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Concrete Enriched with Prickly Pear Cactus Ash: A Leap Towards Sustainable Construction

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This study evaluates the effect of adding prickly pear cactus ash (PPCA) on the mechanical properties of concrete with a design strength of 280 kg/cm², as a sustainable alternative for the construction industry. A quasi-experimental design was employed, analyzing four PPCA dosage levels: 0 %, 1 %, 1.5 %, and 2 %, to assess their impact on the compressive, tensile, and flexural strength of concrete. The results indicated that the addition of 1.5 % PPCA achieved an optimal increase of 8 % in compressive strength, whereas a 2 % addition led to a 1 % reduction compared to the control sample. Similarly, tensile and flexural strengths showed significant improvements, with the 1.5 % dosage being the most effective. Statistical analysis using the ANOVA test confirmed the significant influence of PPCA on the mechanical properties of concrete, with p-values below 0.05, leading to the rejection of the null hypothesis and acceptance of the alternative hypothesis. These findings suggest that PPCA is a promising additive for enhancing concrete performance, contributing to more sustainable construction practices.

1. Introduction

In the field of civil engineering, the search for construction materials that are both sustainable and economical has become urgent due to the increasing cost and ecological impact of conventional components, especially cement, in the era of climate change. This situation highlighted the critical need to find alternatives that meet the technical standards of the sector and the imperative demand to reduce the environmental footprint. In this context, prickly pear cactus ash, prevalent in areas such as the district of San Bartolomé, Huarochirí - Lima, and traditionally considered waste, emerged as a promising option. This agricultural residue, usually accumulated for decomposition or incineration, was proposed as an additive for concrete, with the potential to revolutionize construction practices by improving the mechanical properties of the material and efficiently managing waste. The integration of this ash into concrete mixes was the core of the research, aiming to corroborate its positive impact on the strength and sustainability of concrete and setting a precedent for the valorization of previously underutilized natural resources. According to Medrano-Sánchez et al. (2024), the integration of environmental and climate policies with solid measures at the political, legal, infrastructural, and collaborative levels is crucial to addressing the urgent climate crisis and promoting a greener and more resilient world.

In the search for sustainable alternatives for construction, several studies have evaluated the use of agricultural residues as partial substitutes for cement in concrete, providing a solid theoretical basis for the current research on prickly pear cactus ash (PCA). For instance, Kathirvel et al. (2019) evaluated Prosopis juliflora ash (PJA), finding that a 10 % addition increased the compressive strength of concrete by 6 %, but higher proportions decreased that strength. This finding highlighted the importance of calibrating the additive dosage to optimize the properties of the concrete. Similarly, Aswin et al. (2023) explored the use of corn cob ash (CCA) and corn leaf ash (CLA), discovering that a 5 % addition significantly improved the compressive strength of concrete, with increases of up to 15 % and 7.5 %, respectively.

Bheel et al. (2022) investigated the addition of Costus englerianus bagasse ash (CEBA) and bagasse fiber (BF) in concrete, finding that integrating 5 % CEBA resulted in a 5 % increase in compressive strength and a 4 % increase in flexural strength. Tarekegn et al. (2022) also explored hybrid ashes from coffee husk and sugarcane

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bagasse, determining that a 10 % addition increased compressive strength, while higher proportions decreased tensile strength, highlighting the importance of adequately dosing the additives.
In regional studies, Florez (2021) and Minaya (2018) provided evidence on the use of vegetable residues such as bamboo ash and bamboo leaf powder, respectively, demonstrating improvements in concrete strength with optimal additions of 0.5 % and 20 %. These results coincide with the findings of Coronel et al. (2021), who evaluated sugarcane bagasse ash (SCBA), finding that 5 % SCBA approximated standard compressive strength and 10 % significantly improved flexural strength.
Recent research by Arbeláez et al. (2023) and García et al. (2023) experimented with hybrid mixtures of sugarcane bagasse charcoal and glass waste, as well as residual wood ash, finding significant increases in compressive and flexural strength. Bernedo & Pinchipinchi (2022) examined the effect of prickly pear mucilage (PPM) and superplasticizer (SP) additives in concrete, demonstrating a positive impact on mechanical strength with additions of 2 % PPM and 1.2 % SP.
Finally, studies by da Silva et al. (2020) and Gutiérrez et al. (2019) evaluated other natural additives such as bamboo ash and volcanic ash, finding that moderate additions could improve the properties of concrete. Chambi (2022) investigated cattail ash, revealing that a 3 % addition improved the compressive and tensile strength of concrete.
Given that research highlights the potential of transforming waste into valuable resources for civil engineering, prickly pear cactus ash not only emerges as a promising candidate due to its chemical and physical properties but also as a symbol of innovation towards greener construction practices, crucial in the era of climate change. Therefore, this research aims to answer the question: How does the addition of prickly pear cactus ash affect the mechanical properties of 280 kg/cm² concrete from the Carapongo quarry - Lurigancho in 2023? This central question will guide the work, with data collection instruments validated by expert judgment, ensuring the rigor and precision of the study.

2. Methodology, Materials and Method

2.1 Methodology

The research conducted was of the applied type, employing a quasi-experimental design to evaluate the effect of adding prickly pear cactus ash on the mechanical properties of concrete. The independent variable corresponded to the ash addition in proportions of 0%, 1 %, 1.5 %, and 2 %, while the dependent variable was represented by the compressive, tensile, and flexural strength of the concrete. Regarding the study population, it consisted of aggregates sourced from the Carapongo quarry, located in the Lurigancho district of Lima (see figure 1). A non-probabilistic sample of 450 kg of material was selected from this source and subjected to standardized tests based on Peruvian technical specifications. For data collection, direct observation was used during the execution of laboratory tests, allowing the recording of sample behavior under controlled conditions. Additionally, the process was supplemented with a documentary analysis that contributed to the systematization of the collected information. The validity of the results was ensured through tests conducted in a laboratory accredited by the National Institute of Quality (INACAL), guaranteeing compliance with established standards. Similarly, reliability was ensured through the application of standardized procedures and the use of calibrated equipment, ensuring the accuracy and reproducibility of the tests. Finally, data analysis was performed using SPSS software, version 29.0.2.0. Since the sample size was fewer than 50 units, it was determined that the data followed a parametric distribution. Consequently, the ANOVA statistical test was applied to test the hypotheses, allowing for the evaluation of the influence of prickly pear cactus ash addition on the mechanical properties of concrete.

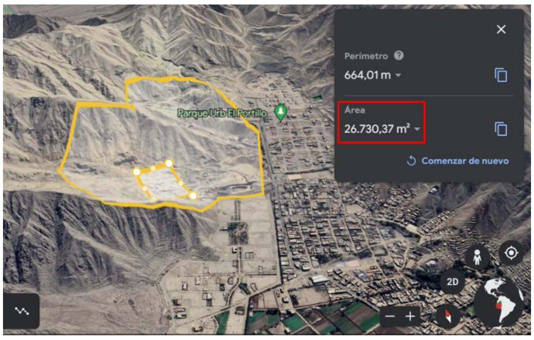

Figure 1: The Carapongo - Geo localization


Figure 2: Prickly pear, prickly pear or prickly pear plant

2.2 Materials

Opuntia ficus-indica, commonly known as prickly pear cactus or nopal, is a species from the cactus family that is highly adaptable to arid regions, demonstrating resistance to extreme temperature variations and requiring minimal water for growth and fruit production (FAO, 2018) (see figure 2). The ash obtained from its calcination at temperatures ranging from 450°C to 800°C results in a fine powder with a color that varies from dark gray to light gray, and it is rich in silica, alkaline and earthy salts, as well as metallic oxides. Additionally, the plant's leaves periodically shed, producing dry mucilage with an average content of 5.6 % moisture, 7.3 % protein, and 37.3 % ash (FAO, 2018).

The fieldwork was conducted in the district of San Bartolomé, Huarochirí province, Lima, at an altitude of 1,600 meters above sea level, in an *Opuntia ficus-indica* cultivation orchard. The material used was obtained from the pruning process, which involved cutting cladodes accumulated in various areas of the plot for natural decomposition. Given that the plant has spines on both the cladodes and fruits, appropriate safety equipment was used. For the characterization of prickly pear cactus ash, the study by Vargas et al. (2019) was taken as a reference, with the results presented in Table 1 and Table 2, which provide detailed information on its physicochemical properties and centesimal composition. Based on these findings, natural open-field calcination was carried out by preparing a specific area where the process was conducted with an initial preheating at 50 °C, progressively increasing the temperature. A metal tray measuring 30 cm wide by 60 cm long was used to prevent external contamination. After 2.5 hours, approximately 6 kg of ash was obtained, which was sufficient for concrete dosage. Finally, the cooled ash was stored in a metal container and transported to the laboratory for further analysis.

Table 1: Ash test results according to Vargas et al. (2019)

	Weight (g)	Stalk Mucilage (g)	Ash (g)	% Ash	Average
I	25.0896	1.0028	0.1028	10.2512	
II	24.4729	1.0689	0.115	10.8055	10.5535
III	26.263	1.0100	0.1071	10.6039	

Table 2: Centesimal composition results according to Vargas et al. (2019)

Element	Weight %	Atomic %
C	45.23	53.67
O	50.01	44.45
Mg	0.35	0.20
K	0.58	0.21
Ca	3.84	1.23
Total	100	

2.3 Method

For the preparation of the concrete mix designed to achieve a compressive strength of f'c = 280 Kg/cm², Portland cement (Sol Type I) was used, along with aggregates sourced from the Carapongo quarry, which were characterized according to Peruvian technical standards (PTS), and prickly pear cactus ash. The first calcination phase was conducted in an open-air environment at an estimated temperature of 50 °C, following the observations of Hernández et al. (2020) regarding mineralogy under wildfire conditions. Subsequently, a second calcination was performed in the laboratory at 500 °C, followed by the pulverization of the ash to achieve a fineness modulus comparable to that of cement. These phases are illustrated in Figure 3.

(a) Calcination 1 *(b) Calcination 2* *(c) Calcination 3*

Figure 3: Calcination phases of the prickly pear leaves

Finally, the cylindrical and beam-shaped specimens were molded, cured in water, and tested at 7, 14, and 28 days, in accordance with the guidelines of NTP 339.034, NTP 339.084, and NTP 339.079 standards, to evaluate their compressive, tensile, and flexural strength, respectively (see Figure 4).

a) Compression *(b) Tensile* *(c) Flexure*

Figure 4: Compression, tensile and flexure tests.

3. Results

Figure 5 details the behavior of the compressive strength of the concrete specimens at ages of 7, 14, and 28 days. It is observed in the mentioned figure that, initially at 7 days, the representative columns of the standard sample, colored in blue, indicate a superior strength with an average value of 297.27 kg/cm^2 compared to the dosages with PPCA, which show lower values for 1 %, 1.5 %, and 2 %. However, as time progresses, specifically at 14 days, the trend reverses; the standard sample, now with a value of 321.17 kg/cm^2, is surpassed by the mixes with PPCA, which register significant increases, especially the column of 1.5 % PPCA, reaching 349.90 kg/cm^2. Therefore, the results indicate that the optimal addition of PPCA is 1.5 %, this concentration being the most effective in surpassing the strength of the standard sample and achieving the goal of improvement in the concrete's compressive strength.

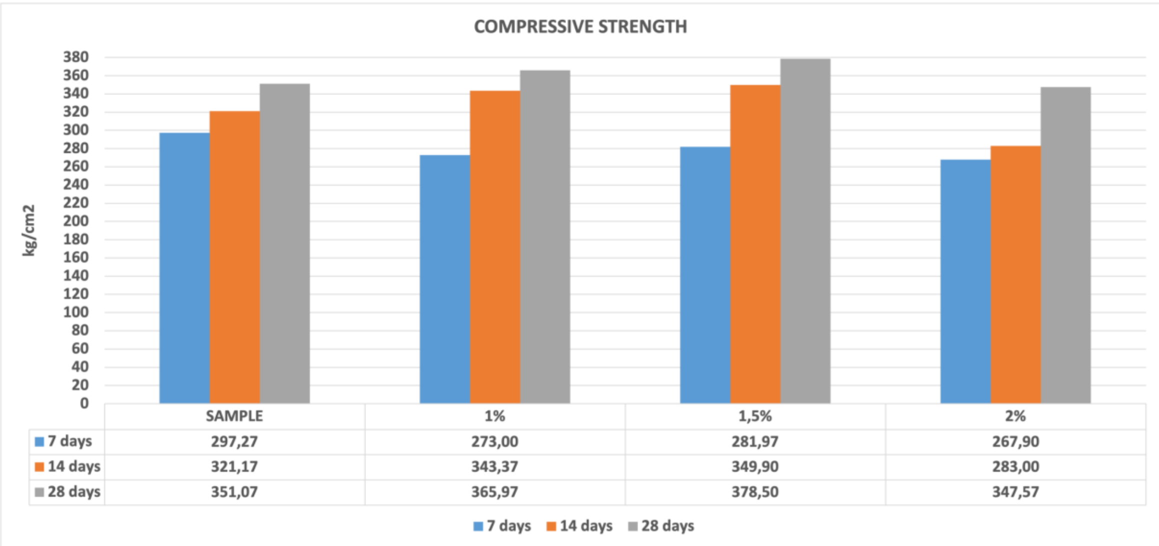

Figure 5: Compressive strength

Regarding the tensile strength (TS) of the samples tested at 7, 14, and 28 days, the results indicated that during the first week, the samples with the addition of PPCA exhibited higher TS compared to the standard sample, showing a positive trend that continued through day 14. At this stage, the performance of the sample with 1.5 % PPCA was particularly noteworthy, registering a 14 % increase in TS compared to the standard sample. By day 28, a significant increase in TS was observed across all PPCA dosages, with improvements of 9 %, 14 %, and 5 % for 1 %, 1.5 %, and 2 % PPCA, respectively, compared to the standard sample.

Regarding the flexural strength (FS) of the concrete specimens tested at 7, 14, and 28 days, it was observed that, from the first week, the samples with the addition of PPCA exhibited higher FS compared to the standard sample, a trend that persisted through day 14. Notably, at 14 days, the samples with 1.5% and 2% PPCA showed significant improvements in FS, achieving increases of 20% and 15%, respectively, compared to the standard sample.To assess the normality of the data, the Shapiro-Wilk test was applied, given that the sample size was less than 50. The results indicated that the data followed a normal distribution, with significance values (p) greater than 0.05. This justified the use of the ANOVA test for inferential analysis, which confirmed that both the general and specific hypotheses rejected the null hypothesis and accepted the alternative hypotheses. The findings demonstrated the influence of prickly pear cactus ash on the compressive strength of concrete.

4. Discussion

The results obtained in this study reveal a significant influence of PPCA on CS of concrete, a finding that resonates with the research by Aswin et al. (2023), where it was observed that the addition of corn cob ash increases the CS in concrete with an f´c of 280 kg/cm^2. This coincidence could be attributed to similar experimental methodologies that emphasize the relevance of agricultural waste as additives in the concrete composition.Tarekegn et al. (2022) and Coronel et al. (2021) reported improvements in CS with the incorporation of hybrid ashes and sugarcane ash, respectively. However, upon exceeding a 5 % ash addition, a decrease in CS was observed, a pattern also identifiable in the present study, where the optimal percentage of PPCA turned out to be 1.5 %. On the other hand, Minaya (2018) achieved an increase in strength in concrete bricks by using 20 % bamboo leaf ash, thus highlighting the variability in the effectiveness of different types of ashes and their optimal concentrations.

Regarding TS, Tarekegn et al. (2022) found that the addition of hybrid ashes from agricultural waste could reduce tensile stress, except with a 10 % hybrid ash that surpassed the reference sample. The present research shows results that are consistent with these findings, underscoring that TS is increased with the addition of 1.5 % PPCA.

As for FS, studies by Coronel et al. (2021) and Bheel et al. (2022) indicated that the addition of 5 % agricultural waste ash contributes positively. In concordance, the current investigation demonstrated an increase in FS with 1.5 % PPCA, reinforcing the idea that these additions are beneficial for the mechanical properties of concrete.

It is important to highlight that the similarities found between the results of the current research and previous studies not only validate the findings but also contribute to a growing body of evidence supporting the use of agricultural waste in enhancing the properties of concrete. The ability of these additives to increase CS, TS, and FS confirms their potential as sustainable alternatives in civil engineering.

Finally, it is corroborated that ashes from agricultural waste have a significant impact on the CS, TS, and FS of concrete. The optimal dosage of PPCA, determined to be 1.5 %, not only improves the mechanical properties of the concrete but also promotes sustainability in the construction sector.

5. Conclusions

The statistical analysis using the ANOVA test confirmed that the addition of prickly pear cactus ash significantly influences the compressive, tensile, and flexural strengths of concrete. In all cases evaluated, the significance value (p) was less than 0.05, leading to the rejection of the null hypothesis and the acceptance of the alternative hypothesis, thus confirming the effect of the ash on the mechanical properties of concrete.

The findings of this research not only demonstrate the positive influence of adding prickly pear cactus ash on the mechanical properties of concrete but also highlight its potential as a sustainable alternative for the construction industry. The incorporation of this agro-industrial byproduct significantly contributes to waste reduction and promotes a circular economy, aligning with current trends in sustainable development. Moreover, the use of prickly pear cactus ash could reduce reliance on conventional materials, thereby lowering the carbon footprint associated with cement production.

While the results obtained under controlled laboratory conditions have been promising, further studies in real-world environments are necessary to evaluate the behavior of concrete with prickly pear cactus ash when exposed to environmental factors such as humidity, temperature, and aggressive agents. Additionally, expanding the scope of research to assess other properties of concrete, such as durability and workability, is suggested to achieve a more comprehensive understanding of its long-term performance.

From a practical perspective, the research findings could serve as a basis for updating construction regulations and standards, facilitating the adoption of sustainable materials in the industry. Furthermore, conducting economic analyses is recommended to assess the feasibility of large-scale implementation of this type of concrete, considering its cost-benefit ratio compared to traditional materials.

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