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Nopal extract and aloe vera to improve structural concrete exposed to saline environments

Extracto de nopal y aloe vera para mejorar concreto estructural expuesto en ambientes salinos

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ABSTRACT: The objective of this study was to examine the impact of Nopal (N) and Aloe Vera (AV) on the physical and mechanical properties of structural concrete in saline environments. Concrete with a compressive strength of 245 kg/cm² was used, adding N and AV extracted from natural plants in the study region. A total of 130 cylindrical specimens, 40 prismatic specimens, and 10 fresh mix samples were analyzed. Percentages of Nopal (2%, 6%, and 10%), Aloe Vera (0.5%, 1.5%, and 3%), and mixed (2%N + 0.5%AV, 6%N + 1.5%AV, 10%N + 3%AV) were added based on the weight of the cement. The control group contained no additives. The best results were obtained with the 2%N + 0.5%AV samples, with the highest compressive strength of 443.4 kg/cm² at 28 days and 445.4 kg/cm² at 56 days, a tensile strength of 41.4 kg/cm² at 28 days, a flexural strength of 66.4 kg/cm² at 56 days and 70.9 kg/cm² at 90 days of curing. The corrosion resistance decreased by a maximum of 0.22 mm/year. The physical and mechanical properties were optimized with the proportion of 2%N + 0.5%AV, indicating that the mixing matrix becomes more compact, and the carbonation rate is reduced, resulting in greater strength and durability.

RESUMEN: El objetivo de este estudio fue examinar el impacto del Nopal (N) y el Aloe Vera (AV) en las propiedades físicas y mecánicas del concreto estructural en ambientes salinos. Se empleó concreto con una resistencia a la compresión de 245 kg/cm², al cual se le añadieron N y AV extraídos de plantas naturales de la región de estudio. Se analizaron 130 probetas cilíndricas, 40 probetas prismáticas y 10 muestras de mezcla para ensayos en estado fresco. Se adicionaron porcentajes de Nopal (2%, 6% y 10%), Aloe Vera (0.5%, 1.5% y 3%), y mixtas (2%N + 0.5%AV, 6%N + 1.5%AV, 10%N + 3%AV), en función al peso del cemento. El grupo control no contenía aditivos. Los mejores resultados se obtuvieron con las muestras 2%N + 0.5%AV, con la máxima resistencia a la compresión de 443.4 kg/cm² a 28 días y 445.4 kg/cm² a 56 días, resistencia a la tracción de 41.4 kg/cm² a 28 días, resistencia a la flexión de 66.4 kg/cm² a 56 días y 70.9 kg/cm² a 90 días de curado. La resistencia a la corrosión disminuyó en un máximo de 0.22 mm/año. Se optimizaron las propiedades físicas y mecánicas con la proporción de 2%N + 0.5%AV, indicando que la matriz de la mezcla se vuelve más compacta y se reduce la velocidad de carbonatación, lo que resulta en una mayor resistencia y durabilidad.

1. Introduction

In the construction sector, concrete is the most widely used construction material in the world and has experienced substantial growth in recent years [1]. It is commonly used in the fields of civil engineering and construction systems due to its low cost, multiple raw material resources, simple preparation, and excellent performance [2]. In addition, it has different properties, including good plasticity, compressive strength, strong bonding with steel, and durability [3]. Considering the Global Cement and Concrete Association recommendations, it is noted

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that the global consumption of concrete for 2020 reached 14 billion m³, of which 40% was allocated for residential construction [4]. However, concrete structures often present different types of failures, which usually occur during the construction stage, such as shrinkage cracks, or during their useful life as a result of physicochemical changes [5]. One of the main problems is corrosion, which is responsible for a significant percentage of structural failures that lead to structural collapse [6].

It is known that the cost of corrosion in the construction industry is 2.5 trillion dollars worldwide, which is equivalent to 3.4% of the global GDP [7]. The most affected structures are those located in tidal areas, due to exposure to chloride during the dry/wet cycle and the load during their useful life [8]. This issue causes durability problems [9] and reduces the strength of the concrete and reinforcement materials, negatively affecting the load capacity of the structure [10]. Therefore, these structures need to be repaired and strengthened. When structures suffer from corrosion, they can collapse and require the construction of new buildings and the production of materials, which generates environmental pollution. In this regard, the massive production of cement causes serious problems for the environment due to the emission of CO_2 [11], releasing up to 8% of anthropogenic CO_2 emissions into the atmosphere [12]. In addition, the CO_2 emissions resulting from the demolition, collection, transport, and waste generated from the structures also contribute to environmental pollution. Buildings made of mortar, concrete, brick, and block generate 93% of the waste in reinforced concrete and concrete-brick structures, while masonry structures reach 81% and wood 72% [13]. The volume of waste increases and distribution ratios differ according to the type of structure, significantly contributing to the CO_2 emissions generated in each phase of the life cycle [13].

The concrete used in construction must have suitable physical and mechanical properties to minimize the multidistribution of movement and prevent the appearance of cracks [14]. Moreover, it is important to reduce the environmental impact and energy requirement in the sustainable production of concrete, as well as to decrease the use of natural materials and the emission of greenhouse gases during cement production [15]. However, many inhibitors are dangerous substances that are being banned due to their negative impact on the environment and on human beings [16]. Therefore, alternative, and environmentally friendly additives are being sought to produce eco-friendly concrete [17].

It has been shown that Nopal derivatives can clog the biopolymer within the pores of the concrete matrix, preventing the conduction of water and chloride [18]. Likewise, polysaccharides influence the strength characteristics, while proteins and fats impact the workability and durability of additive-modified concrete [19]. In addition, the durability of mortar exposed to carbonate environments is improved by adding concentrations of Nopal mucilage at 4 and 8% by mass substitution of water [20]. The addition of additives such as Nopal and Aloe Vera has shown to be favorable for compressive strength, outperforming the standard mix [21, 22]. Some authors [22–24] agree that Aloe Vera increases the compressive strength but decreases the slump with respect to the increase of the percentage used and capillary absorption.

This research provides information on the use of additives based on Nopal and Aloe Vera extracts in concrete, intensifying the use of non-toxic products and their implementation in civil construction. In addition, it provides a solution to avoid structural failures in buildings located in saline areas. The objective of the study is to determine the effect of Nopal and Aloe Vera extract on the physical-mechanical properties of structural concrete in saline environments and to evaluate the corrosion of concrete through the carbonation process.

2. Methodology

2.1 Materials

Type I Portland cement Pacasmayo brand, fine and coarse aggregates from the León quarry, located in the district of Huanchaco, El Milagro sector, potable water, additives obtained from *Opuntia ficus-indica* (Nopal) and *Aloe vera* (Aloe Vera) plants from the highlands of the city of Huamachuco were used. These plants contain a gel of higher production in the warm current period that contains monosaccharides and disaccharides [25].

2.2 Experimentation

For the fabrication of the cylindrical and prismatic specimens, we proceeded in batches of 13 and 4 specimens, respectively. The corresponding proportions are detailed in Tables 1 and 2.

2.3 Production of extracts

Nopal extract: To obtain the Nopal extract, all the thorns were removed from the stalks of the plant and washed. Then, they were cut into small pieces of 1 cm x 1 cm, and the pulp was separated from the peel. The pulp was left in a ratio of 1 kg of Nopal and 1 liter of water for a period of 24 hours. It was then cooked for 20 minutes on a gas stove and cooled to room temperature. Finally, it was strained to eliminate all that was retained.

Table 1 Ratio of materials by weight (kg) for 13 cylindrical specimens of 10cmx20cm

Sample code	Type I Cement	Drinking water	Shaken sand	Crushed stone HUSO 67	Amount of Nopal (kg)	Quantity of Aloe Vera (kg)
CP245 (Control)	11.26	6.03	19.04	29.85	-	-
CP245 + 2%N	11.26	6.03	19.04	29.85	0.225	-
CP245 + 6%N	11.26	6.03	19.04	29.85	0.675	-
CP245 + 10%N	11.26	6.03	19.04	29.85	1.126	-
CP245 + 0.5%AV	11.26	6.03	19.04	29.85	-	0.056
CP245 + 1.5%AV	11.26	6.03	19.04	29.85	-	0.169
CP245 + 3%AV	11.26	6.03	19.04	29.85	-	0.338
CP245 + 2%N + 0.5%AV	11.26	6.03	19.04	29.85	0.225	0.056
CP245 + 6%N + 1.5%AV	11.26	6.03	19.04	29.85	0.675	0.169
CP245 + 10%N + 3%AV	11.26	6.03	19.04	29.85	1.126	0.338

Table 2 Ratio of materials by weight (kg) for 4 prismatic specimens of 15cmx15cmx52cm

Sample code	Type I Cement	Drinking water	Shaken sand	Crushed stone HUSO 67	Amount of Nopal (kg)	Quantity of Aloe Vera (kg)
CP245 (Control)	22.52	12.6	38.08	59.7	-	-
CP245 + 2%N	22.52	12.6	38.08	59.7	0.450	-
CP245 + 6%N	22.52	12.6	38.08	59.7	1.350	-
CP245 + 10%N	22.52	12.6	38.08	59.7	2.252	-
CP245 + 0.5%AV	22.52	12.6	38.08	59.7	-	0.112
CP245 + 1.5%AV	22.52	12.6	38.08	59.7	-	0.338
CP245 + 3%AV	22.52	12.6	38.08	59.7	-	0.676
CP245 + 2%N + 0.5%AV	22.52	12.6	38.08	59.7	0.450	0.112
CP245 + 6%N + 1.5%AV	22.52	12.6	38.08	59.7	1.350	0.338
CP245 + 10%N + 3%AV	22.52	12.6	38.08	59.7	2.252	0.676

Aloe Vera Extract: For its preparation, fresh leaves were used, washing, and having their corners removed due to the presence of thorns. The leaves were submerged in water for a period of 24 hours. They were not subjected to be cooked to prevent the loss of their active compounds - such as enzymes, proteins, vitamins, amino acids, magnesium, titanium, calcium, and potassium, among others - which are heat-sensitive and could decompose during this process. Subsequently, the gel was extracted directly from the leaves through a scraping process, which allowed the preservation of its compounds. This gel was mixed uniformly using a blender. Finally, a straining process was carried out to obtain the pure extract.

2.4 Concrete properties

The behavior of the mechanical properties was determined considering the Peruvian Technical Standards.

Slump

To measure the consistency of the concrete in its fresh state, the Abrams Cone, a compacting bar, a winch, and a ladle were used. The mold was moistened, and the concrete sample was filled with the ladle in three layers; each one was compacted with 25 blows using the compacting bar in a uniform manner. Afterward, the area around the mold was screeded and cleaned. Subsequently, the mold was removed from the concrete vertically, and the slump was measured from the center of the mixture using a winch. Finally, a horizontal rod with the largest diameter was placed over the cone at the top [26].

Compressive strength

Sixty cylindrical specimens of 20 cm in height and 10 cm in diameter were prepared, divided into 3 groups, and cured with an addition of 5% salt [8] at 28 and 56 days. Salt was incorporated into the process to simulate specific conditions, similar to those found in marine environments. By using salt in the curing process, it is attempted to replicate these conditions to evaluate how the concrete reacts and verify if its properties improve in that particular environment. For the test, an ALFA automatic compression machine, model B-001/LCD/2, with a capacity of 2000 kN and a loading speed in accordance with ASTM C39, was used. Once the curing time had elapsed, the specimens were removed, and cleaned, and their diameter was measured. Then, the specimen to be tested was placed together with pads, carefully centering it and verifying that the display showed a reading of 0. The load was applied at a rate that depended on the cross-section and continued compressing until the final load was obtained. Finally, the resistance was recorded in kg/cm^2 [27].

Tensile strength

Thirty cylindrical specimens of 20 cm in height and 10 cm in diameter were made, divided into 3 groups, and cured with an addition of 5% salt after 28 days. For the test, an ALFA automatic compression machine, model B-001/LCD/2, with a capacity of 2000 kN and a loading speed in accordance with ASTM C39, a supplementary support plate and support strips were used. Once the curing time in the saline environment was completed, the tests were carried out by marking the diametrical lines of the core at each end with a ruler and a marker. Then, diameter measurements were taken at both ends and in the middle of the core, coinciding with the marked line, and the length was measured on the marked lines of the core. Next, the machine was enabled, and the specimen was centered so that the drawn centerline corresponded to the center of the strip. Finally, the load was applied continuously until the final reading was obtained on the machine display [28].

Bending strength

Forty beams with dimensions of L=52cm, b=15cm, and h=15cm were prepared, divided into two groups, and cured with an addition of 5% salt at 56 and 90 days. For the test, an ALFA automatic compression machine, model B-001/LCD/2, with a capacity of 2000 kN and a loading speed in accordance with ASTM C39, was used. Once the curing time in the saline environment was completed, the tests were carried out by rotating the beams on one of their sides in relation to the molded position and centering them on the support plates. Three centimeters were measured from the end point of the beam to the center and marked for reference. The beam was then placed in the testing machine, verifying that the marked lines matched the center of the support block and that the load block rested on the third part of the beam span. The load was applied continuously up to the point of rupture. Finally, measurements of the cross-section were taken to calculate the modulus of rupture, its width, and depth, taking three measurements (two at the ends and one in the center) to determine the average width, height, and location of the fracture in the failure section [29].

Evaluation of corrosion by the carbonation process

Forty cylindrical specimens of 20 cm in height and 10 cm in diameter were made, divided into two groups, and cured with an addition of 5% salt at 90 and 145 days. Materials such as phenolphthalein solution, grinder, rigid molds, brush, and ruler were used for the test. The specimens were prepared according to UNE-EN 12390-2, 2001; UNE-EN 12504-1, 2020, and UNE EN 14630, 2007, and were cured in saline solution the following day. Once the established curing times were completed, the tests were carried out. First, the specimens were broken by direct traction using a grinder. Then, the specimens were broken by means of the tensile test, and once the specimen was divided into equal parts, it was cleaned with a brush and sprayed with phenolphthalein on one side. The result showed painted areas corresponding to non-carbonated and unpainted areas corresponding to carbonated areas. Next, measurements were taken of both the lateral faces and the upper face, avoiding measuring in the aggregates. Finally, the rate of carbonation advance was calculated using the average carbonation depth in mm between the time of the tests [30–32].

3. Results and discussion

3.1 Material characterization and mixture design

The results of the aggregate characterization were carried out based on the standards established for compliance with the procedures of each test (Table 3). Likewise, the aggregate grain size was found to be within the maximum and minimum limits (Figures 1 and 2). For the coarse aggregate the nominal maximum size was ¾", fineness modulus 6.77 and its moisture content 0.4%, specific weight 2.73 gr/cm^3, absorption 1%, loose unit weight 1,458 gr/cm^3 and compacted 1,609 gr/cm^3, while, for the fine aggregate its fineness modulus was 2.39, moisture content 0.6%, specific weight 2.63 gr/cm^3, absorption 1.2%, loose unit weight 1,648 kg/cm^3 and compacted 1,824 kg/cm^3. These results vary compared to the reviewed precedents, due to factors such as the origin and different sizes of the aggregates used, the analysis methods employed, the geographical and sampling conditions, and even changes in regulations, highlighting that they all complied with the limits and followed the standardized procedures required by the NTP and ASTM C136-01 standards [18, 19, 21–24, 29].

Likewise, the mix design was carried out according to the ACI 211.1 standard [33] for concrete of f'c = 245 kg/cm^2, considering the water/cement ratio of 0.51, Slump of 3±1 and f'cr 329 kg/cm^2 (Table 4). The proportioning of the mix was carried out by batch per bag of cement (Tables 5 and 6).

3.2 Slump

This test shows that the mix with natural additions is wetter and more workable compared to the standard mix (Figure

Table 3 Physical properties of materials

Material	Specific Weight (kg/m³)	Absorption %	Humidity Content ((%))	Module of Fineness	Dry unit weight (kg/m³)	Compacted unit weight (kg/m³)	Source
Cement Type I	3,120	–	–	–	–	–	Cement Pacasmayo
Drinking water or similar	1,000	–	–	–	–	–	–
Shaken sand	2,630	1.2	0.6	2.39	1,648	1,824	El León Broken Quarry
Crushed stone HUSO 67	2,730	1.0	0.4	6.77	1,458	1,609	
Aloe Vera	1,200	–	–	–	–	–	city of Huamachuco
Nopal	1,250	–	–	–	–	–	

Table 4 Technical specifications of concrete

Identification	Cement Type	f'c (kg/cm²)	f'cr (kg/cm²)	Slump (inch)	Maximum nominal (aggregate size) (inch)	Ratio (A/C)
DP245	I	245	329	3 ± 1	3/4	0.51

Table 5 Proportioning of the standard concrete mix

Material	Dry Weight (kg/m³)	Volume (m³)	Weight SSS (kg/m³)	Wet Weight (kg/m³)	Batch Test (kg)*	Batch per bag of Cement	Remarks
Cement Type I	402.0	0.129	402.0	402.0	11.26	1 Bls	Bag of 42.5 kg
Drinking water or similar	205.0	0.205	205.0	215.5	6.03	23 l	–
Shaken sand	675.9	0.257	684.0	680.0	19.04	2.5 Lat	Can of 18 liters
Crushed stone HUSO 67	1,061.9	0.389	1,072.5	1,066.1	29.85	4.5 Lat	Can of 18 liters
Aloe Vera	0.0	0.000	0.0	0.0	0.000	–	–
Nopal	0.0	0.000	0.0	0.0	0.000	–	–
Trapped air	0.0	0.020	0.0	0.0	0.00	–	–
Total	**2,344.8**	**1.000**	**2,363.5**	**2,363.6**	**66.18**	–	–

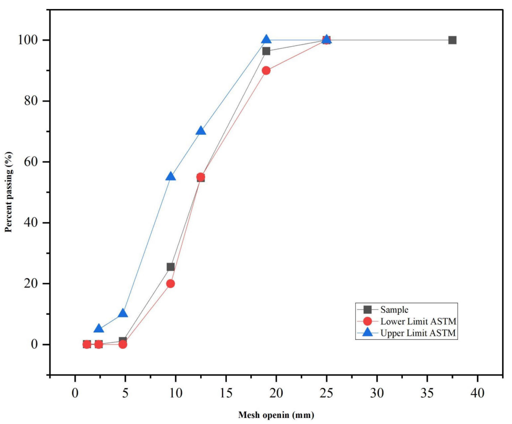

Figure 1 Gradation curve for coarse aggregate

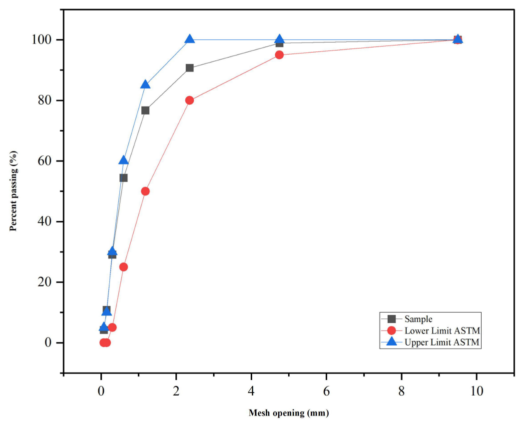

Figure 2 Gradation curve for fine aggregate

3). As the percentage of Nopal (N) and Aloe Vera (AV) increases, the slump also increases, showing values with an increasing trend. For example, the standard concrete presented a slump of 4 1/2", and with the addition of 2%N, it increased to 6"; with 6%N, it increased to 8" and with 10%N, it reached 8 1/4". Similar results are reported in

Table 6 Ratio of the amounts of extracts added to the standard concrete in relation to the weight of cement

Sample code	Amount of Nopal (kg)	Amount of Aloe Vera (kg)
CP245	–	–
CP245 + 2%N	0.225	–
CP245 + 6%N	0.675	–
CP245 + 10%N	1.126	–
CP245 + 0.5%AV	–	0.056
CP245 + 1.5%AV	–	0.169
CP245 + 3%AV	–	0.338
CP245 + 2%N + 0.5%AV	0.225	0.056
CP245 + 6%N + 1.5%AV	0.675	0.169
CP245 + 10%N + 3%AV	1.126	0.338

[21], where it is mentioned that when cactus mucilage is added to the mixture, it tends to present an increase in slump. In [19], it is also noted that cactus extract improves the viscosity and, therefore, the workability of the mix. In this sense, the biopolymer has a relevant role in improving this property, based on the result of the galacturonic acid fraction of pectin present in the bioadditive. Consequently, proteins and fats also have an impact on the workability of concrete. The polysaccharide in the cactus paddles reduces friction and increases the smoothness of the mix, as does the use of oil in the machinery [25]. As for the Aloe Vera extract, the settlements were 5 1/4" at 0.5%, 6" at 1.5%, and 6 1/4" at 3%. These results differ from those reported in [22, 24], indicating that Aloe Vera reduces the slump, making it drier and less workable. In [24], it is stated that the Aloe Vera, having been liquefied, formed a sticky behavior unifying more of the components of the paste. However, they worked according to the weight of water and total mass of the concrete, while in this research, they worked according to the weight of cement, which could be a cause that allowed them to be less workable. In comparison with the Nopal, this extract presented less slump, but not in relation to the standard mix. As a whole, at 2%N+0.5%AV, it presented 5 1/4": at 6%N+1.5%AV, it is 8": and at 10%N+3%AV, it acquired 8 1/4". As in the previous designs, as the addition percentages increase, the slump increases.

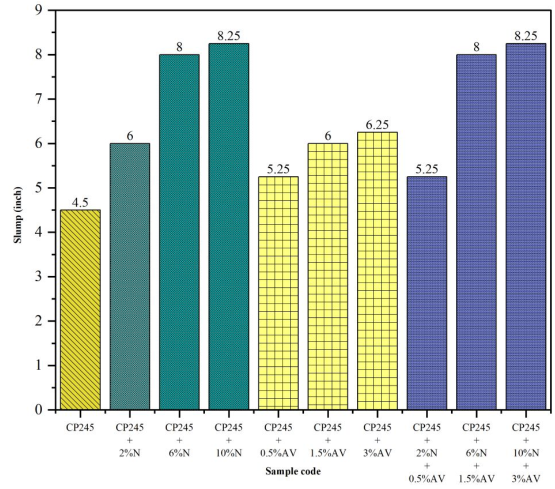

Figure 3 Concrete slump

3.3 Compressive strength

Table 7 shows the results of the compressive strength at 28 days, the gain in strength, and the strength trends at 28 and 56 days (Figure 4). The gain in strength refers to the progressive increase in mechanical strength over time. This phenomenon results from the continuous hydration of the cement components, which strengthens the internal structure of the concrete. This process is essential to ensure that the concrete achieves the necessary strength to withstand structural loads and meet design standards. The additions of the extracts were able to surpass the standard mix, except for the addition of 10%N+3%AV, which decreased by 14.5 kg/cm². The mix with the 2% Nopal extract had a compressive strength of f'c = 379.5 $\mathrm{kg/cm^2}$, being the highest percentage compared to the other groups of additions of this extract. These results are in line with those obtained in different studies in which this additive was used. Favorable results were also obtained in [21], since the 15% Nopal mucilage achieved a compressive strength of f'c 289.03 $\mathrm{kg/cm^2}$, surpassing the control sample. Other authors [22] also state that the compressive strength increases by 19.54% when 2% is used.

On the other hand, in [18], it is noted that the concrete mixes exceed the design value f'c of 30 MPa after 28 days, except for the dehydrated Nopal powder samples (dNp2 and dNp4). The dNp4 mixture did not reach such design value even at 400 days of age, while the dNp2 mixture exceeded it after 90 days. The cactus mucilage exudate improved the compressive strength by 20%, and the cooked cactus mucilage prepared at four ages obtained results between 20% and 40% improvement. In [19], it is also observed that the compressive strength decreases at 7 days of curing regardless of the percentage of the extract, but increases after 28, 56, and 90 days. The reduction in early-stage strength may be an effect of delayed hardening in biopolymer-modified cement due to changes in moisture retention. Polysaccharides function as retarders, allowing delayed strength development at early ages and achieving higher strength after 28 days [25].
The addition of Aloe Vera extract at 0.5% achieved a strength of 416 kg/cm², being higher by 156.3 kg/cm² in relation to the standard sample and the highest strength achieved with respect to this addition. At 1.5% and 3% of this extract, the strength increased compared to the standard sample, but decreased in relation to the lower percentage of addition. These results align with the

Table 7 Results of the compression strength test at 28 and 56 days

Sample code	Curing time day	Average resistance kg/cm²	Standard deviation kg/cm²	Coefficient of variation (%)	Gain in strength (%)
CP245	28	260.30	9.04	3.47%	0.00%
	56	320.80	11.03	3.44%	0.00%
CP245 + 2%N	28	379.50	16.43	4.33%	45.79%
	56	411.90	17.89	4.34%	28.40%
CP245 + 6%N	28	379.00	8.83	2.33%	45.60%
	56	382.70	20.35	5.32%	19.30%
CP245 + 10%N	28	341.80	11.80	3.45%	31.31%
	56	315.60	16.65	5.28%	-1.62%
CP245 + 0.5%AV	28	416.60	19.86	4.77%	60.05%
	56	432.30	0.70	0.16%	34.76%
CP245 + 1.5%AV	28	383.60	4.97	1.30%	47.37%
	56	411.40	7.39	1.80%	28.24%
CP245 + 3%AV	28	373.00	7.02	1.88%	43.30%
	56	405.50	5.71	1.41%	26.40%
CP245 + 2%N + 0.5%AV	28	443.40	35.16	7.93%	70.34%
	56	445.40	12.91	2.90%	38.84%
CP245 + 6%N + 1.5%AV	28	292.20	22.19	7.59%	12.26%
	56	363.30	19.00	5.23%	13.25%
CP245 + 10%N + 3%AV	28	245.80	9.72	3.96%	-5.57%
	56	296.80	15.27	5.15%	-7.48%

findings in [21], stating that Aloe Vera at 1.5% achieved a strength of 281.37 kg/cm². Likewise, at 2%, it improves compression by 20.947% [22], while with the addition of 4% aloe vera gel, it reached its maximum value of 278.91 kg/cm² [23], equivalent to a 23.77% improvement. A viable percentage of 12% Aloe Vera is recommended [34], as it presents a resistance of 266.6 kg/cm² at 7 days, 288.5 kg/cm² at 14 days, and 374.5 kg/cm² at 28 days, surpassing the standard design. In another study [24], a compressive strength of 355 kg/cm² was achieved, resulting in a 41% increase in improvement.

For the designs with both extracts, the 2%N+0.5%AV mixture presented the highest resistance, exceeding the control design and the other designs by 70.34% (equivalent to 183.1 kg/cm²). These results are related to the findings in [20], where OFI (Nopal) mucilage increases approximately 85% of its electrical resistivity and its compressive strength marginally (<19%). Its main benefit in concrete exposed to CO_2 is that it can form trapping internals, since it functions as a super absorbent organic compound, reducing the rate of water transport within the matrix, retaining it and releasing it slowly. The specimens tested at 56 days of curing showed a similar increase as those tested at 28 days, except for the 10%N+3%AV addition percentage, which decreased by 24 kg/cm² compared to the standard design. Of the three cactus extract addition percentages, 2,% presented the highest strength, exceeding the standard sample by 91.1 kg/cm². The 0.5,% Aloe Vera extract achieved the highest strength, exceeding the standard sample by 11.5 kg/cm². Finally, the additions of the extracts together at 2%N+0.5',%AV obtained better results in relation to the standard mixture, exceeding it by 38.84,% (equivalent to 124.6 kg/cm²) and the other designs.

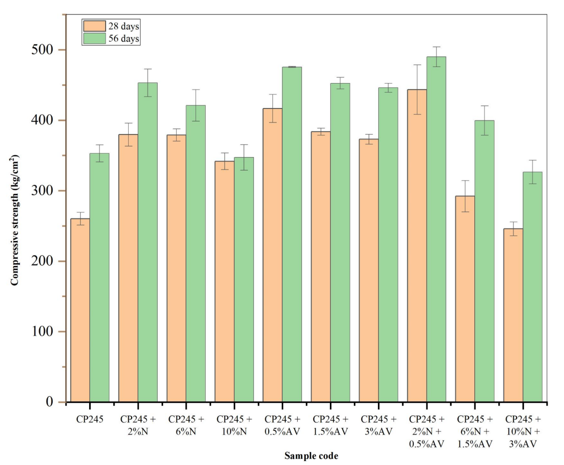

Figure 4 Trend of the compressive strength results at 28 and 56 days

3.4 Tensile strength

Table 8 shows the results of the tensile strength at 28 days. All designs managed to outperform the standard sample, except the 10%N additions, which had the same strength of 28.9 kg/cm² as the standard sample, and the 10%N+3%AV, which decreased by 0.4 kg/cm². With the addition of 2% Nopal extract, it had a tensile strength of f´c = 33.7 kg/cm², exceeding the standard sample by 4.8 kg/cm² and presenting the highest strength of its percentage group. These results are in agreement with [19], where the tensile strength increased by 12.5%, 21.98%, 39.65%, 62.93%, and 89.22% with cactus extract doses of 2%, 4%, 6%, 8%, and 10%, respectively, in contrast to the reference design. On the other hand, 2% nopal improves traction by 18.048% in relation to the standard mixture [22]. As for the Aloe Vera extract, 0.5% obtained a tensile strength of f´c = 38.8 kg/cm², exceeding the standard design by 9.9 kg/cm² and presenting the highest strength compared to 1.5% and 3% additions. These results are related to those reported in [22], where 2% Aloe Vera improves tensile strength by 15.95%. Finally, with the extracts used together, the percentage of 2%N+0.5%AV obtained the highest strength, with f´c =41.4 kg/cm² and exceeding the standard design by 12.5 kg/cm².

3.5 Flexural strength

Table 9 shows the results of flexural strength at 56 days with average values, and the trend of strengths at 56 and 90 days (Figure 5).

The standard sample presented a resistance of 48.7%. The groups of designs with 2% Nopal additions presented a resistance of 56.4 kg/cm², exceeding the standard sample by 7.7 kg/cm² and being the highest resistance in comparison with the 6% and 10% additions. The 0.5% Aloe Vera additions reached the highest resistance in relation to the other percentages of this extract, with 58.8 kg/cm², exceeding the standard sample by 10.1 kg/cm². The additions of the 2%N+0.5%AV extracts together achieved the highest resistance of all the experimental designs and the standard mix, 66.4 kg/cm² and 36.34% (equivalent to 17.7 kg/cm²) higher than the standard design.

For the 90-day tests, the standard mix reached a strength of 53.6 kg/cm². The designs with the 2% Nopal additions presented a resistance of f´c = 56.8 kg/cm², exceeding the reference design by 3.2 kg/cm² and being the highest resistance in comparison with the other percentages of this extract. Of the group with Aloe Vera extract, the percentage of 0.5% presented the highest resistance, with f´c = 65.9 kg/cm² and exceeding the standard design by 12.3 kg/cm².

These results are related to the findings in [19], who point out that the use of Nopal additive allowed the increase in flexural strength because of the polysaccharides present in the extract solution, which act as a binder, creating a strong microstructure of the concrete, reducing shrinkage and subsequent micro-cracking [35]. In addition, the consumption of Ca^{2+} ions by the pectin in the additive enhanced the hydration of particles in concrete [35]. On the other hand, the addition of Aloe Vera gel has been shown to significantly retard the corrosion of steel placed in an acid solution [36].

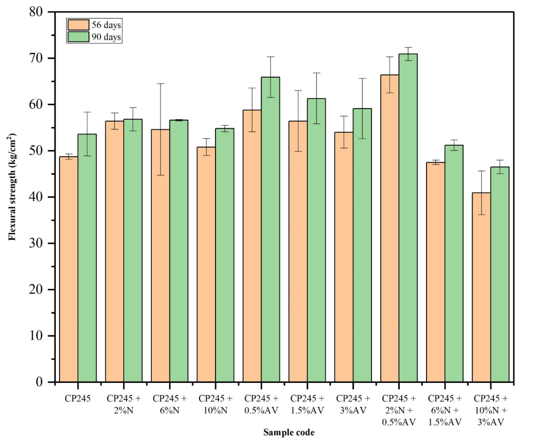

Figure 5 Trend of the flexural strength results at 56 and 90 days

3.6 Carbonation rate

Table 10 shows the results of the carbonation rate, where all the experimental groups were allowed to decrease the carbonation rate in the concrete, both for 90 days and 145 days of curing in saline solution (Figure 6). At 90 days, the standard mixture showed a carbonation rate of 0.26 mm/year. The mixture with additions of 2% and 6% cactus extract showed a rate of 0.08 mm/year, decreasing by 0.18 mm/year compared to the standard mixture. The addition of 10%N and 1.5%AV showed a rate of 0.12 mm/year, which is lower than the rate of the standard mixture. The addition of 0.5%AV and the joint addition of the two extracts at 2%N+0.5%AV showed a rate of 0.04 mm/year, while the design with the addition of 10%N+3%AV reached a rate of 0.20 mm/year.

At 145 days, the standard mixture increased by 0.04 mm/year in relation to the rate of the standard sample at 90 days, presenting a rate of 0.30 mm/year. The additions of Nopal at 2% and 6%N+1.5%AV presented a velocity of 0.12 mm/year, while the additions of Aloe Vera at 0.5%, 1.5%AV, and 3%AV presented velocities of 0.14, 0.16 and 0.22 mm/year, respectively. These results are related to the studies conducted in [18], where they found that adding dehydrated Nopal powder substantially improved chloride transport and reduced the values of the rapid chloride permeability index (RCP) by 10%. In addition,

Table 8 Results of the tensile strength test at 28 days

Sample code	Curing time day	Average resistance (kg/cm²)	Standard deviation (kg/cm²)	Coefficient of variation (%)	Gain in strength (%)
CP245	28	228.90	26.62	22.90%	20.00%
CP245 + 2%N	28	33.70	4.65	13.81%	16.61%
CP245 + 6%N	28	31.30	3.26	10.42%	8.30%
CP245 + 10%N	28	28.90	0.53	1.83%	0.00%
CP245 + 0.5%AV	28	38.80	2.11	5.43%	34.26%
CP245 + 1.5%AV	28	32.10	1.67	5.20%	11.07%
CP245 + 3%AV	28	30.10	1.85	6.14%	4.15%
CP245 + 2%N + 0.5%AV	28	41.40	2.08	5.02%	43.25%
CP245 + 6%N + 1.5%AV	28	30.70	3.64	11.85%	6.23%
CP245 + 10%N + 3%AV	28	28.50	1.40	4.91%	-1.38%

Table 9 Results of the flexural strength test at 56 and 90 days

Sample code	Curing time day	Average resistance (kg/cm²)	Standard deviation (kg/cm²)	Coefficient of variation (%)	Gain in strength (%)
CP245	56	48.7	0.57	1.16%	0.00%
	90	53.6	4.74	8.84%	0.00%
CP245 + 2%N	56	56.4	1.77	3.13%	15.81%
	90	56.8	2.55	4.48%	5.97%
CP245 + 6%N	56	54.6	9.90	18.13%	12.11%
	90	56.6	0.14	0.25%	5.60%
CP245 + 10%N	56	50.8	1.84	3.62	% 4.31%
	90	54.8	0.71	1.29%	2.24%
CP245 + 0.5%AV	56	58.8	4.74	8.06%	20.74%
	90	65.9	4.38	6.65%	22.95%
CP245 + 1.5%AV	56	56.4	6.58	11.66%	15.81%
	90	61.3	5.52	9.00%	14.37%
CP245 + 3%AV	56	54.0	3.46	6.42%	10.88%
	90	59.1	6.51	11.01%	10.26%
CP245 + 2%N + 0.5%AV	56	66.4	3.89	5.86%	36.34%
	90	70.9	1.41	1.99%	32.28%
CP245 + 6%N + 1.5%AV	56	47.5	0.49	1.04%	-2.46%
	90	51.2	1.13	2.21%	-4.48%
CP245 + 10%N + 3%AV	56	40.9	4.74	11.58%	-16.02%
	90	46.5	1.48	3.19%	-13.25%

Table 10 Carbonation rate

Sample code	Average (mm)		Standard deviation		Carbonation rate	
	90 days	145 days	90 days	145 days	90 days	145 days
CP245	0.07	0.15	0.04	0.06	0.26	0.30
CP245 + 2%N	0.02	0.06	0.01	0.04	0.08	0.12
CP245 + 6%N	0.02	0.07	0.02	0.03	0.08	0.14
CP245 + 10%N	0.03	0.07	0.03	0.04	0.12	0.14
CP245 + 0.5%AV	0.01	0.07	0.01	0.03	0.04	0.14
CP245 + 1.5%AV	0.03	0.08	0.04	0.03	0.12	0.16
CP245 + 3%AV	0.04	0.10	0.03	0.05	0.16	0.20
CP245 + 2%N + 0.5%AV	0.01	0.04	0.02	0.02	0.04	0.08
CP245 + 6%N + 1.5%AV	0.02	0.06	0.03	0.04	0.08	0.12
CP245 + 10%N + 3%AV	0.05	0.11	0.04	0.06	0.20	0.22

the Nopal mucilage exudate enhanced by 30%, and the cooked Nopal mucilage prepared at four ages allowed increases of 20% and 40% in relation to the control mix. The concretes modified with the Nopal additive present better durability characteristics in terms of resistance to chloride penetration and better resistance to acid and sulfate attack [19]. The carbonation depth of the evaluated concretes with Opuntia ficus-indica (Nopal) addition turned out to be lower compared to the control design, which resulted in an average decrease of 64% and 56% in carbonation depth [20]. In addition, emissions decrease by up to 43% compared to the control concrete without additions, allowing cement-based materials exposed to CO^2 to double their service life [20]. The concentration of CO_2 in the atmosphere is a parameter that significantly influences the rate of carbonation in concrete [37–39].

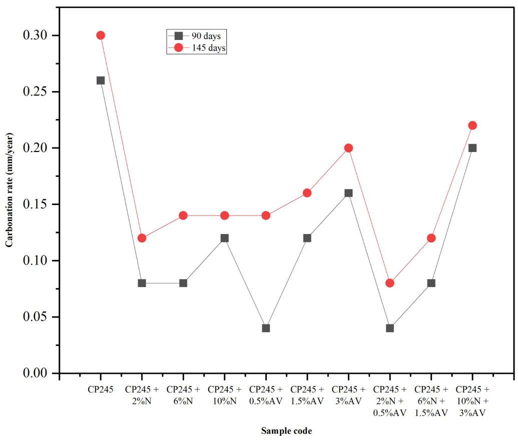

Figure 6 Trend of the carbonation rate at 90 and 145 days

3.7 Statistical analysis

Statistical comparisons of the mechanical properties for compressive and tensile strength were carried out using IBM SPSS software, since three samples were made for each test, and the following results are presented.

Comparison of compressive strength results at 28 dayss

The normality test was applied, from which it was obtained that of the 10 groups, 9 presented a normal distribution of their data because they have a normal distribution $(Sig. > 0.05)$, except for the CP245+10%N+3%AV group. Therefore, the Kruskal-Wallis non-parametric statistical test was applied to verify if there are differences among the groups studied (Table 11).

Table 11 Kruskal-Wallis nonparametric statistical test for group comparison

Kruskal-Wallis Test	
Kruskal-Wallis H	27.168
Degree of freedom	9
Asymptotic significance	0.001

It is observed that the Sig. = 0.000 < 0.05, which indicates that the means of some of the 10 groups present significant differences; therefore, the Mann-Whitney test of independent samples was performed to determine which groups present the most remarkable difference, verifying that there are significant differences between the group: CP245 with CP245+2%N+0.5%AV (Sig. < 0.05). Therefore, it is evident that a combination of 2%N and 0.5%AV is recommended for to CP245 concrete to increase its compressive strength.

Comparison of compressive strength results at 56 days

A normality test was applied, determining that the 10 groups present a normal distribution (Sig. > 0.05). Therefore, we proceed to perform the comparison of the means of the 10 groups through the parametric ANOVA technique for all groups (Table 12).

It shows that the Sig.$= 0.000 < 0.05$, indicating that there are significant differences between the 10 groups; then, the Post Hoc Tukey test was applied to verify which groups have greater significance. A multiple comparison of the 9 experimental groups with the standard group was carried out (Table 13), demonstrating significant differences (Sig. < 0.05) with the standard group in favor of the experimental groups: CP245+2%N, CP245+6%N, CP245+0.5%AV, CP245+1.5%AV, CP245+3%AV, CP245+2%N+0.5%AV, CP245+6%N+1.5%AV. This would indicate that the proportions of Nopal and Aloe Vera used in these groups would be the most favorable for improving the mechanical properties of the concrete. Additionally, the most favorable combination of all is 2%N and 0.5%AV, with a difference well above the value recorded by the standard sample.

Comparison of tensile strength results at 28 days

For this mechanical property, it was statistically determined that there are no significant differences between the experimental groups and the standard group, meaning any combination of the extracts used will not exceed the tensile strength of the standard group.

4. Conclusions

Based on the most significant results of this experimental research on the behavior of the physical and mechanical properties of structural concrete with the incorporation of Nopal extracts, Aloe vera, and the combination of both, the following conclusions can be presented:

Table 12 Anova Test

	Sum of squares	Degrees of freedom	Root mean square	F	Sig.
Among groups	73487.131	9	8165.237	41.205	0.000
Within groups	3963.247	20	198.162	–	–
Total	77450.377	29	–	–	–

Table 13 Multiple group comparisons for compressive strength

	GROUPS	Difference of means	Dev. Error	Sig.	95% Confidence Interval	
					Lower limit	Upper limit
CP245	CP245+2%N	-91.11333*	11.49383	0.000	-131.8142	-50.4124
	CP245+6%N	-61.94667*	11.49383	0.001	-102.6476	-21.2458
	CP245+10%N	5.14333	11.49383	1.000	-35.5576	45.8442
	CP245+0.5%AV	-111.48333*	11.49383	0.000	-152.1842	-70.7824
	CP245+1.5%AV	-90.60333*	11.49383	0.000	-131.3042	-49.9024
	CP245+3%AV	-84.67667*	11.49383	0.000	-125.3776	-43.9758
	CP245+2%N+0.5AV	-124.59000*	11.49383	0.000	-165.2909	-83.8891
	CP245+6%N+1.5AV	-42.51667*	11.49383	0.036	-83.2176	-1.8158
	CP245+10%N+3AV	24.00000	11.49383	0.554	-16.7009	64.7009

- Slump values were determined, and it was observed that as the percentages of extracts increased, the mix became more manageable. In addition, the unit weight of the concrete was carried out, which showed a decreasing trend compared to the standard mix and complied with what was specified by the standard. The increase in the percentages of extracts improved the manageability of the mix and the unit weight of the concrete decreased compared to the standard mix.
- The behavior of the mechanical properties was determined considering the Peruvian Technical Standards, and more favorable results were obtained with the additional percentages of 2%N, 0.5%AV, and 2%N+0.5%AV. The compressive strength increased by 70.34% at 28 days and 38% at 56 days, compared to the standard mix. The tensile strength also increased by 43.25%, and the flexural strength increased by 36.33% at 56 days and 32.37% at 90 days.

- The corrosion of the concrete in its hardened state was evaluated through the carbonation process, and favorable results were obtained. The designs with additions of the used extracts allowed a decrease in the carbonation speed compared to the standard mix. The percentage of CP245+2%N+0.5%AV presented lower carbonation speeds, both at 90 days with 0.04 mm and at 180 days with 0.08 mm.

- It was established that the optimal percentage of each extract for each property of the concrete is 2% for the Nopal, 0.5% for the Aloe vera, and 2%N+0.5%AV for the mix of both extracts. These percentages have shown improvements in workability, compressive strength, traction, bending, and reduction of the concrete's carbonation speed.

- Experimental findings suggest that the addition of Opuntia ficus-indica and Aloe Vera could be useful as corrosion inhibitors for concrete and steel in carbonated materials.

5. Declaration of competing interest

We declare that we have no significant competing interests, including financial or non-financial, professional, or personal interests interfering with the full and objective presentation of the work described in this manuscript.

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7. Author Contributions

E. K. Barco-Tocto y D. S. Agüero-Hualcas: Conceptualization, methodology, formal analysis, research, writing the original draft, project management. M. G. Farfán-Córdova: Methodology, formal analysis, drafting, monitoring.

8. Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article [and/or] its supplementary materials.

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