

Original Article

Evaluation of Prickly Pear Mucilage (Opuntia Ficus-Indica) as a Plasticising Additive in the Behaviour of Structural Concrete in the City of Huancayo

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Abstract - Since time immemorial, different cultures have utilized the extracts of plants to improve the rheological behavior of primitive mortars and concretes, with prickly pear mucilage serving as one of the best examples of traditional construction. In this research, the main aim is to analyze how *Opuntia ficus-indica* mucilage, a plentiful natural material in the region of Huancayo in Peru, influences the properties of structural concrete as a plasticizing and densifying additive. To achieve this, experiments on how the additive works in mixtures having a specified resistance to compression of $f'_c = 280 \text{ kg/cm}^2$ using local aggregates were carried out. The workability of the concrete was assessed by a slump test, while the compressive strength was assessed at 7, 14 and 28 days. The penetration test method was used to find the setting time, and the method of measuring the porous phase was done through gravimetric methods. Results were analyzed through ANOVA in SPSS; the model was found to be among the best ($R_{\text{adjusted}}^2 = 0.993$, $p < 0.001$). The results revealed that the incorporation of the organic additive modifies consistency non-linearly, identifying an overall optimal dosage of 2% by weight of cement. This optimal level maximized the slump up to 3.84 inches in the fresh state and increased the compressive strength at 28 days to 337.90 kg/cm^2 (8.9% higher than the control mixture), while reducing the permeable porosity to a relative minimum of 7.81% without inducing disproportionate delays in the final set. In conclusion, prickly pear mucilage constitutes an eco-friendly and technically viable alternative to optimize the workability and structural safety of sustainable concretes in high-altitude zones.

Keywords - *Opuntia ficus-indica*, Bioadditive, Natural plasticizer, Structural concrete, Compressive strength.

1. Introduction

Since ancient times, various civilizations have turned to organic additives of plant origin to optimize the rheological and mechanical properties of primitive mortars and concretes. In particular, archaeotechnological studies show that Mesoamerican cultures incorporated prickly pear (*Opuntia* spp.) extracts into lime-based mixtures to improve cohesion, increase workability, and extend the durability of the materials, especially in dry climates with high solar radiation. In this regard, prickly pear mucilage, composed mainly of hydrophilic polysaccharides, acts as a viscosity-modifying agent and water retainer, helping to reduce phenomena such as segregation and bleeding in the fresh state. It also promotes more uniform hydration in cementitious matrices, which has a positive impact on the integrity of the hardened material [1-3].

As mentioned earlier, recent research conducted in the disciplines of concrete technology and heritage conservation has validated these advantages scientifically and has

established prickly pear mucilage as a natural additive with a high potential for use in contemporary civil engineering. Not only are there technical advantages to using this material, there are also advantages related to its sustainability, cost-effectiveness, and wide availability across regions such as Peru. For these reasons, prickly pear mucilage is beginning to establish itself as an alternate material to synthetic/chemical additives. Studies have shown that this biopolymer has been able to perform functions similar to traditional plasticizers by increasing workability without significantly increasing the water-to-cement ratio (i.e., the ability to maintain or even enhance the compressive strength of the concrete) [4-7].

With structural/construction concrete being one of the staples of urban and infrastructure development today; however, due to the extensive use of this product there are growing concerns about the negative effects that cement production can have on the environment, especially with greenhouse gas emissions related to cement production.



Based on available literature, one way to reduce the environmental impacts from cement is to innovate in cement-based materials and optimize the functional performance of concrete on-site [8, 9]. Variables such as water-to-cement ratio, workability, durability, and mechanical strength significantly affect the overall utility of concrete as a material. Internationally, initiatives such as the 2030 Agenda for Sustainable Development highlight the importance of advancing more eco-friendly and efficient methods of construction [10].

Attesting to this need for finding more eco-friendly solutions in the concrete industry, chemical additives to modify and improve concrete properties in both the fresh and hardened state have been used extensively throughout the concrete industry for many years. In particular, the use of plasticizers allows the user to increase the workability of concrete without increasing the amount of water in the concrete, which in turn improves the strength and durability of the concrete. In terms of the physical-chemical behavior of these materials, plasticizers act to disperse cement particles allowing for a more uniform distribution of cement hydration and a more uniform distribution of the components of the concrete mix. The effectiveness of these materials, however, can vary due to many different factors - including the composition of the cement used, the characteristics of the aggregate used, and the environment/situation in which the concrete is placed; therefore, conducting initial test to verify performance of a chemical additive is essential [11].

In recent years, there has been increased interest in developing bio-based alternatives to traditional thickeners for altering the flow characteristics (rheology) of cementitious mixtures, particularly biopolymers derived from plants. This is mainly due to the need to reduce dependence on petroleum product and develop more sustainable alternatives. A number of research studies have shown that these kinds of substances have the ability to act as viscosity-altering materials and provide stability, and they can have an effect on the water movement and cement hydration speed, or even the behavior of the material as a whole [1-3].

Of all the kinds of this material, mucilage (which is a plant sap) from prickly pear cactus is the most interesting one because of its special characteristics, like its extraordinary capacity to retain water and its non-Newtonian properties. Moreover, research has found that this material can create thick solutions which can modify the cohesion and solidity of cement mixtures. Thus, if used appropriately, this type of mucilage can help achieve lower bleeding and improved workability in concrete [12-14].

Due to this occurrence, numerous experimental researches have shown their positive findings in relation to the enhancements of the physical characteristics (namely durability) concerning mortars and concrete that were modified with the aid of mucilage. Concerning mortars, the

enhancement of durability is due to the change in the structure of pores of cement-based substances; however, among concrete, improvement occurs because of the increasing strength and improving water movement through concrete with the use of acceptable dosages; while its usage in over-doses proves to be harmful and indicates the necessity of limiting the quantity introduced into the mortar [4-7].

In Peru, the use of the mucilage from prickly pear, *Opuntia ficus-indica*, in cement-based materials has been investigated in numerous studies with satisfactory results in the areas of workability and strength of the final product. The existing studies, however, rely on different extraction methods, concentration levels and evaluation methods resulting in an inconsistency of the results and inability to generate technical guidelines for using mucilage in concrete [15].

While recent research indicates that the mucilage derived from *Opuntia ficus-indica* might be a useful natural additive in cement mixtures, the existing body of evidence has serious shortcomings. Most of the research has been directed toward cement paste and mortar applications, while only limited information is available about its properties in conventional structural concrete. Moreover, the knowledge of how this biopolymer behaves under the local conditions is limited since certain factors like the composition of aggregates, ambient conditions, and manufacturing technology influence the properties of this biopolymer.

There exists a gap in the scientific understanding of how prickly pear mucilage impacts the key characteristics of structural concrete in both its plastic and hardened states. Plus, the inconsistency in the extraction techniques, various methods of applications, and amounts used in earlier studies makes it difficult to determine the technical specifications that would permit evaluating its efficiency as an alternative to conventional chemical plasticizers.

One important point of this study is that it presents a thorough assessment of the use of *Opuntia ficus-indica* mucilage as a natural plasticizer in structural concrete in Huancayo by considering the addition percentage, the physicochemical properties of the additive, the influence of the additive in the fresh and hardened state, and the applicability of the technical solution using the local materials.

Unlike previous studies on organic plasticizers or mucilages, which were primarily limited to evaluating generic dosages or a single mechanical property, this study compares the performance of six levels of mucilage incorporation (0%, 1%, 2%, 3%, 4%, and 5% relative to the cement mass) obtained through an optimized soaking extraction process when used in structural concrete mixtures subjected to multiple standardized tests: slump (ASTM C143/C143M) [16], setting time (ASTM C403/C403M) [17],

compressive strength (ASTM C39/C39M) [18], and porosity. Furthermore, the research identifies the limitations associated with incorporating this natural additive, such as variations in setting time, sensitivity to the origin of the biological material, workability, and a lack of data on long-term durability in high-altitude climates.

Consequently, this study provides a quantitative and standardized approach to facilitate the dosing and use of eco-friendly additives. Consequently, this study provides a quantitative and standardized approach to facilitate the dosing and use of eco-friendly admixtures suitable for the practical production of sustainable structural concrete under local conditions.

2. Materials and Methods

2.1. Research Design and Location

This is an applied research study with a quantitative approach and an experimental design. The experimental phases of the study, which included the extraction of the biological additive, the preparation of concrete mixtures, and the conduct of tests on fresh and hardened concrete, were carried out in the city of Huancayo, Peru, at an altitude of approximately 3,250 m above sea level, using local materials to evaluate technical performance under high-altitude environmental conditions.

2.2. Materials and Characterization

2.2.1. Cement and Aggregates

Type I Portland cement conforming to ASTM C150 [2] was used. It was purchased on the local market in the city of Huancayo and stored under dry conditions, free from moisture and contaminants, to prevent any changes in its physical and mechanical properties [19]. The choice of this cementitious material is based on its satisfactory mechanical properties and suitability in cases where no special sulfate resistance is needed, as indicated by [20]. Also, the fine aggregate and coarse aggregate has been supplied from quarries along the Mantaro River located in the city of Huancayo, thereby meeting the quality standards that qualify its usage in structural concrete [2]. As per the ASTM C33 standard, the fine aggregate was made up of particles that were less than 4.75 mm in size (i.e., passing through sieve No. 4), while the coarse aggregate was made up of crushed stone having a maximum nominal size of 1/2" that was retained on the sieve. The physical properties of both types of aggregates were analyzed in the lab by measuring their properties such as particle size distribution, specific gravity, absorption, and moisture content in accordance with the relevant ASTM standards.

2.2.2. Extraction and Characterization of *Opuntia Ficus-Indica* Mucilage

The organic additive was extracted from freshly collected cladodes (stems) of the prickly pear plant (*Opuntia ficus-indica*), and it is a natural product that contains a

hydrocolloid rich in polysaccharide content with great water retention capacity and rheological qualities to change viscosity in an aqueous medium [22, 23]. Washing the cladodes under water to eliminate superficial impurities initiates the soaking extraction method [22]. After this, the spines and the epidermis (the outer layer of the bark) are removed manually in order to get the parenchyma or internal tissue that holds the greatest amount of mucilage. The tissue is then cut into uniform cubes in order to enhance the contact area and therefore improve mass transfer throughout the process [24].

The fragments were next submerged in distilled water with a weight ratio of 1:1 (weight of the fresh cladode and volume of water), and the solution was let to remain undisturbed for 24 hours in a sealed container at room temperature to allow for the influx of polysaccharides into the solution [22, 23]. After that, the solution underwent uniform mechanized agitation followed by filtration in order to separate it from the solid plant residues present. The final filtered viscous solution was stored in airtight containers for carrying out physicochemical characterization (pH, density, and viscosity) and defining its applicability as a plasticizer in concrete mixes.

Figure 1 shows, in sequence, the steps followed to extract the polydisperse natural component from *Opuntia ficus-indica*. The procedure began with the identification and selection of the plant species in the field, focusing on cladodes in suitable condition for processing (Figure 1(a)). Subsequently, the cladodes were manually sampled and transported to the preparation area (Figure 1(b)). The collected material was washed with water to remove soil particles, dust, and other impurities adhering to its surface (Figure 1(c)). Next, the spines and the outer layer of the cladode were removed to expose the inner parenchyma tissue, where the mucilage-associated polysaccharide compounds are found (Figure 1(d)).

The obtained tissue was cut into uniformly sized cubes to increase the contact area and promote the transfer of soluble compounds into the extraction medium. The fragments were placed in distilled water at a 1:1 ratio between the mass of fresh plant material and the volume of water, and subjected to a soaking process for 24 h at room temperature (Figure 1(e)). During this period, the water-soluble compounds were gradually released from the plant tissue and dispersed into the aqueous medium. Once the soaking was complete, the mixture was stirred to promote the release and homogenization of the mucilage. Subsequently, the mixture was filtered through a fine mesh to separate the remaining solid residues and obtain an extract with fewer particles (Figure 1(f)). Finally, the resulting extract was collected in a clean, airtight container to prevent contamination and preserve its properties until its subsequent characterization and use as a natural additive in concrete mixtures (Figure 1(g)).



Fig. 1 Process for extracting prickly pear mucilage

In order to characterize qualitatively the characteristics of the obtained organic additive, a physicochemical analysis was carried out relying on different experimental parameters. The moisture content was assessed using the oven-dry method in accordance with ASTM D2216 specifications. The relative density of the solution was measured following the water pycnometer method based on ASTM D854 specifications. The viscosity of rheological properties was also assessed through measuring the dynamic viscosity of the sample using a rotational viscometer as per ASTM D2196. Water retention of the extract was assessed using a gravimetric method modified from ASTM C1506 and expressed as a percent of the dry weight of the extract. The acidity of the extract was measured using a pH meter calibrated as per ASTM E70 standards.

2.3. Dosage, Preparation, and Mix Design

The concrete mix design was conducted according to the method described by the American Concrete Institute (ACI 211), which enabled the appropriate proportions of the materials to be established according to the desired strength, workability, and other properties of the aggregates that were characterized previously.

This research has set a design compressive strength (f'_c) of 280 kg/cm², computed on the basis of a needed average strength (f'_{cr}) of 350 kg/cm² for structural adequacy. In the same way, a slump of 3" to 4" has been set, which is applicable

to ordinary structural units by employing coarse aggregate with the maximum nominal size of 1/2". Using these parameters given above, along with the criteria in the ACI design tables, the values of water content and air content were calculated as 215 L/m³ and 2.5%, respectively. After determining the design strength, the w/c ratio was chosen to be 0.48, giving a Type I Portland cement demand of 447.92 kg/m³.

The aggregate proportions have been found from the grading of the aggregate from the Mantaro River in a mixture of 35.09% of fine aggregate and 64.91% of coarse aggregate. The preliminary quantities per cubic meter of dry mix were solved using absolute volume method before arriving at the figures of 447.92 kg of cement, 215 liters of water, 548.96 kg of fine aggregate and 1077.79 kg of coarse aggregate. Analytical corrections were made for the moisture content and absorption capacity of the laboratory aggregates. Thus, the final mixing water was in the amount of 193.43 L/m³, moist fine aggregate was 565.87 kg/m³, and coarse aggregates were 1082.45 kg/m³. A final mix design was obtained with a weight proportion of 1:1.23 : 2.41 (cement : fine aggregate: coarse aggregate) along with a water-to-cement ratio of 0.48, which served as a basis control mix.

The production of modified samples was achieved by studying six levels of *Opuntia ficus-indica* mucilage use as a

natural plasticizer in formulating this control mix. The aforementioned doses of the organic additive were 0% (reference sample), 1%, 2%, 3%, 4%, and 5% of total cement mass. While mixing and dosing, the liquid mucilage was used in the right quantity to take the place of the intended water, yet the total volume of liquid remained the same for all trials to

exclude the effect of the polysaccharide add-on. Nevertheless, because of the characteristic properties of mucilage polysaccharides hydrocolloid nature, it was expected that some water would not act as free moisture necessary for the cement hydration process. Effectively, this effect was the strongest for the highest doses of the add-on (4% and 5%).

Table 1. Mix design proportions per cubic meter of structural concrete

Mix	Mucilage (%)	Cement (kg)	Water (L)	Mucilage (L)	Fine Aggregate (kg)	Coarse Aggregate (kg)
M0	0%	447.92	193.43	0.00	565.87	1082.45
M1	1%	447.92	188.95	4.48	565.87	1082.45
M2	2%	447.92	184.47	8.96	565.87	1082.45
M3	3%	447.92	179.99	13.44	565.87	1082.45
M4	4%	447.92	175.51	17.92	565.87	1082.45
M5	5%	447.92	171.03	22.40	565.87	1082.45

2.4. Test Methods and Evaluation of Parameters

2.4.1. Fresh-State Testing

Immediately after the mechanical mixing process, the fresh-state properties were evaluated to determine the plasticizing and retarding effects of the organic additive:

Slump

Abrams cone slump test was applied to assess the usability and consistency of fresh concrete right after mixing was completed according to the provisions of ASTM C143/C143M. The analysis process involved filling the test mold in three layers with virtually the same volume and compacting each layer with 25 evenly distributed blows with the use of a rounded metal rod.

After that, the mold was taken off vertically without any twisting or lateral movement in period of 5 to 10 seconds. The settlement was calculated according to the difference between the nominal height of the mold and the upper center of the concrete using a high-precision centerpiece.

$$S = H_0 - H_f$$

Where:

S : concrete settlement (cm).

H_0 : original formwork height (cm).

H_f : final concrete height after removing the formwork (cm).

In a consecutive manner, this test was administered at all dosage levels analyzed (M0-M5), to determine the degree of the effect of *Opuntia ficus-indica* mucilage as a plasticizing agent on the initial rheological properties of the composite combinations.

The method chosen for the practical work on measuring the initial consistency of the structural mixtures is demonstrated step-by-step in Figure 2. This description comprises the layered filling and pressing of the material in the mold (Figure 2(a)), the leveling and removal of extra material from the base (Figure 2(b)), and the vertical and continuous removal of the Abrams cone (Figure 2(c)), and the analytical measurement of final settlement using the compaction rod and a graduated ruler (Figure 2(d)).



Fig. 2 Concrete Settlement Test Using the Abrams Cone Method.

Setting Time

Vicat needle tests were utilized to find the initial and final setting times as per the principles given in ASTM C150 and the method of ASTM C191. The purpose of this test was to study the hydration characteristics of type I Portland cement in the presence of various concentrations of *Opuntia ficus-indica* mucilage. In the preparation of the cement paste, organic additives were used to replace the mixing water. The total amount of liquid used in every single batch was precisely consistent with the set specifications that were determined by Vicat plunger penetration of 10 ± 1 mm. The paste was then placed in a given standardized truncated-cone mold after it had been mechanically mixed, and air was taken out.

The penetration value was recorded at regular intervals over time using a Vicat needle (with a diameter of 1 mm),

which was kept in the controlled conditions with respect to temperature (23 ± 2 °C) and relative humidity ($\geq 50\%$), keeping in mind the ambient effects on setting time. The initial setting time was obtained when the penetration level achieved by the needle amounted to 25 mm with respect to the base of the mold. In addition, the final setting time was established when the needle stopped penetrating the surface of the sample.

In Figure 3, the apparatuses and procedures employed to keep track of the decrease in plasticity in the altered pastes are discussed. This illustration displays the preliminary preparation of materials (Figure 3(a)), the positioning and leveling of the sample in the tapered cone mold (Figure 3(b)), and the continuous execution of penetration readings with the Vicat apparatus (Figure 3(c)).

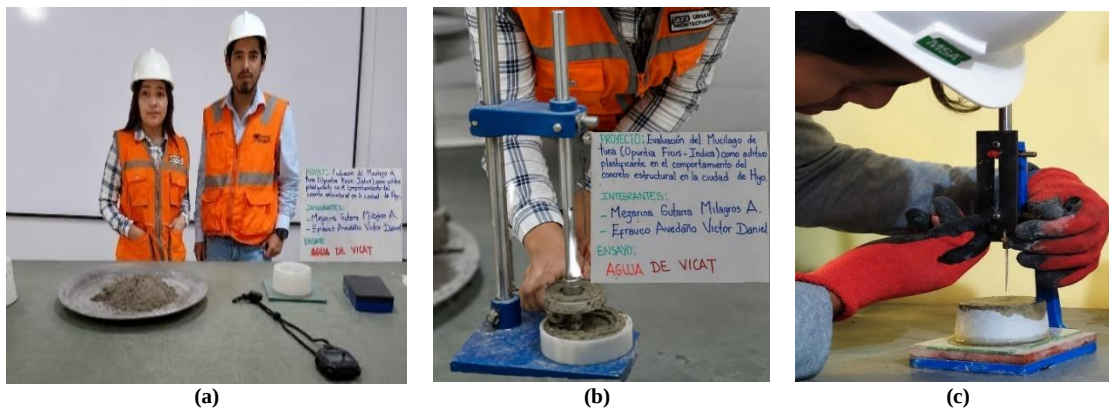


Fig. 3 Cement setting

2.4.2. Testing in the Hardened State

To determine the mechanical and durability characteristics, standard cylindrical test specimens of size 6" $\times$ 12" (150 mm $\times$ 300 mm) were prepared in accordance with ASTM C31 regulations. After the specimens had undergone a period of initial curing, they were demolded 24 hours after fabrication, and the subsequent curing process involved continuous immersion of the specimens in lime-saturated water conditions maintained at a temperature of 23 ± 2 °C until reaching the appropriate test ages, thus achieving uniform hydration of the cementitious matrix.

Compressive Strength

The cylindrical test samples were subjected to tests on the required curing ages of 7, 14, and 28 days, in accordance with the prescribed procedures of ASTM C39/C39M. Compressive strength tests were conducted using an automated hydraulic press, applying a constant loading rate until the specimen failed and recording the maximum load in kN to determine the strength per unit cross-sectional area (kg/cm^2). To assure the reliability of the results, the analysis was performed on $n = 2$ specimens in the case of the 7-day age and $n = 3$ specimens in the case of 14- and 28-day ages for any level of mucilage concentration (from 0% to 5%).

Porosity of Hardened Concrete

The percentage of voids in the concrete that could be filled by a liquid was calculated based on the gravimetric method described in accordance with the guidelines in ASTM C642, given the age of the material at 28 days. In general, the experimental study performed three steps of weighing: first, the samples were dried in the oven to a stable weight to get the weight in a dry state (m_{dry}) before further observations; second, the samples were submerged into water until reaching full saturation to gain the saturated weight with a dry surface (m_{sat}); finally, the apparent submerged weight in water (m_{ssum}) was measured as well. Through these values, the total volume and the volume of voids was calculated theoretically in order to find the percentage of porosity of the material.

2.5. Statistical Analysis

In order to assess the statistical significance of the effect made by *Opuntia ficus-indica* mucilage on concrete characteristics in fresh form (slump and time of setting) and hardened form (compression strength and porosity), the experimental results were subjected to inferential statistical analysis. A one-way analysis of variance (ANOVA) was used with a significance level of 5% ($\alpha=0.05$) in order to check a

null hypothesis about equality of means. The factorial ANOVA was performed using the complete experimental dataset (6 dosage levels $\times$ 3 curing ages), and the residual degrees of freedom correspond to the number of independent experimental observations included in the model after accounting for the main effects and their interaction. In order to assess the statistical significance of the effect made by *Opuntia ficus-indica* mucilage on concrete characteristics in fresh form (slump and time of setting) and hardened form (compression strength and porosity), the experimental results were subjected to inferential statistical analysis. A one-way Analysis of Variance (ANOVA) was used with a significance level of 5% ($\alpha=0.05$) in order to check a null hypothesis about equality of means.

Before applying the ANOVA method, it was ensured that the primary principles of the methodology of normality and

homogeneity of variances were validated using the Shapiro-Wilk test and Levene's test, respectively. If it was established that there were significant statistical differences in the mixtures produced by ANOVA, Tukey's post-hoc tests were used for further analysis. The additional analysis helped to find the concentrations of the natural additive (1%, 2%, 3%, 4%, and 5%) where there were statistically significant results. All data processes and production of the graphs with confidence intervals were carried out with the help of SPSS software (version 26.0).

To summarize the experimental approach followed in this research, Figure 4 presents the comprehensive methodological map of the study, which ranges from the selection of raw materials and the optimized extraction process to mix designs, specimen preparation, and the physical, mechanical, and durability tests conducted in the laboratory.

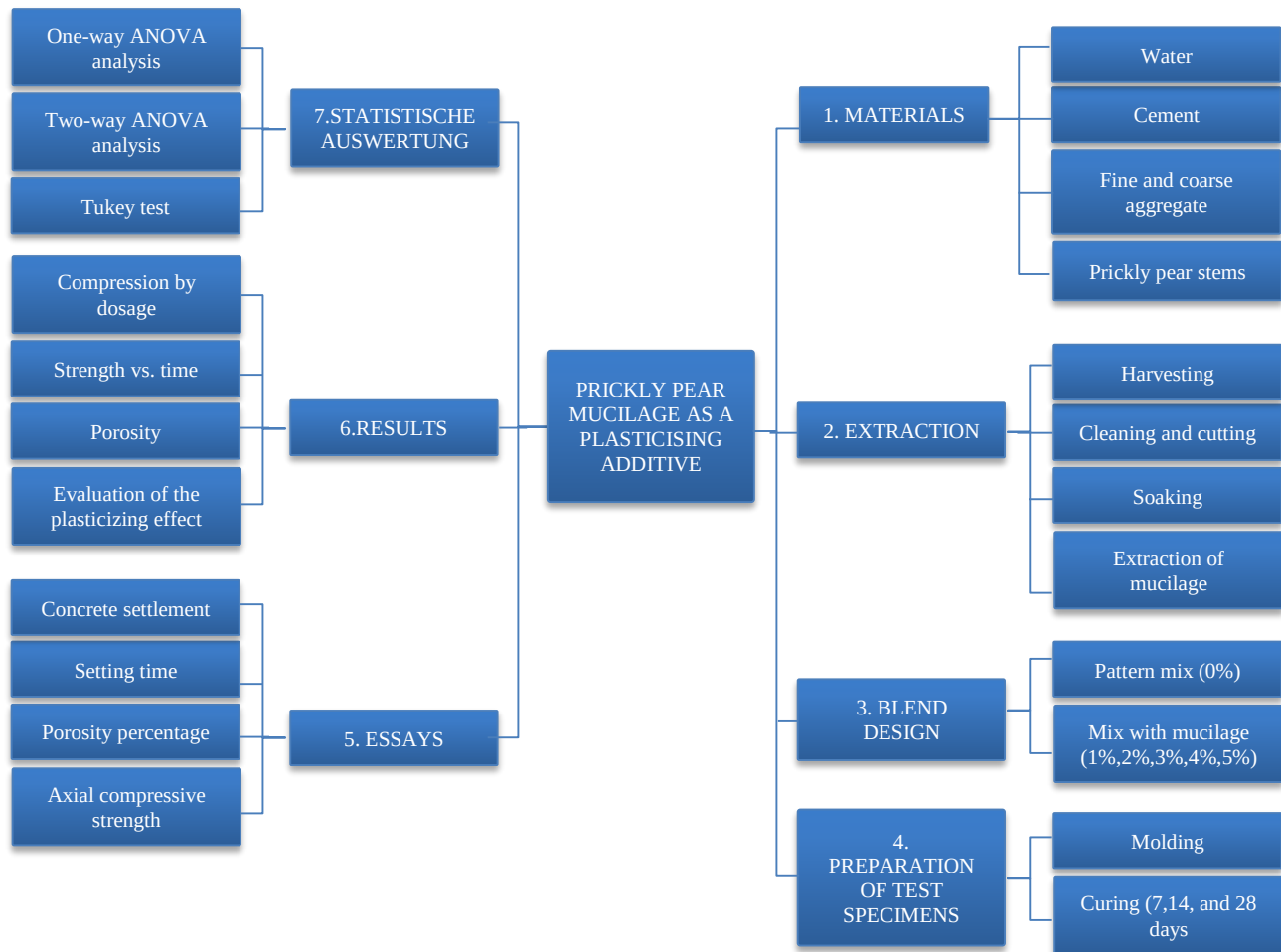


Fig. 4 Methodological outline of the study on the use of prickly pear mucilage as a plasticizing additive in concrete

3. Results

3.1. Physicochemical Properties of *Opuntia Ficus-Indica* Mucilage

Before it was accepted as an organic ingredient in structural concrete mixtures, the basic properties of the

purified liquid nopal extract were checked using standardized tests explained in the methodology section. The quantitative data obtained through this initial characterization are presented in Table 2.

Table 2. Physicochemical properties of mucilage extracted from local opuntia ficus-indica

Parameter Evaluated	Reference Standard	Average Value Obtained	Unit of Measurement
Moisture content	ASTM D2216	93.18	%
Relative density	ASTM D854	1.05	g/cm ³
Dynamic viscosity	ASTM D2196	312.00	mPa·s
Water-holding capacity	ASTM C1506	87.00	%
Hydrogen ion concentration (pH)	ASTM E70	5.18	Adimensional

Note: The values represent the arithmetic mean of the samples characterized at a controlled room temperature in the laboratory.

The data analysis indicates a high moisture content of the extract (93.18%), which means that the aquatic content, both free and bound, is also high in the cellular architecture of the local cladodes. This indicates the rationality of the necessity to deduct the quantity of the additive from the initial quantity of the water during mixing, avoiding thus a change in the water-to-cement ratio. In addition, the relative density equaled 1.05 g/cm³, a result being slightly higher than that of distilled water due to the concentration of total solids and organic substances in suspension.

Regarding the rheological performance of the mucilage, it showed an average dynamic viscosity of 312 mPa·s, indicating the presence of a dense, coherent fluid due to the hydrocolloidal characteristics of the material, which contains a lot of high-molecular-weight polysaccharides. In addition,

the gravimetric test confirmed an impressive water-holding capacity of 87.00%, being a crucial hydrophilic property which points out that this additive can play the role of evaporation regulator and the regulation of the exudation process from the internal part of the fresh cement mix. In the end, the digital potentiometer showed pH of 5.18, which indicates that the extract is a moderately acidic solution, an important chemical control factor that helps to track the kinetics of initial hydration process of Type I Portland cement.

3.2. Fresh-State Test

3.2.1. Slump

Presented in Table 3 are the figures representing the average slump values taken with the Abrams cone for standard mix (M0) and modified mixes with varying amounts of *Opuntia ficus-indica* mucilage (M1 to M5).

Table 3. Settlement test results and statistical significance of the mixtures in their fresh state

Mixture	Mucilage Content (%)	Average Settlement (inches)	Average Settlement (cm)	Significance Group (Tukey)*
M0	0 % (Patrón)	3.28	8.33	b
M1	1 %	3.21	8.15	b
M2	2 %	3.84	9.75	a
M3	3 %	3.75	9.53	a
M4	4 %	3.57	9.07	ab
M5	5 %	3.45	8.76	ab

Note: The measurements in centimeters are derived from the standard conversion (1 inch is equal to 2.54 centimeters). Various letter in the final column indicate substantial differences ($p < 0.05$) following Tukey's post hoc analysis.

The analysis of the quantitative data reveals that the use of organic additive changes the initial rheology of concrete blends in a nonlinear way. The slump for the reference mixture M0 was 3.28 inches. Adding 1% of mucilage (M1) leads to a small decrease in slump of up to 3.21 inches. However, an increase of dosages to the level of 2% (M2) causes an increase of the slump up to 3.84 inches (9.75 cm), which is the highest level of the mobility and workability reported by the experimental program.

After the optimal dosage has been reached, increments in the additive dosage to 3%, 4%, and 5% resulted in reductions in slump to 3.75, 3.57, and 3.45 inches, respectively. This shows that moderate use of the additive makes it function as a natural plasticizer and promotes cement dispersion. (4% or higher) produces the opposite effect due to the increase in the intrinsic kinematic viscosity of the hydrocolloid in the aqueous medium.

In terms of statistical model validation, results of the one-way ANOVA indicated a significant variation between the treatments studied ($p < 0.05$). Based on Tukey's multiple comparison test, 2% and 3% additive mixture treatments (M2 and M3) belong to the higher statistical group (Group a) and differ significantly from the standard control mixture (M0 - Group b). In contrast, treatments M1, M4, and M5 did not show statistically significant differences compared to the control sample, demonstrating that the optimal range for effectively maximizing the workability of concrete produced in Huancaayo is around 2% of the cement mass.

3.2.2. Setting Time

The initial and final setting times determined using the Vicat needle method to evaluate the hardening kinetics of the standard cement paste (M0) and the samples modified with different concentrations of *Opuntia ficus-indica* mucilage (M1 through M5) are summarized in Table 4.

Table 4. Experimental results on setting times and their statistical significance

Mix	Mucilage Content (%)	Initial Setting Time (min)	Final Setting Time (min)	Significance Group (Tukey)*
M0	0 % (Patrón)	127.50	385.00	c
M1	1 %	130.00	405.00	c
M2	2 %	134.00	415.00	b
M3	3 %	141.00	432.00	b
M4	4 %	148.00	455.00	a
M5	5 %	155.00	480.00	a

Note: The values represent chronological readings of normalized consistency behavior in accordance with ASTM C191. *Different letters in the last column indicate statistically significant differences ($p < 0.05$) according to Tukey's multiple comparison test.

Analysis of the quantitative results demonstrates a direct, progressive, and dosage-dependent influence of the organic additive on the loss of plasticity in the binder. The M0 control design (0% additive) exhibited typical behavior for a general-purpose Type I Portland cement without additives, recording an initial setting time of 127.5 minutes at the standard penetration threshold of 25 mm, and reaching final setting at 385.0 minutes.

When a low dosage of 1% (M1) was incorporated, the initial setting time was 130.0 minutes, showing minimal variation compared to the control; however, the subsequent hardening rate increased significantly, reaching final setting at 405.0 minutes, representing a net increase of 20 minutes in the completion of the physical process.

Furthermore, when the concentration of the natural additive was increased from 2% to 5% (mixtures M2 through M5), a systematic and progressive delay in the hardening time curves was observed, breaking the linearity of the base mixture. The initial setting time increased from 134.0 minutes in mixture M2 to 155.0 minutes for mixture M5. Likewise, the final setting time was also on a progressive upward trend, with times of 415.0, 432.0, 455.0, and 480.0 minutes achieved for 2%, 3%, 4%, and 5% content, respectively. In other words, the use of large amounts of the additive delayed the accomplishment of the final setting phase by 15-95 minutes when compared to the control sample without an additive.

When considering cement chemistry, it must be mentioned that this development is driven by the fact that *Opuntia ficus-indica* extract is composed of polysaccharides (like arabinogalactan and galacturonic acid) that make the extract hydrocolloidal.

The above-mentioned organic compounds that are characterized by hydrophilicity trap some of the water contained in the cement paste (this has been proved by the 87% holding capacity that was expressed in the results of the study) and stick to the particles of cement so that they form a film that restricts the ionic exchange for a while and reduces the rate of forming and growing of hydrated calcium silicate crystals, which delays the setting of the mixture.

The analysis of statistical significance indicated the kinetic effects of organic additive. One-way analysis of variance indicated a significant difference ($p < 0.05$) in final setting time as influenced by mucilage concentration.

Tukey's post-hoc multiple comparison test differentiated results into three different homogenous groups. Control mix M0, and 1% mix (M1) were included in the baseline group (group c), whereas 2% (M2) and 3% (M3) mixes were included in the intermediate group (Group b).

Finally, the 4% and 5% concentrations (M4 and M5) were classified in the subgroup with the greatest delay (Group a). These results scientifically demonstrate that prickly pear mucilage acts as an efficient natural rheological modifier and retarder, the dosage of which must be technically controlled in cold climates or high-altitude areas such as Huancayo to optimize the operational cycles for structural formwork removal on-site.

3.3. Testing of Hardened Specimens

3.3.1. Compressive Strength

A two-factor Analysis of Variance (ANOVA) was performed to evaluate the impact of curing days (7, 14, and 28 days) and different dosage levels (0.00%, 1%, 2%, 3%, 4%, and 5%) on the compressive strength of the material under study.

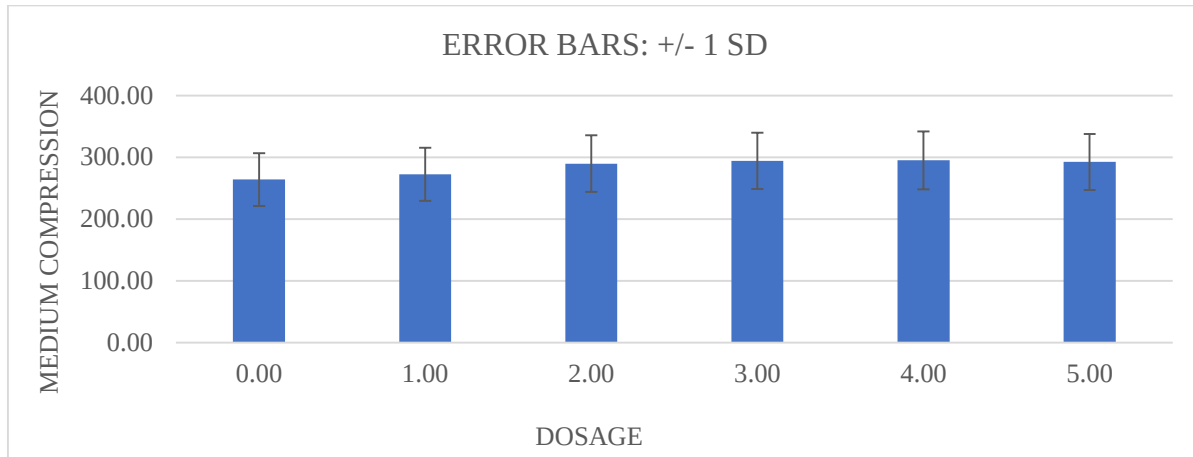
The results of the generalized linear model revealed a statistically significant main effect of large magnitude for the Curing Days factor, $F(2, 30) = 3254.90$, $p < .001$. Similarly, a statistically significant main effect was determined for the Dosage factor, $F(5, 30) = 92.23$, $p < .001$.

In contrast, the interaction between the two factors (Days $\times$ Dosage) was not statistically significant, $F(10, 30) = 0.98$, $p = .48$, which empirically demonstrates that the influence of the addition levels behaves similarly and independently throughout the different time stages of curing.

The final model demonstrated an outstanding fit, explaining 99.3% of the total variability in the mechanical property. ($R^2_{ajustada} = .993$). The data from the analysis of variance are summarized in Table 5.

Table 5. Two-factor Analysis of Variance (ANOVA) for compressive strength

Source of Variation	Sum of Squares (SS)	Degrees of Freedom (df)	Mean Square (MS)	F-Statistic	Significance (p)
Days	85739.96	2	42869.98	3254.90	< .001
Dosage	6074.62	5	1214.93	92.23	< .001
Days × Dosage	128.53	10	12.85	0.98	.48
Error (Residue)	395.20	30	13.17		
Corrected Total	92338.31	47			

**Fig. 5 Average compressive strength observed as a function of the dosage levels applied**

Note: The bars represent the arithmetic mean for each group, and the vertical error bars represent ± 1 standard deviation (SD).

Table 6. Tukey's Multiple Comparisons for the Dosage Factor in Compressive Strength

(I) Dosage	(J) Dosage	Difference in means (I-J)	Standard Error	Significance (p)
0.00%	1.00	-8.53*	1.79	< .001
	2.00	-25.82*	1.79	< .001
	3.00	-30.37*	1.79	< .001
	4.00	-31.11*	1.79	< .001
	5.00	-28.56*	1.73	< .001
1.00%	2.00	-17.29*	1.79	< .001
2.00%	3.00	-4.55	1.79	.141
	4.00	-5.29	1.79	.059
	5.00	-2.73	1.73	.620
3.00%	4.00	-0.74	1.79	.998
	5.00	1.81	1.73	.899
4.00%	5.00	2.56	1.73	.682

Note: The negative sign indicates that the initial group (I) has a lower mean than the comparison group (J).

* The difference in means is significant at the 0.05 level.

Because the Dosage factor showed significant overall differences, Tukey's HSD post hoc test was applied to identify specific performance clusters (Table 6). Pairwise comparisons revealed that the control sample without an additive (0%) alone exhibited significantly lower compressive strength compared to all other conditions ($p < .001$). In a second group with lower performance, the 1% dosage significantly outperformed the control (mean difference = 8.53, $p < .001$), but remained critically below the levels of the higher dosages ($p < .001$).

A key analytical finding for the technical optimization of the material was identified when evaluating the highest concentrations. The results indicated that there were no other statistically significant differences in the experimental groups consisting of 2%, 3%, 4% and 5% concentrations of the substance. None of the pairwise comparisons indicated a significant difference between the concentrations, either, with the difference between the 2% concentration and the 3% and 4% concentrations being 0.141 and 0.059, respectively. The same applied in the case of the 3% and 4% concentrations

group, which showed statistical equivalence with the results for 3% and 4% groups being 0.998. The results of the analysis have shown that the saturation limits begin to be reached at the concentration of 2%, since higher dose concentrations did not yield higher mechanical strength.

Table 7. Tukey's multiple comparisons for the "days" factor in compressive strength

(I) Days	(J) Days	Difference in Means (I-J)	Standard Error	Significance (p)
7.00	14.00	-44.81*	1.33	< .001
	28.00	-105.62*	1.32	< .001
14.00	28.00	-60.81*	1.17	< .001

Note: A negative sign indicates that the initial group (I) has a lower mean than the comparison group (J).

* The difference in means is significant at the .05 level.

The results of several comparisons made regarding the "Days of Curing" factor via Tukey's HSD indicate very significant changes in the progress of the trait ($p < .001$ for all mentioned comparisons above). The first 7-day period occurred to have the lowest values of compressive strength, which increased considerably by the time they reached the

14-day period (mean difference = -44.81, $p < .001$). This tendency for the virtues to rise continued in the course of the curing till 28 days, having been registered as a great increase in comparison to 14 days (mean difference = -60.81, $p < .001$). More comparisons on this variable are displayed in Table 7.

3.3.2. Porosity

A one-way Analysis of Variance (ANOVA) was carried out to figure out whether the innovative material had statistically significant differences in porosity by various dosages of prickly pear mucilage (0%, 1%, 2%, 3%, 4%, and 5%).

The statistical analysis showed that the Dosage factor did not significantly affect the matrix porosity, $F(5, 12) = 2.04$, $p = .145$. Since the significance obtained was higher than the conventional alpha level (.05), the null hypothesis is accepted, proving that the differences between the sample groups are stable enough and due to the natural variation of the laboratory tests rather than to the influence of the organic additive in the mix. The results of the variance analysis are presented in Table 8.

Table 8. Analysis of Variance (ANOVA) for the porosity variable by dosage

Source of Variation	Sum of Squares (SS)	Degrees of Freedom (df)	Mean Square (MS)	F-Statistic	Significance (p)
Between groups	.57	5	.11	2.04	.145
Within groups	.67	12	.06		
Total	1.24	17			

Note: Numerical values have been rounded to two decimal places in accordance with the formal criteria standardized by APA 7

In order to provide evidence for the descriptive analysis and display the spread of void data throughout the compacted matrix, Figure 6 shows the average porosity values together

with the standard deviation, which correspond to each level of addition.

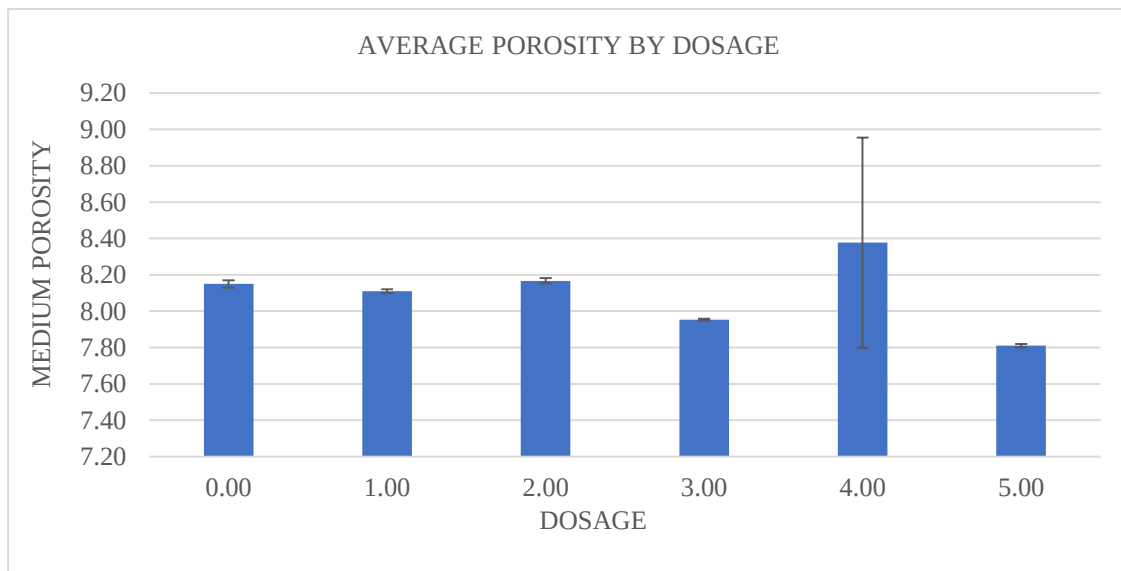


Fig. 6 Average porosity observed as a function of prickly pear mucilage dosage levels.

Note: The blue bars represent the arithmetic mean for each group, and the vertical error bars represent ± 1 standard deviation (SD).

Despite the absence of overall statistical significance indicated by ANOVA, visually examining means shows a slight change in internal structure of the blend. The control group without any additive (0%) has shown an average porosity of 8.15%. The additions of 1% and 3% of the additive led to a negligible decrease of pore size recorded at 8.11% and 7.95%, respectively.

On the other hand, the 4% concentration reversed this pattern, reaching the highest dispersion and the largest increase in porosity at 8.71%. However, the maximum dosage - 5% - showed the lowest average value in this study of 7.81%. Finally, the study shows the incorporation of prickly pear mucilage changes the structure of the material by changing the nature of the distribution of the voids in a non-linear way without increasing or decreasing the nature of the property in question substantially.

4. Discussion

The discovery of nonlinear rheological behavior in the new state of the system, as well as the changes in mechanical properties in the hardened state, confirm that the mucilage extracted from *Opuntia ficus-indica* can be defined as a complex organic agent in structural concrete in Huancayo, as both statistical and gravimetric analysis shows that the natural substance exerts a double effect subject to strict limitation due to the content and hydration kinetics of Type I Portland cement.

In its fresh state, the maximum efficiency in workability experienced at 2% dosage is 3.84 inches of slump (as opposed to 3.28 inches slump for the reference mix at 0%), confirming the efficiency of mucilage as an effective natural substance of influence. The characteristics of the material as a biopolymer are responsible for this aspect, mainly its capability to retain water, thereby enhancing the cohesion and homogeneity of the mixture. In relation to this physical effect, L Medina-Torres et al. [25] note that mucilage behaves non-Newtonian in terms of rheology, meaning that it is capable of producing significant changes in the viscosity of the system without increasing the water quantity of the mixture.

The plasticizing behavior is showing resistance to typical trends observed in the literature by Rivasplata, who stated that moderate amounts of prickly pear mucilage significantly improved flowability and slump of concrete mixes without causing harmful aggregate segregation. On the other hand, large additions of gum (4 and 5% amount) resulted in a decrease in the slump (3.57 and 3.45 in). The trend described is produced by the high viscosity of the systems under conditions of high concentrations; large concentrations of natural polymers give rise to very cohesive and not very fluid mixtures that limit intergranular movement, or viscoelastic behavior described by E. Rojas et al. [27]. These results correlate well with the findings made by Guevara, whose studies indicated that natural biopolymers perform better in

dispersion at a middle amount of biopolymer dosage (2% to 3%) of natural biopolymers, since in this case an optimal dispersion occurs without separation [28].

As for timing results, it is clear from Vicat test data that the additive contributes to fluidity loss in a controlled manner. For instance, the control mix (0% additive) shows typical hydration behavior with progressive decline in penetration and initial and final settings at 127.5 and 385 minutes, respectively. Mucilage addition causes changes in the reaction kinetics of the matrix due to its ability to form a film around the anhydrous cement grains, which temporarily hinders the interaction of the cement grains with free water. Medina-Torres et al. indicated that mucilages can retain high amounts of water and form viscous solutions that slow down the capillary diffusion processes, which leads to increased duration of hydration and explains the gradual decrease in penetration. Likewise, Sáenz, Sepúlveda, and Matsuhira state that mucilage has a hydrocolloid character and can modify the viscosity and affect the physicochemical processes of the binder [29]. As a result, the higher dose makes the setting time of the composition controllable; although large doses (4% and 5%) increase the retarding effect, reaching values between 405.0 and 480.0 minutes.

This kinetic retardation at high dosages establishes a near-empirical link to the experimental study documented by Picker and his colleagues. This indicates that, under conditions of saturated nopal extract concentration, initial crystal formation is inhibited due to the creation of passivating polysaccharide layers. According to Rojas and his colleagues, this is explained by the appearance of low-density organic protective layers on the clinker surface, which prevent crystal nucleation. However, the parameters demonstrate that the material offers superior performance within an intermediate range (1% to 3%), as it extends the effective working time without causing excessive delays that would affect formwork removal times.

The stability of our structural concrete mix in its fresh state was assessed by measuring the free water which separated to the top according to ASTM C232. Comparative tests revealed that the addition of the regional organic additive had a positive effect on the stability, in which bleeding decreased by 31.00% when compared to the reference mix M0. This quantifiable outcome substantiates the effectiveness of nopal mucilage as an efficient agent in stabilizing the strength of fresh mixtures.

The polysaccharides present in the extract make a strong three-dimensional polymeric matrix that creates the molecular retention force, restricting the upward movement of mixing water through the capillary openings when the materials are compacted and minimizing the chances of segregation and ensuring better uniformity of the composition in case of setting.

The hardening condition was subjected to a two-way factorial Analysis of Variance (ANOVA), which yielded an excellent statistical fit ($R^2 = 0.993$) and statistically confirmed ($p < 0.001$) that the presence of mucilage in the mixture significantly improves the compressive strength of the concrete compared to the control mixture M0 (310.27 kg/cm²). The evolution of stresses at 7, 14, and 28 days demonstrated that the additive optimizes load-bearing capacity, showing a progressive increase that rises from the control sample to reach its maximum at the 3% (343.86 kg/cm²) and 4% (343.43 kg/cm²) levels, representing a net mechanical gain of 10.80% at 28 days. As early as 7 days, the increase is already evident, rising from 209.34 kg/cm² in the control to 236.00 kg/cm² in the modified mixtures.

The increasing trend of axial stress development is in line with the research conducted by Zapata, which was published in the Universidad Católica de Trujillo. In this research, prickly pear mucilage is added to the concrete in controlled quanta between 1% and 3%, thus resulting in an enhanced compressive strength observed after 28 days of curing [31]. The continuous evolution of the study substantiates the claim of mucilage functioning as an internal curing agent, as the water that is held molecularly in the hydrocolloid is released through the chemical reactions progressing during the process that is conducive to improved hydration processes occurring at later stages and better claim development in terms of the transition zone between the paste and ½" coarse aggregate.

This microstructural densification effect strongly confirms what was reported by L Medina-Torres and associates, who found that mucilages have a beneficial effect on the distribution of free water in a mixture, thus providing better hydration of cement particles. Moreover, the current research shows that formulations loaded with the organic extract show superior mechanical properties at each stage of evaluation (7, 14, and 28 days), indicating the improvement in kinetics of cementitious matrix formation and development. In this regard, Carmen Sáenz, Eduardo Sepúlveda, and Berta Matsuhira state that mucilage is a hydrocolloid with a high molecular water-holding capability. This physical phenomenon helps retain moisture within the concrete, which facilitates internal curing; this, in turn, activates the hydration of the remaining cement, ultimately leading to an increase in compressive strength over time. The phenomenon demonstrated here fits well with the data obtained at the Huancayo laboratory since the increase in mechanical strength becomes more evident and significant at the 14th and 28th days of wet curing.

Nonetheless, an important methodological similarity can be revealed when we compare the current study with the world scientific literature concerning the fact that the natural additive possesses a positive effect only under certain dosages. In this study, when the mucilage content was increased to 4% and even to 5%, the compressive strength stopped increasing

and showed a tendency to decrease. The verification of this plateau or mechanical deterioration due to organic matter saturation was conducted by Geraldo Fábio Alves de Souza et al. [32] through various experiments conducted in national academic repositories, confirming the fact that the incorporation of natural polymers beyond the equilibrium thresholds has a negative impact on the physical parameters of density and water absorption in compacted structural mixtures. This behavior is in line with the findings described by [27] Rojas et al., who assert that high dosages of natural compounds bring about adverse effects on concrete microstructure, disturbing hydrated gels' crystallinity and mechanical bonding, thus affecting compressive strength. In the same vein, the results corroborate the conclusions by F. Guevara, who demonstrate that natural bio-based compounds can positively influence the mechanical properties of the building material to a much greater extent at moderate concentrations (namely, 2% and 3%), and leads to better internal compactness and smaller size of the intergranular capillary voids.

This type of physical aggregation tallies perfectly with the outcomes from the porosity discovery assay (ANOVA, $p = 0.145$), as it seems the variable of doses brings no specific or adverse changes in the value of void ratio, which remains constant in the limits of 7.81% and 8.71%. The change in porosity found at the concentrations of nearly 3% and 5% is most likely attributed to the formation of gel structures created by the additive, which improve the internal distribution of water and limit the interconnection of capillary pores. As stated by Medina-Torres and all [25] and Sáenz and all.

The effective property and hydrophilic nature of the gel affect the distribution of free moisture in the media, resulting in effective dehydration and shrinkage of the structure to create a denser media. At the same time, the minor increase in porosity after four percent of the dose (8.71%) indicates non-linear behavior typical of natural polymers, where certain loading of the solution can result to minor dispersion differences or minor trapping of microbubbles due to the viscosity of the solution.

Results obtained in the local study are consistent and provide evidence for the effectiveness of the *Opuntia ficus-indica* mucilage as a natural additive; the increase of compressive strength occurs for all ages, regardless of the fact that it should be noted that only the monitored range during the process of the incorporation of this mucilage is the right one for the increase of compressive strength.

In this respect, it should be reiterated that the optimum percentage of addition is from 2% to 3%, which ensures the greatest efficiency of the combination of mechanical characteristics, improved workability in the fresh state, and microstructural compactness of the ecologically-friendly concrete produced in Huancayo.

5. Conclusion

The experimental study confirmed that the use of *Opuntia ficus-indica* mucilage as a natural plasticizer has a significant effect on the properties of fresh and hardened structural concrete in Huancayo. The application of the statistical model was validated by using the two-way ANOVA analysis with SPSS, which resulted in a very good coefficient of determination. ($R^2_{adjusted} = 0.993$). The mathematical statistic mentioned above validates that factorial design proposed indicates 99.30% of total variation in mechanical characteristics, which shows that a moderate quantity of this organic biodegradable additive has been able to attain maximum efficiency in the two aspects of the flowability and the load-bearing capacity of the mixtures in solid condition.

According to ASTM C143/C143M, the slump test performed on the fresh mix showed it contained prickly pear mucilage, which can be used as an efficient plasticizer and has the ability to alter the initial characteristics of the mixture non-linearly. The best use of prickly pear mucilage to ensure maximum workability of the mortar was identified at the rate of 2% with respect to the mass of cement, providing a slump of 3.84 inches compared to the control mix slump of 3.28 inches (0%). However, adding rather too much (with dosages equal to or greater than 4%) results in the drying effect due to the increasing viscosity of the hydrocolloid. Simultaneously, Vicat needle tests carried out in compliance with ASTM C191 assured that the physicochemical features of the nature-derived material, the properties reflected in retention of water and pH of 5.18, worked as a secure modifier of rheology and a supplementary retarder. The 1% dosage increased the final setting time from 385 to 405 minutes, whereas higher dosages produced a progressive increase to 415, 432, 455, and 480 minutes for the 2%, 3%, 4%, and 5% mixtures, respectively. These results indicate that the retarding effect is dosage-dependent and should be controlled for practical structural concrete applications. Moreover, it was established that the polymer structure of the additive generates the intermolecular force, preventing capillary segregation and resulting in 31.00% decrease of bleeding in accordance with ASTM C232.

Compressive strength tests were conducted on 6" × 12" cylindrical specimens of hardened concrete in accordance with ASTM C39/C39M, revealing that the addition of mucilage further increased the compressive strength at 7, 14,

and 28 days of wet curing. An overall analysis of all properties considered has shown that 2% incorporation of mucilage causes the best overall effect on the properties of the concrete mixture. At 28 days of testing, the 1% dosage (M1) produced the maximum stress of 316.87 kg/cm², however, the use of the Tukey HSD multiple comparison test in SPSS revealed no significant differences in mechanistic performance between the two dosages tested. It can be concluded that the 2% dosage (M2) gave a good maximum strength of 337.89 kg/cm² which surpassed the required design strength of $f'_c=280$ kg/cm² with the best workability and handling properties. This observation of microstructural densification is in perfect agreement with the results of the gravimetric technique for permeable porosity used according to ASTM C642, in which ANOVA confirmed that the dosage factor has no harmful or damaging influence on the void ratio of the structural matrix [$F(5, 12) = 2.04$, $p = 0.145$], since the percentage of permeable pores was fixed within a narrow range of 7.81% to 8.71%.

The primary scientific achievement of this research consists of showing that an application rate of 2% increases the structure of capillary porosity and creates a structurally stronger and durable matrix due to the internal curing of the concrete caused by the blockage effects of the biopolymer gel. The practical meaning of these results for local construction is that they result in the production of very workable concrete, which makes placement, compacting, and finishing on site significantly easier, because it reduces the chances of physical segregation during pouring and guarantees the full safety of the construction in relation to structural stability in the challenging altitude environment typical for the region. In conclusion, for future research aiming at enhancing this green technology, it is advised to examine the long-term durability characteristics of these modified mixtures through freeze-thaw cycles typical for Huancayo's Andean climate and to supplement the microstructural characterization with advanced Scanning Electron Microscopy (SEM) tests to measure the morphology density of the hydrated calcium silicate gels.

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References

- [1] Youstra Boutouam et al., "A Comprehensive Review of Plant-based Biopolymers as Viscosity-Modifying Admixtures in Cement-Based Materials," *Applied Sciences*, vol. 14, no. 10, pp. 1-24, 2024. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [2] Nicolás Ortiz-Álvarez et al., "Rheological Properties of Cement-based Materials using a Biopolymer Viscosity Modifying Admixture (BVMA) under Different Dispersion Conditions," *Cement and Concrete Composites*, vol. 124, 2021. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [3] A. Arizzi, and P.F.G. Banfill, "Rheology of Lime Pastes with Biopolymer-based Additives," *Materials and Structures*, vol. 52, no. 1, 2019. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]

- [4] Wilfrido Martinez Molina et al., “Cement-based Materials Enhanced Durability from Opuntia Ficus Indica Mucilage Additions,” *ACI Materials Journal*, vol. 112, no. 1, pp. 165-172, 2015. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [5] Andres Antonio Torres-Acosta, and Alejandra Díaz-Cruz, “Concrete Durability Enhancement from Nopal (Opuntia Ficus-indica) Additions,” *Construction and Building Materials*, vol. 243, 2020. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [6] Andrés A Torres-Acosta, “Water and Chloride Permeability of Cement-based Mortar with Additions of Dehydrated Cacti,” *Journal of Chemical Technology & Biotechnology*, vol. 94, no. 11, pp. 3488-3494, 2019. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [7] Durgadevagi Shanmugavel et al., “Interaction of a Viscous Biopolymer from Cactus Extract with Cement Paste to Produce Sustainable Concrete,” *Construction and Building Materials*, vol. 257, pp. 1-8, 2020. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [8] G. Habert et al., “Environmental Impacts and Decarbonization Strategies in the Cement and Concrete Industries,” *Nature Reviews Earth & Environment*, vol. 1, no. 11, pp. 559-573, 2020. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [9] Karen L. Scrivener et al., “Eco-Efficient Cements: Potential Economically Viable Solutions for a Low-CO₂ Cement-based Materials Industry,” *Cement and Concrete Research*, vol. 114, pp. 2-26, 2018. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [10] United Nations, “*Transforming our world: The 2030 Agenda for Sustainable Development*,” Department of Economic and Social Affairs Sustainable Development, pp. 1-32, 2015. [[Google Scholar](#)] [[Publisher Link](#)]
- [11] “ACI 212.3R-10: Report on Chemical Admixtures for Concrete,” American Concrete Institute, pp. 1-61, 2010. [[Google Scholar](#)] [[Publisher Link](#)]
- [12] A. Cárdenas, Higuera-Ciapara, and F.M. Goycoolea, “Rheology and Aggregation of Cactus (Opuntia ficus-indica) Mucilage in Solution,” *Journal of the Professional Association for Cactus Development*, vol. 2, pp. 152-159, 1997. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [13] Francisco Rodríguez-González et al., “Influence of Age on Molecular Characteristics and Rheological Behavior of Nopal Mucilage,” *Food Science & Nutrition*, vol. 9, no. 12, pp. 6776-6785, 2021. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [14] Ahmed Elshewy et al., “Egyptian Opuntia Ficus-Indica (OFI) Residues: Recovery and Characterization of Fresh Mucilage from Cladodes,” *Horticulturae*, vol. 9, no. 7, pp. 1-15, 2023. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [15] Carlos Fernando Burga Delgado, and Wilson Bryan Hurtado Carrero, “*Mechanical Behavior of Concrete with Added Prickly Pear Mucilage and Corn Husk Fibers*,” Thesis, Sipán University, pp. 1-252, 2023. [[Google Scholar](#)] [[Publisher Link](#)]
- [16] ASTM International, *ASTM C143/C143M-12 Standard Test Method for Slump of Hydraulic-Cement Concrete*, pp. 1-4, 2012. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [17] ASTM International, *ASTM C39/C39M-21 Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens*, pp. 1-8, 2021. [[CrossRef](#)] [[Publisher Link](#)]
- [18] ASTM International, *ASTM C403/C403M-16 Standard Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance*, pp. 1-7, 2016. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [19] A.M. Neville, *Properties of Concrete*, 5th ed., Pearson Education Limited, 2011. [[Google Scholar](#)] [[Publisher Link](#)]
- [20] Carmen Sáenz et al., *Agro-Industrial Utilization of Cactus Pear*, Food and Agriculture Organization of the United Nations, pp. 1-168, 2013. [[Google Scholar](#)] [[Publisher Link](#)]
- [21] Carmen Sáenz, Elena Sepúlveda, and Betty Matsuhira, “Opuntia SPP Mucilage's: A Functional Component with Industrial Perspectives,” *Journal of Arid Environments*, vol. 57, no. 3, p. 275-290, 2004. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [22] Yusuf O. Mukaila, Jerry O. Adeyemi, and Olaniyi A. Fawole, “Towards Sustainable Biopolymer Innovation: A Review of Opuntia Ficus-Indica Mucilage,” *Processes*, vol. 13, no. 12, pp. 1-26, 2025. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [23] Xudong Liu et al., “Extraction, Purification, Structural Features, Biological Activities, and Applications of Polysaccharides from Opuntia Ficus-Indica (L.) Mill. (Cactus): A Review,” *Frontiers in Pharmacology*, vol. 16, pp. 1-18, 2025. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [24] María Carmen Fernández-Martínez et al., “Extraction of Opuntia Ficus-Indica Mucilage by Microfiltration and its Physicochemical Characteristics,” *Polymers*, vol. 16, no. 23, pp. 1-21, 2024. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [25] L Medina-Torres et al., “Rheological Properties of the Mucilage Gum (Opuntia Ficus Indica),” *Food Hydrocolloids*, vol. 14, no. 5, pp. 417-424, 2000. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [26] Ortiz Tinta, Mónica Lizbeth, and Miguel Ángel Pumayalla, “*Addition of Nopal Mucilage to Improve the Physical Properties of Structural Concrete in Nuevo Chimbote*,” Thesis, National University of Santa, 2022. [[Google Scholar](#)] [[Publisher Link](#)]
- [27] Eliseo Efraín Rojas Muñoz, and Tommy Brandon Palacios Berrios, “*Influence of Nopal Mucilage (Opuntia Ficus-Indica) as a Natural Additive on the Mechanical Properties of Concrete*,” Thesis, Hermilio Valdizán National University, pp. 1-164, 2024. [[Google Scholar](#)] [[Publisher Link](#)]
- [28] Fernando Julio Guevara Cardenas, “*Use of Nopal Mucilage to Improve the Mechanical Properties of Concrete*,” Thesis, Sipán University, pp. 1-215, 2023. [[Google Scholar](#)] [[Publisher Link](#)]
- [29] E. Sepúlveda et al., “Extraction and Characterization of Mucilage in Opuntia spp,” *Journal of Arid Environments*, vol. 68, no. 4, pp. 534-545, 2007. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]

- [30] Andreas Picker et al., “Influence of Polymers on the Nucleation of Calcium Silicate Hydrates,” *Cement and Concrete Research*, vol. 174, pp. 1-13, 2023. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [31] Katherine Li Zapata Santiago, “*Prickly Pear Mucilage and Concrete Compressive Strength in the Laboratory SLC Geotechnical Engineering SAC Lima, 2025*,” Thesis, Catholic University of Trujillo, pp. 1-99, 2026. [[Google Scholar](#)] [[Publisher Link](#)]
- [32] Geraldo Fábio Alves de Souza et al. “Opuntia Ficus-Indica Mucilage: A Sustainable Bio-Additive for Cementitious Materials,” *Construction and Building Materials*, vol. 456, 2024. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]