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Influence on Physical and Mechanical Properties of Concrete Using Crushed Hazelnut Shell

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Abstract: Concrete production requires a significant amount of natural resources, with aggregates comprising between 55% and 80% of the total volume. However, the over-exploitation of natural aggregates has led to the exploration of alternative materials for use in concrete production. In this study, crushed hazelnut shells were investigated as a partial replacement for fine aggregate, addressing the problem of natural resource depletion and offering a second use for this important agricultural waste product available in Chile. Hazelnut shells were incorporated in percentages of 2.5%, 5%, and 10% by weight of sand for water/cement ratios of 0.4 and 0.5. The compressive strength at 7 and 28 days and bending strength at 28 days were determined, alongside physical properties such as the workability, temperature, air content, fresh density, and hardened density of the concrete. Our findings showed that replacing 2.5% of the fine aggregate with hazelnut shells led to a higher compressive strength at 28 days, exceeding the strength of the standard specimens by 9.5%, whereas replacing 5% of the fine aggregate led to the highest bending strength, exceeding the strength of the standard specimens by 3.5%. Moreover, the 0.4 w/c ratio consistently led to better results for both compressive and bending strength, with fewer and lower reductions in mechanical strength compared to the standard mixture. Our results suggest that concrete mixes with hazelnut shells as a replacement for fine aggregate at a percentage of up to 2.5% can be used in construction systems with a compression strength lower than 17 MPa, and mixtures with up to 10% hazelnut shell replacement can be used in structures with tensile bending stress requirements lower than 6 MPa. Overall, the use of hazelnut shells as a partial replacement for fine aggregate in concrete production presents an environmentally friendly and cost-effective solution for the construction industry.

Keywords: concrete production; natural aggregates; alternative materials; hazelnut shells; concrete strength; sustainable construction

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1. Introduction

Concrete is perhaps the most used construction material in history. Worldwide, more than 10 billion tons of this material are produced each year. A few reasons for this popularity are its excellent mechanical strength under compression, durability, ability to be molded into almost any shape, relative fire strength, and ability to satisfy almost any reasonable set of performance specifications [1]. In Chile, concrete is the predominant material used for building construction due to its capacity to withstand severe seismic loading conditions without reaching failure states or collapse, a critical aspect for countries prone to earthquakes. However, the concrete construction industry faces sustainability challenges. Firstly, it consumes significant amounts of virgin materials, which contributes to natural resource depletion. Secondly, the primary binder in concrete is Portland cement, which is responsible for significant greenhouse gas emissions, implicated in global warming and climate change. Finally, the lack of durability of many concrete structures negatively impacts the resource productivity of the industry [2]. These issues pose a challenge to the long-term sustainability of the construction industry and require urgent attention.

To produce concrete, various proportions of cement, coarse and fine aggregates, and water are mixed together to obtain a fresh paste that sets with time. Each individual component plays fundamental roles in the final mechanical strength of concrete. In particular, aggregates are used as a low-cost inert filler, being a main component in the mix since they occupy between 55% and 80% of the total volume of the concrete [3]. Therefore, this material is responsible for the unit weight, elastic modulus, and dimensional stability of the concrete. Because of the over-exploitation of aggregates, warnings have been issued in the past that if alternatives are not sought for aggregate use, the concrete industry will annually consume between 8 and 12 billion tons of natural aggregates. For this reason, the use of recycled aggregates or their substitution is targeted [3,4]. Several authors have investigated concrete strength when the sand content is partially replaced. For instance, recycled glass, plastic, copper slag, and rubber have been used as sand replacements [1,5]. Other researchers have studied recycled concrete in the form of both fine- and coarse-aggregate replacement in high-strength concrete [3]. At the same time, the use of organic materials in the manufacture of concrete has been evaluated in the form of reinforcement with vegetable fibers. Concrete is inherently weak in terms of tension, and the addition of natural fibers can effectively mitigate the formation and propagation of cracks. Furthermore, the incorporation of natural fibers can enhance the durability and resistance of concrete to environmental conditions [6,7]. For instance, sisal fibers have been studied for use in fiber-reinforced concrete. These fibers exhibit a higher water absorption capacity compared to polypropylene fibers. This characteristic may result in the development of microcracks and a decrease in strength in the region where the cement slurry comes into contact with sisal fibers. Additionally, when incorporating sisal fibers into concrete, the fluidity of the mixture is reduced due to the larger surface area of the fibers, which absorb water from the concrete during wetting [8,9]. Coconut fibers have been investigated by a number of researchers. Ramli et al. [10] performed an experimental study applied to marine structures, which are subjected to harsh environments caused by ocean waves and endure demanding tasks such as handling heavy loads during shipments and withstanding significant seismic forces. Ahmad et al. [11] studied different coir contents to asses concrete permeability and carbonation. The studies revealed that as the coir percentage increased, the concrete became more porous, leading to a significant increase in permeability. Additionally, in fiber-reinforced mixes, the interfacial transit zones between the fibers and cement paste were found to contribute to the elevated permeability and carbonation rate. Shukla et al. [12] presented a review article to summarize strategies of utilizing rice straw in fiber or ash form to manufacture construction materials. The components manufactured from rice straw or rice straw ash can be used for façades, envelopes, composite bricks, backfills, mortar, rigid pavements, and hard wood composites. Paddy straw fibers, a locally available agricultural waste material, pose significant environmental hazards due to disposal issues and pollution caused by burning. This study focused on exploring the potential of using paddy straw fibers as a partial replacement for fine aggregates in concrete. Various mixes with different aspect ratios and replacement rates of paddy straw fibers were experimentally investigated by Sharma and Singh [13]. The mechanical properties, including compressive strength and split tensile strength, were analyzed for the different concrete mixes. The results indicated that the concrete achieved its highest compressive and split tensile strengths when 1% paddy straw fiber replacement was used, and these strengths decreased with a higher fiber content. In summary, these studies suggest the potential for using organic material in concrete mixes to improve its mechanical properties under specific conditions or its physical and thermal characteristics.

Chemical analysis, scanning electron microscopy, organic matter content determination, and pozzolanic analysis are crucial for characterizing a material, determining if it reacts chemically with calcium hydroxide to produce cementitious compounds, and revealing how this process takes place during hydration. Such studies can effectively provide relevant information regarding components, and they are widely used when the cementitious material is replaced by an alternative solution [14–16]. For instance, Xu et al. [17] provided a comprehensive review of the application of sugar cane bagasse ash as a construction material. This material has pozzolanic characteristics, which can enhance both fresh and hardened concrete properties. Important factors affecting pozzolanic activity, such as the calcination and recalcination temperature and duration, fineness, loss on ignition (LOI), and crystal silicon dioxide, were discussed in detail. The paper concluded by recommending further research to optimize and broaden the utilization of sugar cane bagasse in construction materials.

Organic material burned until ash is obtained has also been used as a partial replacement for cement due to the pozzolanic characteristics of the ash powder. For instance, the effect of maize cob ash as a supplementary cementitious material on the mechanical properties of concrete was studied in [18,19]. Generally, it can be concluded that maize cob ash can be used as a partial replacement for cement in concrete. Sugarcane bagasse ash has been studied as a replacement for sand content, producing mortars with better mechanical results than the reference samples [20–22]. Hazelnut shell ash was studied in [23,24] to quantify the pozzolanic reaction when cement was replaced. The assessment of incorporating hazelnut shell in the manufacturing processes of cement and concrete holds potential for advancing the sustainability objectives of the cement industry while concurrently addressing the issue of waste accumulation from the hazelnut processing sector.

In order to find alternative materials that could partially replace fine aggregates without significantly compromising the properties of concrete, great efforts have been put into the study and characterization of waste organic materials. One such material is crushed hazelnut shell (herein referred as HS), an agricultural waste that is generated in large quantities. In Chile, it is estimated that by the year 2030 there will be 60,000 ha planted, with a production scale in the order of 88,000 tons. More than 50% of the weight of a hazelnut corresponds only to the shell, which makes it an important waste or by-product of this industry [25]. Nowadays, this waste material is used only as fuel, and the remainder is disposed. Hazelnut shells can be considered as a candidate for partially replacing traditional fine aggregates in construction materials. The suitability of hazelnut shells as a substitute for fine aggregates can be attributed to several factors. This organic material is readily available in large quantities, primarily as a by-product of the hazelnut industry. This makes it a sustainable option for construction materials, especially in regions with significant hazelnut production. Also, hazelnut shells are rich in lignocellulosic materials, which are complex structural components found in plant cell walls. This composition includes cellulose, hemicellulose, and lignin. Utilizing hazelnut shells in construction would reduce waste in the hazelnut industry, as more than 50% of the weight of a hazelnut consists in its shell. This sustainable approach aligns with efforts to reduce waste and promote environmental responsibility. Nevertheless, this material's successful integration into concrete mixes requires further investigation, including the optimization of processing techniques and the evaluation of its micromechanical properties.

The long-term effects of substituting organic materials for fine aggregates in concrete have been studied and offer various advantages. Research has shown that the application of organic materials in concrete can enhance its physical and thermal properties, leading to the improved long-term performance of the concrete [26,27]. Furthermore, the use of organic materials as a substitute for fine aggregates in concrete can contribute to sustainable concrete development. By utilizing industrial and organic wastes such as rubber tires, crushed glass pieces, and groundnut shells, it is possible to not only reduce the environmental impact and waste generation, but also improve the mechanical and durability properties of the concrete. One type of organic material commonly used in concrete is nanosilica-like organics derived from agro-waste. This material serves as a substitute for fine aggregate and provides a supplementary pozzolanic property in the production of concrete. Moreover, the use of these materials can improve the resistance of concrete to chemical attack and increase its durability over the long term. Another long-term effect of substituting organic materials for fine aggregates in concrete is the potential reduction in overall production costs [28]. Using alternative green materials as a replacement for natural fine aggregates significantly lowers the cost of concrete production. This is because organic materials often come from waste sources, which are typically free or cheaper compared to the extraction and transportation of natural fine aggregates. Additionally, substituting organic materials for fine aggregates can also have positive environmental implications. It can reduce the need for landfill sites for waste disposal and promote the efficient use of resources [29].

Overall, concrete is by far the most frequently used construction material in the building sector [30]. In the production process, this material uses a large volume of fine aggregates. Thus, the main novelty of the present work was the investigation of the performance of concrete in which this fine aggregate was replaced by an environmentally friendly alternative material. That is, a non-renewable material resource was replaced by crushed hazelnut shell, a secondary industrial waste from agricultural production. The impact of this solution is that it could considerably reduce the use of fine aggregate in the concrete matrix (i.e., reducing the amount of sand needed) via the use of crushed hazelnut shell. In this investigation, crushed hazelnut shell was used as a partial substitute for fine aggregates in percentages of 2.5%, 5%, and 10% by weight of sand to determine the physical and mechanical properties of concrete specimens according to ASTM standards. In addition, a statistical study was performed to correlate the mechanical response of the concrete cylinders with their physical properties. The aim was to determine the optimum percentage of HS replacement in concrete that would not compromise its strength. The results of this study could contribute to the development of sustainable concrete mixtures and reduce the environmental impact of the construction industry.

2. Materials and Methods

2.1. Cement

Concrete mixtures were designed using a commercially available pozzolanic cement. This cement was specially formulated for producing concrete that requires a high initial level of the specified strength at 28 days. The specification of this material is type IP (pozzolanic Portland cement) based on the ASTM C595 standard [31].

2.2. Additives

Sika ViscoCrete-6000 is used as hyperplasticizer addition to the concrete mix. This product is an aqueous chemical solution that reduces the water content in the production of concrete without negatively affecting the workability, but improving the performance of the hardening fresh paste [32]. A dose of 0.35% of the cement weight was carefully diluted in 20 milliliters of tap water and poured into the fresh concrete during mixing. The intention here was to disperse both the HS and cement particles more effectively, allowing them to hydrate more completely and form stronger bonds.

2.3. Aggregates

Fine and coarse aggregates (gravel of maximum nominal size 12.5 mm) were used for the concrete mix in a 2.5:3 proportion. Sieve analysis was performed for the grading of both aggregates, as shown in Table 1 and according to the ASTM C136-06 standard [33]. The combined aggregate was adjusted to the curves specified in the ASTM C33/C33M-18 standard [34] for aggregates with a maximum nominal size of 19 mm, as presented in Figure 1. The curve of the combined aggregate fell between the lower curve, corresponding to more granular concrete mixtures, and the upper curve, corresponding to more docile concrete mixtures. In this investigation, the experimental curve represented a balanced amount of both fine and coarse aggregate [35].

Table 1. Fine and coarse aggregate sieve test results.

Sieve Testing Results		
	Fine Aggregate	**Coarse Aggregate**
Sieve mm	**Passing Percentage (%)**	**Passing Percentage (%)**
25	100	100
19	100	94
12.5	100	48
9.5	100	23
4.75	99	1
2.36	74	0
1.18	50	0
0.6	34	0
0.3	19	0
0.15	7	0

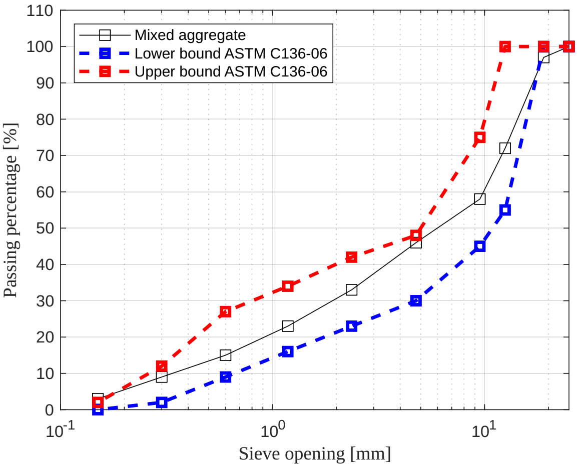

Figure 1. Sieve test results and comparison with curves of combined aggregate according to ASTM C33/C33M-18 standard [34].

2.4. Crushed Hazelnut Shell

Hazelnut shells were collected in clean bags directly from the industrial cellar to avoid contamination and to keep the product dry from exterior humidity.

2.5. Test Methodology

In this experimental study, a comprehensive investigation was conducted to examine the mechanical properties of concrete mixtures with different w/c ratios and varying percentages of crushed hazelnut shell. The specimens were categorized into two main groups based on the w/c ratio: one group with a w/c ratio of 0.4, and another with a w/c ratio of 0.5. Within each w/c ratio group, four different percentages of crushed HS were included in the concrete mixtures: 0%, 2.5%, 5%, and 10% by weight of sand. To ensure accurate and reliable results, three samples were prepared for each mixture combination.

2.5.1. Crushing Method for Hazelnut Shell

Once in the laboratory, the shells were crushed using a hand-made device consisting of an aluminum pot and an angle grinder with steel blades. Figure 2 shows the crushed hazelnut shell powder in standard brass sieves. The process to obtain different grain sizes was performed at 1100 rpm. After grinding, the material was dried in a temperature-controlled oven for 72 h at 60 °C and then sieve-sized to evaluate its similarity with the fine aggregate by comparing it with the specifications in the ASTM C33/C33M-18 standard [34].

In Figure 3 a comparison between the sieve tests performed on three samples of crushed hazelnut shell and the limits for a normal or medium-sized sand are presented. The aim was to show in a illustrative manner where the sieve test results for the HS fell in comparison with the standardized band defined for fine aggregates according to ASTM C136-06 [33]. The graph indicates that greater particle sizes were obtained from the grinding process, resulting in lower passing percentages.

Figure 2. Crushed hazelnut shell powder in standard brass sieves.

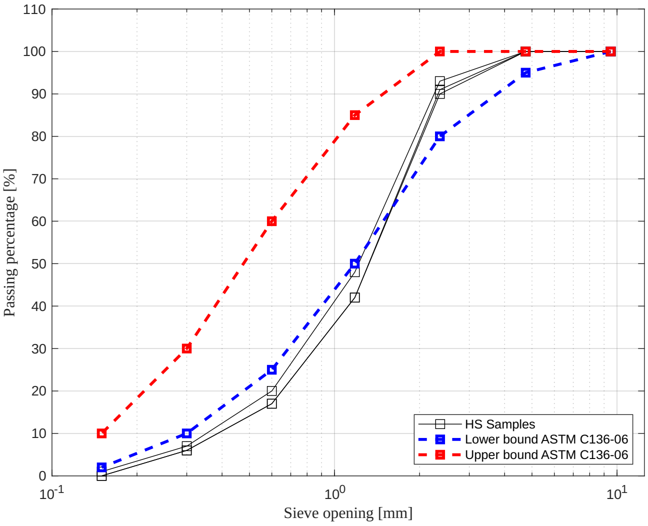

Figure 3. Sieve test results for HS and comparison with granulometric types of fine aggregate.

2.5.2. Concrete Sample Preparation

A total of 72 specimens were cast to evaluate the compressive strength at 7 and 28 days and the bending strength at 28 days, as shown in Table 2. The materials were sequentially added into a mechanical mixer in a specific order. Firstly, half of the water was added to the gravel and sand and mixed for 30 s until a uniform mixture was obtained. Then, the cement was added and mixed for a duration of one minute. Subsequently, the remaining water was added, and the mixture was mixed again for one minute. Lastly, the additive was introduced and mixed for a duration of three minutes. In samples using crushed HS, the material was pre-mixed with the fine aggregate prior to being added to the mixer.

To prepare the samples, a total of six cylindrical molds with a diameter of 10 cm and a height of 20 cm were used for each mixture, along with three prismatic molds measuring 10 cm in height, 10 cm in width, and 40 cm in length [36]. The cylindrical molds were filled in two layers, while the prism molds were filled in one layer and were compacted either manually or mechanically, depending on the docility obtained from the slump test. For manual compaction, a standardized rod was used to tamp the concrete cylinder 25 times per layer until it was completely filled with fresh paste, while for mechanical compaction, internal vibration was used. After compacting the samples, 10–15 strikes of a mallet were applied to eliminate gaps resulting from the chosen method. The setting time for the cylindrical specimens was 20 ± 4 h, while for prism specimens, it was set to 44 h for added safety before demolding, as per the ASTM C192 [37] standard.

Table 2. Specimen nomenclature utilized in the experimental procedure.

Mixture	w/c	HS (%)	Specimen Nomenclature: Compressive Strength at 7 Days	Specimen Nomenclature: Compressive Strength at 28 Days	Specimen Nomenclature: Bending Strength at 28 Days
M-0.4-0	0.4	0	M-0.4-0-C-7-A M-0.4-0-C-7-B M-0.4-0-C-7-C	M-0.4-0-C-28-A M-0.4-0-C-28-B M-0.4-0-C-28-C	M-0.4-0-T-28-A M-0.4-0-T-28-B M-0.4-0-T-28-C
M-0.4-2.5	0.4	2.5	M-0.4-2.5-C-7-A M-0.4-2.5-C-7-B M-0.4-2.5-C-7-C	M-0.4-2.5-C-28-A M-0.4-2.5-C-28-B M-0.4-2.5-C-28-C	M-0.4-2.5-T-28-A M-0.4-2.5-T-28-B M-0.4-2.5-T-28-C
M-0.4-5	0.4	5	M-0.4-5-C-7-A M-0.4-5-C-7-B M-0.4-5-C-7-C	M-0.4-5-C-28-A M-0.4-5-C-28-B M-0.4-5-C-28-C	M-0.4-5-T-28-A M-0.4-5-T-28-B M-0.4-5-T-28-C
M-0.4-10	0.4	10	M-0.4-10-C-7-A M-0.4-10-C-7-B M-0.4-10-C-7-C	M-0.4-10-C-28-A M-0.4-10-C-28-B M-0.4-10-C-28-C	M-0.4-10-T-28-A M-0.4-10-T-28-B M-0.4-10-T-28-C
M-0.5-0	0.5	0	M-0.5-0-C-7-A M-0.5-0-C-7-B M-0.5-0-C-7-C	M-0.5-0-C-28-A M-0.5-0-C-28-B M-0.5-0-C-28-C	M-0.5-0-T-28-A M-0.5-0-T-28-B M-0.5-0-T-28-C
M-0.5-2.5	0.5	2.5	M-0.5-2.5-C-7-A M-0.5-2.5-C-7-B M-0.5-2.5-C-7-C	M-0.5-2.5-C-28-A M-0.5-2.5-C-28-B M-0.5-2.5-C-28-C	M-0.5-2.5-T-28-A M-0.5-2.5-T-28-B M-0.5-2.5-T-28-C
M-0.5-5	0.5	5	M-0.5-5-C-7-A M-0.5-5-C-7-B M-0.5-5-C-7-C	M-0.5-5-C-28-A M-0.5-5-C-28-B M-0.5-5-C-28-C	M-0.5-5-T-28-A M-0.5-5-T-28-B M-0.5-5-T-28-C
M-0.5-10	0.5	10	M-0.5-10-C-7-A M-0.5-10-C-7-B M-0.5-10-C-7-C	M-0.5-10-C-28-A M-0.5-10-C-28-B M-0.5-10-C-28-C	M-0.5-10-T-28-A M-0.5-10-T-28-B M-0.5-10-T-28-C

2.5.3. Compressive Strength

The compressive strength of the concrete samples was determined to assess the mechanical performance of the mixtures. This assessment was conducted at two specific time points, 7 and 28 days, which are common intervals for evaluating the development of concrete strength. The testing procedure followed the guidelines outlined in ASTM C39 [38]. Cylindrical specimens with a standard diameter of 100 mm and a height-to-diameter ratio of approximately 2:1 were prepared from each concrete mixture. These dimensions conformed to the ASTM C39 requirements for cylindrical specimens. Then, fresh concrete was placed into cylindrical molds in layers, and each layer was compacted using a mechanical tamper to ensure proper consolidation and the elimination of air voids. After casting, the specimens were covered with a plastic sheet to prevent moisture loss and maintain a suitable curing environment. The curing conditions were controlled to meet the ASTM recommendations.

A Tecnotest hydraulic press (model KE 300/A, serial number 2907) manufactured in Modena, Italy, with a maximum compression capacity of 3000 kN, 100 kN in flexion, and equipped with a loading system capable of applying a step load, was employed for conducting the compressive strength tests. During the testing process, a step load was applied to the cylindrical specimens at a constant rate. The rate of loading was set at

0.25 MPa/s to maintain a consistent testing procedure (refer to Figure 4a). This loading rate was in accordance with ASTM C39 and allowed for the gradual application of pressure.

Each cylindrical specimen was placed between the platens of the hydraulic press, ensuring that the load was evenly distributed over the entire surface of the specimen. This prevented any localized stress concentrations that could affect the results. As the hydraulic press applied the step load, the corresponding compressive forces and deformation were continuously monitored and recorded throughout the testing duration. Three specimens from each concrete mixture were tested at both the 7-day and 28-day intervals. The average compressive strength values obtained from these replicates were used for analysis.

The compressive strength values were obtained directly from the hydraulic press, where each value was calculated by dividing the maximum load applied to the specimen by the cross-sectional area of the cylinder. Finally, the recorded compressive strength values for each concrete mixture were analyzed to assess the overall strength characteristics at 7 and 28 days of age.

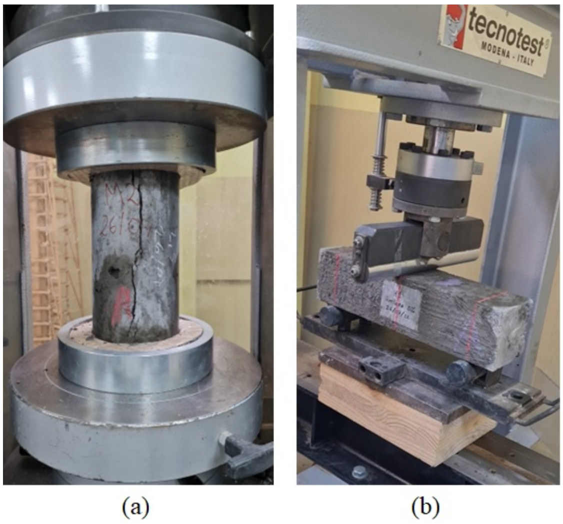

Figure 4. Concrete samples for experimental tests: (**a**) compressive strength test, (**b**) bending strength test.

2.5.4. Bending Strength

The bending strength of the concrete samples was determined to assess their ability to resist tensile stresses. This assessment was carried out specifically at 28 days of age, a common interval for evaluating the development of concrete strength according to ASTM C293 [39]. Prismatic specimens, with dimensions of 100 mm × 100 mm × 400 mm, were prepared from each concrete mixture. These dimensions conformed to the ASTM C293 requirements for prismatic specimens used in bending strength tests.

Fresh concrete was placed into the prismatic molds and compacted to ensure proper consolidation and eliminate air voids. After molding, the specimens were covered with a plastic sheet to maintain a suitable curing environment and prevent moisture loss. A Tecnotest hydraulic press (model KE 300/A, serial number 2907) manufactured in Modena, Italy, with a maximum compression capacity of 3000 kN, 100 kN in flexion, and equipped with a loading system capable of applying a step load, was employed for conducting the bending strength tests according to ASTM C293 [39]. During the testing process, a step load was applied to the prismatic specimens at a constant rate of 0.02 MPa/s to ensure a gradual and controlled application of tensile forces. Each prismatic specimen was positioned horizontally on the supports of the hydraulic press, ensuring that the load was evenly distributed along the length of the specimen. This setup prevented any localized stress concentrations that could affect the results.

The bending strength values were obtained directly from the hydraulic press, where each value was calculated using the maximum load applied to the specimen and its geometrical properties, such as the cross-sectional area and span length, in accordance with ASTM C293.

3. Results

3.1. Aggregates

3.1.1. Absorption Test

The absorption testing of the aggregates was conducted according to ASTM C127-15 [40] and UNE-EN 1097-8:2021 [41] for coarse aggregates and ASTM C128-22 [42] for fine aggregates. The results are shown in Table 3.

3.1.2. Density Test

The density testing of the aggregates was conducted according to ASTM C127-15 [40] and UNE-EN 1097-8:2021 [41] for coarse aggregates and ASTM C128-22 [42] for fine aggregates (refer to Table 3).

Table 3. Aggregate absorption and density test results.

Property	Coarse Aggregates	Fine Aggregates
Absorption (%)	1.4	1.9
Density (kg/m^3)	2630	2660

3.2. Crushed Hazelnut Shell

Density and Water Absorption

Studies on the density and water absorption rate of the crushed hazelnut shell were conducted according to ASTM C128-22 [42], and the results are shown in Table 4. This standard can be used to determine the real and net density and absorption of fine aggregates used in mortars and concretes. However, to the best of the authors' knowledge, there is no international standard to determine these properties for crushed HS. In this investigation, these parameters were assessed because they can affect the physical and mechanical response of an organic material, such as the strength, stiffness, and dimensional stability, and therefore modify the concrete's mechanical behavior.

Additionally, the crushed HS density was calculated empirically by means of the Archimedes principle. This modified procedure to obtain the absorption property of the HS was performed using eight unwashed, oven-dried samples submerged in non-ionized water. These samples were agitated in a LabTech heavy-duty orbital shaker, model LSI-020, for 1 h at 150 rpm. Two samples were filtered after 1, 2, 4, and 24 h using a vacuum pump to obtain a wet (saturated) sample. The final mass of the sample was then measured, and the absorption percentage % (mass/mass) was calculated using Equation (1). The water absorption data used in the design of the mixture corresponded to the average between the results obtained by these two methods in % (mass/mass) at 24 h, as shown in Table 4.

$$\text{Water absorption } (\%) = \frac{\text{mass wet material} - \text{mass dry material}}{\text{mass dry material}} \cdot 100 \tag{1}$$

Table 4. Crushed HS absorption and density test results.

Property	Value
Density (saturated-surface-dry) (kg/m^3)	1316
Density (oven-dry) (kg/m^3)	999
Apparent relative density (kg/m^3)	1462
Water absorption (% of mass/mass)	38

3.3. Fresh Concrete Tests

Prior to setting, fresh concrete mixtures were subjected to tests in order to characterize their properties. These tests were conducted to obtain information about the workability, consistency, and homogeneity of the mixtures. Once the mixtures were characterized, the results were compared to the mechanical strength obtained from compression and tensile tests. This allowed for an investigation of any potential correlations or relationships between the properties of the fresh concrete and the mechanical strength of the hardened concrete.

3.3.1. Slump Test

Slump tests were performed according to the ASTM C143 [43] standard. These results informed the method of consolidation used to construct the cylindrical and prismatic specimens for the compression and tensile strength tests. In essence, for slump values lower than 5 cm, the vibration method was used, whereas for slump values greater than 5 cm, the rodding method was used, as shown in Table 5. The rodding method was applied for specimen M-0.5-2.5 despite the fact that the slump was greater than the upper limit described in the ASTM standard.

3.3.2. Air Content and Bulk Density

The air content of the concrete was determined following the guidelines of ASTM C231 [44] using an air meter that comprised a bowl and a cover assembly. The air content measurement was performed within the first 15 min after the mixing process and after the slump test was completed. The appropriate consolidation method was chosen based on the slump value achieved. Subsequently, the cover assembly was securely placed and sealed according to the standard instructions. Through this procedure, the air content in the concrete mixture was determined as a percentage.

The bulk density was determined by weighing the content of the bowl after it was consolidated. This procedure was performed according to the ASTM C138/C138M [45] standard. For the air content and bulk density results, refer to Table 5.

Table 5. Slump test results, consolidation method, air content, and bulk density in fresh concrete mixtures.

Mixture	Slump (cm)	Consolidation Method	Air Content (%)	Bulk Density (kg/m^3)
M-0.4-0	10.5	Rodding	1.40	2426
M-0.4-2.5	14.0	Rodding	1.50	2394
M-0.4-5	8.5	Rodding	1.10	2394
M-0.4-10	3.5	Vibration	1.70	2377
M-0.5-0	4.5	Vibration	1.00	2419
M-0.5-2.5	-	Rodding	1.30	2374
M-0.5-5	11.0	Rodding	1.90	2377
M-0.5-10	11.0	Rodding	2.50	2347

3.4. Hardened Concrete Tests

3.4.1. Compressive Strength

The target compressive strength for the concrete was 20 MPa, categorizing our concrete as G20 according to the Chilean standard. The experimental resistance for the 0% mix design was on average 16.02 MPa. The difference between the target and actual compressive strength could be attributed to several factors. Among them, the use of admixtures, such as plasticizers; the adjustment of the water-to-cement ratio by the moisture content; and environmental factors such as temperature and humidity could have affected the concrete curing and strength development. Nevertheless, the comparative analysis in this paper was performed by considering the actual (observed) concrete strength.

3.4.2. Bending Strength

The experimental bending strength for the 0% mix design was 6.34 MPa for a w/c ratio of 0.4, while a bending strength of 5.72 MPa was obtained for concretes with a w/c ratio of 0.5. Similarly to the compressive strength results, the bending strength fell below the expected resistance due to the use of admixtures, the adjustment of the w/c ratio by the moisture content, and environmental factors such as temperature and humidity. Again, the comparative analysis in this paper was performed by considering the actual (observed) bending strength.

4. Discussion of the Results

4.1. Influence of Physical Properties on Mechanical Strength

The influence of the physical properties on the mechanical strength was evaluated by calculating the data presented in Table 6. Additionally, Table 7 shows the relationship between the density of the fresh and hardened concrete and the crushed HS replacement percentage. To conduct these analyses, a normality test using the Shapiro–Wilks method was initially performed on each set of data. Then, the correlation test method was selected based on the distribution of the data: Pearson for normally distributed data, and Spearman for non-normally distributed data. A regression analysis was also conducted for each correlation to illustrate the behavior of each relationship graphically and determine the adjustment coefficient. The relationships presented in Table 6 had a correlation coefficient greater than 0.6 or lower than -0.6 and were deemed significant based on a 5% error significance test [4].

Our findings indicated that the choice of water-to-cement (w/c) ratio significantly influenced the compressive strength of the concrete specimens. Specifically, specimens with a 0.4 w/c ratio consistently exhibited higher strength compared to those with a 0.5 w/c ratio. This observation could be attributed to the well-established principle that a lower w/c ratio results in a denser and more compacted concrete matrix, which generally leads to higher strength. However, the relationship between the w/c ratio and HS content added complexity to this phenomenon.

The impact of the HS replacement percentage on the concrete strength was variable. For instance, for the 0.4 w/c ratio specimens, a decreasing trend in strength as the HS replacement percentage increased was observed. This trend could be attributed to the inherent properties of the hazelnut shells, which introduced porosity and discontinuities in the concrete matrix. In contrast, for the 0.5 w/c ratio specimens, an increase in strength was noted with higher HS replacement percentages, indicating a more complex interaction between the w/c ratio and HS content.

Notably, the maximum strength was achieved with 2.5% HS replacement for the 0.4 w/c ratio, approaching the standard concrete strength. An important contributing factor to this observation was the improved workability of the mixture, as reflected by the larger slump values. The enhanced workability reduced the challenges encountered during compaction, ultimately leading to improved strength. This correlation between workability and strength, as supported by the strong direct relationship (correlation coefficient, $rs = 0.8$) highlights the interplay of multiple factors in determining concrete properties.

Table 7 reveals a significant inverse correlation between the HS replacement percentage and both the fresh and hardened densities. Specifically, as the HS replacement percentage increased, the bulk and hardened densities of the concrete decreased. This behavior could be attributed to the lower density of crushed HS compared to traditional aggregates, which resulted in the lower overall density of the composite. Hence, the reduced mass of the specimens containing HS was the underlying reason for the observed lower densities, indicating that the HS had a diluting effect on the composite.

Table 6. Correlation analysis between compressive and bending strength and fresh density, and between compressive strength and hazelnut shell content.

Variable		Correlation Analysis				Regression Analysis	
Dependent	**w/c**	**Independent**	***p*-Value**	**rs**	**Coefficients**	**Equation**	R^2
Compressive strength at 28 days—CS (MPa)	0.4	Docility—D (cm)	$p < 0.05$	0.8	a = 0.0635 b = −0.645 c = 14.447	CS = a(D)2 + b(D) + c	0.595
	0.5	Air content—AC (%)	$p < 0.05$	−0.6	a = 10027 b = 245.32 c = 12.223	CS = a(AC)2 + b(AC) + c	0.606
	0.4	Hazelnut shell content—HS (%)	$p < 0.05$	−0.6	a = 322.18 b = −72.321 c = 16.873	CS = a(HS)2 + b(HS) + c	0.366
	0.5		$p < 0.05$	−0.6	a = −145.21 b = −3.143 c = 13.8	CS = a(HS)2 + b(HS) + c	0.670
Bending strength—TS (MPa)	0.5	Air content—AC (%)	$p < 0.05$	−0.8	a = −54.05 b = 5.9968	TS = a(AC) + b	0.618
		Docility—D (cm)	$p < 0.05$	−0.8	a = −0.1362 b = 6.3363	TS = a(AC) + b	0.8874
		Hazelnut shell content—HS (%)	$p < 0.05$	−0.9	a = 150.1 b = −24.163 c = 5.6561	TS = a(HS)2 + b(HS) + c	0.8237

Table 7. Correlation and regression analysis for density and HS replacement percentage.

Variable		Correlation Analysis				Regression Analysis	
Dependent	**w/c**	**Independent**	***p*-Value**	**rs**	**Coefficients**	**Equation**	R^2
Hardened density at 7 days (for compressive strength)—HD (kg/m^3)	0.4	Hazelnut shell content—HS (%)	$p < 0.05$	−0.8	a = 483.8 b = −654.81 c = 2407	HD = a(HS)2 + b(HS) + c	0.765
	0.5		$p < 0.05$	−0.8	a = 1469.2 b = −511.74 c = 2379.4	HD = a(HS)2 + b(HS) + c	0.605
Hardened density at 28 days (for compressive strength)—HD (kg/m^3)	0.4		$p < 0.05$	−0.6	a = 6976.9 b = 360.02 c = 2381.4	HD = a(HS)2 + b(HS) + c	0.520
	0.5		$p < 0.05$	−0.8	a = 224.29 b = −493.74 c = 2384	HD = a(HS)2 + b(HS) + c	0.620
Hardened density at 28 days (for bending tensile strength)—HD (kg/m^3)	0.4		$p < 0.05$	−0.6	a = 10,101 b = −1587.6 c = 2405	HD = a(HS)2 + b(HS) + c	0.639
	0.5		$p < 0.05$	−0.6	a = 52,653 b = 1364.7 c = 2375.2	HD = a(HS)2 + b(HS) + c	0.434
Bulk density—BD (kg/m^3)	0.4		$p < 0.05$	−0.9	a = 5078.2 b = −964.86 c = 2423.3	BD = a(HS)2 + b(HS) + c	0.908
	0.5		$p < 0.05$	−0.8	a = 5713 b = 1230.1 c = 2414.1	BD = a(HS)2 + b(HS) + c	0.894

A critical aspect that merits further investigation is the microstructure of hazelnut shells, which is rough, fibrous, and porous. This inherent porosity was a limiting factor for concrete compressive strength, resulting in an inverse relationship between HS replacement percentage and strength. The porous nature of the hazelnut shells introduced voids within the concrete matrix, reducing its overall density and strength. Additionally, the w/c ratio directly affected the porosity of the concrete mixture, increasing the impact of the HS content.

Finally, our findings aligned with studies involving other organic materials as partial substitutes for traditional aggregates. These studies, such as those involving polypropylene fibers and waste slag aggregates (WSAs), demonstrated that the effect on compressive strength depended on the specific properties of the replacement material and its impact on the concrete microstructure. The comparison highlights the need for a refined understanding of the interaction between organic materials and concrete properties.

4.2. Influence on Compressive Strength

Figure 5 shows the results of compressive strength tests at 7 days for different HS replacement percentages and water/cement ratios. The data indicate that the specimens prepared with a 0.4 w/c ratio had a higher strength than those prepared with a 0.5 w/c ratio. Furthermore, a decreasing trend in strength was observed as the HS replacement percentage increased for the 0.4 w/c ratio specimens, whereas an increase in strength was noted with an increasing HS replacement percentage for the 0.5 w/c ratio specimens. The maximum strength was achieved at a 2.5% HS replacement percentage for the 0.4 w/c ratio specimens, almost reaching the value of the standard.

Figure 6 presents the compressive strength results at 28 days, with higher strength values compared to those at 7 days. The specimens with a 0.4 w/c ratio had a higher strength than those with a 0.5 w/c ratio, with a maximum increase of 9.5% observed for the 2.5% HS replacement percentage compared to the standard. This increase in strength may be attributed to the improved workability of the mixture, as reflected by the larger slump values observed for this HS replacement percentage in Table 5. The better workability may have reduced the difficulties encountered during the compaction by tamping, resulting in better strength. Additionally, a strong direct relationship was found between these two variables, with a correlation coefficient, r_s, of 0.8 (Table 6).

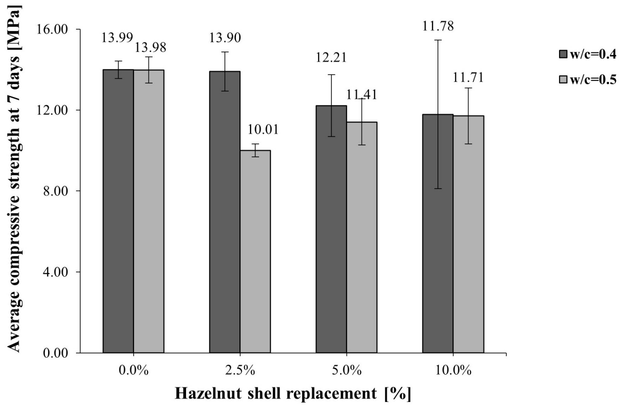

Figure 5. Average compressive strength results at 7 days for 0.4 and 0.5 water/cement ratios.

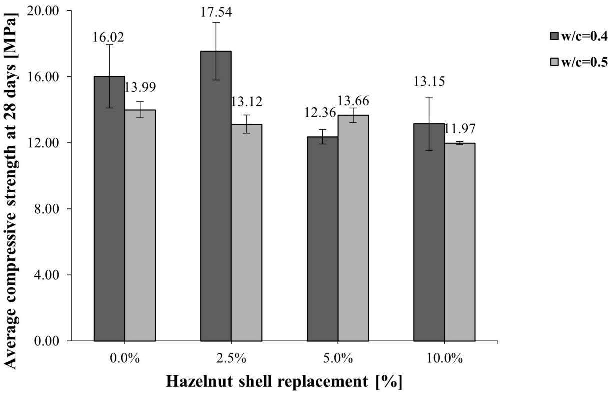

Figure 6. Average compressive strength results at 28 days for 0.4 and 0.5 water/cement ratios.

In Table 6, it can be observed that the r_s correlation coefficients between HS replacement percentage and compressive strength at 28 days were −0.6 for both w/c ratios, indicating a moderate inverse relation. This suggests that an increase in the HS replacement percentage led to a decrease in the compressive strength. The maximum reduction in strength for both w/c ratios was around 23% compared to the standard specimens. The inverse correlation between the percentage of organic material replacement and the final strength of concrete when using organic material can be attributed to several key factors. For instance, organic materials are typically much weaker than traditional fine aggregates like sand. This inherent weakness in organic materials can lead to a reduction in the overall strength of the concrete. Also, they can absorb moisture from the concrete mix, leading to a reduction in the water/cement ratio. As the percentage of organic replacement increases, the water/cement ratio decreases, negatively impacting strength. Moreover, organic materials often contain voids or pores that can create weak points within the concrete. As the percentage of replacement increases, these voids become more prevalent, increasing the overall porosity of the concrete. A higher porosity can reduce the compressive strength of concrete. The suitability of different organic materials as replacements for fine aggregates in concrete has been explored in other studies. For example, Ndoke [46] investigated the suitability of palm kernel shells as a partial replacement for coarse aggregates in asphalt concrete. Azunna [47] conducted a study on the behavior of concrete slabs incorporating sawdust and palm kernel shells as replacements for fine and coarse aggregates, respectively. The study found that the production of lightweight concrete slabs was possible with a lower replacement value of 25% sawdust and palm kernel shells. Similarly, Divakar et al. [48] investigated the use of granite fines as a replacement material for fine aggregates. They assessed the replacement of fine aggregates in five different proportions, ranging from 5% to 50%. Their study revealed that as the percentage of granite fines used as a replacement increased, there was an inverse correlation with the final strength of the concrete. This inverse correlation between the percentage of replacement and the final strength suggests that while organic materials can be used as replacements for fine aggregates in concrete, there is a trade-off between the environmental benefits and the structural integrity of the concrete. This observation aligns with the findings of Olanipekun et al. [49] and Dadzie and Kaliluthin [50], who compared the performance of coconut shells and palm kernel shells as substitutes for coarse aggregates in concrete.

Furthermore, the w/c ratio directly affected the porosity of the concrete mixture. A higher w/c ratio led to increased porosity, which resulted in the lower strength of the concrete specimens. Hence, it could be inferred that the compressive strength results for a 0.4 w/c ratio would be greater than those obtained for a 0.5 w/c ratio. Our findings indicated that the choice of water-to-cement (w/c) ratio significantly influenced the compressive strength of the concrete specimens. Specifically, specimens with a 0.4 w/c ratio consistently exhibited higher strength compared to those with a 0.5 w/c ratio. This observation could be attributed to the well-established principle that a lower w/c ratio results in a denser and more compacted concrete matrix, which generally leads to a higher strength. However, the addition of hazelnut shell (HS) content introduces complexity to this relationship. For instance, a lower w/c ratio means that there is less water in the mix relative to the amount of cement [51,52]. This results in a more densely packed and compacted concrete matrix. A denser matrix generally leads to higher compressive strength because there is less porosity and a greater amount of cementitious material available for bonding. Moreover, with a lower water content, there is less excess water to create voids in the concrete. This reduced porosity limits the potential pathways for crack formation, increasing the overall strength of the concrete [53,54]. Additionally, lower w/c ratios often require more efficient curing techniques to prevent the concrete from drying out too quickly. Lastly, hazelnut shells introduce unique physical properties to the concrete mix. The size, shape, and surface characteristics of the HS particles can affect their distribution in the mixture (i.e., HS particles may interact differently with the cement matrix based on their size and shape). As a consequence, the overall packing and distribution of the solid materials in the mix can be influenced. Interestingly, the correlation between the compressive strength and air content of the mixture for the 0.5 w/c ratio at 28 days was moderately inverse, with an r_s coefficient of -0.6.

It can be observed that the compressive strength was higher for lower w/c ratios (w/c = 0.4). This trend suggests that the density is directly proportional for conventional concretes, and similar conclusions can be found for other organic materials used as replacements for fine aggregates [55]. However, this relationship did not hold for concretes with higher percentages of hazelnut shell, which is lighter and more porous than regular aggregates. Consequently, the density of the concrete with a higher hazelnut shell content was lower, resulting in an increased air percentage and a reduction in concrete strength. For instance, in a study conducted by Qudoos et al. [56], polypropylene fibers and waste slag aggregates (WSAs) were employed as partial substitutes for cement in concrete. The results indicated a reduction in compressive strength and an enhancement in flexural strength upon the inclusion of polypropylene fibers. Conversely, the incorporation of WSAs led to a densification of the microstructure, attributed to its pozzolanic activity. Arif et al. [57] obtained similar patterns when incorporating sugarcane bagasse ash as a filler in concrete. It was observed that the density of the hardened concrete increased when the replacement level reached 20%, despite a decrease in compressive strength at that particular replacement level. This increase in density was attributed to the filler effect of the sugarcane bagasse ash at higher replacement percentages.

Additionally, a comprehensive set of criteria should be defined for the acceptance of a specified strength for concrete mixes using hazelnut shell. The criteria must be applicable to any concrete intended for use in structures designed according to the specified requirements or local standards. It should be noted here that there may be instances where test results do not meet these criteria, as in the case of concretes with a higher hazelnut shell content, even when the strength and uniformity of the concrete are satisfactory (likely occurring in approximately 1 out of 100 tests). Tolerances should be established for such statistically predictable deviations when deciding whether the produced strength level is adequate or not. When the concrete fails to meet any of the strength requirements, measures should be taken to increase the average results of the concrete tests.

It is important to highlight that the equations for concrete mix design are based on a probability of 1 out of 100 that a test may fall below the specified strength (f'_c) by more than 3.5 MPa or below 0.9 (f'_c), respectively [58].

4.3. Influence on the Bending Strength

The bending strength results for both water/cement ratios are shown in Figure 7. For the 0.4 w/c ratio, the bending strength varied by −8.8%, +3.5%, and 0.3% for HS replacement percentages of 2.5%, 5%, and 10%, respectively, compared to the standard specimens. These results indicate that the strength tended to remain stable or even slightly increase as the HS replacement percentage increased.

However, for the 0.5 w/c ratio, a progressive decrease in the strength was observed as the HS replacement percentage increased. This was consistent with the strong inverse correlation ($r_s = -0.9$) presented in Table 6, indicating that the bending strength decreased as the HS replacement percentage increased. These findings are in agreement with the results presented in Figure 7.

The compressive strength results for a w/c ratio of 0.4 were found to be higher than those for a w/c ratio of 0.5. In the case of the latter, a strong inverse correlation was observed between the strength results and the docility of the mixture (indicated by a slump test), as well as the air content of the mixture. Both of these correlations were characterized by a strong negative Spearman's correlation coefficient (r_s=-0.8), as shown in Table 6.

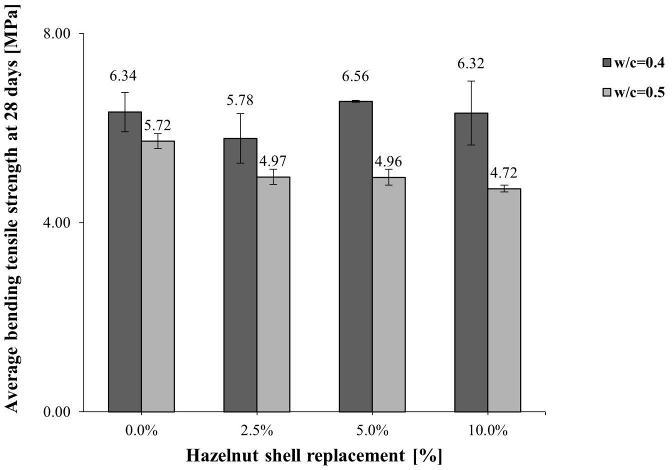

Figure 7. Average tensile strength results at 28 days for 0.4 and 0.5 water/cement ratios.

5. Conclusions

In this paper, the fine aggregate in concrete mixes was partially replaced by crushed hazelnut shells to study the influence on the mechanical compressive and tensile strength. Standardized concrete cylinders were tested according to the ASTM standards. A statistical study was performed to correlate the mechanical response with the physical properties. Based on these results, the following conclusions and recommendations could be drawn:

- The findings indicated a non-linear relationship between the water/cement ratio and compressive strength. For the specimens with a w/c ratio of 0.4, a 9.5% increase in compressive strength at 28 days was observed in one specimen, while the other two specimens showed a decrease of approximately 20%. Similarly, for a w/c ratio of 0.5, the compressive strength at 28 days exhibited a decrease ranging from 2% to 14% compared to the original specimen. This non-linear behavior highlights the complex interplay between the water/cement ratio and compressive strength.
- The results suggested that an optimal w/c ratio exists for achieving the highest compressive strength. In this particular study, a w/c ratio of 0.4 resulted in a slight increase in compressive strength in one specimen, indicating that this ratio might be more conducive to optimal strength development. Conversely, a higher w/c ratio of 0.5 resulted in a slight decrease in compressive strength compared to the original specimen, implying that an excessive water content may have a detrimental effect on the strength of the concrete.
- For the specimens with a w/c ratio of 0.4, the tensile strength exhibited a general increase as the percentage of crushed hazelnut shell inclusion increased from 2.5% to 5%, reaching a peak value of 6.56 MPa. However, a further increase to 10% resulted in a slight decrease in tensile strength to 6.32 MPa. This suggests that an optimal percentage of crushed hazelnut shell inclusion exists, beyond which the tensile strength starts to decline.
- For the specimens with a w/c ratio of 0.5, the inclusion of crushed hazelnut shell resulted in a general decrease in tensile strength across all inclusion percentages. As the percentage of inclusion increased from 2.5% to 10%, the tensile strength decreased from 4.97 MPa to 4.72 MPa. This indicated that the higher w/c ratio negatively influenced the strength enhancement effect of crushed hazelnut shell inclusion.
- The use of a 0.4 w/c ratio consistently produced better results for both compressive and bending strength, with fewer and lower reductions in mechanical strength compared to the standard mixture. The correlation analysis showed that the strength results were inversely related to the w/c ratio and air content of the mixture.
- Based on the results obtained, concrete mixes with a HS replacement percentage of 2.5% could be used in constructive systems with a compression strength requirement lower than 17 MPa.

- Concrete mixtures with a HS replacement percentage of at most 10% of the fine aggregate could be used in structures with tensile bending stress requirements lower than 6 MPa. These results indicate that the use of hazelnut shells as a partial replacement for fine aggregates is a viable option for reducing the environmental impact and improving the mechanical properties of concrete. However, it is important to consider the specific requirements of each application when determining the optimal percentage of HS replacement.

To conclude, from the outcomes of the present work, it is possible to identify a few areas of interest for future research. First, in future studies it is advised to increase the number of tests or repetitions performed. The aim of this would be to collect a larger number of results, which could help to reduce the experimental uncertainty. Furthermore, it would be relevant to investigate the compressive and tensile strength of concrete mixes with cure times above 28 days—for example, 90 days. The latter could provide valuable insight into the long-term effects and aging of concrete structures. By subjecting the concrete to various environmental conditions over an extended period, one could evaluate its ability to withstand external factors and predict its performance over time. Also, to better understand the strength of the newly proposed concrete mixes under corrosion and environmental effects, it would be relevant to perform durability tests. Furthermore, hazelnut shells, being organic materials, can decompose over time when exposed to moisture, microbes, and environmental factors. This decomposition could weaken the concrete and reduce its long-term durability and structural integrity, introducing additional porosity into the concrete matrix over time. However, inside the concrete matrix, the high alkalinity (high pH) could have a significant impact on the presence and activity of bacteria [59]. The alkaline environment could deter many common bacteria from flourishing within the concrete matrix, as it would disrupt their metabolic processes and could be inhospitable. Bacteria typically thrive in a more neutral or slightly acidic pH range, typically between 6 and 8. Last but not least, a natural next step would be to study the performance of concrete mixes in which the fine aggregate is partially replaced by HS ash. Among other things, this could aid in understanding the influence of the pozzolanic reaction of HS ash on the mechanical and physical properties of the material.

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