	0.0	100.0
Nº 08	2.38	0.0	0.0	0.0	100.0
No. 16	1.19	0.0	0.0	0.0	100.0
No. 30	0.60	0.0	0.0	0.0	100.0
No. 50	0.30	2.7	0.9	0.9	99.1
No. 100	0.15	9.0	3.0	3.9	96.1
No. 200	0.075	33.7	11.2	15.1	84.9
Bottom		254.60	84.9	100.0	0.0

Table 3. RHA chemical composition proportion percentage comparison

Chemical Composition	Mass Ratio (%) NTP 334.104 - Class N	Analysis Report
Silicon dioxide (SiO_2) + aluminum oxide (Al_2O_3) + iron oxide (Fe_2O_3) (min. %)	70.00	94.92
Sulphur trioxide (SO_3) (max. %)	4.00	0.02
Moisture content (max. %)	3.00	-
Loss on calcination (max. %)	10.00	1.60

Table 4. RHA granulometry

Mesh ASTM E11	Opening (mm)	Retained Material (g)	(%)	Accumulated (%) Retained	Come in
1/2"	12.50	0.0	0.0	0.0	100.0
3/8"	9.50	0.0	0.0	0.0	100.0
No. 04	4.76	0.0	0.0	0.0	100.0
No. 08	2.38	0.0	0.0	0.0	100.0
No. 16	1.19	0.0	0.0	0.0	100.0
No. 30	0.60	0.0	0.0	0.0	100.0
No. 50	0.30	2.6	0.9	0.9	99.1
No. 100	0.15	36.0	12.0	12.9	87.1
No. 200	0.075	60.9	20.3	33.2	66.8
Bottom		200.50	66.8	100.0	0.0

With respect to the loss due to burning, 1.60% was obtained, complying with the regulatory requirement of not exceeding 10.00% of the aforementioned standard.

Table 4 presents the granulometric analysis carried out at the RHA, whose objective was to obtain a smaller particle size that passes through the No. 200 mesh, obtaining 66.8% with respect to the percentage by mass. All through, ash from the No. 200 mesh was used for the mixing design of the specimens.

4. RESULTS

Table 5 shows that, regarding slump, the mixture containing 5% SCBA maintained the same value as the control (11.43 cm, 0% variation). In contrast, the most pronounced reductions were observed for mixtures with 10% SCBA, 10% RHA, and 10% SCBA+RHA, with decreases of up to −28% compared to the control mixture ($p < 0.05$). These reductions in slump indicate lower workability at higher replacement levels, which can be attributed to the increased fineness and water absorption capacity of the ashes. Consequently, adjustments in the water-to-cement ratio or the incorporation of plasticizing admixtures may be required.

The unit weight values ranged from 2317 to 2332 kg/m³, with maximum variations of −0.6% relative to the control mixture. This result confirms that partial replacement of cement with SCBA or RHA does not significantly affect the density of hardened concrete. This finding is particularly relevant for structural applications in which concrete mass is a critical parameter, as load-bearing capacity is not compromised by minor density variations.

Regarding final bleeding, the most significant reductions were recorded for mixtures containing 10% RHA (3.30%) and 10% SCBA+RHA (3.20%), representing decreases of up to −18% compared to the control and showing statistically significant differences ($p < 0.05$). This reduction indicates improved mixture cohesion and enhanced water retention capacity, which contributes to reduced bleeding and a lower risk of segregation. Such behavior is especially advantageous in pumped concretes or thin structural elements where homogeneity is essential.

From a practical perspective, moderate replacement levels (5%) do not adversely affect workability, whereas higher replacement levels (10%) improve cohesion and reduce bleeding. However, compensation for slump loss is required to ensure adequate workability and efficient concrete placement.

Table 6 shows that, at a curing temperature of 10°C, the control mixture achieved a compressive strength of 229.63 kg/cm². The incorporation of 5% SCBA+RHA increased this value by 13%, reaching 258.90 kg/cm², while the mixture containing 10% RHA exhibited an increase of 6%, with a compressive strength of 243.00 kg/cm². Both improvements were statistically significant ($p < 0.05$). These results indicate that, even under low-temperature curing conditions, partial substitution of cement with reactive agro-industrial ashes can enhance strength development, likely due to the contribution of amorphous silica and aluminates that participate in early pozzolanic reactions.

Table 5. Average physical properties at 28 days

Mixture	Settlement (cm)	Unit Weight (kg/m³)	Final Oozing (%)	Significance vs. Pattern ($p < 0.05$)
Boss	11.43	2331.8	3.91	-
5% SCBA	11.43	2326.49	3.5	Yes
10% SCBA	8.26	2319.07	3.4	Yes
5% RHA	9.53	2329.32	3.8	No
10% RHA	8.26	2324.37	3.3	Yes
5% SCBA+RHA	9.53	2325.43	4.1	No
10% SCBA+RHA	8.26	2317.3	3.2	Yes

Table 6. Compressive strength (kg/cm²) at 28 days

Mixture	10°C	25°C	35°C	% Max Improvement vs. Boss	Global Significance ($p < 0.05$)
Boss	229.63	291.46	298.64	-	-
5% SCBA	240.96	306.43	309.58	14%	Yes
10% SCBA	233.89	292.98	317.9	6%	Yes
5% RHA	238.5	300	305	4%	Yes
10% RHA	243	305	310	5%	Yes
5% SCBA+RHA	258.9	333.77	340.4	14%	Yes
10% SCBA+RHA	235	317.34	325	9%	Yes

At a curing temperature of 25°C, the control mixture reached a compressive strength of 291.46 kg/cm². The greatest improvement was again observed for the mixture containing 5% SCBA+RHA, which achieved 333.77 kg/cm², corresponding to an increase of 14%. This was followed by the mixtures with 5% SCBA and 10% RHA, both showing strength increases of 5% relative to the control. These results confirm that moderate curing temperatures optimize hydration kinetics and pozzolanic reactivity, thereby promoting greater densification of the cementitious matrix.

At 35°C, the control mixture exhibited a compressive strength of 298.64 kg/cm². The incorporation of 5% SCBA+RHA resulted in a compressive strength of 340.40 kg/cm², representing a 14% increase. In addition, mixtures containing 10% SCBA and 10% SCBA+RHA showed improvements of 6% and 9%, respectively. The consistent performance of the SCBA+RHA combination across the entire thermal range suggests a synergistic effect that enhances the formation of cementitious hydration products and contributes to a reduction in capillary porosity.

In all cases, the reported percentages correspond to the variation in compressive strength relative to the control mixture, which was cured at the same temperature.

From a practical perspective, the combined use of SCBA and RHA, particularly at a replacement level of 5%, provides sustained increases in compressive strength under cold, temperate, and hot curing conditions. This behavior supports its applicability as a robust alternative for structural concrete in regions characterized by significant thermal variability.

Table 7 shows that, at a curing temperature of 10°C, the control mixture achieved an indirect tensile strength of 22.75 kg/cm². The incorporation of 10% RHA resulted in a reduction of 17%, yielding a tensile strength of 18.83 kg/cm², while the mixture containing 10% SCBA+RHA exhibited a decrease of 16%, reaching 19.18 kg/cm². Both reductions were statistically significant ($p < 0.05$). These results indicate that, under low-temperature curing conditions, higher replacement levels may negatively affect the tensile resistance of concrete before cracking, likely due to incomplete hydration and limited early formation of C–S–H.

At 25°C, the control mixture reached an indirect tensile strength of 24.91 kg/cm². The greatest improvement was observed for the mixture containing 10% SCBA, which achieved 27.05 kg/cm², corresponding to an increase of 9%. This improvement suggests the development of a denser cementitious matrix with enhanced paste–aggregate adhesion. Minor increases were recorded for mixtures containing 5% RHA (+0.36%) and 5% SCBA+RHA (+3.45%); however, these values did not exceed the performance achieved with 10% SCBA.

Table 7. Indirect tensile strength (kg/cm²) at 28 days

Mixture	10°C	25°C	35°C	% Max Improvement vs. Boss	Global Significance ($p < 0.05$)
Boss	22.75	24.91	23.53	-	-
5% SCBA	22.5	24.81	24.81	4%	No
10% SCBA	22	27.05	26.06	9%	Yes
5% RHA	23	25	27.3	14%	Yes
10% RHA	18.83	24.5	26.68	13%	Yes
5% SCBA+RHA	22	25.77	24.5	3%	No
10% SCBA+RHA	19.18	25.5	24	2%	Yes

At 35°C, the mixture containing 5% RHA achieved an indirect tensile strength of 27.30 kg/cm², representing a 14% increase relative to the control mixture. Similarly, the mixture with 10% RHA reached 26.68 kg/cm², corresponding to a 13% increase. These results confirm that RHA is particularly effective in enhancing indirect tensile strength under warm curing conditions. This behavior can be attributed to its high fineness and chemical purity, which promote the development of a more homogeneous interfacial transition zone between the cement paste and the aggregate.

In all cases, the reported percentages correspond to the variation in indirect tensile strength relative to the control mixture, which was cured at the same temperature.

From a practical perspective, in cold-curing conditions, the use of 10% RHA or SCBA + RHA may compromise indirect tensile strength. In contrast, under hot curing conditions, RHA at replacement levels between 5% and 10% constitutes an effective option to improve tensile performance. Therefore, the selection of the supplementary material should consider not only compressive strength, but also tensile behavior as a function of the project's climatic conditions.

5. DISCUSSION

The results obtained demonstrate that the incorporation of SCBA and RHA differentially modifies concrete properties as a function of curing temperature, confirming that their performance is strongly governed by hydration kinetics and the pozzolanic characteristics of each addition [16-18].

At medium and high curing temperatures (25–35°C), the observed increase in compressive strength of up to 14% for the mixture containing 5% SCBA+RHA can be attributed to the synergistic interaction between both ashes. Their high contents of amorphous silica (SiO_2) and alumina (Al_2O_3) react with the calcium hydroxide ($Ca(OH)_2$) released during cement hydration, leading to the formation of additional calcium silicate hydrate (C–S–H) and, to a lesser extent, calcium aluminate hydrates (C–A–H) [13, 19, 20]. This microstructural refinement reduces capillary porosity and increases matrix densification, which is consistent with previous findings reported for RHA [16, 19], SCBA [20], and other agro-industrial pozzolanic materials [21, 22].

In contrast, at a curing temperature of 10°C, pozzolanic reactions are significantly slowed due to reduced solubility of reactive compounds and limited ion diffusion within the pore solution, which restricts early C–S–H formation [23]. This behavior explains the limited improvements or even reductions observed in indirect tensile strength, such as the 17% decrease recorded for the mixture containing 10% RHA. Similar trends have been reported in previous studies [24, 25], which indicate that pozzolanic additions in cold climates require extended curing periods or thermal control to fully develop their reaction potential.

Regarding physical properties, the reduction in slump observed for mixtures with 10% replacement levels (up to −28% relative to the control) reflects decreased workability. This effect is mainly associated with the higher proportion of fine particles, increased specific surface area, and internal porosity of the ashes, which intensify initial water absorption [13]. However, these same characteristics contribute to a reduction in bleeding (up to −18%), thereby enhancing mixture cohesion and reducing the risk of segregation. Similar behavior has been reported for other fine mineral additions, such as fly ash and microsilica [26, 27].

A comparative analysis between SCBA and RHA indicates that RHA exhibits superior performance in indirect tensile strength at 35°C, with increases of up to 14%. This behavior can be associated with its high chemical purity and fineness, which promote the development of a more homogeneous and mechanically efficient interfacial transition zone (ITZ) between the cement paste and the aggregates [16, 26]. Conversely, SCBA showed more consistent improvements in compressive strength, possibly due to its higher content of aluminates and metal oxides, which favor the formation of secondary hydration products capable of resisting compressive loads, such as calcium aluminate hydrates [20, 28].

From a practical standpoint, these findings suggest that in coastal and jungle regions of Peru, where curing temperatures commonly exceed 20°C, the incorporation of SCBA and RHA—particularly in combined proportions of 5%—can simultaneously enhance mechanical performance and mixture cohesion, contributing to more durable and sustainable concrete. In high Andean regions, where curing temperatures may approach or fall below 10°C, extended curing durations or temperature-controlled curing regimes are recommended to prevent performance losses, especially in terms of tensile strength [24, 25].

Notably, the maximum strength gains observed in this study (up to 14% in compressive strength at 25–35°C) exceed the improvements typically reported in previous studies involving similar agro-industrial pozzolanic additions, which generally range from 8% to 12% under comparable curing conditions [16, 19, 21]. This enhanced performance suggests a pronounced synergistic effect resulting from the combined use of SCBA and RHA, likely due to the complementarity of their chemical composition and particle size distribution, which optimizes cementitious matrix densification.

Despite these findings, the study presents certain limitations, including the absence of microstructural characterization techniques, such as scanning electron microscopy (SEM) and X-ray diffraction (XRD), to directly confirm the morphology and composition of hydration products. Additionally, long-term durability aspects—such as carbonation resistance, sulfate attack, and freeze–thaw behavior—were not evaluated. Future research incorporating these analyses will strengthen the conclusions, refine technical recommendations for different climatic conditions, and assess the feasibility of applying SCBA and RHA in infrastructure projects with stringent structural and durability requirements.

6. CONCLUSIONS

The incorporation of SCBA and RHA, at replacement levels of 5% and 10%, significantly influences the physical and mechanical behavior of concrete designed for f'c = 210 kg/cm², with a response strongly dependent on curing temperature. Mixtures incorporating SCBA, RHA, and their combination exhibited relevant improvements in strength and cohesion, particularly at medium and high curing temperatures, supporting their suitability as partial cement replacements under favorable or controlled climatic conditions.

Concrete without mineral additions exhibited its best mechanical performance at a curing temperature of 25°C, confirming this condition as optimal for strength development. However, the control mixture did not provide improvements in water retention or reductions in bleeding when compared to mixtures incorporating agro-industrial ashes.

Regarding SCBA, replacement levels of up to 10% proved technically feasible, as density was maintained and bleeding was reduced. At curing temperatures of 25°C and 35°C, mixtures containing 10% SCBA demonstrated improved indirect tensile strength relative to the control mixture, indicating the development of a denser cementitious matrix with enhanced paste–aggregate interaction.

In the case of RHA, reductions in slump were observed, while higher replacement levels improved water retention. In terms of mechanical performance, mixtures containing 10% RHA showed superior compressive behavior across all curing temperatures, and tensile performance was particularly enhanced under warm curing conditions, confirming the effectiveness of RHA in hot climates.

The combined use of SCBA and RHA resulted in the most consistent mechanical performance. Specifically, the 5% SCBA+RHA mixture achieved the highest compressive strength across all curing temperatures, while tensile strength values remained stable and within acceptable variation ranges, ensuring uniformity and structural reliability.

Curing temperature was identified as a key factor governing performance. Increasing the curing temperature from 10°C to 35°C enhanced pozzolanic activity and promoted the formation of calcium silicate hydrate (C–S–H), especially in mixtures containing RHA and SCBA+RHA. Conversely, under low-temperature curing conditions, mechanical development was slower, and reductions in tensile strength were observed in some mixtures, highlighting the need for extended curing durations or thermal control in high Andean regions.

From a practical perspective, the results indicate that SCBA and RHA represent sustainable and technically viable supplementary cementitious materials (SCMs) for concrete applications in the coastal and jungle regions of Peru. In low-temperature environments, the implementation of thermal curing strategies or prolonged curing periods is recommended to ensure optimal mechanical performance and structural reliability.

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