

Article

Experimental Study of the Mechanical Properties of Mortar with Biobío Region Clam Shells Used as a Partial Replacement for Cement

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Abstract: The use of seashells as a partial substitute for cement in construction not only offers an innovative solution for marine waste management but also contributes to reducing the carbon footprint of the cement industry, decreasing the CO₂ emissions associated with cement production and promoting more sustainable construction practices. This study addresses the mechanical behavior of mortar specimens with partial cement replacement using crushed Biobío region clam shells, both calcined and uncalcined, at substitution rates of 5% and 10%. This approach allows the analysis of their effect on the mechanical strength and properties of the mortar, which has not been widely investigated in the Chilean context or with this particular species of shell. For the mechanical characterization of the specimens, tensile flexural tests and compressive tests were conducted at ages of 3, 7, 14, and 28 days. The compressive strengths of the samples that incorporated calcined residue with partial cement replacements of 5% and 10% were 83.69% and 78.27%, respectively, of the average strength of 20.97 MPa reached by the standard sample. In terms of their tensile flexural strength, these samples reached average strengths of 104.31% and 104.04% of the strength of 12.12 MPa obtained by the standard sample. In the case of the uncalcined samples, the 5% and 10% replacements reached 103.55% and 102.64% of the tensile strength of 15.54 MPa obtained by the standard sample, while they reached 92.32% and 80.07% of the compressive strength of 27.81 MPa achieved by the standard sample. From these results, it is determined that the calcined shells did not improve the mechanical resistance of the mortar, suggesting that the calcination process must be studied in depth.

Keywords: Biobío clam shell; partial cement replacement; mortar



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1. Introduction

Cement is the most widely consumed material in construction, and its production significantly impacts the environment due to high energy consumption [1,2]. The production of cement generates 630 kg of CO₂ per ton accounting for 8% of global CO₂ emissions. This is not a result of the fuel burned during its production processing but also due to the decomposition of limestone [3]. Global temperatures have increased by an average of 0.6 °C over the past in the last century, and it is predicted to rise by 1.4–5.8 °C in the present century. To address global warming and prevent climate change, several studies have been carried out to replace cement with other materials.

Several materials have been used as a cement replacements, including Egyptian corn-stalk ash, used by Salem et al. [4]; rock dust, used by Dobiszewska et al. [5]; coal bottom ash, used by Chindasiriphan et al. [6]; sewage sludge ash, used by Danish and Ozbakkaloglu [7]; waste glass powder [8,9]; and silica fume [10]. Other studies have examined on the influence of ceramic waste powder on the shear performance of environmentally friendly reinforced concrete beams [11], the properties and structure of functional concrete mixtures modified with river shell powder [12], and the flexural behavior of reinforced concrete beams incorporating waste marble powder for sustainable concrete applications [13].

In Chile, seashells are an abundant waste material that has been proposed as a substitute for conventional materials, such as cement, sand, and coarse aggregate in construction [14]. The main component of the seashells is calcium carbonate (CaCO_3) mainly in the form calcite; their chemical composition is predominantly calcium oxide (CaO) varying between 48% and 87.2% for oyster, mussel, cockle, and clam shells, with small amounts of other oxides are also present [14]. The microstructure observed in powdered clam, mussel, oyster, and cockle shells reveals irregularly shaped particles, multi-angled shapes, thin particles, and needle-like particles with sizes ranging from 13.6 μm to 29.9 μm [15]. The impurity levels ranged from 0.014 to 0.51% for chloride ion content and from 0.27 to 2.15% organic matter, exceeding the limits set by the Chilean Standard (NCh170) for chloride content. These limits are 0.25 kg (Cl^-)/ m^3 for prestressed concrete and 1.20 kg (Cl^-)/ m^3 for reinforced concrete [16]. However, these values can be reduced through a calcination process [17]. Given the salinity content (35%) of seashells present, [18,19] suggest using them as a substitute for up to 10–20% of concrete aggregate.

Seashells have been used as both coarse and fine aggregates, with sizes ranging from 0.074 to 9.5 mm [15,18,20]. In the case of fine aggregates, increased friction among particles has been observed, resulting in reduced workability, as presented by Wang et al. [21]. However, this can be improved by using additives, as presented by Yang et al. [22], or by increasing the aggregate substitution up to 20%, as presented by Kuo et al. [23]. On the other hand, particle size does not significantly affect the setting time, as presented by Yang et al. [22], although slower curing has been reported. This could be mitigated by increasing the replacement level up to 20% when fine aggregate is used [15,23,24].

In terms of the mechanical properties, the compressive strength is negatively impacted by an increase in the amount of shell aggregate. Replacing more than 20% of mussel shells led to 63% decrease [25], while substituting over 50% of the oyster shells resulted in a 46% decrease [15]. In contrast, an increase of over 14% in compressive strength was observed when the oyster shell was replaced 15% of the lime [26]. Additionally, a 5% increase was noted when the oyster shell was used to replace 5% of the cement [18]. Similarly, tensile strength was influenced by the inclusion of marine shells was from 10 to 30% [27–29]. At the same time, the elastic modulus of concrete showed decreases of 10% and 25% when 20% and 25% of the oyster shells [19,22] and mussel shells [15] were used, respectively.

A mortar rich in calcite from seashells, which obtained a compressive strength of 22 MPa after 28 days of curing [30]. The use of scallop shells, with a particle size of 63 μm as a partial cement in mortar achieved a compressive strength of 50 MPa with a 30% replacement, indicating a 43% increase over the standard sample [31]. The use of acanthocardia tuberculata shells as a partial aggregate replacement reduces flexural strength due to the shells' water absorption, which adversely affects cement hydration [32].

Various researchers have discussed the advantages of replacing cement with alternative materials, as this can lead to a reduction in CO_2 emissions from an environmental perspective. For example, the use of 400,000 tons of coal fly ash in concrete contributed to an annual reduction of almost 250,000 tons of CO_2 emissions. They also noted that the production of one ton of calcinated clays, such as metakaolin, consumed 2.2 MJ/ton, which is 80% less than the energy needed to manufacture one ton of Portland cement. In contrast, cement is produced at temperatures ranging from 1400 °C and 1500 °C, while substitute materials like calcined clays (e.g., metakaolin) and natural hydraulic lime are obtained at temperatures below 850 °C to 1200 °C and from 450 °C to 900 °C, respectively. Regarding

the carbon footprint, the CO₂ emissions generated by the production of cement represent approximately 930 kg/ton, while materials such as natural hydraulic lime, limestone, and calcinated clays, like metakaolin generate 335–568 kg/ton, 17 kg/ton, and 175 kg/ton, respectively [33].

Chile has a vast market of seashells; for example, in the year 2020, the following landings were reported: 400.30 tons of *Mytilus chilensis* bivalve mollusk; 11,288 tons of clams; 6314 tons of *Aulacomya Atr* bivalve mollusk; 3170 tons of *Ensis Macha* bivalve mollusk, among others, which have different dispositions, either for internal consumption or exportation, providing a wide opportunity for their use in research. In this way, the present research aims to develop and characterize a green mortar with Biobío region clam shells as a partial replacement for cement.

The main novelty of the presented work lies in the use of clam shells from the Biobío region as a partial substitute for cement in mortars. The study focuses on evaluating the impact of 5% and 10% replacements of cement with calcined and non-calcined shells, instead of conventional materials. This approach allows us to analyze their effect on the mechanical strength and properties of the mortar, something that has not been widely investigated in the Chilean context or with this species of shells.

The distinction of this work from what is presented in the introduction lies in its specific focus. While the introduction covers previous studies on the use of different types of waste as a replacement for cement (including rice husk ash and seashell powder), this research narrows in on clam shells from a region of Chile, considering both calcined and non calcined forms. The findings provide a more localized and nuanced perspective, highlighting the unique mechanical properties of these mortars and addressing technical challenges, such as the reduction in strength attributed to calcification.

2. Materials and Methods

2.1. Materials

Special Bío Bío brand cement was used, with the following specifications: special pozzolanic cement of current grade, which was purchased locally in 25 kg format. Regarding its technical characteristics, the manufacturer indicates that it complies with the requirements set out in NCh 148 [34]. Drinking water was used to make the mortar. This water complies with NCh 409 [35] regulations because it comes from the public network. Bío Bío brand sand was used, which has a real dry saturated aggregate density of 2732.58 [kg/m³], real dry aggregate density of 2674.24 [kg/m³], net density of 2839.9 [kg/m³] and water absorption of 2.18%. The seashells used were clam shells from the La Poza Artisanal Fishing Terminal market, located in the town of Talcahuano in the city of Concepción, which is located in the Biobío Region (VIII) in Chile.

The particle size of seashells used by various authors varies according to the literature from 15 µm to 125 µm. The most repeated values are between 75 and 90, as shown in Figure 1, where the quantity of articles is indicated in the y-axis and the size of the particle in the x-axis. Some authors use a particle size of 90 µm, obtaining the best results in compressive strength for a 5% replacement of cement. Meanwhile, other authors use a particle size of 90 µm obtaining the best results in compressive strength for 25% cement replacement. For this reason, in this work, we decided to use a particle size of 90 µm.

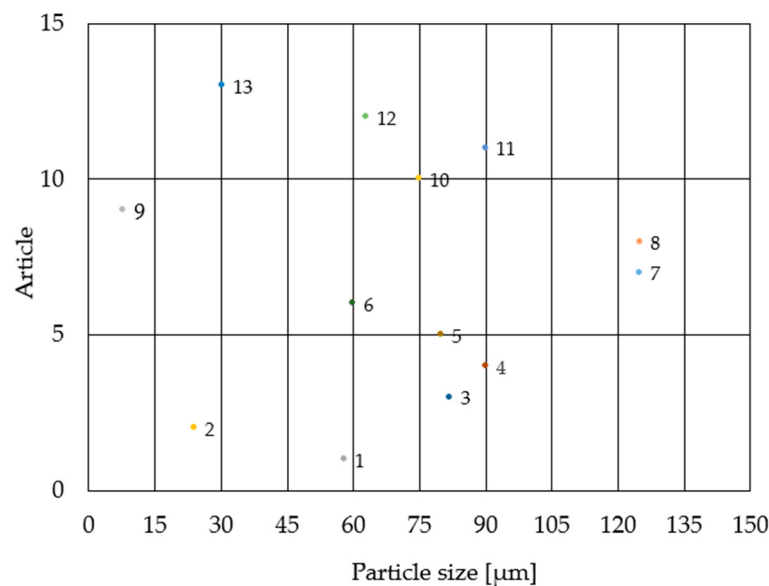


Figure 1. Particle sizes of seashell from literature [31,32,36–46].

From the consulted literature, it is evident that as the percentage of shell powder as a cement replacement increases, the mechanical properties decrease. This can be seen in the results obtained by Olivia et al. [47], who used 2%, 4%, 6% and 8% of cockles as a partial replacement for cement, obtaining the best result of compressive strength of 32.34 MPa for a 4% replacement, with respect to the control that presented results of 35 MPa. Rollakanti et al. [44] used 2.5%, 5% and 7.5% of seashells as a partial substitute for cement, where the 5% replacement presented a compressive strength of 34 MPa, while the control presented a value of 30 MPa. Also, Tayeh et al. [43] used 5%, 10%, 15% and 20% of bivalve clams as a partial cement replacement; the highest compressive strength of 29.73 MPa compared to the control 29.38 MPa was obtained for the 5% group. Considering these results presented in the literature, we decided to work with partial cement replacements of 5% and 10% since they have shown the best results in resistance.

2.2. Specimen Preparation and Manufacturing

The clam shells were washed to remove organic remains and dried in the sun to remove excess water. Afterward, they were crushed manually using a mortar and pestle and sifted through a No. 6 mesh sieve to simplify subsequent grinding; see Figure 2a. In the grinding process, a Marcy-type ball mill was used, manufactured by EDEMET in AISI 316 steel, with a capacity of 5.4 L and a speed of 130 rpm. After grinding, the moisture was removed from the material to facilitate sieving. This was carried out in a drying oven manufactured in AISI 304 stainless steel by Labtech Hebro, model DO0.8ME of 9 kW at approximately 100 °C for 30 min. In Figure 2b, it can be seen the material after being passed through the #170 mesh sieve, which corresponds to an opening of 90 (μm).

The same samples were used for grinding and were calcined in a conventional Nabertherm muffle furnace, model N50, with a maximum capacity of 1280 [°C] and a power of 3.3 [kW]. Before starting the process, the initial weight of the shells is measured in order to determine the percentage of loss due to calcination. The material is then spread in a thin layer to obtain a homogeneous calcination. The time it takes to reach the desired temperature is recorded, and then it is kept at a constant 800 [°C] for one hour. Finally, it is turned off and allowed to cool for a period of 6 to 8 h. Figure 3 shows a schematic of the temperature curve corresponding to the applied heat treatment, which shows that it took 5 h to reach 800 [°C], which remained constant for a period of 2 h, followed by a cooling period of 8 h.

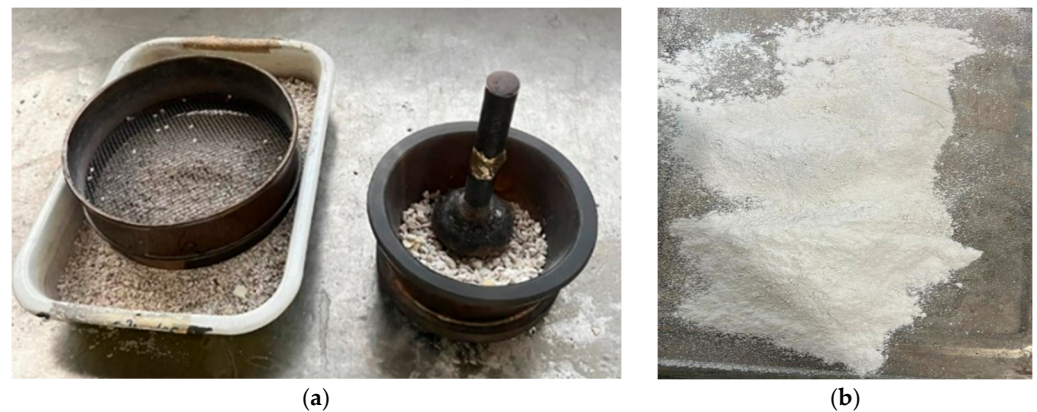


Figure 2. Milling results: (a) manual grinding material and (b) grinding with particles less than 90 μm.

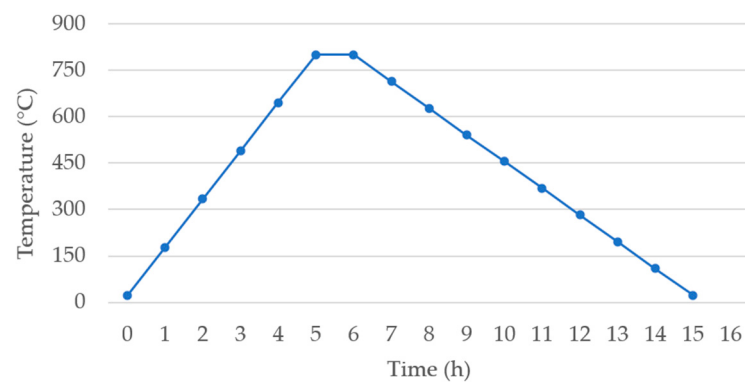


Figure 3. Temperature profile.

The mass of the sample before calcination is 722.3 [g], and after calcination, the result is 584.6 [g], which means a 19.06% of loss, a percentage lower than the 45% recorded in [46]. The calcined shells can be observed in Figure 4.

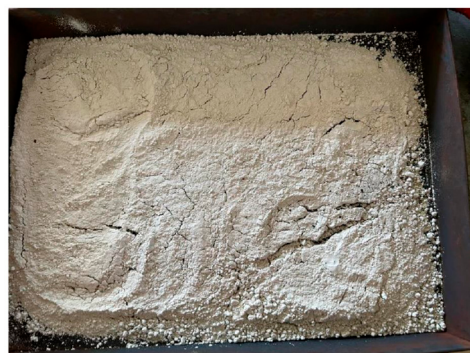


Figure 4. Calcined clam shell.

The dosage used to make the different test specimens for the mechanical tests was 1.502 kg of cement, 0.751 kg of water and 4.506 kg of sand. This calculation was based on the fact that 4 molds were used per casting; therefore, 12 specimens were made per casting. The ratio used was 1:3:0.5 of cement–sand–water. It should be noted that an error estimate of 15% was made in the calculation; this, error was an empirical determination, which was attributed to the loss due to the mixing process. This losses percentage was based on those associated with the handling of materials, absorption and retention of water in the materials, adherence to mixing equipment and environmental conditions. Thus, the dose

summary can be seen in Table 1 (A), where MR-00, MR-05 and MR-10 correspond to the specimens with 0%, 5% and 10% of uncalcined shells, respectively.

Table 1. Dosing by pouring mortar.

	Nomenclature	MR-00	MR-05	MR-10
(A) Pouring dosage for specimens, prior to correction of the aggregate for moisture content.	Cement [g]	1501.87	1426.77	1351.68
	Clam shell [g]	0	75.09	150.19
	Water [g]	750.93	750.93	750.93
	Sand [g]	4505.6	4505.6	4505.6
(B) Pouring dosage for specimens with uncalcined shells, after correction of the aggregate for moisture content.	Cement [g]	1727.15	1640.79	1554.43
	Clam shell [g]	0	86.36	172.71
	Water [g]	863.57	863.57	863.57
	Sand [g]	5295.15	5295.15	5295.15
	Nomenclature	MRC-00	MRC-05	MRC-10
(C) Pouring dosage for specimens with calcined shells, after correction of the aggregate for moisture content.	Cement [g]	1727.15	1640.79	1554.43
	Clam shell [g]	0	86.36	172.71
	Water [g]	949.93	949.93	949.93
	Sand [g]	5295.15	5295.15	5295.15

The MR-00 standard specimens were prepared, followed by the MR-05 and MR-10 replacement specimens. The aggregate correction is carried out to determine the amount of water present due to the calculated humidity; see Equation (1).

$$\text{Humidity content} = \frac{\text{Wet dough} - \text{Dry dough}}{\text{Dry dough}} \cdot 100\% \quad (1)$$

Knowing the percentage of humidity (2.2%), the dosage correction is made, and the mixture is started. The moisture content corrected dosages for both the uncalcined shell (MR) and calcined shell (MRC) specimens are presented in Table 1 (B) and Table 1 (C), respectively.

The mixing was carried out with a homogeneous mixture of sand and cement, and then it was continued mixing with the corresponding replacement percentage. This mixture was made with an electric hand mixer; after that, the water was added in small quantities, making sure that the mixture had all the water poured in. Once the preparation stage of the mixture was completed, its workability was measured using a truncated conical mold. Finally, the molds were filled, and compaction was carried out on a LH 13.00 vibrating table. Each mold is divided into three prismatic compartments which allow the production of three samples with dimensions of 40 [mm] × 40 [mm] × 160 [mm] [48]. The specimens were left to set for 3 days protected with plastic at room temperature.

After three days, the test pieces were separated from each specimen to perform the early age test and the rest were taken to the curing chamber to be tested again at 7, 14 and 28 days. The curing chamber has a temperature between 17 and 23 °C and a 90% of humidity.

2.3. FTIR Analysis

FTIR analysis was performed to identify and characterize the molecular vibrations and functional groups present in the calcined and uncalcined clam shell samples, seeking key information about their chemical structure and possible changes in their composition after specific treatments, such as calcination.

The equipment used was a Fourier transform infrared spectroscopy (FTIR) in a Perkin Elmer 1760-X equipment (Waltham, MA, USA). For each sample, 0.5 mg of carbon fiber powder mixed with KBr (potassium bromide) was prepared.

2.4. Mechanical Characterization Tests

The flexural tensile test was performed on a simple compression apparatus adapted to the mortar bending device. The load is applied to the middle of the specimen, and the reading indicates the displacement, as can be seen in Figure 5a. Equation (2) transforms the displacement into a load measured in [kgf]. This formula is taken from the NCh 158 standard [49], which is determined empirically because there is no conversion of displacement to kilograms of force [kgf].

$$P[\text{kgf}] = \text{lectura} \cdot 3.4 + 15.25 \quad (2)$$

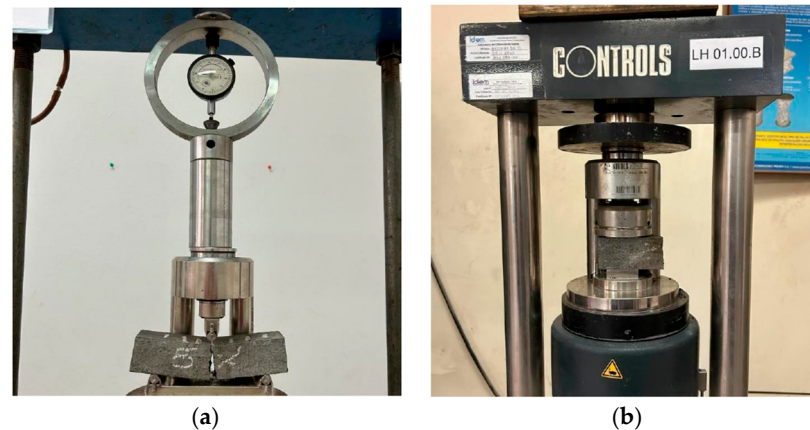


Figure 5. Mechanical characterization: (a) tensile flexural test and (b) compression test.

The compression test was performed on the Controls Sercomp 7 LH 01.00.B universal testing machine, whose load application speed is 0.3 [MPa/s], which is lower than the speed specified in the Chilean standard (0.35 [MPa/s]) [49]. The test was performed on the halves resulting from the flexural test immediately after it had finished, as can be seen in Figure 5b. The resistance values are obtained directly from the equipment.

3. Results

3.1. FTIR Analysis Results

FTIR analysis was performed to identify and characterize the molecular vibrations and functional groups present in the calcined and uncalcined clam shell samples. The main objective was to obtain key information about their chemical structure and to observe possible changes in their composition after specific treatments, such as calcination, which affects the structure of the material. The FTIR analysis result is presented in Figure 6a for the uncalcined clam shell sample and in Figure 6b for the calcined clam sample.

The band initially observed in the uncalcined clam powder spectra at 709 cm^{-1} were found to persist in the calcined clam powder with a slight shift in wavenumbers. These bands are typical characteristics of $(\text{CO}_3)^{2-}$ functional group and the formed new carbonates in the activated systems [30,50,51]. The 1080 cm^{-1} band in the uncalcined clam shell confirms the presence of calcite, and its disappearance in the calcined clam shell can be explained by the structural transformation of the unreacted CaCO_3 as well as the formation of new carbonates [51]. The peak around 1482 cm^{-1} arises from the asymmetric stretching vibrations and out-of-plane vibrations of CO_3^{2-} in calcium carbonate [50,51]. The 1787 cm^{-1} and 1805 cm^{-1} peaks of both samples indicate symmetric CO_3 stretching plus symmetric CO_3 deformation [50]. The bands at 2518 cm^{-1} and 2522 cm^{-1} are attributed to the C–O asymmetric stretching mode in the CO_2 molecule [30]. The bands at 2920 cm^{-1} and 2978 cm^{-1} are attributed to the asymmetric stretching in the CO_3 molecule [50]. In addition, the bands 3642 cm^{-1} in the calcined clam shell and 3744 cm^{-1} in the uncalcined clam shell represent a stretching vibrational band of –OH in silicates that have more intensity at the calcined clam shell [52,53].

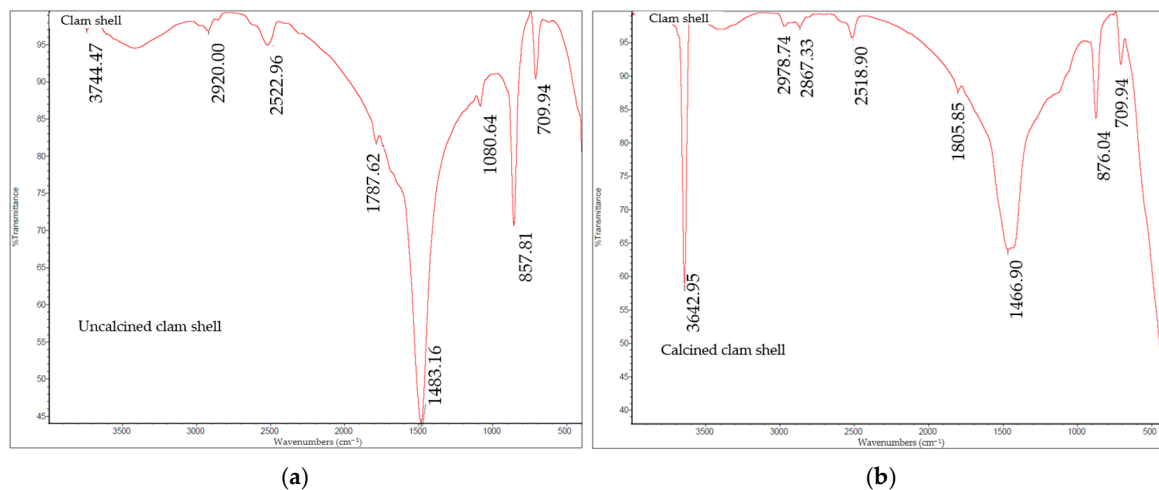


Figure 6. FTIR analysis results: (a) uncalcined clam shell and (b) calcined clam shell.

3.2. Workability

The results of the truncated cone measurements are presented in Table 2. The effect of changing the water dosage on workability is clearly observed, since for the same aggregate–cementitious dosage, adding a higher percentage of water results in greater workability.

Table 2. Workability results.

Nomenclature	Cone Settlement [cm]
MR-00	1
MR-05	2
MR-10	2
MRC-00	3.5
MRC-05	2.5
MRC-10	2.5

The data in Table 2 show that the workability of the mortar changes when replacing the cement with an uncalcined clam shell. For MR-00, the cone slump is 1 cm; however, when replacing 5% of the cement with the clam shell in MR-05 specimen, the cone slump increases to 2 cm, indicating an improvement in workability. This same slump value is maintained when 10% of the cement is replaced in the MR-10 specimen. This suggests that the inclusion of uncalcined clam shell improves the workability of the mortar compared to conventional mortar [43], although the increase in the replacement percentage from 5% to 10% does not seem to have a significant additional effect on workability, with the slump remaining constant at 2 cm.

The workability of the MRC specimens that include the replacement of cement by calcined clam shell decreases with increasing cement replacement. The conventional mortar MRC-00 has a cone slump of 3.5 cm, indicating considerably high workability. However, when 5% of the cement is replaced by a calcined clam shell in MRC-05, the slump decreases to 2.5 cm. This same value is maintained when the replacement is 10% in MRC-10.

The results suggest that the incorporation of calcined clam shell reduces workability compared to conventional mortar, but increasing the replacement percentage from 5% to 10% does not produce a significant additional decrease in workability. It should be noted that the results of the MRC specimens are superior to the MR specimens and that this may be due to the increase in the amount of MRC in the mixture. The decrease in workability in MRC samples, where part of the cement is replaced by a calcined clam shell, can be explained due to its physical and chemical nature. A calcined shell tends to absorb more water due to its high specific surface area and porosity compared to conventional cement, which reduces the amount of free water available in the mix to lubricate the particles,

thus decreasing the fluidity or workability. Furthermore, the chemical composition of the calcined shell, rich in calcium carbonate (CaCO_3), can influence the interactions between particles and water, increasing the water demand in the mix [54,55].

3.3. Flexural Tensile Strength

The results of the flexural tensile test at 28 days of age showed a slight increase of 0.04% and 0.03% in the strength of the specimens with uncalcined shells, MR-05 and MR-10, respectively, and an increase of 0.05% in the strength of the specimens with calcined shells, MRC-05 and MRC-10, compared to the control specimen MR-00. However, these results do not confirm that the strength is definitively greater in the specimens with shell replacements due to the observed deviations. The detailed results of the flexural tensile strength are presented in Table 3.

Table 3. Flexural tensile strength results.

Specimen	#	Flexural Tensile Strength [MPa] at Age:				Standard Deviation at 28 Days
		3 Days	7 Days	14 Days	28 Days	
MR-00	1	7.10	10.29	13.74	15.03	0.87
	2	7.05	10.20	16.92	16.55	
	3	6.41	9.36	13.14	15.03	
MR-05	1	5.21	8.72	13.93	15.59	0.97
	2	5.53	9.68	14.33	15.47	
	3	5.31	8.98	12.76	17.21	
MR-10	1	5.91	8.62	12.79	17.53	1.44
	2	5.21	9.39	12.79	15.58	
	3	5.94	10.78	13.19	14.72	
MRC-00	1	3.75	8.14	9.55	11.25	0.81
	2	3.41	7.28	10.24	12.26	
	3	3.07	8.72	9.68	12.84	
MRC-05	1	3.15	6.57	10.51	12.92	0.25
	2	3.23	7.10	9.87	12.45	
	3	2.25	6.99	10.53	12.55	
MRC-10	1	3.09	6.28	9.28	13.22	0.57
	2	2.83	7.22	8.16	12.08	
	3	2.47	7.22	8.87	12.53	

Figure 7a,b shows a graphical representation of the results of the flexural tensile test. From these, it can be seen that calcination did not provide improvements in strength, since this decreases at 28 days of age by 0.21% in the MRC-05 and MRC-10 specimens compared to their MR-05 and MR-10 counterparts, respectively.

Calcination decreases flexural tensile strength due to changes in the chemical and physical structure of the material resulting from this process. During calcination, the calcium carbonate (CaCO_3) present in seashells breaks down into calcium oxide (CaO) and carbon dioxide (CO_2). This change reduces the amount of cohesive material that can contribute to the mechanical strength of the mortar.

Furthermore, calcination can also generate a more porous and less dense microstructure in the material, which affects negatively its ability to resist tensile stresses. This additional porosity allows more microcracks to form under load, which decreases strength. Overall, the calcination process, if not properly controlled, can reduce the quality of the material in terms of mechanical strength, as demonstrated by the decrease observed in the experimental results.

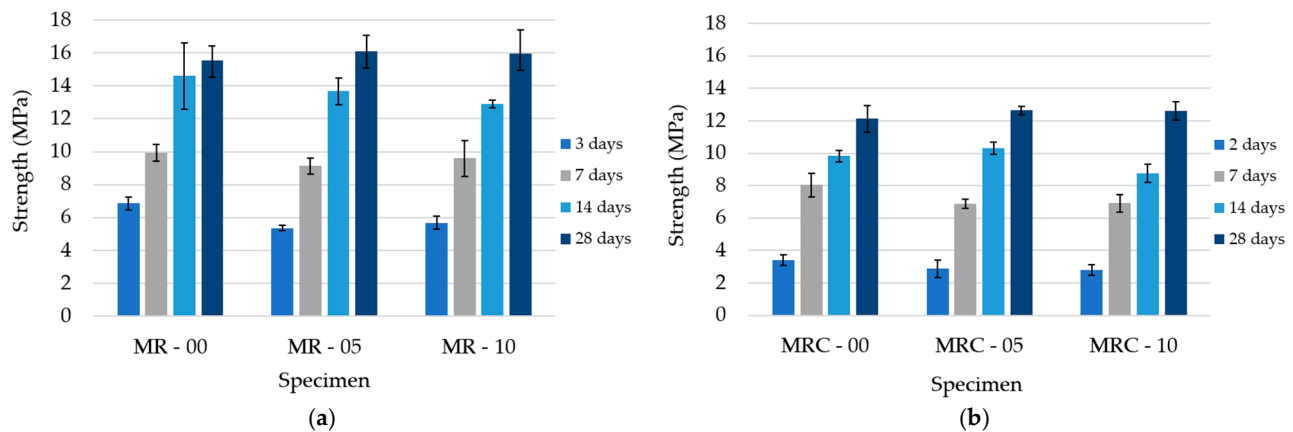


Figure 7. Summary of flexural tensile strength results: (a) specimens with uncalcined shell and (b) specimens with calcined shell.

The trend of these results is similar to those observed in [43]. The tensile strength at 28 days shows the best results for cement replacements with bivalve clams at 5% and 10%, achieving 2.92 MPa and 2.97 MPa, respectively, which are above the 2.22 MPa presented by the standard. Additionally, the work conducted with the *Cardiidae* species [56] at 5% and 10% replacements does not reach the strength of 9.9 MPa achieved by the standard sample, obtaining only 8.72 MPa and 8.70 MPa, respectively.

3.4. Compressive Strength

Table 4 presents the results of the compression test for the specimens with uncalcined and calcined shells. These results were obtained by testing the halves from the flexural tensile test, which are referred to in the table as P1 and P2.

Table 4. Compressive strength results.

Specimen	#	Compressive Strength [MPa] at Age:								Standard Deviation at 28 Days
		3 Days ¹		7 Days		14 Days		28 Days		
		P1	P2	P1	P2	P1	P2	P1	P2	
MR-00	1	7.54	7.80	14.79	15.98	22.85	22.54	22.72	27.29	2.61
	2	8.03	7.85	15.63	16.02	22.97	22.32	29.61	29.86	
	3	7.57	8.08	15.42	15.64	21.34	20.87	28.50	28.18	
MR-05	1	6.10	6.20	14.29	13.91	19.59	19.83	25.78	26.25	0.98
	2	6.23	6.27	12.81	12.97	20.90	20.14	26.98	25.91	
	3	6.18	6.37	12.63	12.86	19.38	19.33	24.22	24.90	
MR-10	1	5.54	5.57	11.65	11.38	19.11	19.24	21.95	22.00	0.5
	2	5.61	5.59	12.03	11.84	20.25	17.71	22.99	22.53	
	3	5.34	5.79	12.19	12.92	18.98	18.40	22.53	21.61	
MRC-00	1	3.34	3.18	9.67	11.40	15.52	15.37	19.36	20.46	1.03
	2	3.42	3.29	9.36	10.02	15.44	14.72	21.31	20.83	
	3	3.73	3.31	9.82	10.80	16.11	14.53	22.44	21.41	
MRC-05	1	2.88	2.93	9.02	10.41	13.64	13.66	17.76	18.32	1.17
	2	2.64	2.97	9.55	9.40	13.34	14.30	18.74	17.71	
	3	2.80	2.98	10.03	9.56	13.58	13.53	17.40	15.36	
MRC-10	1	2.91	2.88	7.73	8.64	13.46	13.08	16.64	18.10	2.66
	2	2.69	2.78	9.28	9.25	12.36	12.53	12.80	13.49	
	3	2.82	2.31	8.17	8.61	12.48	12.49	19.07	18.37	

¹ For calcined specimens (MRC) it corresponds to 2 days.

The compressive strength of the specimens tested at 28 days of age decreased by 0.03% and 0.16% in the specimens with uncalcined shells MR-05 and MR-10, respectively, and by 0.32% and 0.39% in the specimens with calcined shells, MRC-05 and MRC-10, respectively, compared to the control sample MR-00. Considering the dispersion of the data, the results of the standard sample show a clear advantage over the samples with 10% replacement, while for the sample with 5% replacement, the ranges generated with the dispersion partially coincide with MR-00 specimen.

A graphical representation of the results is presented in Figure 8. From this, it is perceived that there is no improvement in the compressive strength at 28 days of age in the specimens when cement is replaced with calcined clam shells since the MRC-05 and MRC-10 specimens decreased their strength by 0.32% and 0.26% compared to their MR-05 and MR-10 peers. These results may be due to the effect of calcination, which, when not well controlled, leads to a reduction in strength due to changes in the microstructure and increased porosity, which seems to be in line with what was observed in this study.

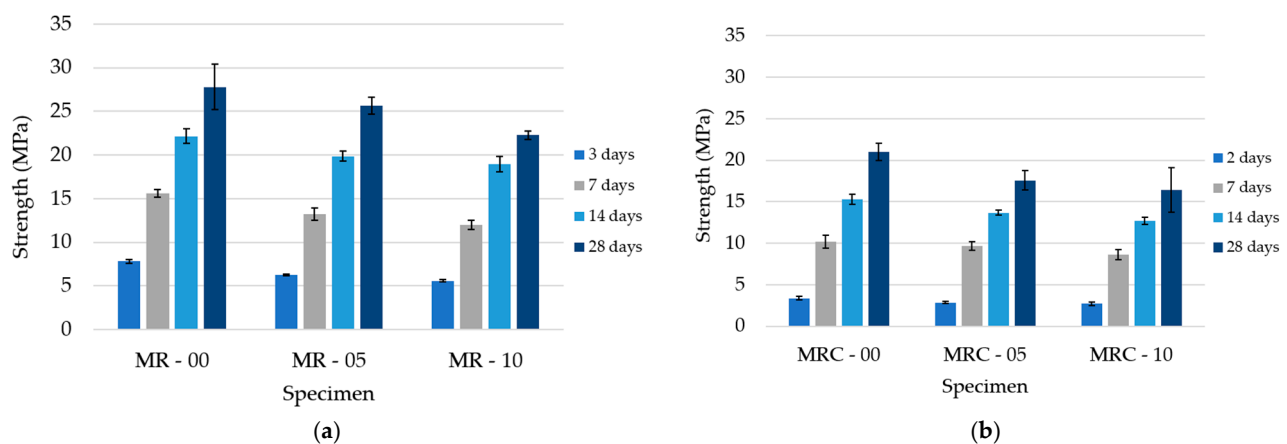


Figure 8. Summary of compressive strength results: (a) specimens with uncalcined shell and (b) specimens with calcined shell.

The results obtained do not coincide with those obtained by [16], where the compressive strength with a 5% replacement of bivalve clams by cement, exceeded the magnitude recorded by the standard sample, reaching up to 101% of this value. In this same way, Cardiidae [19] obtained an improvement of up to 91% in compressive strength compared to the standard specimen, using a partial replacement of 5% of shells by cement.

Given the results obtained in this work, we consider it necessary for future work to adjust the calcination temperature and time since this could help reduce the porosity of the resulting material and improve internal cohesion. It is important to ensure that the temperature is sufficient to decompose the calcium carbonate, but not so high as to cause an excessively porous microstructure.

Homogeneity is also required during the calcining process to ensure even calcination throughout the shell mass. This can be achieved by using thinner layers for calcining or by using some device that keeps the mass mixed during the process.

On the other hand, it must be ensured that the seashells are well crushed and that the particle size is small enough to act as a good filler in the mortar matrix. A finer particle size could help improve the density of the material and therefore its compressive strength, as presented by Hasnaoui et al. [30], who performed partial replacements of scallop shells with a particle size of 63 by cement with percentages of 10%, 20% and 30%, obtaining a compressive strength of 50 MPa for the 30% replacement, which exceeded the control sample whose strength was 35 MPa. Wang et al. [41] carried out a partial replacement of cement using residual seashells with a particle size of 60 in percentages of 5%, 10%, 20% and 40%, obtaining for the last one a compressive strength increase in 353–473% order.

Also, the use of additives that improve the adhesion between the shell particles and the cementitious matrix, such as superplasticizers or cohesion-enhancing agents, could improve compressive strength. Finally, additional pretreatment, such as longer drying or chemical cleaning of the shells, could be considered to remove impurities that interfere with the quality of the final material.

3.5. Economic Analysis

In order to compare the per cubic cost associated with the fabrication of conventional mortar and mortar with cement replacement, an economic analysis was developed. This analysis considers both the direct value of the materials on the market and the obtaining of the residue, considering the time to carry out the calcining and grinding processes, which are expressed in terms of kilowatt-hours [kWh]. For the evaluation of the value of the [kWh], a monthly use greater than 1000 [kWh] is considered. Table 5 presents a summary of the reference values used in the estimation of the economic savings that occur in the mixtures with partial cement replacement.

Table 5. Reference values.

	Format	Unit	Price (\$USD)	Unit Price (\$USD/unit)
Cement	25	kg	4.04 [57]	0.16
Water	1	L	0.0015 [58]	0.0015
Sand	25	kg	1.68 [59]	0.067
Uncalcined shells	1	kg	0.0050	0.0050
Calcined shells	1	kg	0.096	0.096
Energy	1	kWh	2.5 [60]	2.5

The unit costs presented in Table 5 were brought to values proportional to 1 [m³] determining the average weight of the mortar samples obtained in this study, which was 0.5632 [kg], which is equivalent to a total of 2200 [kg] of mix for each [m³] of mortar. The results for a mix of 1 [m³] are presented in Table 6.

Table 6. Dosing costs in mixture of 1 [m³].

Specimen	MR-00	MR-05	MR-10	MRC-00	MRC-05	MRC-10
Replacement percentage	0%	5%	10%	0%	5%	10%
Sand (\$USD)	98.53	98.53	98.53	97.45	97.45	97.45
Water (\$USD)	0.37	0.37	0.37	0.40	0.40	0.40
Cement (\$USD)	79.08	75.12	71.17	78.21	74.30	70.39
Residue (\$USD)	0	0.12	0.24	0	2.43	4.86
Total (\$USD)	177.98	174.14	179.31	176.06	174.58	173.1
Savings compared to the standard mix	0%	2.16%	4.31%	0%	0.84%	1.68%

Table 6 shows that the use of seashells as a partial replacement for cement in mortars can be economically viable. By substituting 5% and 10% of the cement in the MR-05 and MR-10 mixes, respectively, a cost reduction of 2.16% and 4.31% is achieved compared to the standard mix MR-00. Similarly, in the mixes with calcined shells, MRC-05 and MRC-10, the savings are lower, at 0.84% and 1.68%, respectively. These savings arise mainly from the reduction in the cost of cement, which is partially replaced by low-cost waste (seashells). However, the savings are more notable in the case of direct replacement, suggesting that the economic viability depends in part on additional processing, such as calcination.

4. Conclusions

In this study, the feasibility of using Biobío clam shells as a partial replacement for cement in mortars was investigated, analyzing its impact on the mechanical properties of the material. Comparative tests were performed on samples with different replacement

percentages, both with calcined and non-calcined shells, to evaluate their compressive and flexural tensile strength. The results obtained provide a comprehensive view of the advantages and limitations of this alternative, allowing us to identify key areas for optimization in future works. The main conclusions of the study are presented below:

The results indicate that, although the use of uncalcined shells at replacement percentages of 5% and 10% shows a slight increase in flexural tensile strength, these increases are not significant enough to ensure consistent improvements compared to the control sample. On the other hand, calcined shells not only do not improve the mechanical strength of the mortar but also show a decrease in compressive and flexural strength.

The results obtained in this study differ from some previous studies that reported improvements in strength when using seashells as a partial substitute for cement. In particular, the compressive strength results were lower than those reported in the literature, indicating the need for adjustments in experimental parameters such as calcination temperature and time.

To improve the feasibility of using seashells in mortars, it is recommended to optimize the calcination process, reduce the particle size of the shells, and explore the use of additives that improve the internal cohesion of the material. Furthermore, further research is needed to better understand how these factors affect the microstructure and mechanical properties of the mortar.

Despite technical challenges, the use of seashells as a partial substitute for cement remains a promising option from an environmental perspective. Reducing the use of Portland cement and valorizing abundant waste such as seashells could contribute to sustainability in construction, provided that processes are optimized to ensure adequate mechanical performance.

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