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Influence of the Addition of Carob Ash to Concrete Under High Water Pressure

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ABSTRACT

This study evaluates the effect of incorporating carob ash as a partial addition to a concrete mix with a strength of f'c = 210 kg/cm², focusing on improving its mechanical behavior and resistance to water penetration under pressure. The main objective was to determine how percentages of 3%, 6%, 9%, and 12% ash influence the compressive strength, diametrical compressive strength, modulus of elasticity, and impermeability of concrete. To this end, 141 cylindrical specimens were prepared, and tests were performed according to ACI, ASTM, and UNE-EN standards, using a quantitative approach and quasi-experimental design. The results demonstrated that the addition of 6% carob ash produced significant improvements in mechanical properties: reaching 269.40 kg/cm² in compression, 36.24 kg/cm² in tension, and a modulus of elasticity of 276,983.01 kg/cm². It also presented the lowest water penetration depth at 72 hours, demonstrating greater durability and impermeability. In contrast, higher dosages (9% and 12%) showed a decrease in overall performance. It is concluded that 6% is the optimal dosage, not only due to its technical benefits but also for its contribution to sustainability by recovering available agro-industrial waste, offering an economical, ecological, and effective solution to the limitations of traditional concretes.

1. INTRODUCTION

Concrete is the most widely used material in modern and contemporary construction due to the high global demand for buildings and infrastructure. Concrete structures are expected to have high quality and durability properties to withstand adverse environmental conditions, such as cold, heat, and rain, throughout their design life [1]. Despite this belief, numerous studies have shown that microcracks and the permeability of concrete allow the penetration of environmental liquids and gases, which can degrade and deteriorate the material directly or indirectly, reducing its lifespan [2].

The existence of this problem is common, and in recent years, positive studies have been conducted on the incorporation of different products into the construction industry, such as carob ash, for concrete. Australia is one of the countries with the highest annual waste utilization rate, where carob ash is among its main wastes used to manufacture concrete [3]. It is well known that carob ash, as a cementitious aggregate, meets physicochemical requirements and can promote binding properties when combined with cement. This improves the performance of concrete by making it more workable, resistant, and durable. Furthermore, this results in economic gains and environmental benefits, according to their online article [3].

Over the years, the population and housing construction have increased, and these are often built informally. This is, for many, the only option left for building their own homes at a low price. Without professional advice, they generate cost overruns, making their housing unsafe. It was then identified that due to this need, there are leaks in some concrete structures. These leaks can be caused by heavy rains, rising water tables, since these constructions are often built near rivers. The most frequent phenomena that cause penetration are: capillarity, penetration of water under pressure or permeability [4].

The increasing concern over environmental problems caused by the production and destruction of aggregates, and the insufficient storage area for the generated waste, has prompted many countries to explore waste reuse and recycling. Numerous studies have been conducted on these topics [5]. This growing global concern about energy and material consumption in the construction industry has sparked a growing interest in the use of organic-based materials in recent years. Furthermore, organic-based building materials can provide several advantages, such as improved thermal insulation, significantly improved concrete mechanics, and reduced weight in conventional building structures. They are also environmentally friendly due to the reuse of waste [6]. The problem of waste accumulation is a global problem and has become a concern in today's society, causing enormous environmental damage. Thus, the production of cement, as a chemical compound, generates highly polluting CO_2, as well as the longevity of concrete [7]. Given this situation, there is a need to explore alternative materials that can reduce the environmental impact, improve the durability of concrete, and utilize currently underutilized waste. One way to reduce its environmental impact and also increase its durability is to reuse this waste in new materials such as carob ash [8].

In this context, the use of agro-industrial waste, such as carob ash (CA), appears to be a promising alternative. This ash, generated from the combustion of carob wood residues, has been shown to have pozzolanic properties that can improve the mechanical strength and impermeability of concrete, in addition to contributing to more sustainable construction [3].

The construction sector is among the largest consumers of natural resources, leading to precious resources depleted each year and the environmental damage caused by their extraction. The construction industry generates a large amount of solid waste, commonly referred to as construction waste, which is often disposed inadequately [9]. The agricultural sector produces a large amount of different waste that can be studied for application in the construction industry. One of these wastes, considered in this article, carob ash (CA), can serve as a filler material in concrete. The development of sustainable concrete using agro-industrial waste responds to this need, reducing the consumption of natural resources, mitigating pollution, and improving the energy efficiency of the construction sector [10].

In the Puno region, a notable problem is the low strength of concrete. This is due to multiple factors such as low temperatures, high water pressure, constant humidity, and technical deficiencies, among others. As a result, concrete suffers from cracking, detachment, and low compressive strength [11]. Therefore, the application of this type of modified concrete can represent a practical and economical solution. Currently, there are problems caused by excessive stormwater runoff, as well as the lack of drainage systems in many cities, flash floods in urban areas, groundwater contamination, water shortages, increased contaminated water, and environmental impacts [12].

International and national studies have reported significant increases in compressive strength, tensile strength, modulus of elasticity, and water penetration in concrete when using plant-based ash as a partial substitute for cement [3, 8, 13, 14]. In addition to the structural benefits, its use contributes to mitigating the environmental impact of conventional concrete by reusing agro-industrial waste that would otherwise be discarded.

According to the study conducted by Sarabia Orihuela et al. [13], the objective of their project in Brazil is to evaluate the performance of using carob ash as a percentage substitute for cement. The method used is quantitative experimental. After 28 days of sample curing, compressive strengths of 26.52 MPa at 0%, 30.59 MPa at 6%, 29.38 MPa at 10%, and 31.21 MPa at 14%, respectively, were found. Therefore, it was concluded that the ideal proportion to improve compressive strength was 6% ash. According to Bernaola Fuentes and Guardapuclla Espinoza [14], in their project in Cusco, the objective is to evaluate the influence of eucalyptus trunk ash on the physical and mechanical properties of concrete with a density of 210 kg/cm^2. For this purpose, he uses a practically experimental and applied methodology. His research found a sample of 0% standard concrete along with three samples for the ash percentages of 5%, 9% and 13% of the additive. When breaking the concrete during the 7 days of curing, it presented average compressive and flexural strengths of 148.13 kg/cm^2 and 3.83 MPa for 0%, 149.11 kg/cm^2 and 3.98 MPa for 5%, 149.96 kg/cm^2 and 4.21 MPa for 9%.

In the study [15], the behavior of concrete with a design strength of 210 kg/cm^2 was evaluated by incorporating carob ash calcined at 600℃ in proportions of 5%, 6%, and 7%. The results after 28 days of curing indicated that the 6% addition produced the best results: 336 kg/cm^2 in compressive strength, 25 kg/cm^2 in tensile strength, and 26.4 kg/cm^2 in flexural strength, significantly surpassing the standard concrete. However, increasing the proportion to 7% resulted in a reduction in mechanical properties, with a compressive strength of only 260 kg/cm^2. A 6% addition was found to improve compressive, tensile, and flexural strength compared to the standard concrete. However, it was observed that exceeding this percentage resulted in decreased strength, highlighting the importance of determining the optimal dosage to maximize benefits without compromising concrete quality [16]. This study evaluated the effect of incorporating dry carob ash into concrete paving stones, using percentages of 0.75%, 2%, 4%, 6% and 8%. The results showed that the mixture with 6% carob ash showed the greatest improvement in compressive strength, reaching a value of 413.34 kg/cm^2, standing out as the strongest mixture compared to the other additions. However, when the addition of ash was increased to 8%, the strength began to decrease, suggesting that there is an optimal limit of ash to obtain the best results without compromising the strength of the concrete.

This research evaluates the resistivity and resistance of conventional concrete of 210 kg/cm^2, incorporating the ash derived from the calcination of firewood obtained from carob trees destined for the production of Junín wood, located in the province of Manabí. The ash was used as a partial replacement for cement at 5%, 10% and 15%, which makes a comparison between aggregates from two quarries, one located in the province of Manabí (Quarry "A") and the other in the province of Santo Domingo de los Tsáchilas (Quarry "B"). To produce the ash, sugarcane bagasse was calcined at a controlled temperature of 700℃ for 2 hours. Cylindrical specimens measuring 10 cm×20 cm were prepared and subjected to measure surface resistivity and perform the respective compression tests for ages of 7, 14, 21 and 28 days of curing. The results indicated an improvement in concrete strength compared to the standard design at 5% and 10%, with a decline observed at 15% CA replacement in both quarries. In addition, the resistivity range remains moderate for the standard design, 5% and 10% replacements, while reaching a high range at 15% CA replacement in both quarries.

The study aims to investigate the use of murumuru bark ash (MBA), an agro-industrial waste generated specifically in the Amazon region, as a partial replacement for cement in structural concrete. It also evaluates the physical, chemical, and mineralogical characteristics of the ash as a filler in concrete, as well as its fresh and hardened properties [17]. To this end, the MBA was subjected to physical-mechanical characterization tests, such as specific mass, pozzolanic activity with Portland cement, pozzolanic activity with lime, and BET testing. Mineralogical and chemical analyses of the ash were also performed. The results demonstrated the technical feasibility of partially replacing 6% of MBA in cement using a plasticizing additive to improve workability, demonstrating an improvement in the physical-mechanical and durability properties of the concrete.

The Ilo 21 thermal power plant generates electricity from coal and whose residue is fly ash, an environmentally polluting material, which is used as an additive in cement for the manufacture of concrete for different civil works, in this sense the objective of this study was to determine the dosage of concrete mixtures with fly ash in such a way that it does not decrease the resistance and helps mitigate the environment [3]. The material and method used is normal concrete with additions of fly ash in proportions of 2.5%, 5.0%, 10.0% and

15.0% for breaks at 7, 14, 28 and 90 days. The results indicate that, at 28 days, the average strengths were 221 kg/cm^2 for normal concrete, 223 kg/cm^2 for concrete with 2.5% fly ash, 231 kg/cm^2 for 5.0%, 200 kg/cm^2 for 10.0% and 192 kg/cm^2 for 15.0% fly ash. In conclusion, it is recommended to use fly ash as a substitute for cement in proportions less than 10%. Beyond this value, the strength of the concrete decreases, which can be detrimental when performing quality controls.

The purpose of this research was to analyze the behavior of low-permeability concrete with compressive strengths of f'c = 175 kg/cm^2, 210 kg/cm^2, 245 kg/cm^2, and 280 kg/cm^2 under high hydraulic pressure conditions [18]. During the development of the research, 56 specimens were prepared at 28 days of age, primarily for compressive strength, indirect tensile strength, and water penetration depth tests at a pressure of 50 mca (meters of water column), according to the European standard UNE-EN-12390-08 [19]. The conclusion was that concrete with a design of 210 kg/cm^2 is the most suitable for hydraulic construction, as it favors economic savings and minimizes potential damage to infrastructure and society. In this context, this research aims to evaluate the effect of different percentages of cement replacement with carob ash on the performance of structural concrete with a design strength of f'c = 210 kg/cm². The objective is to determine whether this addition improves the concrete's compressive strength, diametrical compressive strength, and modulus of elasticity, as well as its behavior under high-pressure water penetration. It also aims to identify the optimal percentage of ash that maximizes these properties. Ultimately, this study is expected to provide technical evidence on the viability of using carob ash as an alternative for the production of stronger, more economical, and environmentally friendly concrete.

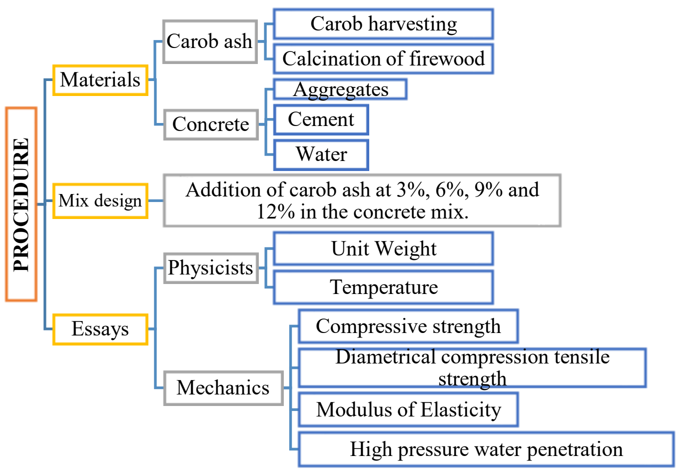
2. METHODOLOGY

This research is an applied study because the purpose of this study is to generate new knowledge about the behavior of sustainable concrete with carob ash. Additionally, data and knowledge obtained from laboratory experiments were used to evaluate the effects of incorporating carob ash in proportions of 3%, 6%, 9%, and 12% on the mechanical and physical properties of concrete, in order to determine its potential use for the benefit of society [20]. According to the research design, it is experimental because the data and test results are necessary for the analysis of changes in the population, which will allow comparison of results and thus reach conclusions based on this background [20]. A quantitative approach was used since the data were obtained by taking measurements and collecting laboratory tests, and a mathematical analysis of the data was carried out. In addition, the hypotheses raised in this study will be evaluated and tested using numerically represented results. The study is descriptive in the sense that quantitative information can be collected to compare, identify, and display characteristics based on the study's objectives. It can also be used to make statistical inferences through data analysis.

The independent variable is carob ash, manipulated to add different percentages of 3%, 6%, 9%, and 12% to the concrete. The dependent variable is the mechanical properties of the concrete, which include determining compressive strength, diametrical tensile strength, modulus of elasticity, and water penetration.

The sample for this study consisted of all 210 kg/cm^2 specimens, with a total of 141 specimens tested (15 cm in diameter and 30 cm in height).

The sample for this study consisted of 141 cylindrical concrete specimens (15 cm in diameter and 30 cm in height) with ash incorporated in proportions of 3%, 6%, 9%, and 12% relative to the weight of the cement. The specimens were distributed as follows: 45 for compression tests, using three specimens per curing age (7, 14, and 28 days) in five mixtures: standard sample and mixtures with 3%, 6%, 9%, and 12% ash; 45 for diametrical compression tensile tests, with the same distribution as for compression; 6 for the determination of the modulus of elasticity, evaluated only at 28 days in the standard mix and in the mix with 6% ash (considered the optimal proportion); and 45 for water penetration tests, performed at 12, 24, and 72 hours in the five aforementioned mixes. The tests were conducted in a laboratory under controlled conditions, following standardized protocols for evaluating the effects of the mixes on the physical and mechanical properties of concrete. The effects on the dependent variable were evaluated through direct and participatory observation, since participants participated fully, comprehensively, and personally in the tests, presenting themselves in an organized manner for proper data collection. Data collection instruments used were software such as Microsoft Excel, field notebooks, technical sheets, and laboratory equipment such as sieves, electronic scales, ovens, hydraulic presses, Los Angeles molds, and cylindrical molds, among others, in accordance with the corresponding technical standards. The detailed concrete procedure is shown in Figure 1.



Source: own elaboration.

Figure 1. Research procedure

Collection of materials

The carob firewood was collected from the forests of Lambayeque, in the Batan Grande settlement, Pativilca hamlet. The carob ash was calcined in a kiln at a temperature of 800°C for a period of 3 to 4 hours. The ash was carefully collected and stored in a clean, dry container to prevent moisture and any contamination. It was then transported to the "El Trébol" laboratory for analysis of its chemical properties.

Sample Preparation: The carob ash sample was previously sieved through a 50-mesh sieve to ensure particle size homogeneity, achieving an average size of 35.87 µm. A sample of 50.0316 g was then weighed and subjected to a kiln calcination process at a temperature of 800±3°C, ensuring the removal of organic matter and moisture before chemical analysis.

Measurement Conditions: Chemical composition analysis was performed using a BRUKER S2-PICOFOX energy-dispersive X-ray fluorescence spectrometer. The X-ray source used was a molybdenum (Mo) tube, with a measurement time of 2000 seconds per sample.

Standardization and Calibration: The international standard for Gallium (Ga) was used as a reference to quantify the elements present, ensuring the reliability and traceability of the results obtained. The concentration (g/L) was measured in accordance with the guidelines of ASTM C618, USAQ volumetry.

The quarries from which the materials for these tests were obtained were the "TRES TOMAS" quarry (crushed stone) and the "LA VICTORIA" quarry (fine sand), located in the province of Ferreñafe. The ash used in the mixtures was previously subjected to a chemical analysis in the "EL TRÉBOL" laboratory, and subsequently sieved through the N°200 sieve, in order to guarantee an adequate granulometry for its incorporation into the concrete.

The physical properties of the aggregates and mesquite ash are presented in Table 1. The following tests were performed:

- Particle size analysis (ASTM C33/C33M – 18)
- Loose and compacted unit weight (MTC E-203 / ASTM C-29 standards)
- Moisture content in aggregates (MTC E-203 / ASTM C-29 standards)
- Specific gravity and aggregate absorption (MTC E-205, E-206 / ASTM C-127, C-128 / AASHTO T-84, T-85)

The physical properties of the aggregates and carob ash used as constituent materials for the concrete were determined. These results are summarized in Table 1.

Table 1. Physical properties of carob aggregates and ash

Test	Fine Aggregate	Coarse Aggregate	Mesquite Ash
Moisture Content	1.92%	1.31%	0.37%
Nominal Maximum Size	-	3/4"	
Fineness Modulus	3.01	7.22	
Loose Bulk Density	1589	1473	1325
Compact Bulk Density	1758	1612	1486
Specific Gravity	2539	2732	1220
Absorption	1.7	0.88	1.74

Fresh concrete testing

- Unit Weight of Concrete (N.T.P 339.046: 2008 (revised 2018))

Table 2 presents a summary of the unit weight values of fresh concrete with different proportions of alternative pozzolanic material (CA) incorporated into the mix.

Table 2. Summary of unit weight (density) of concrete with the addition of CA

Sample	Pattern	CA 3%	CA 6%	CA 9%	CA 12%
No 1	2370	2364	2366	2294	2293
No 2	2377	2368	2355	2300	2292
No 3	2372	2365	2361	2296	2290

- Slump or Settling of Fresh Concrete (N.T.P. 339.035:2009)

Table 3 presents the result of the settlement (slump) of the standard concrete and the concrete with different additions of calcined carob residue in different percentages.

Table 3. Settling of standard concrete and concrete with the addition of CA in different percentages

Addition CA	Settlement	
	Obtained (inches)	Obtained (cm)
Pattern	3	7.62
3%	4	10.16
6%	3 1/2	8.89
9%	4	10.16
12%	4	10.16

- Temperature (N.T.P. 339.184)

Table 4 presents the results of the temperature of the standard concrete and concrete in which different percentages of CA were added.

Table 4. Temperature of standard concrete and concrete with the addition of CA in different percentages

Concrete	Temperature (°C)
Pattern	26.3
3%	26.0
6%	26.1
9%	25.7
12%	25.9

Mix Design (ACI Committee Standard 211.1)

The ACI 211.1 method was used in the concrete f'c 210 kg/cm2. Where 5 dosages were proposed with the addition of carob ash in relation to the weight of the cement 0% (design of the standard concrete), 3%, 6%, 9% and 12%.

Testing of hardened concrete

The concrete specimens were cured in the laboratory under controlled conditions using a moist curing process involving immersion in water, ensuring an environment of 100% relative humidity for a period of 28 days, in accordance with ASTM C511. The average temperature of the curing environment was maintained at around 26°C, with minimal variations between the different mixtures.

- Compressive Strength (MTC E-704 / ASTM C-39 / AASHTO T-22)

45 test specimens. Three test specimens per age (7, 14, and 28 days) were used in five mixtures: standard sample and ash additions of 3%, 6%, 9%, and 12%. Cylindrical specimens were 15 cm in diameter and 30 cm high.

The tests were carried out using a 100,000 kgf concrete press with digital readout, TÉCNICAS brand, model TCP341, equipped with a HIWEIGHT model X8 system and a resolution of 10 kgf.

Although the exact load rate applied during the tests was not recorded, efforts were made to follow the procedure established by the standard, which recommends a load application rate of 0.25 ± 0.05 MPa/s over the cross-section of the specimen. For the 15 cm diameter specimens, this corresponds to an approximate rate of 442 kgf/s. This speed seeks to ensure a continuous and impact-free load application, allowing a reliable determination of concrete strength.

- Diametric Compressive Tensile Strength (ASTM C496/C496M-17)

45 specimens. Three specimens per age (7, 14, and 28 days) were used in five mixtures: standard sample and ash additions of 3%, 6%, 9%, and 12%. Cylindrical specimens were 15 cm

in diameter and 30 cm high.

In this test, a TÉCNICAS brand digital press, model TCP341, with a capacity of 100,000 kgf and a resolution of 10 kgf, was used.

For the diametrical compression tensile test, the load must be applied progressively and controlled, within the range of 0.02 MPa/s to 0.06 MPa/s over the cross-sectional area of the specimen. The loading rate will be between 36.04 kgf/s (minimum) and 108.15 kgf/s (maximum). This loading rate ensures that the test is performed according to best practices and that the results obtained are consistent and comparable with other studies that follow this regulation.

- Modulus of Static Elasticity (ASTM C469)

There will be 6 specimens. After 28 days of curing (3 standard samples and 3 with 6% ash content), the specimens are cylindrical, 15 cm in diameter and 30 cm high.

A TÉCNICAS brand concrete press, model TCP341, with a capacity of 100,000 kgf and a resolution of 10 kgf, equipped with a HIWEIGHT digital measuring system, was used. ASTM C469 specifies that the load should be applied in a controlled manner until reaching 40% of the maximum load the concrete could withstand in a compression test, ensuring that the concrete remains within its elastic range. The loading rate was adjusted to 0.2 MPa/min, in accordance with the standard's recommendations to obtain accurate strain measurements. The modulus of elasticity was calculated from the slope of the stress-strain curve in the linear region, between a unit strain of 0.00005 and the stress corresponding to 40% of the maximum load.

- Water Penetration Test (UNE-EN 12390-8)

45 test specimens were tested at 12, 24, and 72 hours for the same five mixtures mentioned above. Cylindrical specimens were 15 cm in diameter and 30 cm high.

A hydraulic system was used, consisting of a hydraulic pump that generates pressure, a sealed chamber where the specimen is placed, a pressure gauge that constantly monitors the water pressure, and control valves that ensure the pressure remains uniform. The constant pressure allows water to flow through the concrete pores, allowing the material's permeability and durability against water penetration to be assessed. A constant pressure of 0.5 MPa (equivalent to 50 meters of water column) or 500 kPa was applied for 12, 24, and 72 hours, at a water temperature between 20℃ and 25℃. Upon completion, the specimens were split longitudinally to measure the maximum depth of water penetration, expressed in millimeters. Whose criterion indicates that the lower the penetration, the greater the impermeability.

3. RESULTS

In this project, a mix design was carried out for a concrete of 210 kg/cm^2, in which different percentages of carob ash (3%, 6%, 9% and 12%) are added, carrying out different laboratory tests.

- Recognize the chemical composition of carob ash to be used in concrete f'c=210 kg/cm^2.

The ash was fired at 800°C and sieved through a 50 mesh screen. Table 5 shows that the chemical analysis revealed 58.14% SiO_2, 15.12% Al_2O_3, and 6.19% Fe_2O_3, giving a combined total of 79.45%. Other components were also identified, such as 0.74% SO_3, 9.06% CaO, and 1.34% MgO. Table 6 compares this composition with the limits established by ASTM C618 for class F materials, showing that the material meets the requirements for use as a pozzolanic admixture in concrete mixtures.

- To determine how much the addition of 3%, 6%, 9% and 12% carob ash influences the compressive strength of concrete f'c=210 kg/cm^2 subjected to high water pressures, Lambayeque 2024.

The compressive strength results after 7 days of curing show a significantly influenced behavior by the incorporation of CA in the concrete mix. The control sample reached an average strength of 155.52 kg/cm², corresponding to 74% of the design strength, which is consistent with the typical progress in mechanical development at that age. The addition of 3% CA generated a moderate increase of 8.5%, reaching 168.77 kg/cm², while the 6% dosage presented the maximum value at 190.27 kg/cm², which represents an increase of 22.3% compared to the standard concrete (Table 7). This behavior suggests that, at this proportion, carob ash acts as an effective pozzolanic addition, reacting with the free lime produced by cement hydration, promoting the additional formation of cementitious compounds such as hydrated calcium silicate (C-S-H), responsible for the increase in mechanical strength. In contrast, the 9% dosage showed a strength of 189.46 kg/cm², similar to the 6%, which would indicate a possible saturation of the pozzolanic effect, where a higher content does not lead to a proportional improvement. Finally, with a 12% addition, the strength decreased to 162.28 kg/cm², which can be attributed to a dilution effect of the cement content, in addition to possible physical interference with matrix compaction, reducing the effectiveness of the hydration process. These results indicate that there is an optimal addition threshold, and that excessive CA. content can compromise the mechanical properties of concrete.

The ANOVA test showed statistically significant differences between groups ($F = 2031.497$, $p < 0.001$), indicating that the addition of CA influences concrete strength (Table 8). The highest strengths were obtained with the 6% and 9% CA dosages (190.27 and 189.46 kg/cm², respectively). The confidence intervals reveal that these groups with higher activated ash content are clearly differentiated from the standard concrete, confirming a notable improvement in compressive strength (Table 9). The overall trend shows that the percentage increase in activated ash improves strength up to a certain point, before beginning to decrease slightly at 12%.

The ANOVA test performed between the 6% and 9% carob ash dosages showed a value of $F = 3.618$ and $p = 0.130$ (Table 10), indicating no statistically significant difference between the two compressive strengths. This suggests that, statistically, both dosages offer similar performance.

Table 5. Chemical composition of carob ash

Chemical Composition	Results	Method Used
Silicon dioxide (SiO_2)	58.14	
Aluminum Trioxide (Al_2O_3)	15.12	
Calcium oxide (CaO)	9.064	
Iron Trioxide (Fe_2O_3)	6.19	
Potassium oxide (K_2O)	0.96	
Magnesium oxide (MgO)	1.34	X-ray fluorescence spectrometry
Phosphorus oxide (P_2O_5)	1.56	
Copper oxide (CuO)	0.83	
Sulfur Trioxide (SO_3)	0.74	
Zinc oxide (ZnO)	0.051	
Manganese oxide (MnO)	0.045	
Ignition loss	5.96	

Table 6. Comparison of the chemical properties of the CA, according to the ASTM C618 standard

Requirements	Class F-Astm C618	C. Carob (%)
$SiO_2 + Al_2O_3 + Fe_2O_3$	Min 70%	79.45
Sulfur trioxide (SO_3)	Max 4%	0.74
Calcium oxide (CaO)	Max 10%	9.064
Manganese oxide (MgO)	Max 5%	1.34
Moisture content	Max 3%	0.37
Ignition loss	2% - 10%	5.96

Table 7. Compressive strength at the age of 7 days

Compressive Strength (7 days)		
Description	**Description**	**Standard Deviation**
Control Concrete	155.52	0.43
3% Dosage	168.77	0.91
6% Dosage	190.27	0.58
9% Dosage	189.46	0.45
12% Dosage	162.28	0.53

Table 8. ANOVA test for 7-day compressive strength for all CA ratios

Source of Variation	Sum of Squares	Df	Mean Square	F	Sig.
Between Groups	3021.459	4	755.365	2031.497	0.000
Within Groups	3.718	10	0.372		
Total	3025.177	14			

Table 9. Confidence intervals for compressive strength at 7 days of age

Compressive Strength (14 days)			
Description	**Margin of Error**	**Confidence Intervals**	
		Lower Limit	**Upper Limit**
Control Concrete	0.54	154.98	156.06
C + 3% CA	1.13	167.64	169.90
C + 6% CA	0.72	189.55	190.99
C + 9% CA	0.56	188.90	190.02
C + 12% CA	0.66	161.62	162.94

Table 10. ANOVA test on 7-day compressive strength for 6% and 9% CA

Source of Variation	Sum of Squares	Df	Mean Square	F	Sig.
Between Groups	0.976	1	0.976	3.618	0.130
Within Groups	1.079	4	0.270		
Total	2.055	5			

After 14 days of curing, the concrete reached an advanced stage of mechanical strength development, with the standard sample recording an average value of 197.78 kg/cm², equivalent to 94.2% of the design strength (f'c = 210 kg/cm²), which is consistent with the levels expected at that age. The incorporation of carob ash, an agro-industrial waste with pozzolanic potential, showed varying effects depending on its dosage. With 3%, an average strength of 214.21 kg/cm² was obtained, exceeding conventional concrete by 8.3%, demonstrating a functional improvement within the concept of sustainable concrete. The mixture with 6% reached maximum performance with 243.20 kg/cm², representing an increase of 22.9%, suggesting an optimal interaction between the cement compounds and the reactive characteristics of the ash. In contrast, when using 9%, the strength decreased slightly to 229.97 kg/cm², indicating decreasing efficiency from this point on. Finally, with 12% replacement, the strength decreased to 208.89 kg/cm², implying a 4.5% loss relative to the standard mix, possibly due to the supersaturation of non-reactive fine particles that interfere with the proper development of the cementitious matrix (Table 11).

The standard concrete has a margin of error of 0.19, giving a confidence interval between 197.59 and 197.97 kg/cm². In the case of 6%, it had a margin of error of 0.84, and a range between 242.36 and 244.04 kg/cm². These results reflect a significant improvement in the concrete's strength with the ash, while maintaining narrow and consistent confidence intervals (Table 12).

Analysis of variance (ANOVA) indicated statistically significant differences in 14-day compressive strength between the various carob ash dosages ($p < 0.001$) (Table 13). The 6% dosage presented the highest strength (243.2 kg/cm²), with a 23% increase compared to the standard concrete (197.78 kg/cm²), demonstrating a positive effect of the additive up to that point. From then on, with 9% and 12%, the strength decreased, although it remained above the standard value. To further compare the higher dosages, a second ANOVA was performed only between 6% and 9%, which also showed statistically significant differences ($F = 715.683$; $p < 0.001$), confirming that 6% is statistically superior to 9% in terms of strength (Table 14). The low standard deviation across all groups supports the consistency of the results and suggests that the optimal dosage for improving concrete strength with carob ash is 6%.

Table 11. Compressive strength at 14 days of curing

Compressive Strength (14 days)		
Description	**Average (kg/cm²)**	**Standard Deviation**
Control Concrete	197.78	0.15
3% Dosage	214.21	0.29
6% Dosage	243.20	0.68
9% Dosage	229.97	0.52
12% Dosage	208.89	0.20

Table 12. Confidence intervals for compressive strength at 14 days of age

Compressive Strength (14 days)			
Description	**Margin of Error**	**Confidence Intervals**	
		Upper Limit	**Upper Limit**
Control Concrete	0.19	197.59	197.97
C + 3% CA	0.36	213.85	214.57
C + 6% CA	0.84	242.36	244.04
C + 9% CA	0.64	229.33	230.61
C + 12% CA	0.25	208.64	209.14

Table 13. ANOVA test on compressive strength at 14 days

Source of Variation	Sum of Squares	Df	Mean Square	F	Sig.
Between Groups	3844.669	4	961.167	5467.806	0.000
Within Groups	1.758	10	0.176		
Total	3846.427	14			

Table 14. ANOVA test on compressive strength at 14 days for the 6% and 9% CA ratios

Source of Variation	Sum of Squares	Df	Mean Square	F	Sig.
Between Groups	262.417	1	262.417	715.683	0.000
Within Groups	1.467	4	0.367		
Total	263.884	5			

Table 15. Compressive strength at 28 days of curing

Compressive Strength (28 days)		
Standard Deviation	Standard Deviation	Standard Deviation
Control Concrete	217.51	0.40
3% Dosage	234.97	0.90
6% Dosage	269.40	0.20
9% Dosage	256.23	0.37
12% Dosage	226.82	0.20

Table 16. Confidence intervals for compressive strength at 28 days of age

Compressive Strength (28 days)			
Description	Confidence Intervals	Confidence Intervals	
		Upper Limit	Upper Limit
Control Concrete	0.5	217.01	218.01
C + 3% CA	1.11	233.86	236.08
C + 6% CA	0.25	269.15	269.65
C + 9% CA	0.46	255.77	256.69
C + 12% CA	0.25	226.57	227.07

Table 17. Result of the analysis of variance for compressive strength at 28 days

Source of Variation	Sum of Squares	Df	Mean Square	F	Sig.
Between Groups	5483.733	4	1370.933	5803.957	0.000
Within Groups	2.362	10	0.236		
Total	5486.095	14			

Table 18. ANOVA test on compressive strength at 28 days for the 6% and 9% CA ratios

Source of Variation	Sum of Squares	Df	Mean Square	F	Sig.
Between Groups	260.042	1	260.042	2956.139	0.000
Within Groups	0.352	4	0.088		
Total	260.394	5			

After 28 days of curing, the standard stage for evaluating the final mechanical strength of concrete, the standard mix reached an average strength of 217.51 kg/cm², exceeding the design value by 3.6% (f'c = 210 kg/cm²) and satisfactorily meeting the established structural requirements. The inclusion of carob ash, an agro-industrial waste with pozzolanic potential, produced differentiated effects depending on the percentage used. With 3%, a strength of 234.97 kg/cm² was obtained, representing increases of 8% compared to the standard mix and 12% compared to the design, indicating a moderate improvement attributed to the cementing contribution of the ash. With a 6% proportion, maximum performance was achieved at 269.40 kg/cm², equivalent to an increase of 23.9% compared to the standard and 28.3% compared to the design value. This result reaffirms that this dosage optimizes concrete matrix densification and favors the formation of additional hydrated products, consolidating its application in high-performance sustainable concrete. In contrast, the 9% strength registered a strength of 256.23 kg/cm², still high (17.8% higher than the standard), but without exceeding the response obtained with the 6%, suggesting a saturation threshold in the reactivity of the supplementary material. Finally, the use of 12% yielded a strength of 226.82 kg/cm², which, while slightly exceeding the standard (4.3%), reflects a significant reduction compared to optimal dosages (Table 15). This decrease can be attributed to the excess of non-reactive material, which interferes with cement hydration and reduces the compactness of the system. Together, the results reinforce the potential for using agro-industrial ashes in the formulation of sustainable concrete, provided they are used in appropriate proportions to maximize concrete performance without compromising its structural properties.

The standard concrete reached 217.51 kg/cm², with a margin of error of 0.50 (range 217.01-218.01). The 6% ash content reached 269.40 kg/cm², with a margin of error of 0.25 (range 269.15-269.65), showing the greatest improvement. The 3% content also improved, reaching 234.97 kg/cm² (range 233.86-236.08). These results highlight that carob ash, especially at 6%, significantly improves strength with small and consistent margins of error (Table 16).

The ANOVA performed on the 28-day compressive strength results showed that the differences between the mixtures with the addition of carob ash are statistically significant (Table 17). When specifically comparing the two dosages of 6% and 9%, it was observed that the mixture with 6% carob ash showed superior performance, reaching a strength of 269.4 kg/cm², compared to 256.23 kg/cm² obtained with 9%. These results indicate that, although both mixtures improved strength compared to the standard concrete, the 6% dosage maximizes the benefit of the carob ash, providing a considerable increase in strength without reaching the negative effects observed when using higher doses. The F value obtained in the ANOVA (2956.139) and the p value < 0.001 reinforce the validity of this difference, highlighting the effectiveness of 6% as the most optimal dosage for this type of addition in improving the mechanical properties of concrete (Table 18).

- To evaluate how much the addition of 3%, 6%, 9% and 12% carob ash influences the tensile strength of concrete f'c=210 kg/cm² subjected to high water pressures, Lambayeque 2024.

The results of diametrical compressive tensile strength after 7 days of curing show a significant improvement in the mechanical behavior of the concrete with the addition of carob ash, an agro-industrial waste with pozzolanic properties. The standard mix, with a design strength of 210 kg/cm², reached an average tensile strength of 18.49 kg/cm², used as a reference to evaluate the effect of the different formulations. The mix with 3% ash showed a strength of 20.06 kg/cm², equivalent to an 8.5% increase compared to the standard. With 6% ash, the maximum value of 24.35 kg/cm² was recorded, representing a 31.7% improvement, suggesting a notable strengthening of the matrix due to the formation of additional hydrated products and greater internal cohesion. The 9% mixture showed similar performance, reaching 24.19 kg/cm² (30.9% increase), although it did not exceed the 6% mixture, which would again indicate a saturation point in the efficiency of the supplementary material. Finally, with a 12% replacement, the strength was 21.51 kg/cm², with a 16.3% increase, although lower than the maximum levels obtained (Table 19). These results confirm that, in addition to improving compressive strength, carob ash also contributes to the development of tensile strength, especially when used in optimal proportions, reaffirming its viability in the design of high-performance sustainable concretes.

The standard concrete had a standard deviation of 0.03 and a margin of error of 0.04, with a confidence interval between 18.45 and 18.53. With the addition of ash, the strength increased significantly, reaching 24.35 kg/cm² with 6% ash (standard deviation of 0.05) and 24.19 kg/cm² with 9% (standard deviation of 0.03). The margin of error in these mixtures was 0.06 and 0.03, respectively, giving confidence intervals between 24.29 and 24.41 for 6% and between 24.16 and 24.22 for 9% (Table 20).

Table 19. Diametric compression tensile strength 7 days of curing

Diametral Compression Tensile (7 days)		
Standard Deviation	**Standard Deviation**	**Standard Deviation**
Control Concrete	18.49	0.03
3% Dosage	20.06	0.01
6% Dosage	24.35	0.05
9% Dosage	24.19	0.03
12% Dosage	21.51	0.06

Table 20. Confidence intervals for tensile strength at 7 days of age

Diametral Compression Tensile (7 days)			
Description	**Confidence Intervals**	**Confidence Intervals**	
		Lower Limit	**Upper Limit**
C. Patrón	0.04	18.45	18.53
C + 3% CA	0.02	20.04	20.08
C + 6% CA	0.06	24.29	24.41
C + 9% CA	0.03	24.16	24.22
C + 12% CA	0.07	21.44	21.58

Table 21. Result of the analysis of variance for tensile strength at 7 days

Source of Variation	Sum of Squares	Df	Mean Square	F	Sig.
Between Groups	78.789	4	19.697	12721.9	0.000
Within Groups	0.015	10	0.002		
Total	78.805	14			

Table 22. ANOVA test on tensile strength at 7 days for the 6% and 9% CA ratios

Source of Variation	Sum of Squares	Df	Mean Square	F	Sig.
Between Groups	0.039	1	0.039	23.585	0.008
Within Groups	0.007	4	0.002		
Total	0.045	5			

The ANOVA test for all addition percentages revealed a highly significant difference between groups (F = 12721.9, p = 0.000), indicating that the addition of ash significantly affects tensile strength (Table 21). Focusing solely on the 6% and 9% concentrations, the ANOVA test also showed a significant difference (F = 23.585, p = 0.008), confirming that, although both concentrations improved strength, there are statistical differences between them (Table 22). These results highlight the effectiveness of carob ash in improving tensile strength, especially at 6% concentrations, with small and consistent margins of error.

The diametrical compressive tensile strength of the concrete at 14 days showed variations that depend on the percentage of carob ash used as a supplementary cementing material. In the standard concrete, the average strength was 21.71 kg/cm² (Table 23). With the addition of 3% ash, the strength increased to 25.75 kg/cm², indicating a significant improvement. When using 6% ash, the strength reached 29.32 kg/cm², the highest value observed. However, when using 9% ash, the strength decreased slightly to 28.75 kg/cm², and with 12%, the strength decreased to 24.71 kg/cm². These results suggest that increasing the ash ratio improves strength up to 6%, but higher concentrations (9% and 12%) appear to negatively affect the cohesion and hydration process of the concrete, which may explain the reduction in strength. The standard concrete had a margin of error of 0.11 and a confidence interval between 21.60 and 21.82 kg/cm² (Table 24). The 6% and 9% dosages showed low levels of dispersion (standard deviations of 0.10 and 0.17, respectively) and small margins of error (0.12 and 0.21), reflecting good consistency in the data.

The general ANOVA test showed statistically significant differences between groups (F = 2280.811, p = 0.000) (Table 25), and when specifically comparing the 6% and 9% dosages, a significant difference was also found (F = 26.204, p = 0.007) (Table 26). These results confirm that the addition of ash, especially at 6%, consistently and significantly improves the tensile strength of concrete.

Table 23. Diametric compression tensile strength 14 days of curing

Diametral Compression Tensile (14 days)		
Standard Deviation	**Standard Deviation**	**Standard Deviation**
Control Concrete	21.71	0.09
3% Dosage	25.75	0.04
6% Dosage	29.32	0.10
9% Dosage	28.75	0.17
12% Dosage	24.71	0.13

Table 24. Confidence intervals for tensile strength at 14 days of age

Diametral Compression Tensile (14 days)			
Description	**Confidence Intervals**	**Confidence Intervals**	
		Lower Limit	**Upper Limit**
C. Patrón	0.11	21.60	21.82
C + 3% CA	0.04	25.71	25.79
C + 6% CA	0.12	29.20	29.44
C + 9% CA	0.21	28.54	28.96
C + 12% CA	0.16	24.55	24.87

Table 25. Result of the analysis of variance for tensile strength at 14 days

Source of Variation	Sum of Squares	Df	Mean Square	F	Sig.
Between Groups	116.232	4	29.058	2280.811	0.00
Within Groups	0.127	10	0.013		
Total	116.360	14			

Table 26. ANOVA test on tensile strength at 14 days for the 6% and 9% CA ratios

Source of Variation	Sum of Squares	Df	Mean Square	F	Sig.
Between Groups	0.496	1	0.496	26.204	0.007
Within Groups	0.076	4	0.019		
Total	0.572	5			

Table 27. Diametric compression tensile strength 28 days of curing

Diametral Compression Tensile (28 days)		
Standard Deviation	**Standard Deviation**	**Standard Deviation**
Control Concrete	27.00	0.09
3% Dosage	31.85	0.05
6% Dosage	36.24	0.07
9% Dosage	34.90	0.11
12% Dosage	29.96	0.04

Table 28. Confidence intervals for tensile strength at 28 days of age

Diametral Compression Tensile (28 days)			
Description	**Confidence Intervals**	**Confidence Intervals Lower Limit**	**Upper Limit**
C. Patrón	0.11	26.89	27.11
C + 3% CA	0.06	31.79	31.91
C + 6% CA	0.09	36.15	36.33
C + 9% CA	0.13	34.77	35.03
C + 12% CA	0.05	29.91	30.01

Table 29. Result of the analysis of variance for tensile strength at 28 days

Source of Variation	Sum of Squares	Df	Mean Square	F	Sig.
Between Groups	166.690	4	41.673	7180.200	0.000
Within Groups	0.058	10	0.006		
Total	166.748	14			

Table 30. ANOVA test on tensile strength at 28 days for the 6% and 9% CA ratios

Source of Variation	Sum of Squares	Df	Mean Square	F	Sig.
Between Groups	2.709	1	2.709	327.522	0.000
Within Groups	0.033	4	0.008		
Total	2.742	5			

The strength results of concrete with different percentages of carob ash show that, for the standard concrete with a design f'c of 210 kg/cm², the average strength was approximately 27 kg/cm², which is lower than the expected value. However, when carob ash is incorporated, a progressive improvement in strength is observed, with 3% being the first significant increase with an average of 31.85 kg/cm², exceeding the standard concrete by 17.3%. Upon reaching 6% ash, the average strength increased to 36.24 kg/cm², standing out as the highest value in this series, exceeding the standard by 34.5% and 3% by 13.8%. This behavior suggests that at this dosage, a greater activation of the ash's pozzolanic properties is achieved, favoring the formation of hydrated products that reinforce the concrete matrix. However, increasing the dosage to 9% resulted in a decrease in strength to 34.90 kg/cm², which is still 29.2% higher than the standard, but lower than the strength obtained with 6%. At 12%, the strength dropped to 29.96 kg/cm², which is only 11.4% higher than the standard concrete, and is also lower than 9% and 6% (Table 27). This behavior indicates that the incorporation of carob ash improves strength up to an optimal limit (6%), beyond which higher concentrations (9% and 12%) can negatively alter concrete cohesion, possibly due to an oversaturation of non-reactive fine particles that interfere with cement hydration and affect the internal structure of the material.

The standard concrete had a standard deviation of 0.09, with a margin of error of 0.11 and a confidence interval between 26.89 and 27.11 kg/cm². The highest strength was achieved with the 6% dosage, followed by the 9% dosage, both with low margins of error (0.09 and 0.13, respectively) and consistent data (Table 28).

The results of the ANOVA test performed to compare the diametrical compressive tensile strength between the different carob ash dosages showed highly significant differences between the groups. In the overall analysis of all addition percentages (0%, 3%, 6%, 9%, 12%), the F value was 7180.200 with a p value = 0.000, indicating that at least one of the dosages differed significantly compared to the others (Table 29). This difference reflects the significant effect of adding carob ash on improving compressive tensile strength.

When comparing the 6% and 9% additions, the ANOVA analysis also showed a significant difference, with an F value of 327.522 and p = 0.000 (Table 30). This suggests that, although both percentages show an increase in strength compared to the standard, the 6% percentage performs significantly better in terms of tensile strength.

- Determine how much the addition of 6% carob ash influences the elasticity of concrete f'c=210 kg/cm^2 subjected to high water pressures, Lambayeque 2024.

Table 31. Elasticity modulus with 0% and 6% M. A addition

Description	Modulus of Elasticity	Standard Deviation
Control Concrete	235799.65	201.52
C. + 6% CA	276983.01	339264.597

Table 32. Confidence intervals for tensile strength at 28 days of age

Modulus of Elasticity (28 Days)			
Description	**Confidence Intervals**	**Confidence Intervals Lower Limit**	**Upper Limit**
Control Concrete	322.98	235476.67	236122.63
C + 6% CA	543747.63	-266764.62	820730.64

Table 33. ANOVA test of the modulus of elasticity at 28 days

Source of Variation	Sum of Squares	Df	Mean Square	F	Sig.
Between Groups	2544141600.17	1	2544141 600.17	243.959	0.000
Within Groups	41714307.33	4	1042857 6.83		
Total	2585855907.50	5			

The results of the modulus of elasticity (Ec) test show that the standard concrete had an average value of 235,799.65 kg/cm². By incorporating 6% carob ash, the modulus of elasticity increased significantly to 276,983.01 kg/cm², representing an increase of 17.4%. This increase in the modulus of elasticity suggests that the addition of carob ash in this proportion improves the concrete's stiffness, indicating greater resistance to deformation under load. The improvement in the mechanical properties of the concrete with 6% carob ash can be explained by the activation of the ash's pozzolanic properties, which favor the formation of additional hydration products, thus strengthening the material's internal structure and optimizing its structural behavior (Table 31, Table 32 and Table 33). The standard deviation of the mixture with 6% ash is notably higher (339,264.60) compared to the standard concrete (201.52), suggesting a greater dispersion in the results of the mixture with ash, possibly indicating variability in its behavior. The margin of error and confidence intervals also reinforce this difference: while the standard concrete has a relatively narrow confidence interval (235,476.67–236,122.63), the interval for the mixture with 6% ash is much wider, reflecting the high uncertainty associated with the measurement of this material (between -266,764.62 and 820,730.64).

The ANOVA test shows that the difference between groups is highly significant, with an F value of 243.96 and a p-value of 0.000, indicating that the incorporation of carob ash into the concrete mix has a significant impact on the modulus of elasticity. This supports the belief that the observed variations are not due to chance, but rather to the addition of carob ash. Despite the high dispersion in the mix with 6% ash, the results point to a substantial change in the concrete's properties, suggesting that ash, while increasing variability, can also improve some mechanical properties, although these should be considered with caution due to the high uncertainty in the results.

- Determine the depth of water penetration under pressure of concrete f'c=210 kg/cm² with the addition of carob ash, Lambayeque 2024.

In the water penetration test, a pressure of 500 kPa was applied for 12 hours at 28 days of curing. The results showed good uniformity between the A and B sides of the samples. For the standard concrete, without the addition of CA, the average maximum penetrations were 25.69 mm, 25.62 mm, and 25.70 mm (Table 34). When incorporating 3% carob ash, a decrease in the size of the water penetration was observed, with average values of 17.00 mm, 25.62 mm, and 25.7 mm, suggesting an improvement in the impermeability of the concrete. However, increasing the carob ash dosage to 6% recorded an increase in penetrations, with values of 22.58 mm, 22.43 mm, and 22.67 mm. For mixtures with 9% and 12% ash, the average maximum penetrations were 24.08 mm, 24.00 mm, 24.13 mm, 24.12 mm, 23.96 mm, and 24.17 mm, respectively. These results indicate that 3% carob ash improves concrete's resistance to water penetration, while higher concentrations do not improve this property and, in some cases, may even impair it.

The margin of error for the standard concrete is relatively small (4.44 to 4.61 mm), indicating greater certainty in the penetration values, while mixtures with higher carob ash content have wider margins of error (1.31 to 3.01 mm), especially at 9%, reflecting greater variability, as shown in Table 35. The confidence intervals for the penetrations in the standard concrete and the mixtures with carob ash are fairly consistent, noting that the 3% ash intervals (15.67 to 18.29 mm) are narrower, reflecting greater reliability in the penetration values for that dosage. The standard deviation varies between the different groups, with lower values in the mixtures with a higher percentage of ash, suggesting greater consistency in the results as the ash addition increases.

Table 34. Maximum penetrations with CA addition (0%, 3%, 6%, 9%, 12%) – 12 hours

Sample No	Maximum Penetration (mm)	Standard Deviation
M1-0%	25.69	3.19
M2-0%	25.62	3.16
M3-0%	25.70	3.07
M1-3%	17.00	1.03
M2-3%	16.98	0.91
M3-3%	17.09	0.95
M1-6%	22.58	1.37
M2-6%	22.43	1.41
M3-6%	22.67	1.36
M1-9%	24.08	2.08
M2-9%	24.000	2.07
M3-9%	24.13	1.93
M1-12%	24.12	1.57
M2-12%	23.96	1.51
M3-12%	24.17	1.43

Table 35. Confidence intervals for the water penetration test after 12 hours of exposure

Water Penetration – 12 Hours			
Sample No	Margin of Error	Confidence Intervals	
		Lower Limit	Upper Limit
M1-0%	4.61	21.08	30.30
M2-0%	4.57	21.05	30.19
M3-0%	4.44	21.26	30.14
M1-3%	1.48	15.52	18.48
M2-3%	1.31	15.67	18.29
M3-3%	1.38	15.71	18.47
M1-6%	1.98	20.60	24.56
M2-6%	2.03	20.40	24.46
M3-6%	1.96	20.71	24.63
M1-9%	3.01	21.07	27.09
M2-9%	3.00	21.00	27.00
M3-9%	2.79	21.34	26.92
M1-12%	2.27	21.85	26.39
M2-12%	2.19	21.77	26.15
M3-12%	2.07	22.10	26.24

Table 36. ANOVA test of the water penetration test at 12 hours of exposure

Source of Variation	Sum of Squares	Df	Mean Square	F	Sig.
Between Groups	269.177	4	67.294	29.336	0.000
Within Groups	57.348	25	2.294		
Total	326.525	29			

Table 37. ANOVA test in the water penetration test after 12 hours of exposure to the 3% and 6% CA ratios

Source of Variation	Sum of Squares	Df	Mean Square	F	Sig.
Between Groups	92.0194	1	92.019	107.486	0.000
Within Groups	8.5611	10	0.856		
Total	100.5805	11			

The results of the ANOVA test for maximum water penetration at 12 hours reveal a statistically significant difference between the different percentages of carob ash, with an F value = 29.336 and a p value = 0.000, indicating that the differences observed between the groups are not due to random variability (Table 36).

The ANOVA test also shows a clear difference between the results for 3% and 6% carob ash (F = 107.486, p = 0.000), according to Table 37, reinforcing the idea that mixtures with carob ash have a considerable impact on water penetration. In summary, the percentage of ash has a significant impact on water penetration. However, this relationship is not beneficial for concrete waterproofing at higher ash concentrations.

In the water penetration test, a pressure of 500 kPa was applied for 24 hours after 28 days of curing. The results showed good uniformity between the A and B sides of the samples. For the standard concrete, without the addition of carob ash (CA), the average maximum penetrations were 38.84 mm, 38.93 mm, and 38.76 mm (Table 38). When 3% carob ash was added, a decrease in the water penetration depth was observed, reaching average values of 28.76 mm, 28.78 mm, and 28.83 mm. This behavior suggests an improvement in the impermeability of the concrete with a low additive dosage. With 6% carob ash, penetration increased slightly, with average values of 34.30 mm, 34.23 mm, and 33.72 mm, indicating that this percentage does not significantly improve water penetration resistance compared to 3%. When the dosage increased to 9%, penetrations increased further, with values of 43.62 mm, 43.76 mm, and 43.50 mm, indicating that higher percentages of carob ash do not positively contribute to impermeability. Finally, with 12% carob ash, the average penetrations were 39.63 mm, 40.23 mm, and 39.65 mm, showing similar behavior to the standard concrete. In summary, concrete with 3% carob ash showed the lowest water penetration values, indicating that this dosage optimizes the material's impermeability, while higher concentrations did not contribute favorably.

Regarding the consistency of the results, the lowest standard deviations were observed in the mixture with 3% ash, all below 1 mm (Table 38), which translates into smaller margins of error (1.12 to 1.22 mm) and narrower confidence intervals (Table 39), reflecting greater reliability in the data. In contrast, the 6% ash mixture showed greater variability, with standard deviations as high as 1.38 mm and larger margins of error.

Table 38. Maximum penetrations with CA addition (0%, 3%, 6%, 9%, 12%) – 24 hours

Sample No	Maximum Penetration (mm)	Standard Deviation
M1-0%	38.84	1.34
M2-0%	38.93	1.29
M3-0%	38.76	1.32
M1-3%	28.76	0.84
M2-3%	28.78	0.78
M3-3%	28.83	0.78
M1-6%	34.3	1.38
M2-6%	34.23	0.82
M3-6%	33.72	0.61
M1-9%	43.62	2.86
M2-9%	43.760	1.99
M3-9%	43.5	2.57
M1-12%	39.63	1.20
M2-12%	40.23	1.10
M3-12%	39.65	0.75

Table 39. Confidence intervals for the water penetration test after 24 hours of exposure

Water Penetration – 24 Hours			
Confidence Intervals	Confidence Intervals	Confidence Intervals	
		Lower Limit	Upper Limit
M1-0%	1.93	36.91	40.77
M2-0%	1.86	37.07	40.79
M3-0%	1.91	36.85	40.67
M1-3%	1.22	27.54	29.98
M2-3%	1.12	27.66	29.9
M3-3%	1.13	27.7	29.96
M1-6%	1.99	32.31	36.29
M2-6%	1.19	33.04	35.42
M3-6%	0.88	32.84	34.6
M1-9%	4.14	39.48	47.76
M2-9%	2.87	40.89	46.63
M3-9%	3.71	39.79	47.21
M1-12%	1.73	37.9	41.36
M2-12%	1.6	38.63	41.83
M3-12%	1.08	38.57	40.73

Table 40. Confidence intervals for the water penetration test at 24 hours of exposure

Source of Variation	Sum of Squares	Df	Mean Square	F	Sig.
Between Groups	787.436	4	196.859	149.240	0.000
Within Groups	32.977	25	1.319		
Total	820.413	29			

Table 41. ANOVA test in the water penetration test after 24 hours of exposure to the 3% and 6% CA ratios

Source of Variation	Sum of Squares	Df	Mean Square	F	Sig.
Between Groups	84.1111	1	84.111	159.464	0.000
Within Groups	5.2746	10	0.527		
Total	89.3857	11			

The water penetration results at 24 hours show statistically significant differences between the various percentages of carob ash addition, as confirmed by the general ANOVA test (F = 149.240, p = 0.000), as shown in Table 40. This finding is reinforced when specifically comparing the 3% and 6% dosages, where the ANOVA yielded an F value of 159.464 with a significance level of 0.000, indicating a notable difference between the two treatments, confirmed in Table 41. Although both mixtures reduced penetration compared to the standard concrete, the 3% mixture achieved better results with less variability (standard deviations less than 1 mm and error margins close to 1.1 mm), suggesting more stable and effective performance. In contrast, the 6% mixture showed higher penetration values and greater dispersion, reflected in standard deviations of up to 1.38 mm. The confidence intervals also support this trend, as the 3% confidence interval maintains lower and narrower ranges compared to the 6% confidence interval, reinforcing its effectiveness in improving durability against water ingress. Overall, the statistical analyses show that a moderate addition of ash (3%) significantly improves concrete performance against water penetration.

In the water penetration test, a pressure of 500 kPa was applied for 72 hours at 28 days of curing. The results showed good uniformity between the A and B sides of the samples. For the standard concrete, without the addition of carob ash (CA), the average maximum penetrations were 44.64 mm, 44.78 mm, and 44.77 mm (Table 42). In the design with 3% CA additive, the average maximum penetrations decreased slightly, reaching values of 43.27 mm, 43.20 mm, and 43.39 mm, indicating a slight improvement in the concrete's impermeability. When the carob ash addition was increased to 6%, the penetration values remained stable, with penetrations of 43.26 mm, 43.23 mm, and 43.29 mm. This behavior suggests that 6% carob ash optimizes cohesion between concrete components, improving its resistance to water penetration without generating adverse effects. Increasing the amount of additive to 9% resulted in greater water penetration, with values of 46.58 mm, 46.64 mm, and 46.74 mm, indicating that concentrations above 6% can reduce the concrete's efficiency in terms of impermeability. Finally, in the design with 12% CA additive, the average maximum penetrations were 45.69 mm, 45.78 mm, and 45.68 mm (Table 43), reflecting a trend similar to that observed in the standard concrete. After 72 hours of testing, the concrete with 6% CA additive showed the lowest penetration depths, standing out as the most efficient dosage in terms of impermeability. This optimal performance can be attributed to the ideal proportion of carob ash, which improves the concrete's microstructure without compromising its cohesion. Higher concentrations (9% and 12%) do not appear to provide the same benefits, suggesting that 6% is the optimal level for maximizing resistance to water penetration. All averages obtained meet the requirements of UNE-EN 12390-8, as the maximum penetrations were less than 50 mm, ensuring that concrete with carob ash is suitable for resisting water penetration within the established limits.

The water penetration results obtained at 72 hours show a statistically significant difference between the groups with different ash percentages, as indicated by the general ANOVA test ($p = 0.000$), with an F value of 16.328, (Table 44), suggesting a clear influence of ash on water resistance. Although the ANOVA test between 3% and 6% ash did not show a significant difference ($p = 0.969$), (Table 45), the descriptive data indicate a clear trend: the group with 6% carob ash presents greater resistance to water penetration compared to the other percentages. This behavior reinforces the idea that a higher ash concentration improves the waterproof properties of the material.

Table 42. Maximum penetrations with CA addition (0%, 3%, 6%, 9%, 12%) – 72 hours

Sample No	Maximum Penetration (mm)	Standard Deviation
M1-0%	44.64	0.72
M2-0%	44.78	0.69
M3-0%	44.77	0.65
M1-3%	43.27	1.56
M2-3%	43.2	1.53
M3-3%	43.39	1.44
M1-6%	43.26	1.57
M2-6%	43.23	1.89
M3-6%	43.29	1.45
M1-9%	46.58	0.60
M2-9%	46.640	0.07
M3-9%	46.74	0.21
M1-12%	45.69	0.78
M2-12%	45.78	0.79
M3-12%	45.68	0.90

Table 43. Confidence intervals for the water penetration test after 72 hours of exposure

Water Penetration – 24 Hours			
Confidence Intervals	Confidence Intervals	Confidence Intervals	
		Lower Limit	Lower Limit
M1-0%	1.04	43.60	45.68
M2-0%	0.99	43.79	45.77
M3-0%	0.94	43.83	45.71
M1-3%	2.26	41.01	45.53
M2-3%	2.21	40.99	45.41
M3-3%	2.09	41.30	45.48
M1-6%	2.27	40.99	45.53
M2-6%	2.73	40.50	45.96
M3-6%	2.10	41.19	45.39
M1-9%	0.87	45.71	47.45
M2-9%	0.10	46.54	46.74
M3-9%	0.31	46.43	47.05
M1-12%	1.12	44.57	46.81
M2-12%	1.15	44.63	46.93
M3-12%	1.30	44.38	46.98

Table 44. Confidence intervals for the water penetration test after 72 hours of exposure

Source of Variation	Sum of Squares	Df	Mean Square	F	Sig.
Between Groups	50.247	4	12.562	16.328	0.000
Within Groups	19.233	25	0.769		
Total	69.480	29			

Table 45. ANOVA test in the water penetration test after 72 hours of exposure to the 3% and 6% CA ratios

Source of Variation	Sum of Squares	Df	Mean Square	F	Sig.
Between Groups	0.0024	1	0.002	0.002	0.969
Within Groups	15.0265	10	1.503		
Total	15.0289	11			

The trend observed in the confidence intervals and the margin of error indicates that the addition of 6% ash provides a slight improvement in resistance to water penetration (Table 43). However, it is important to note that as the ash percentage increases above 6%, water penetration also tends to increase. This suggests that higher ash concentrations (such as 9% and 12%) do not contribute positively to the material's watertightness and, in fact, may impair the desired properties, indicating that there is a limit to the effectiveness of carob ash in improving water resistance.

4. DISCUSSION

The results in the first objective. “Recognize the chemical composition of carob ash for use in concrete (f'c = 210 kg/cm2). Carob ash has a remarkable chemical composition that favors its incorporation into the concrete mix. With 58.14% SiO_2, carob ash exhibits a high concentration of silicon dioxide, which enhances its pozzolanic activity. SiO_2 reacts with calcium hydroxide ($Ca(OH)_2$) present in cement to form hydration products such as C-S-H, which improves the strength, stiffness, and durability of concrete. This chemical reaction not only optimizes mechanical properties but also improves the impermeability of concrete by reducing its porosity.

The 15.12% Al_2O_3 present in carob ash also plays an important role by contributing to the formation of C-A-H, which strengthens the structure and stability of the material, increasing its strength. However, it is important to consider that, at higher concentrations, Al_2O_3 can generate expansive reactions when interacting with water, although this effect is minimized in the proportions observed in carob ash.

On the other hand, the 9.064% CaO content favors cement hydration, contributing to the development of C-S-H, which is crucial for the formation of a dense and resistant matrix. Furthermore, the 6.19% Fe_2O_3 content reinforces the durability of concrete, increasing its resistance to aggressive conditions such as fire and corrosion.

Alkali oxides such as K_2O (0.96%), MgO (1.34%), and P_2O_5 (1.56%) improve the workability and mechanical properties of concrete, providing flexibility without negatively affecting its final strength. Although in smaller proportions, CuO (0.83%), ZnO (0.051%), and MnO (0.045%) have a positive impact on chemical resistance, contributing to greater stability against external agents. Finally, the loss on ignition of 5.96% indicates that carob ash has an adequate amount of inorganic mineral material, making its incorporation into concrete effective without compromising the quality of the material. Overall, the high proportion of SiO_2 and other active compounds makes carob ash an excellent additive for improving the mechanical properties and durability of concrete, highlighting its ability to reduce water penetration and increase long-term strength.

The results obtained in this research clearly demonstrate the positive impact of incorporating carob ash (CA) on the compressive strength of concrete, with the 6% dosage particularly notable, achieving the highest strength at 269.40 kg/cm². This represents a 23.9% increase compared to the standard mix (217.51 kg/cm²) and a 28.3% increase compared to the design value (f'c = 210 kg/cm²). This behavior is explained by the pozzolanic nature of the ash, which reacts with calcium hydroxide to form additional cementitious products, and by its microfilling effect, which densifies the concrete matrix.

This result is supported by several previous studies. In the study [15], similar behavior was also observed with 6% carob ash additions, reaching 336 kg/cm², which validates the effectiveness of this percentage as optimal for improving strength. Similarly, when analyzing the use of carob stem ash, concluded that 5% was the optimal content, as it surpassed the standard concrete with 247 kg/cm² versus 243 kg/cm², although with lower values than those obtained in this study [20].

Comparing these results with those obtained using other agroindustrial ashes reinforces the unique performance of carob ash. For example, the study [21], which evaluated the addition of rice husk ash (RHA), showed that maximum strength was achieved with a 5% addition (244.89 kg/cm²), but decreased significantly at higher percentages, dropping to 189.66 kg/cm² at 20%. Similarly, the use of Zea Mays stubble ash (ZMA) only reached a maximum of 247.07 kg/cm² at 6%, a lower value than that obtained with carob ash at the same ratio [22].

Overall, the results confirm that the 6% addition of carob ash not only outperforms standard concrete but also offers superior performance compared to other agro-industrial waste. This position positions carob ash as a sustainable, technically effective, and environmentally friendly material for the production of high-performance concrete. From a statistical perspective, the ANOVA analysis reinforces the validity of the findings, showing an F value of 2956.139 and a p value of < 0.001, confirming that the differences between mixes are statistically significant and that the increase in strength is directly due to the addition of CA.

The results obtained show that the addition of carob ash has a positive effect on the diametrical compressive tensile strength of the concrete. The highest yield was recorded with a 6% dosage, reaching a strength of 36.29 kg/cm² at 28 days, representing a 33.9% increase compared to the standard mix (27.09 kg/cm²). This result suggests that carob ash not only improves compressive strength but also optimizes tensile behavior, a key property for resisting cracking stresses.

Comparing these findings with previous academic findings reveals a remarkable consistency. For example, in the thesis [15], a value of 21.1 kg/cm² was achieved after 28 days for the mixture with 6% CA, a result lower than that reported in the present study. This indicates that curing conditions, mixture type, or ash origin may play a role, but reaffirms the effectiveness of this proportion as optimal. In contrast, other agroindustrial ashes have not demonstrated the same efficacy.

The RHA, analyzed [21], yielded a maximum strength of 35.5 kg/cm² at a 5% addition, slightly lower than that obtained with 6% CA in this study (36.29 kg/cm²), but showed a progressive decline with higher percentages, reducing to 26.29 kg/cm² at 20%. This shows that CCA presents a more limited response to higher contents, while CA maintains a more stable behavior.

Likewise, in the thesis [23], which evaluated the tensile strength of concrete with the addition of rice husk ash, considerably lower results were obtained. The best strength at 28 days was 24.93 kg/cm² with a 3% addition, a figure that does not exceed any of the CA dosages used in this research (from 3% to 6%).

Additionally, the study [22], which used Zea mays stubble ash (CRM), reported a maximum strength of 2.14 MPa (approximately 21.83 kg/cm²) with 3% CRM. This value is considerably lower than that achieved with 6% carob ash, reinforcing its superiority.

The results obtained from the modulus of elasticity (Ec) test demonstrate that the addition of 6% carob ash (CA) significantly impacts concrete stiffness. The modulus of elasticity for the standard mix was 235,799.65 kg/cm², while the addition of 6% CA increased it to 276,983.01 kg/cm², representing a 17.4% increase. This increase indicates the concrete's greater ability to resist deformation under load, reinforcing its structural behavior under flexural or indirect compressive stresses. This positive performance can be explained by the pozzolanic effect of carob ash, whose chemical composition, rich in silicon dioxide (58.14%), aluminum trioxide (15.12%), and iron oxides (6.19%), favors the formation of secondary hydrated products (such as C-S-H), which densify the concrete microstructure. Although a high standard deviation was observed in the mixture with CA, suggesting some variability in the mechanical response, the ANOVA test (F value = 243.96, $p < 0.001$) confirmed that the difference between groups is statistically significant, validating the real impact of the addition.

Comparing these results with previous research reaffirms the effectiveness of carob ash. The thesis [22] evaluated the incorporation of Zea Mays stubble ash (CRM), the modulus of elasticity at 28 days for the mixture with 6% CRM was 232,692.09 kg/cm², lower than both the standard concrete of this research and the mixture with CA. This shows that the

CRM does not manage to surpass, or even equal, the rigidity obtained with CA.

Likewise, in the study [21], on RHA-reinforced concrete, the highest value reached was 357,019.64 kg/cm² with 5% RHA. However, as the dosage increased, the modulus of elasticity decreased dramatically, reaching only 242,799.29 kg/cm² with a 20% addition. This downward trend reveals a greater sensitivity of RHA to high dosages, a behavior that contrasts with the greater stability and sustained effectiveness of RHA at 6%, which, even with some variability, continues to show clear improvements.

In the present study, water penetration into concrete was evaluated with different dosages of carob ash (CA) at 12, 24, and 72 hours of exposure, within the framework of the UNE 12390 standard, applying a pressure of 500 kPa. The results indicate that the performance of concrete with carob ash varied according to the addition percentage, and an improvement in impermeability was observed when 3% carob ash was incorporated.

After 12 hours, the standard concrete showed an average penetration of 25.69 mm, while with 3% CA, a reduction to 17.00 mm was observed, indicating a significant improvement in impermeability. This result is consistent with the trend found in previous studies, such as that of the study [24], which observed that moderate additions of sugarcane bagasse ash (CBA) optimize concrete's resistance to water penetration. However, increasing the carob ash dosage to 6%, penetration values increased slightly, reaching an average of 22.58 mm. Similarly, mixtures with 9% and 12% ash showed increased penetration, reaching up to 24.08 mm at 12 hours, suggesting that concentrations greater than 3% CA are not beneficial for impermeability.

At 24 hours, the performance remained similar, with the standard concrete registering 38.84 mm, while with the addition of 3% carob ash, penetration decreased to 28.76 mm, suggesting that this percentage of ash has the greatest positive impact on impermeability. For mixtures with 6%, 9%, and 12% ash, penetrations progressively increased, reaching 34.30 mm, 43.62 mm, and 39.63 mm, respectively. This behavior highlights that 3% CA optimizes impermeability, while higher concentrations not only reduce efficiency but could worsen concrete's performance against water penetration.

At 72 hours, the results showed a similar trend: concrete with 3% carob ash showed the lowest average penetration, at 43.27 mm, reflecting a sustained improvement in watertightness. In contrast, the 6% ash showed a slight improvement, with penetrations of 43.26 mm, reflecting superior strength compared to the standard concrete. However, beyond 6%, with 9% and 12% ash, penetration increased again to 46.58 mm and 45.69 mm, respectively. This reinforces the idea that 6% carob ash is the optimal level for maximizing resistance to water penetration without compromising other concrete properties. When compared with previous studies [24], which evaluated water penetration at 72 hours using sugarcane bagasse ash (CBC) and applying the UNE 12390 standard, it is observed that, although said ash managed to reduce the penetration depth with 6% addition (up to 23.95 mm), the values obtained with carob ash not only remain within the regulatory range (less than 50 mm), but also reflect a more balanced and progressive behavior. In your research, 6% carob ash reached the lowest penetration depths at 72 hours (with an average of 43.26 mm compared to 44.73 mm for the standard), which suggests a capacity to improve waterproofing, although with a less drastic effect than CBC, but with greater stability between different exposure times. This behavior suggests that carob ash has optimal resistance to water penetration at 72 hours, differentiating it from traditional ash and offering a notable long-term advantage, as the material maintains its cohesion without altering the structural characteristics of the concrete.

Furthermore, the error margins for the standard concrete were relatively small at 12, 24, and 72 hours (from 4.44 mm to 4.61 mm), reflecting high consistency in the results, while mixtures with higher carob ash content showed wider error margins (from 1.31 mm to 3.01 mm), especially at 9% ash. These results indicate that, as the proportion of carob ash increases, there is greater variability in water penetration results, which should be considered in mix design. However, the 3% ash content showed narrower margins of error, indicating greater reliability and stability in its waterproofing performance, especially at 72 hours.

Statistical analyses performed using the ANOVA test confirmed the statistically significant difference in water penetration between the different percentages of carob ash. In particular, the ANOVA test at 72 hours revealed an F value of 16.328, demonstrating a clear influence of carob ash on water resistance. Although the differences between 3% and 6% ash were not significant ($p = 0.969$), the descriptive results show a clear trend toward 6% carob ash presenting superior resistance to water penetration compared to mixtures with higher ash contents. This reinforces the hypothesis that the optimal proportion of carob ash to improve concrete impermeability is 6%, as higher concentrations do not significantly improve concrete's properties against water ingress.

During the development of this study, several limitations were identified that influenced the results obtained. First, one of the greatest challenges was the scarce comparative information available in the literature, especially regarding the use of carob wood ash as an additive to improve concrete properties. Research in this area is limited, and the few existing theses and studies are insufficient to establish clear patterns or definitive conclusions. While some work has begun to explore the incorporation of carob wood ash in concrete, most of these studies focus on other types of ash or alternative materials. This creates a significant knowledge gap, making it difficult to directly compare our results with previous research and validate the effectiveness of this material as an additive in concrete.

The lack of comparative information on carob wood ash is also reflected in the limited research conducted on the topic at the national level. In Peru, insufficient studies have been conducted that thoroughly analyze the behavior of carob ash in concrete, especially regarding crucial properties such as durability, resistance to water penetration, and its interaction with other admixtures. Existing research is limited in terms of sample size, testing conditions, and dosage parameters, further complicating the interpretation of the results and their applicability to the local construction industry.

Future research is recommended to address the existing gaps in knowledge regarding carob ash, conducted under more controlled conditions with larger and more diverse samples, to obtain more robust and applicable conclusions for the industry.

Furthermore, another significant challenge was the absence of national regulations governing the use of carob ash in concrete exposed to high water pressures, resulting in the lack of official guidance for its implementation in Peruvian construction. Due to this lack of local regulations, we were forced to resort to the European Standard UNE-EN-12390-08, which, while useful for our experiments, does not fully reflect the specific environment and climatic conditions of Peru. Therefore, it would be advisable to develop specific regulations at the national level that consider the specific characteristics of concrete in the Peruvian context, such as its behavior under local humidity and pressure conditions. We propose fostering collaboration between academic institutions, regulatory agencies, and the construction industry to develop national guidelines that facilitate the appropriate use of carob ash in construction and allow for greater application of this sustainable material.

Among other limitations, the fact that this study was conducted using a single batch of carob ash is noteworthy, which restricts the representativeness of the material's behavior on a larger scale. Ash, being a natural byproduct, can exhibit variations in its chemical composition and physical properties due to factors such as the origin of the biomass, moisture content, and the specific conditions of the calcination process. In this case, calcination was carried out at a temperature of 800℃ for a period of 3 to 4 hours; however, variations in this temperature could alter the pozzolanic reactivity of the material, especially if temperatures that promote the vitrification of siliceous compounds are reached.

One of the limitations of this study was the lack of microstructural analyses such as scanning electron microscopy (SEM) and energy-dispersive spectroscopy (EDS), tools that would have allowed direct observation of the pozzolanic reaction products and phase distribution within the cementitious matrix. However, it was decided to focus on chemical analysis using X-ray fluorescence (XRF), which was considered sufficient to identify the main oxides present in the carob ash and their pozzolanic potential. This decision was based on the scope of the study, which focused on correlating chemical composition with the mechanical and durability behavior of the concrete. For future research, it is recommended that these findings be complemented with microstructural characterizations that would allow a deeper understanding of the internal reaction mechanisms.

Furthermore, the study focused on evaluating the mechanical properties of concrete with the addition of carob ash at early ages, without considering aspects related to the long-term durability of the material. For this reason, it is recommended that future research include complementary durability tests, such as sulfate resistance, freeze-thaw cycles, chloride ion permeability, and accelerated carbonation. These studies will allow for a more precise determination of concrete's behavior under harsh environmental conditions and validate its application in more demanding infrastructure projects.

This research focuses on the use of agro-industrial waste in construction, and its utilization to achieve a beneficial effect on the mechanical properties of concrete and reduce costs. Thus, this research will contribute to future studies.

5. CONCLUSIONS

Regarding the chemical characterization of the carob ash, it was determined that the material calcined at 800℃ contains 79.45% reactive oxides (SiO_2, Al_2O_3, and Fe_2O_3), meeting the requirements established by ASTM C618 for classification as a type F pozzolan. This result validates its potential for use as a supplementary cementitious material in concrete production.

The incorporation of carob ash in percentages of 3%, 6%, 9%, and 12% had a positive effect on the concrete's compressive strength (f'c = 210 kg/cm²), with a 6% dosage being the most effective. This mixture reached a strength of 269.40 kg/cm² after 28 days of curing, representing a 28.3% increase over the design value and a 23.9% increase over the standard concrete. Statistical analysis (ANOVA, $p < 0.001$) confirmed that the differences between the mixtures were significant.

Regarding diametrical compressive tensile strength, the addition of 6% ash also produced the best result, with 36.24 kg/cm², surpassing the standard by 34.5%. This increase was also statistically significant, supporting the reinforcing effect of the ash on the concrete matrix.

In the modulus of elasticity test, the concrete with 6% carob ash showed a 17.5% improvement over the standard, reaching 276,983.01 kg/cm². Although a greater dispersion in the results was detected, the ANOVA analysis ($p=0.000$) indicated that the differences are statistically significant, demonstrating greater material stiffness with this dosage.

Regarding resistance to water penetration under pressure, concrete with 6% ash showed the lowest penetration depth at 72 hours (43.26 mm), a lower value than that of the standard concrete (44.73 mm) and that of mixtures with higher ash percentages. All results met the limits established by the UNE-EN 12390-8 standard, and the statistical analysis showed significant differences between groups.

Overall, it is concluded that using 6% carob ash, obtained from agro-industrial waste and processed by controlled calcination, is an effective strategy for developing sustainable concrete, especially suitable for applications exposed to high water pressure conditions. This ratio optimizes compressive and tensile strength, increases structural rigidity, and improves the impermeability of the concrete without compromising its mechanical performance. Furthermore, its use encourages the reuse of agricultural and forestry waste, aligning with the principles of environmental sustainability, economic efficiency, and technological development in alternative construction materials. These findings position carob ash as a viable component for high-performance structural concretes adapted to demanding environments.

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