sustainability

MDPI

Article

Assessing Durability Properties and Economic Potential of Shellfish Aquaculture Waste in the Construction Industry: A Circular Economy Perspective

Begoña Peceño [1,*], José Bakit [2,3,*], Niris Cortes [1], Bernabé Alonso-Fariñas [4], Enzo Bonilla [1] and Carlos Leiva [4]

[1] Escuela de Prevención de Riesgos y Medioambiente, Facultad de Ciencias del Mar, Universidad Católica del Norte, Larrondo 1281, Coquimbo 1780000, Chile; ncortes@ucn.cl (N.C.); ebonilla@ucn.cl (E.B.)
[2] Departamento de Acuicultura, Facultad de Ciencias del Mar, Universidad Católica del Norte, Larrondo 1281, Coquimbo 1780000, Chile
[3] EqualSea Lab-CRETUS, Departamento de Economía Aplicada, Universidad de Santiago de Compostela, 15705 Santiago de Compostela, Spain
[4] Departamento de Ingeniería Química y Ambiental, Escuela Técnica Superior de Ingeniería, Universidad de Sevilla, Camino de los Descubrimientos s/n 41092, 41004 Seville, Spain; bernabeaf@us.es (B.A.-F.); cleiva@us.es (C.L.)
* Correspondence: begopc@ucn.cl (B.P.); jbakit@ucn.cl (J.B.)

Abstract: The construction industry's high demand for natural resources, combined with the waste generated by agriculture, creates an opportunity for the circular economy. This experiment used the $CaCO_3$ found in scallop shells as an ingredient for the manufacture of fire-resistant materials, replacing gypsum in compositions of 40% and 50% by weight. The mechanical compressive strength was estimated for both freeze-thaw cycles and acid and sulfate attacks. The cost of disposing of scallop shell waste in landfills, savings from substitution, and the payback period relative to the amount of production were determined. The compressive strength of the materials decreased by 80% when subjected to freeze-thaw cycles and sulfate attack. In response to acid attack, they showed a 100% increase in strength during the first three weeks and a decrease thereafter. The savings amounted to $46.36 (22.4%) for 40% replacement and $58.93 (28.4%) for 50%. Respectively, return on investment is achieved at 800- and 630-per-metric ton produced. The difference between the costs of waste disposal (in aquaculture) and the potential savings from using $CaCO_3$ as a raw material (in construction) creates an opportunity for commercialization between the two industries, serves as a reference for decision-makers, and complies with circular economy principles, reducing both inputs of raw materials and outputs of waste.

Keywords: construction materials; durability; circular economy; aquaculture waste; *Argopecten purpuratus*; seashells wastes; freeze-thaw cycles; recycling

check for updates

Citation: Peceño, B.; Bakit, J.; Cortes, N.; Alonso-Fariñas, B.; Bonilla, E.; Leiva, C. Assessing Durability Properties and Economic Potential of Shellfish Aquaculture Waste in the Construction Industry: A Circular Economy Perspective. *Sustainability* **2022**, *14*, 8383. https://doi.org/10.3390/su14148383

Academic Editors: Jinhui Li and Abhishek Kumar Awasthi

Received: 7 June 2022
Accepted: 2 July 2022
Published: 8 July 2022

1. Introduction

The construction industry has the highest demand for natural resources worldwide: 44% of mineral resources [1], 40% of energy resources [2], 12% of water [3], and also produces 40% of all waste [3]. Urban expansion and densification can also lead to further soil degradation and deterioration [4]. According to projections from the United Nations [5], if there is no change in how the construction sector operates, these impacts will be exacerbated by the scarcity of material resources, land use changes, and growing populations. In order to reduce the impacts of construction, the incorporation of waste as a raw material [6,7] or proposals to improve the mechanical properties of the material or the maintenance of buildings [8,9] are essential.

Although there is no official record of waste produced by the aquaculture industry, shells account for approximately 40% to 70% of the total weight of shellfish waste [10].

Seashells have little to no commercial value and are generally dumped into the sea or deposited in landfills [11]. Incorrect management of this waste causes:

- Environmental problems: these wastes can produce odors due to the decomposition of organic matter or of salts contained in the shells, emitting gases such as H_2S, NH_3 (ammonia) and organic compounds such as amine [11].
- Economic problems: pollution and odors have an economic impact on tourism given that aquaculture enterprises are located on seashores with heavy tourism [12].
- Health problems: illegal dumping of these wastes attracts biological vectors such as rats and mosquitoes in nearby populations [13].
- Social problems: currently, there are few economic and effective solutions for managing shell waste, which has led to the proliferation of illegal waste dumping near populated areas [14]. The foul odors and contamination from dumping have led to protests and complaints from neighboring communities [15].

Seashells are primarily composed of $CaCO_3$ [12]. As such, recycling has been widely studied as a source of $CaCO_3$ or as CaO [16–21]. Seashell wastes were used in 15th-century Latin America as a raw material for the manufacture of Tabby concrete [22]. Currently, 9% of global seashell waste is recycled as a substitute for limestone in fertilizers and feed additives in poultry farming [23–25]. There are research studies that have analyzed the use of $CaCO_3$ and CaO as adsorbents in polluted waters [26–28], as a catalyst in biodiesel production [29,30], and as polymer fillers [31–33]. In the construction sector, seashell wastes have been studied for use as fine and/or coarse aggregates in concretes and mortars [34–37], as a cement substitute [38,39], as a raw material for cement clinker [40,41], and as cement blocks [42]. Fireproofing materials prevent or retard the passage of extreme heat in order to protect more important elements, such as steels that lose their mechanical properties at high temperatures, and prevent the spread of fire throughout the floors of a building. When heated, such as during a fire, gypsum undergoes endothermic decomposition according to the reaction:

$$CaSO_4 \cdot 2H_2O \rightarrow CaSO_4 \cdot 1/2H_2O + 3/2H_2O \quad (1)$$

$$CaSO_4 \cdot 1/2H_2O \rightarrow CaSO_4 + 1/2H_2O \quad (2)$$

Reaction 1 starts at around 120 °C when semi-hydrate gypsum is produced. In reaction 2, semi-hydrate gypsum is converted to anhydrous gypsum at around 200 °C [43–45]. Both Reactions 1 and 2 are endothermic reactions, in which heat is removed from the environment. $CaCO_3$ exhibits similar behavior. At high temperatures (600 °C and 800 °C), $CaCO_3$ undergoes endothermic decomposition (reaction 3):

$$CaCO_3 \rightarrow CaO + CO_2 \quad (3)$$

The use of aquaculture wastes as inputs for materials from other industries is a productive strategy that has been developed in recent decades [46–50]. Initially recognized as recycling strategies and studied through economic or life cycle cost (LCC) analysis, they are nowadays associated with circular economy strategies and studied using life cycle assessment (LCA). LCA- and LCC-type economic analyses are very flexible and can be used for economic evaluation in areas as different as building material reuse [51,52], e.g., as PET for manufacturing blankets [53], and extending the life of household appliances [54]. Some findings indicate that LCA and LCC economic analyses indicate that high resource and energy consumption, direct emissions, and the transport of raw materials during cement production are the main processes contributing to most environmental categories and economic costs [52,55].

In order to address both environmental and economic impacts, trends in concrete technology are currently moving towards sourcing sustainable alternative materials for making concrete to minimize over-reliance on natural resources [56]. In this scenario, the use of waste from aquaculture, specifically scallop shell waste, appears to be a promising solution [11,38], capable of bringing about a circular economy between aquaculture and construction. However, the implementation of a circular economy between these industries must address challenges in both accessing capital and strengthening the trade network between supply and demand, identified as barriers, and in strengthening the organizational culture of every company [57]. To advance a circular economy, a qualitative estimate has been conducted in 2021 of the economic benefits of using scallop shell powder as a cement substitute in the development of blended cements [58], not only to improve sustainability, but also to reduce production costs. An approach to the utilization of seashell wastes, specifically scallop (*Argopecten purpuratus*), as fine and coarse additives in the manufacture of building materials has been carried out [55]. The authors present these wastes as an alternative that consumes little energy in recycling compared to raw materials coming from mining and find that despite the additional cost of substituting scallop shells, the associated benefits include longer pavement life and better resistance to deformation and humidity.

Looking at the performance of the aquaculture and construction industries in Chile allows us to identify linear economic models, where scallop shell waste is discarded without use [46,59] and more than 70% of raw materials for construction materials come from virgin natural resources [60]. Figure 1 shows both the amount of calcium carbonate and gypsum extracted to supply the resource demand for the production of construction materials, and the amount of scallop landings (i.e., muscle and shells). Producers of building materials make up the demand for natural resources and are identified in green on the central map among the industries where a circular economy could emerge. The performance of scallop shells as an ingredient in the fabrication of building materials has been addressed in the literature, which nonetheless indicates challenges such as the economic evaluation of substitution [38] and comparison with the production cost of conventional materials [11].

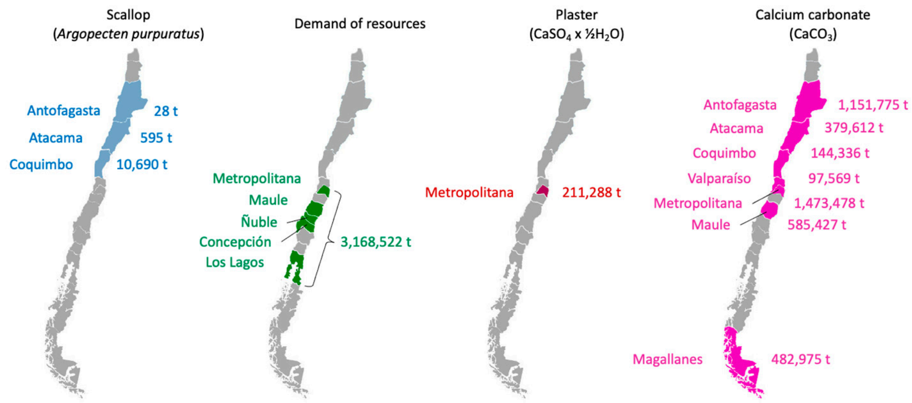


Figure 1. Geographical distribution in Chile of raw, whole scallops, including shells in metric tons (t) versus resource demands (t) in the construction industry.

The recycling of mollusk shells into fireproof materials has been evaluated in this context [46]. However, the durability of building materials using scallop shell waste has not been evaluated for these applications. In order to contribute to the knowledge of how to implement a circular economy strategy between the construction and aquaculture industries, the objectives of this study are: (1) to evaluate the durability properties of the construction material with gypsum substitution by $CaCO_3$ from scallop (*Argopecten purpuratus*) aquaculture waste. (2) The economic performance of the experience was measured to evaluate the circular economy potential between the two industries.

2. Materials and Methods

2.1. Materials

Our study used Chilean scallops (*Argopecten purpuratus*) produced using aquaculture, hereinafter scallops (S), from Invertec, located in Tongoy (Coquimbo Region) and commercial gypsum (G) in accordance with European Standard EN 13279-1 [61]. The scallop shells were washed in a tank to remove salt from their surface, using 1.5 L of water per kg of scallop shells to be treated. Subsequently, organic matter was eliminated using an electric oven at 300 °C for 3 h. The scallop shells were crushed using a jaw crusher and sieved to 600 µm. Figure 2 shows the particle-size distribution of scallop shells and gypsum.

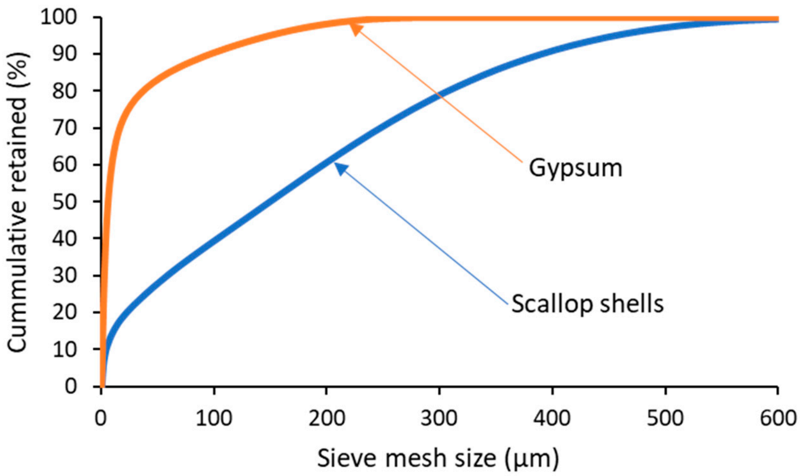


Figure 2. Particle-size distribution.

The chemical compositions of the scallop shells and gypsum were determined according to American standards, ASTM D3682 [62], using an absorption spectrometer (Model 3100, Perkin-Elmer, Waltham, Massachusetts). The specific gravity of the materials used in this study was determined according to American standards, ASTMD854 [63]. As seen in Table 1, the majority component of the scallop shells was $CaCO_3$. Losses due to calcination were high, mainly because $CaCO_3$ decomposes due to reaction 1, which is represented in the table as loss on ignition (LOI). Commercial gypsum is primarily composed of $CaSO_4$. The average scallop shell particle size was almost 72 times larger than the average gypsum particle size. Furthermore, the specific gravities of scallop shells and gypsum were similar.

Table 1. Chemical composition (weight), average particle size (µm) and specific gravity (g/cm^3).

	S (%) [(1)]	**G (%)** [(2)]
SiO_2	N.D. [(3)]	0.88
Al_2O_3	N.D. [(3)]	0.18
Fe_2O_3	N.D. [(3)]	N.D. [(3)]
MnO	N.D. [(3)]	0.02
MgO	N.D. [(3)]	N.D. [(3)]
CaO	54.76	40.56
Na_2O	0.57	0.07
K_2O	N.D. [(3)]	N.D. [(3)]
TiO_2	N.D. [(3)]	N.D. [(3)]
P_2O_5	0.13	N.D.
SO_3	0.32	45.56
PC	44.42	12.52
Median size (µm)	180	25
Specific gravity (g/cm^3)	2.76	2.77

Note: [(1)] S: scallop shells, [(2)] G: gypsum, [(3)] N.D: not detectable.

Product samples were fabricated following a simple, low-cost method under standard laboratory conditions (temperature: 25 °C and 45% humidity). To prepare the samples, the solid components were weighed in compositions of 40% scallop shells and 60% gypsum (40% S), 50% scallop shells and 50% gypsum (50% S), and the control sample, 100% gypsum (0% S). The technical feasibility of using shells in these compositions for this application was shown in [46]. All solids were mixed into a homogeneous mixture using a mixer, and water was added at a water/solid ratio equal to 0.5. The water ratio was kept constant for the fabrication of all samples [44]. It was mixed again until a homogeneous paste was obtained. All the flame retardant materials were removed from their molds after 24 h and cured at room temperature (20 °C on average) with constant humidity (45% relative humidity on average) for an additional 28 days. The specimens were created using cylindrical molds with a diameter of 34 mm and a height of 40 mm.

2.2. Methods

2.2.1. Product Durability Tests

The durability of the material was determined using three aspects: resistance to acid attack, resistance to sulfate attack, and resistance to freeze-thaw cycles. Compressive strength was analyzed each week for 10 weeks total. Before undergoing durability tests, the manufactured materials (0% S, 40% S, 50% S) were measured for compressive strength and bulk density. The compressive strength (Sc) of the samples was determined using a compression testing machine (Controls, 65-L28F12, 300 kN), in accordance with the European standard, EN 13279-2, [64]. The method described in the American standard, ASTM E 605 [65], was used to measure density (d). For compressive strength and bulk density, 3 tests were performed for each composition. Compressive strength and bulk density were the arithmetic mean of 3 specimens tested. For each of the compositions and properties (compressive strength and bulk density), the standard deviation was determined.

- Resistance to Acid Attack

Resistance to acid attack (Ra) was determined using the procedure detailed in previous studies [66]. The specimens were first cured for 28 days. Half of the fabricated samples were immersed in water (reference samples) (Figure 3a) and the other half in 1 N sulfuric acid (Figure 3b). As shown in Equation (4), the compressive strength of the attacked samples was measured each week and compared with the compressive strength of the reference samples. Resistance to acid attack was sampled in three specimens each week for 10 weeks.

$$Ra = \frac{CS_{acid}}{CS_{water}} \quad (4)$$

where, CS_{acid} is compressive strength of samples attacked by acid and CS_{water} is Compressive strength of samples attacked by water.

(**a**) (**b**)

Figure 3. Submerged samples during (**a**) water immersion and (**b**) acid immersion.

- Resistance to Sulfate Attack

Resistance to sulfate attack was determined in accordance with the American standard, ASTM C 1012-13 [67]. The samples were immersed in a dilution of Na_2SO_4 at a concentration of 50 g/L of Na_2SO_4 (Figure 4). Each week, three specimens were tested for compressive strength over a period of 10 weeks.

Figure 4. Samples were submerged in sulfate salts.

- Resistance to Freeze-Thaw Cycles

Resistance to freeze-thaw was determined in accordance with the European standard, EN 12390-9 [68]. The samples were subjected to freezing phases at −18 ± 3 °C for 8 h during the day and thawing phases at 20 ± 2 °C for 16 h. Three specimens were tested for compressive strength each week over a period of 10 weeks.

2.2.2. Economic Analysis

- Benefits/Savings Related to The Use of $CaCO_3$—Construction

The economic analysis was carried out to determine both the costs (e.g., scallop shell conditioning, construction material manufacturing) and benefits (e.g., revenue, savings) of using scallop shells to substitute gypsum [46]. For the economic analysis, two different compositions, by weight, of gypsum and calcium carbonate from scallop shells were used: the first composition was 40% scallop shells and 60% gypsum (40% S), and the second composition was 50% scallop shells and 50% gypsum (50% S), which were compared with the commercial material (gypsum, 0% S). Scallop shell pre-treatment accounted for the costs incurred for the consumption of wash water required for removing impurities and the energy costs required for both the milling process and the calcination of the scallop shells. Costs were calculated based on one metric ton of material. The average exchange rate used was 792 Chilean pesos for each US dollar ($) [69]. The analysis does not incorporate transportation costs or other costs that may be associated with shell availability.

To calculate the benefits/savings related to the replacement of gypsum with $CaCO_3$, the manufacturing costs of construction materials were determined, including both raw materials (gypsum and calcium carbonate) and inputs (energy and water). Given the absence of a market to commercialize building materials with added calcium carbonate from scallop shells, the benefits (e.g., savings) were defined as the difference between the total cost value of building material production and those achieved with the different compositions produced.

- Scallop Shell Generation Potential and Disposal Cost—Aquaculture

The landings data for Chile were collected from the annual statistical reports of Sernapesca (National Fisheries and Aquaculture Service). Landings of scallop shells were differentiated by fishery (extraction) and aquaculture (farming). To calculate scallop shell availability, the Condition Index (CI) ratio was used, which allows for differentiating the meat and shell weight of bivalve mollusks [70]. The CI varies according to inherent factors such as gonad weight and muscle growth and other environmental factors that influence the reproductive stage and feed supply. Due to the small number of producers (large-, medium-, and small-scale), the final costs of scallop shell disposal (waste) were collected in a semi-structured interview. The selected producers are located in the region of Coquimbo, where most of Chile's production is concentrated (Figure 1).

- Modified Payback Period

The payback period is a financial indicator to determine the time it takes for investments to pay off, i.e., the time it takes for revenue to cover costs. The shorter the payback period, the lower the return on investment. However, given the difficulty of establishing production times, we worked with the modified payback indicator, which contrasts savings versus production, thus quantifying the amount of construction material required to recover the amount of the initial investment. Laboratory adjustments and the acquisition of equipment were considered as initial investments and amounted to $36,995. The performance of the quantity produced versus the savings obtained was graphed.

- Circular Economy—Construction and Aquaculture

The economic evaluation was complemented by determining the function that calculates the cost of final disposal of scallop shells (given their waste condition). For the construction industry, savings from the addition of scallop shell as a raw material were evaluated. The savings scenarios of 40% S and 50% S scallop shell substitution were graphed individually against aquaculture waste disposal costs.

3. Results and Discussion

3.1. Durability

3.1.1. Initial Properties

As can be seen in Table 2, the density and compressive strength (Sc) of the materials decrease with the addition of scallop shell waste. Density decreased because the waste has a higher particle size distribution than gypsum, increasing the porosity between particles. Regardless of their proportion, and in accordance with the European standard, EN 13279-1 [61], all materials would have a compressive strength greater than 2.0 MPa and, therefore, all mortars produced met this requirement. According to the European standard, EN 12859 [71], all materials were classified as high density.

Table 2. Compressive strength and density.

	Density (kg/m^3)	Compressive Strength (MPa)
0% S	1528.16 ± 2.10	13.51 ± 1.37
40% S	1474.00 ± 12.54	13.10 ± 1.53
50% S	1468.15 ± 16.01	10.88 ± 0.54

Note: 0% S: 100% gypsum, 40% S: 40% scallop and 60% gypsum and 50% S: 50% scallop and 50% gypsum.

3.1.2. Acid Attack

During the first 3 weeks, in the materials with scallop shells (40% S and 50% S) subjected to acid immersion, the compressive strengths were reduced to 6.1 MPa. However, in the case of the materials subjected to water immersion, the compressive strengths were reduced to 2.2 MPa. After week 3, at 40% S and 50% S, the compressive strengths of the materials subjected to acid immersion dropped drastically to 2.5 MPa. As shown in Figure 5, as the amount of waste increases in the 40% S (40% scallop and 60% gypsum) and 50% S (50% scallop and 50% gypsum) samples, resistance to acid attack (Ra) increases and remains above 1 until week 5. This is because, in an acidic medium, part of the calcium in the scallop shells dissolves in water as Ca^{2+} and reacts with SO_4^{2-}, producing $CaSO_4$ (gypsum), as shown in Figure 6. The gypsum that forms around the material has a compressive strength of 5 MPa [44]. However, after week 3, resistance to acid attack (Ra) begins to decrease, and by week 5, Ra is less than 1. As shown in Figure 6c, this is because the fabricated gypsum produces a volumetric expansion of the material and leads to spalling of the surface layers and, consequently, a decrease in compressive strength [72].

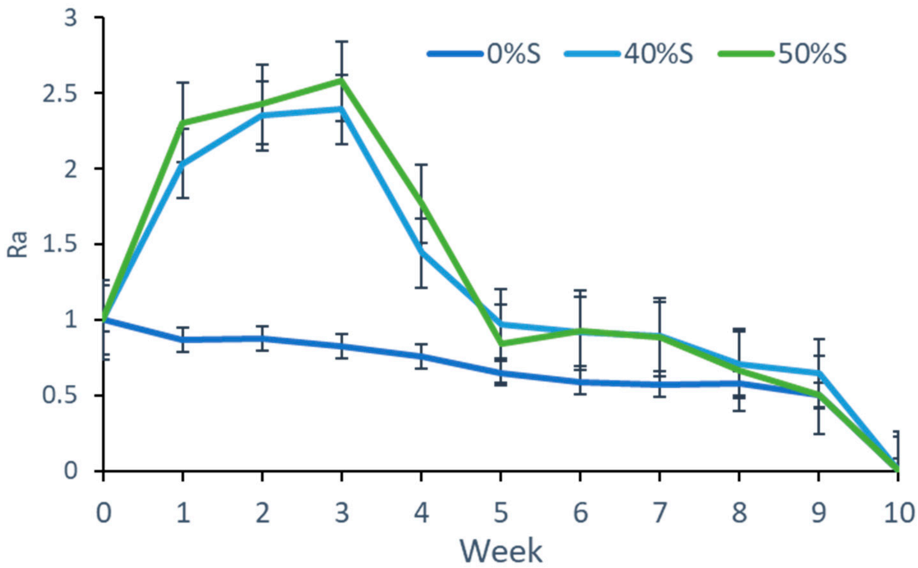
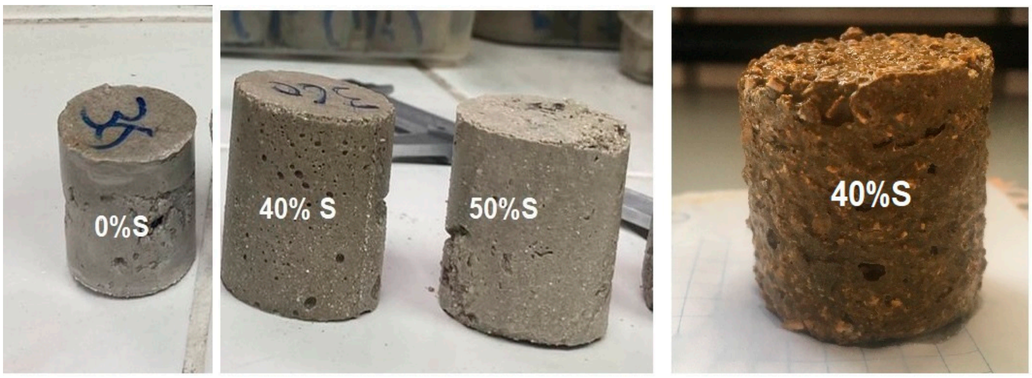


Figure 5. Variation of compressive strength against acid attack. Note: 0% S: 100% gypsum, 40% S: 40% scallop and 60% gypsum and 50% S: 50% scallop and 50% gypsum.



(**a**) (**b**) (**c**)

Figure 6. (**a**) 0% S (gypsum), (**b**) 40% S (40% Scallop and 60% gypsum), 50% S after two weeks of acid immersion and (**c**) 40% S after five weeks of acid immersion.

3.1.3. Sulfate Attack

Sulfate attack is one of the most important aggressive risks to construction materials, causing losses in mechanical properties [73]. As shown in Figure 7, the compressive strength of 40% S and 50% S suffered a drop of almost 80% compared to 0% S (gypsum), which dropped 70%. After the first week, the mechanical strengths decreased further, and the 40% S and 50% S samples broke completely in the sixth week. During the first 3 weeks, the compressive strength was between 2.3 and 2.5 MPa. From the fourth week, the compressive strength was reduced below 2 MPa (minimum compressive strength required [61]). The deterioration seems to be related to the sedimentation of the products of physical crystallization, causing a higher pressure in the open pores of the material [74]. As shown in Figure 2, the scallop shells had a larger particle size, causing greater porosity [75].

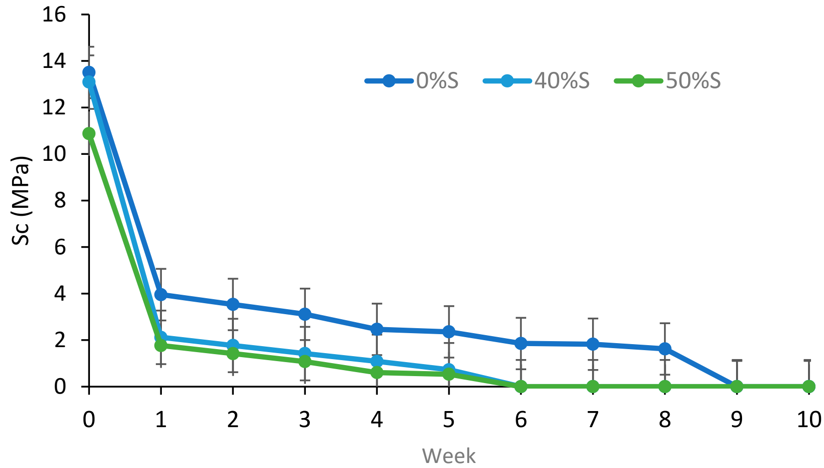


Figure 7. Variation of compressive strength against sulfate attack. Note: 0% S: 100% gypsum, 40% S: 40% scallop and 60% gypsum and 50% S: 50% scallop and 50% gypsum.

3.1.4. Resistance to Freeze-Thaw

All the mixtures exhibited a decrease in compressive strength after freezing and thawing (Figure 8). The 40% S and 50% S samples suffered a 70% decrease as of cycle 28 (week 4). After the first week of freeze-thaw cycles, the mechanical strengths of the scallop shell materials (40% S and 50% S) were reduced to 10.5 MPa for 40% S and 8.5 MPa for 50% S. In the fourth week, the compressive strengths of the materials with scallop shells (40% S and 50% S) were reduced below 2 MPa. However, in the case of gypsum (0% S), the compressive strength decreased more slowly. After the tenth week, the compressive strength of the gypsum remained above 2 MPa. This was because the scallop shells had a larger particle size, as shown in Figure 2, causing greater porosity. Therefore, the water permeated more when frozen, and as a consequence, generated microcracks [76].

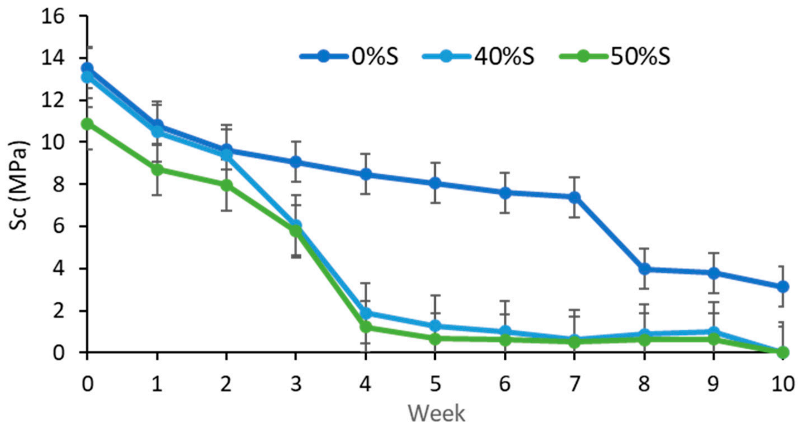


Figure 8. Variation of the compressive strength against the cycles of freezing and thawing. Note: 0% S: 100% gypsum, 40% S: 40% scallop and 60% gypsum and 50% S: 50% scallop and 50% gypsum.

3.2. Economic Analysis

3.2.1. Benefits/Savings Related to the Use of $CaCO_3$—Construction

The conditioning treatment for scallop shells to be used as ingredients to manufacture building materials results in production costs [11]. Pretreatment includes costs such as wash water for the removal of impurities and the energy expended in grinding and calcination. Table 3 shows the details of the costs for 40% S and 50% S compositions of scallop shell substitution for gypsum. It also shows that the pre-treatment cost is mainly determined by propane gas consumption and that the total cost increases as the composition of the pre-treated shell increases.

Table 3. Pre-treatment costs (US$) of scallop shells (S) by composition.

Pre-Treatment	Cost (US$)		
	0% S	40% S	50% S
Wash water	0	2.12	2.70
Propane consumption	0	25.23	32.07
Grinding energy	0	0.60	0.76
Pre-treatment cost	0	27.95	35.53

Note: 0% S: 100% gypsum, 40% S: 40% scallop and 60% gypsum and 50% S: 50% scallop and 50% gypsum.

The addition of calcium carbonate from scallop shells generates savings in the manufacture of building materials compared to the cost of materials with only gypsum. The breakdown of material production costs (Table 4) shows that, although pretreatment of the scallop shells entails costs, they are lower than the use of gypsum alone. For a composition of 40% S, the pretreatment cost was $27.95, a cost that was covered by the savings, which in total amounted to $46.36 (22.4% of the cost without adding shells). For compositions of 50% S, the cost of pretreatment increases to $35.53, and savings increase to $58.93 (28.4% of the cost without adding shells). Table 4 also shows that water and energy consumption costs are negligible in relation to the total cost. The total production cost decreases inversely proportional to the addition of scallop shell [46], due to the reduced cost of pretreating them. The reduced energy consumption responds to the challenges indicated by Hass et al. [77]. However, it does not provide a solution to the demand for fossil fuels in the pretreatment of scallop shells.

Table 4. Construction material manufacturing costs by the composition of scallop shells (US$).

Construction Material	Manufacturing Cost (US$)		
	0% S	40% S	50% S
Gypsum	206.77	132.43	112.27
Pre-treated scallop shell	0.0	27.95	35.53
Water	0.39	0.41	0.41
Energy	0.12	0.12	0.12
Total production costs	207.28	160.92	148.35

Note: 0% S. 100% gypsum, 40% S: 40% scallop and 60% gypsum and 50% S: 50% scallop and 50% gypsum.

3.2.2. Scallop Shell Generation Potential and Disposal Cost—Aquaculture

From the view of current research, the availability of scallop shells as waste from the extraction and cultivation of bivalve mollusks (aquaculture) creates a business opportunity to use them in the manufacture of various materials [48,50]. The availability of shells in a circular economy model creates a supply of raw materials and, at the same time, provides environmental relief by eliminating the need to dispose of scallop shells in landfills or dumps [78,79]. Table 5 shows the availability of scallop shells in Chile according to their geographic distribution. The calculation made for the year 2019 was based on the meat yield, which represents the difference calculated from the proportion of the weight of the hydrobiological resource and the fresh meat it contains. In addition, it was established that the amount of shells produced differs from the amount of scallop shells available due to the fact that the marketing of scallop shells arranges the meat on the half shell [59]. Scallop shell generation coincides with the region of extraction because it occurs in plants located close to farming centers. Small-scale fisheries (SSF) do not contribute to the generation of scallop shells due to the closure that prohibits extraction from natural habitats, allowing only aquaculture [80–82].

Waste management for the scallop industry is limited to final disposal in dumps or landfills. The main incentives for this waste management are the limited options for using this waste, the ease of access to these waste management units, and the relatively low cost of their use, a situation that differs from waste management in Europe, where taxes discourage disposal in landfills [56]. In addition, waste management costs also depend on the distance between where the waste is generated and the location of the landfill, which averages 45 km in the region of Coquimbo. Table 6 shows the individual costs of disposing of scallop waste and gives a value of $30.30 per metric ton.

Table 5. Availability of scallop shells in metric tons (t) by region.

	Scallop Landings (t)		Scallop Shells (t)	
Region	**SSF**	**Aquaculture**	**Generation**	**Availability**
Antofagasta	-	28	16.8	8.4
Atacama	-	595	357	178.5
Coquimbo	-	10.690	6.414	3.207
Total	-	11,313	6787.8	3393.9

Table 6. Costs of final scallop shell disposal in landfill sites using a 10 metric ton volumetric capacity waste transport system.

Description	Units	Value
Cost associated with waste transport	US$	101.01
Cost of landfill disposal	US$/kg	0.02
Total cost	US$	303.03

3.2.3. Modified Payback Period

The accumulation of savings per metric ton of building material with gypsum substitution by $CaCO_3$ from scallop shell recovery is presented in Figure 9. The starts of both savings functions (40% S and 50% S substitution) are at $36,995, which corresponds to the amount of the initial investment. Cost functions were constructed as savings were recorded. A return on investment for the 40% S strategy of replacing gypsum with scallop shell is reached at 800 metric tons produced, while an earlier return on investment is envisioned for the 50% S strategy, which is projected at 630 metric tons produced. The establishment of a market for construction materials from aquaculture waste in the future will allow for revenues to be determined (necessary to establish the economic balance between costs and benefits), as well as generate a circular economy framework between the construction and aquaculture industries.

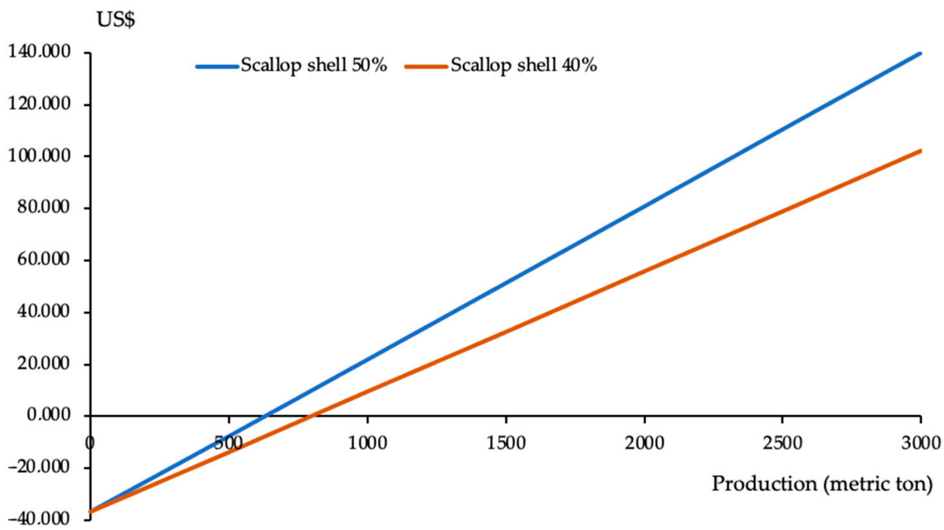


Figure 9. Modified payback period. Return on the initial investment for different shell compositions. Note: 40% S: 40% scallop and 60% gypsum and 50% S: 50% scallop and 50% gypsum.

3.2.4. Benefits/Savings Related to the Use of $CaCO_3$—Construction

A circular economy arrangement requires modifying a linear model of production to a circular one, where waste is reused as a raw material, and minimizing over-reliance on natural resources [56]. Adding value to scallop shell waste [83], makes it possible to establish the alternative potential of a circular economy between the aquaculture and construction industries, establishing a space for commercialization between both industries. This space for commercialization is open due to the difference between the cost of disposing of the aquaculture waste and the savings obtained by the construction industry by replacing gypsum with calcium carbonate from scallop shells. Figures 10 and 11 connect the cost/savings functions of the quantities generated/required for the different aquaculture/construction industries. The area opened between the costs and savings curves represents the marketing space between the construction and aquaculture industries. As production/requirement increases, the space for negotiation expands. The prices of commercialization will depend on each industry's supply chain, the elasticity of each savings/cost function, and the forward/backward integration capability of each industry. Entrepreneurial initiatives to reuse construction waste in new buildings present high-profit potential, even without incentives from the government [51,52].

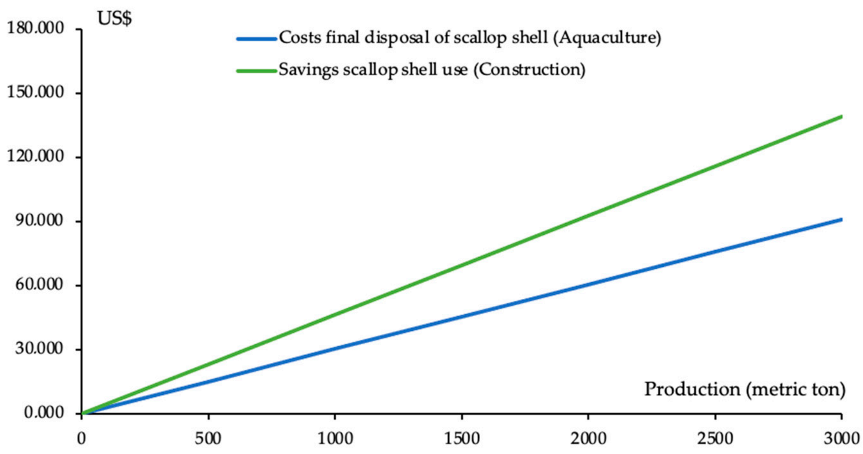


Figure 10. Circular economy. Commercialization space between the aquaculture and construction industries. Note: 40% S: 40% scallop and 60% gypsum).

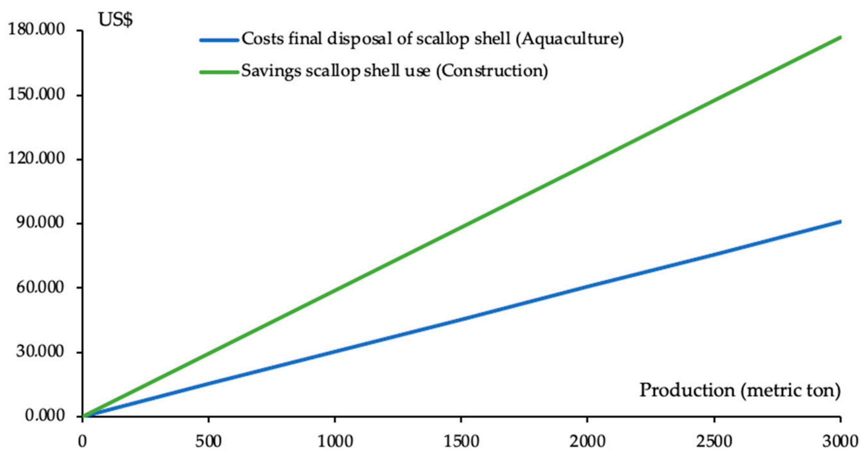


Figure 11. Circular economy. Commercialization space between the aquaculture and construction industries. Note: 50% S: 50% scallop and 50% gypsum).

4. Conclusions

Regarding the durability of materials with 40% and 50% scallop shell waste against acid attacks, resistance to acid attacks increased in the first few weeks. After the fourth week, the resistance to acid attacks begins to decrease. On the other hand, the durability of materials with 40% and 50% scallop shell waste had a greater deterioration of compressive strength (up to 80% less compared to gypsum) after sulfate attacks and freeze-thaw cycles. Materials with 40% and 50% scallop shell waste present lower mechanical properties than commercial standards during sulfate attacks and freeze-thaw cycles.

The replacement of gypsum with calcium carbonate is economically feasible for both 40% S and 50% S ingredient substitution. There is a direct relationship between the percentage of shell substitution and the savings generated. The difference between disposing of scallop shells as aquaculture waste and the potential savings from the use of calcium carbonate as an ingredient in the fabrication of construction materials creates a space that allows for commercialization between both industries and complies with the principles of the circular economy, reducing both inputs of virgin materials and outputs of waste.

These findings offer an encouraging scenario for projecting the replacement of seashells in larger scale prototype production and thus assessing the performance of the equipment to establish the exact payback time. Other future challenges that emerge from the present research are to determine the characteristics such as thermal insulation and to evaluate the durability of using seashells from the different species of seashell (mussel, clam, oyster). In addition, it is necessary to establish mechanisms that facilitate different resource flows from linear to circular models by both public and private decision-makers.

Author Contributions: Conceptualization, B.P. and J.B.; methodology, B.P. and J.B.; validation, B.P., J.B. and C.L.; formal analysis, B.P., J.B., N.C., C.L., B.A.-F. and E.B.; investigation, N.C., C.L., B.A.-F. and E.B.; resources, N.C., C.L., B.A.-F. and E.B.; data curation, B.P. and J.B.; writing—original draft preparation, B.P. and J.B.; writing—review and editing, B.P. and J.B.; supervision, B.P.; project administration, B.P.; funding acquisition, B.P. and J.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Fondo de Innovación para la Competitividad–FIC-R from Regional Government of Coquimbo (Chile), grant number BIP 40014353-0.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors would like to thank Ostimar S.A., Caleta San Pedro-La Serena, Cooperativa M31, MÁSMAR Transforma, Transforma Mejillón de Chile, and Cámara Chilena de la Construcción-La Serena for their collaboration and provision of industry data. The authors would also like to thank the editorial office and anonymous reviewers for their constructive observations and corrections.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Secher, A.Q.; Collin, C.; Linnet, A. Construction Product Declarations and Sustainable Development Goals for Small and Medium Construction Enterprises. *Procedia CIRP* **2018**, *69*, 54–58. [CrossRef]
2. Ingrao, C.; Arcidiacono, C.; Bezama, A.; Ioppolo, G.; Winans, K.; Koutinas, A.; Schmid, A.G. Virtual Special Issue on sustainability issues of by-product and waste management systems to produce building material commodities. *Resour. Conserv. Recycl.* **2017**, *126*, A4–A5. [CrossRef]
3. Alawneh, R.; Mohamed Ghazali, F.E.; Ali, H.; Asif, M. Assessing the contribution of water and energy efficiency in green buildings to achieve United Nations Sustainable Development Goals in Jordan. *Build. Environ.* **2018**, *146*, 119–132. [CrossRef]
4. Qin, G.; Zhang, P.; Wang, Y. Investigating an assessment model of system oil leakage considering failure dependence. *Environ. Sci. Pollut. Res.* **2020**, *27*, 40075–40087. [CrossRef] [PubMed]
5. UNEP. One Planet Network. Available online: https://www.unenvironment.org/explore-topics/resource-efficiency/what-we-do/one-planet-network (accessed on 2 June 2021).

6. Şahin, O.; İlcan, H.; Ateşli, A.T.; Kul, A.; Yıldırım, G.; Şahmaran, M. Construction and demolition waste-based geopolymers suited for use in 3-dimensional additive manufacturing. *Cem. Concr. Compos.* **2021**, *121*, 104088. [CrossRef]
7. Pasternak, G.; Ormeno-Cano, N.; Rutkowski, P. Recycled waste polypropylene composite ceramic membranes for extended lifetime of microbial fuel cells. *Chem. Eng. J.* **2021**, *425*, 130707. [CrossRef]
8. Zhou, Z.; Hu, J.; Li, F.; Zhang, J.; Lei, M. Elastic Modulus Prediction Model of Foamed Concrete Based on the Walsh Formula. *Appl. Sci.* **2022**, *12*, 5142. [CrossRef]
9. Zhou, Z.; Zhang, J.; Gong, C. Automatic detection method of tunnel lining multi-defects via an enhanced You Only Look Once network. *Comput.-Aided Civ. Infrastruct. Eng.* **2022**, *37*, 762–780. [CrossRef]
10. Tayeh, B.A.; Hasaniyah, M.W.; Zeyad, A.M.; Yusuf, M.O. Properties of concrete containing recycled seashells as cement partial replacement: A review. *J. Clean. Prod.* **2019**, *237*, 117723. [CrossRef]
11. Eziefula, U.G.; Ezeh, J.C.; Eziefula, B.I. Properties of seashell aggregate concrete: A review. *Constr. Build. Mater.* **2018**, *192*, 287–300. [CrossRef]
12. Kwon, H.B.; Lee, C.W.; Jun, B.S.; Yun, J.D.; Weon, S.Y.; & Koopman, B. Recycling waste oyster shells for eutrophication control. *Resour. Conserv. Recycl.* **2004**, *41*, 75–82. [CrossRef]
13. Felipe-Sesé, M.; Eliche-Quesada, D.; Corpas-Iglesias, F.A. The use of solid residues derived from different industrial activities to obtain calcium silicates for use as insulating construction materials. *Ceram. Int.* **2011**, *37*, 3019–3028. [CrossRef]
14. La voz de Galicia. Los Conserveros Plantean la Posibilidad de Verter Concha de Mejillón en el Mar. Available online: https://www.lavozdegalicia.es/noticia/arousa/2000/08/25/conserveros-plantean-posibilidad-verter-concha-mejillon-mar/0003_169074.htm (accessed on 2 June 2021).
15. La voz de Galicia. Eliminan un Vertido a la Ría Causado por un Depósito de Concha de Mejillón. Available online: https://www.lavozdegalicia.es/noticia/arousa/2020/04/26/eliminan-vertido-ria-causado-deposito-concha-mejillon/0003_202004A26C10993.htm (accessed on 2 June 2021).
16. Ngii, E.; Mustika, W.; Sukri, A.S.; Balaka, R.; Sriyani, R.; Welendo, L. The effect of clamshells partial substitution of coarse aggregates on the mechanical properties of shellfish concrete (Berang). *IOP Conf. Ser. Earth Environ. Sci.* **2020**, *419*, 12064. [CrossRef]
17. Ndoke, P.N.; Ndoke, P. Performance of Palm Kernel Shells as a Partial replacement for Coarse Aggregate in Asphalt Concrete. *Leonardo Electron. J. Pract. Technol.* **2006**, *9*, 145–152. Available online: https://www.researchgate.net/profile/Peter-Ndoke/publication/26449133_Performance_of_Palm_Kernel_Shells_as_a_Partial_replacement_for_Coarse_Aggregate_in_Asphalt_Concrete/links/0a85e536f94d5d1f70000000/Performance-of-Palm-Kernel-Shells-as-a-Partial-replacement-for-Coarse-Aggregate-in-Asphalt-Concrete.pdf?_sg%5B0%5D=started_experiment_milestone&origin=journalDetail (accessed on 28 April 2022).
18. Richardson, A.E.; Fuller, T. Sea shells used as partial aggregate replacement in concrete. *Struct. Surv.* **2013**, *31*, 347–354. [CrossRef]
19. Seo, J.H.; Park, S.M.; Yang, B.J.; Jang, J.G. Calcined oyster shell powder as an expansive additive in cement mortar. *Materials* **2019**, *12*, 1322. [CrossRef]
20. Talha Zaid, S.; Ghorpade, V.G.; Pradesh Anantapur, A.; Pradesh, A. Experimental Investigation of Snail Shell Ash (SSA) as Partial Repalacement of Ordinary Portland Cement in Concrete. *Int. J. Eng. Res.* **2014**, *3*, 2278-0181.
21. Umoh, A.A.; Ujene, A.O. Improving the strength performance of high volume periwinkle shell ash blended cement concrete with sodium nitrate as accelerator. *JCEST* **2015**, *6*, 18–22. [CrossRef]
22. Sickels-Taves, L.B.; Sheehan, M.S. *The Lost Art of Tabby Redefined: Preserving Oglethorpe's Architectural Legacy*, 1st ed.; Architectural Conservation Press: Southfield, MI, USA, 1999; pp. 1–200.
23. Asaoka, S.; Yamamoto, T.; Kondo, S.; Hayakawa, S. Removal of hydrogen sulfide using crushed oyster shell from pore water to remediate organically enriched coastal marine sediments. *Bioresour. Technol.* **2009**, *100*, 4127–4132. [CrossRef]
24. Bolan, N.S.; Adriano, D.C.; Curtin, D. Soil acidification and liming interactions with nutrient and heavy metal transformation and bioavailability. *Adv. Agron.* **2003**, *78*, 5–272.
25. Lee, C.H.; Lee, D.K.; Ali, M.A.; Kim, P.J. Effects of oyster shell on soil chemical and biological properties and cabbage productivity as a liming material. *Waste Manag.* **2008**, *28*, 2702–2708. [CrossRef] [PubMed]
26. Bozbaş, S.K.; Boz, Y. Low-cost biosorbent: Anadara inaequivalvis shells for removal of Pb(II) and Cu(II) from aqueous solution. *Process Saf. Environ. Prot.* **2016**, *103*, 144–152. [CrossRef]
27. Du, Y.; Lian, F.; Zhu, L. Biosorption of divalent Pb, Cd and Zn on aragonite and calcite mollusk shells. *Environ. Pollut.* **2011**, *159*, 1763–1768. [CrossRef] [PubMed]
28. Wu, Q.; Chen, J.; Clark, M.; Yu, Y. Adsorption of copper to different biogenic oyster shell structures. *Appl. Surf. Sci.* **2014**, *311*, 264–272. [CrossRef]
29. Kaewdaeng, S.; Sintuya, P.; Nirunsin, R. Biodiesel production using calcium oxide from river snail shell ash as catalyst. *Energy Procedia* **2017**, *138*, 937–942. [CrossRef]
30. Boro, J.; Thakur, A.J.; Deka, D. Solid oxide derived from waste shells of Turbonilla striatula as a renewable catalyst for biodiesel production. *Fuel Process. Technol.* **2011**, *92*, 2061–2067. [CrossRef]
31. Norazlina, H.; Fahmi, A.R.M.; Hafizuddin, W.M. $CaCO_3$ from seashells as a reinforcing filler for natural rubber. *J. Mech. Eng. Sci.* **2015**, *8*, 1481–1488. [CrossRef]

32. Chong, M.H.; Chun, B.C.; Chung, Y.-C.; Cho, B.G. Fire-retardant plastic material from oyster-shell powder and recycled polyethylene. *J. Appl. Polym. Sci.* **2006**, *99*, 583–1589. [CrossRef]
33. Zhang, J.; Han, B.; Zhou, N.-L.; Fang, J.; Wu, J.; Ma, Z.-M.; Mo, H.; Shen, J. Preparation and characterization of nano/micro-calcium carbonate particles/polypropylene composites. *J. Appl. Polym. Sci.* **2011**, *119*, 3560–3565. [CrossRef]
34. Martínez-García, C.; González-Fonteboa, B.; Martínez-Abella, F.; Carro-López, D. Performance of mussel shell as aggregate in plain concrete. *Constr. Build. Mater.* **2017**, *139*, 570–583. [CrossRef]
35. Bamigboye, G.O.; Nworgu, A.T.; Odetoyan, A.O.; Kareem, M.; Enabulele, D.O.; Bassey, D.E. Sustainable use of seashells as binder in concrete production: Prospect and challenges. *J. Build. Eng.* **2021**, *34*, 101864. [CrossRef]
36. Bamigboye, G.O.; Okara, O.; Bassey, D.E.; Jolayemi, K.J.; Ajimalofin, D. The Use of *Senilia senilis* seashells as a Substitute for Coarse Aggregate in Eco-friendly Concrete. *J. Build. Eng.* **2020**, *32*, 101811. [CrossRef]
37. Zhang, Y.; Chen, D.; Liang, Y.; Qu, K.; Lu, K.; Chen, S.; Kong, M. Study on engineering properties of foam concrete containing waste seashell. *Constr. Build. Mater.* **2020**, *260*, 119896. [CrossRef]
38. Soltanzadeh, F.; Emam-Jomeh, M.; Edalat-Behbahani, A.; Soltanzadeh, Z. Development and characterization of blended cements containing seashell powder. *Constr. Build. Mater.* **2018**, *161*, 292–304. [CrossRef]
39. Tayeh, B.A.; Hasaniyah, M.W.; Zeyad, A.M.; Awad, M.M.; Alaskar, A.; Mohamed, A.M.; Alyousef, R. Durability and mechanical properties of seashell partially-replaced cement. *J. Build. Eng.* **2020**, *31*, 101328. [CrossRef]
40. Her, S.; Park, T.; Zalnezhad, E.; Bae, S. Synthesis and characterization of cement clinker using recycled pulverized oyster and scallop shell as limestone substitutes. *J. Clean. Prod.* **2021**, *279*, 123987. [CrossRef]
41. Rodríguez-Galán, M.; Alonso-Fariñas, B.; Baena-Moreno, F.M.; Leiva, C.; Navarrete, B.; Vilches, L.F. Synthetic Slag Production Method Based on a Solid Waste Mix Vitrification for the Manufacturing of Slag-Cement. *Materials* **2019**, *12*, 208. [CrossRef]
42. Chiou, I.J.; Chen, C.H.; Li, Y.H. Using oyster-shell foamed bricks to neutralize the acidity of recycled rainwater. *Constr. Build. Mater.* **2014**, *64*, 480–481. [CrossRef]
43. Féjean, J.; Lanos, C.; Mélinge, Y.; Baux, C. Behaviour of fire-proofing materials containing gypsum, modifications induced by incorporation of inert filler. *Chem. Eng. Res. Des.* **2003**, *81*, 1230–1236. [CrossRef]
44. Leiva, C.; García Arenas, C.; Vilches, L.F.; Vale, J.; Gimenez, A.; Ballesteros, J.C.; Fernández-Pereira, C. Use of FGD gypsum in fire resistant panels. *Waste Manag.* **2010**, *30*, 1123–1129. [CrossRef]
45. Thomas, G. Thermal properties of gypsum plasterboard at high temperatures. *Fire Mater.* **2002**, *26*, 37–45. [CrossRef]
46. Peceño, B.; Alonso-Fariñas, B.; Vilches, L.F.; Leiva, C. Study of seashell waste recycling in fireproofing material: Technical, environmental, and economic assessment. *Sci. Total Environ.* **2021**, *790*, 148102. [CrossRef] [PubMed]
47. Hou, E.J.; Huang, C.S.; Lee, Y.C.; Chu, H.T. Upcycled aquaculture waste as textile ingredient for promoting circular economy. *Sustain. Mater. Technol.* **2022**, *31*, e00336. [CrossRef]
48. Zhan, J.; Lu, J.; Wang, D. Review of shell waste reutilization to promote sustainable shellfish aquaculture. *Rev. Aquac.* **2021**, *14*, 477–488. [CrossRef]
49. Wang, W.; Wei, W.; Gao, S.; Chen, G.; Yuan, J.; Li, Y. Agricultural and Aquaculture Wastes as Concrete Components: A Review. *Front. Mater.* **2021**, *8*, 762568. [CrossRef]
50. Morris, J.P.; Backeljau, T.; Chapelle, G. Shells from aquaculture: A valuable biomaterial, not a nuisance waste product. *Rev. Aquac.* **2019**, *11*, 42–57. [CrossRef]
51. Coelho, A.; de Brito, J. Economic viability analysis of a construction and demolition waste recycling plant in Portugal—Part I: Location, materials, technology, and economic analysis. *J. Clean. Prod.* **2013**, *39*, 338–352. [CrossRef]
52. Yang, D.; Fan, L.; Shi, F.; Liu, Q.; Wang, Y. Comparative study of cement manufacturing with different strength grades using the coupled LCA and partial LCC methods—A case study in China. *Resour. Conserv. Recycl.* **2017**, *119*, 60–68. [CrossRef]
53. Zhang, R.; Ma, X.; Shen, X.; Zhai, Y.; Zhang, T.; Ji, C.; Hong, J. PET bottles recycling in China: An LCA coupled with LCC case study of blanket production made of waste PET bottles. *J. Environ. Manag.* **2020**, *260*, 110062. [CrossRef]
54. Iraldo, F.; Facheris, C.; Nucci, B. Is product durability better for environment and for economic efficiency? A comparative assessment applying LCA and LCC to two energy-intensive products. *J. Clean. Prod.* **2017**, *140*, 1353–1364. [CrossRef]
55. Ruiz, G.; Chávez, F.; Santamaría, S.; Araujo, W.; Timaná, J.; Schmitt, R. Laboratory evaluation of seashell used as fine aggregate in hot mix asphalt. *Int. J. Pavement Eng.* **2020**, *21*, 620–628. [CrossRef]
56. Di Maria, A.; Eyckmans, J.; Van Acker, K. Downcycling versus recycling of construction and demolition waste: Combining LCA and LCC to support sustainable policy making. *Waste Manag.* **2018**, *75*, 3–21. [CrossRef] [PubMed]
57. Rizos, V.; Behrens, A.; van der Gaast, W.; Hofman, E.; Ioannou, A.; Kafyeke, T.; Flamos, A.; Rinaldi, R.; Papadelis, S.; Hirschnitz-Garbers, M.; et al. Implementation of circular economy business models by small and medium-sized enterprises (SMEs): Barriers and enablers. *Sustainability* **2016**, *8*, 1212. [CrossRef]
58. Soltanzadeh, F.; Behbahani, A.E.; Pereira, E.N.B.; Teixeira, C.A. A life-cycle approach to integrate environmental and mechanical properties of blended cements containing seashell powder. *Sustainability* **2021**, *13*, 13120. [CrossRef]
59. Uribe, E.; Sfeir, R.; Bakit, J. Informe Final FIPA 2017-12. Análisis del Desarrollo Histórico y Colapso del Cultivo del Ostión del Norte Como Herramienta Para el Re-Impulso de la Actividad en la III y IV Regiones. *Coquimbo.* 2018. Available online: https://www.researchgate.net/profile/Jose-Bakit/research (accessed on 28 April 2022).
60. SERNAGEOMIN. Servicio Nacional de Geología y Minería. In Anuario de la Minería de Chile. 2020. Available online: https://www.sernageomin.cl/anuario-de-la-mineria-de-chile (accessed on 28 April 2022).

61. *EN 13279-1*; Yesos de Construcción y Conglomerantes a Base de Yeso Para la Construcción—Parte 1: Definiciones y Especificaciones. European Committee for Standardization: Brussels, Belgium, 2009.
62. *ASTM D3682*; Standard Test Method for Major and Minor Elements in Combustion Residues from Coal Utilization Processes. ASTM International: West Conshohocken, PA, USA, 2013. [CrossRef]
63. *ASTM D 854*; Standard Test Methods for Specific Gravity of Soil Solids by Water Pycnometer. ASTM International: West Conshohocken, PA, USA, 2014. [CrossRef]
64. *EN 13279-2*; Gypsum Binders and Gypsum Plasters—Part 2: Test Methods. European Committee for Standardization: Brussels, Belgium, 2014.
65. *ASTM E 605*; Standard Test Methods for Thickness and Density of Sprayed Fire-Resistive Material (SFRM) Applied to Structural Members. ASTM International: West Conshohocken, PA, USA, 2015. [CrossRef]
66. Cerulli, T.; Pistolesi, C.; Maltese, C.; Salvioni, D. Durability of traditional plasters with respect to blast furnace slag-based plaster. *Cem. Concr. Compos.* **2003**, *33*, 1375–1383. [CrossRef]
67. *ASTM C 1012-13*; Standard Test Method for Length Change of Hydraulic-Cement Mortars Exposed to Sulphate Solution. ASTM International: West Conshohocken, PA, USA, 2013.
68. *EN 12390-9*; Testing Hardened Concrete—Part 9: Freeze–Thaw Resistance. Scaling Brussels. European Committee for Standardization: Brussels, Belgium, 2008.
69. Servicio de Impuestos Internos. Dólar Observado. Available online: https://www.sii.cl/valores_y_fechas/dolar/dolar2020.htm (accessed on 28 April 2022).
70. Guerrero-Rios, R.J.; Hernández, N.T.; Espinoza-Rodríguez, N.; Barrios-Garrido, H.; Montiel, M.; Morales, F. Condition index and size of the estuarine clam at Curarire, Zulia State, Venezuela. *Zootec. Trop.* **2015**, *33*, 327–336.
71. *EN 12859*; Gypsum Blocks—Definitions, Requirements and Test Methods. European Committee for Standardization: Brussels, Belgium, 2012.
72. Vafaei, M.; Allahverdi, A.; Dong, P.; Bassim, N. Acid attack on geopolymer cement mortar based on waste-glass powder and calcium aluminate cement at mild concentration. *Constr. Build. Mater.* **2018**, *193*, 363–372. [CrossRef]
73. Collepardi, M.; Borsoi, A.; Collepardi, S.; Ogoumah Olagot, J.J.; Troli, R. Effects of shrinkage reducing admixture in shrinkage compensating concrete under non-wet curing conditions. *Cem. Concr. Compos.* **2005**, *27*, 704–708. [CrossRef]
74. Zhang, Y.; Hua, Y.; Zhu, X. Investigation of the durability of eco-friendly concrete material incorporating artificial lightweight fine aggregate and pozzolanic minerals under dual sulfate attack. *J. Clean. Prod.* **2022**, *331*, 130022. [CrossRef]
75. Prieler, R.; Langbauer, R.; Gerhardter, H.; Kitzmüller, P.; Thumser, S.; Schwabegger, G.; Hochenauer, C. Modelling approach to predict the fire-related heat transfer in porous gypsum based on multi-phase simulations including water vapour transport, phase change and radiative heat transfer. *Appl. Therm. Eng.* **2022**, *206*, 118013. [CrossRef]
76. Colak, A. The long-term durability performance of gypsum-Portland cement-natural pozzolan blends. *Cem. Concr. Res.* **2002**, *32*, 109–115. [CrossRef]
77. Haas, W.; Krausmann, F.; Wiedenhofer, D.; Heinz, M. How circular is the global economy? An assessment of material flows, waste production, and recycling in the European union and the world in 2005. *J. Ind. Ecol.* **2015**, *19*, 765–777. [CrossRef]
78. Luhar, S.; Cheng, T.W.; Luhar, I. Incorporation of natural waste from agricultural and aquacultural farming as supplementary materials with green concrete: A review. *Compos. Part B Eng.* **2019**, *175*, 107076. [CrossRef]
79. Barros, C.; Bello, P.; Valiño, S.; Bao, M.; Arias, J. Odours Prevention and Control in the Shell Waste Valorisation. In Proceedings of the International Symposium on EcoTopia Science, Nagoya, Japan, 7 February 2007.
80. von Brand, E.; Abarca, A.; Merino, G.E.; Stotz, W. Scallop fishery and aquaculture in Chile: A history of developments and declines. *Dev. Aquac. Fish. Sci.* **2016**, *40*, 1047–1072. [CrossRef]
81. Kluger, L.C.; Taylor, M.H.; Wolff, M.; Stotz, W.; Mendo, J. From an open-access fishery to a regulated aquaculture business: The case of the most important Latin American bay scallop (*Argopecten purpuratus*). *Rev. Aquac.* **2019**, *11*, 187–203. [CrossRef]
82. Bakit, J.; Uribe, E.; Sfeir, R.; Carmona, R. Relación de la Producción en Chile del Ostión del Norte *Argopecten purpuratus* con Aspectos Ambientales, Comerciales y de Desarrollo Científico. In Proceedings of the VIII Congreso Nacional de Acuicultura, Arica, Chile, 11 September 2007.
83. Barros, M.C.; Bello, P.M.; Bao, M.; Torrado, J.J. From waste to commodity: Transforming shells into high purity calcium carbonate. *J. Clean. Prod.* **2009**, *17*, 400–407. [CrossRef]