ASSESSMENT OF MUSSEL SHELLS BUILDING SOLUTIONS: A REAL-SCALE APPLICATION

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Abstract

The construction sector is a key generator of greenhouse emissions, so the use of alternative low-emission building materials is a growing tendency. This work describes and analyses an innovative sustainable building that includes mussel shells in all its constructive elements. This material is a by-product of the canning industry that is nowadays landfilled. Mussel shells were used as aggregate in the concrete strip footing (foundation) and in the exterior and interior coating mortars (walls), and as loose-fill material for the whole envelope insulation (floor, walls, and roof). The results from both the laboratory and the constructive process were useful to improve the solutions and to develop a building with low energy consumption. Finally, the energy demand of the building was assessed using the Passive House Planning Package (PHPP) software and the blower door test was carried out to measured air tightness. It can be concluded that mussel shell materials meet the requirements of Passive House standard for energy efficient buildings: simulation results showed a primary energy consumption of 86 kWh/(m^{2}yr), that is a 28.3% lower than the value fixed by the standard.

Keywords:

Recycled mussel shells; loose-fill insulation; coating mortars; wood structure; energy efficiency; thermal transmittance.

Highlights:

- Mussel shells were used as aggregate in the concrete foundation and for the coating mortars
- The whole envelope insulation was solved with mussel shells as loose fill material
- Applicability of all mussel shell solutions has been demonstrated

- U-values of building solutions with mussel shells meet the energy efficiency standard
- The experimental building achieved very low energy consumption

1 Introduction and objectives

In 2011, the construction sector was responsible for almost 20% of the total CO_2 emissions in Spain, and according to the World Energy Outlook, these values will be increased by 21% by 2035 (Mañanas, 2015). Thus, buildings are key to reduce global warming effects. There is an interest to develop sustainable solutions for new constructions, and this is entwined with the need to use renewable solutions that provide an adequate quality of the erected buildings (Bardage, 2017).

In recent years, a series of regulatory measures tightening building efficiency requirements have been adopted (European Parliament and E.U. Council, 2010). The Spanish legislative framework that regulates the building energy efficiency is described in the Technical Building Code (CTE by its Spanish acronym) (CTE-DB-HE, 2019) and has been modified several times. A major change introduced in 2013 was the reduction of the maximum U-value in building envelope elements. Furthermore, the *Passivhaus* design principles have been widely applied to residential buildings across Europe. These requirements have been useful to substantially reduce the heating demand in buildings (Goncalves et al., 2021; Qu et al., 2021). Passive houses are buildings with low heating energy demand (i.e., below 15 kWh/m^2 year). The total primary energy demand from non-renewable sources for heating, hot water and electricity should not exceed 120 kWh/m^2 year, and the airtightness should be a maximum 0.6 changes per hour (ACH) at a 50 Pa pressure.

The general objective of this work is to demonstrate that mussel shells can be used as a construction material to design buildings with a high level of energy efficiency. To achieve this, an experimental building is designed and both design and constructive process allow for outlining the following specific objectives:

- The first one is the applicability of mussel shells as building material. To do that, building solutions based on the previous experimental campaign conducted in the laboratory are designed, and during the constructive process, their applicability is checked.
- The second objective is to assess the energy performance of the building once it is finished, and check that the energy consumption meets the Passive House standard requirements.

The results enable to draw useful conclusions and recommendations that will contribute to disseminate the know-how of the materials and solutions developed in the field of the technology of recycled mussel shells.

2 Literature review

Previous research works develop by the authors allow for drawing several conclusions regarding the use of mussel shells as building materials. Mussel shells are produced in the region of Galicia (in the north-west of Spain) due to the high quality of the water of the Rias (Carolina Martínez-García et al., 2017). For this reason, there are many farming facilities and canning industries in this region, thus constituting the largest mussel producer region in the European Union, as well as one of the largest worldwide (Caballero Míguez et al., 2009). Shells are composed by biomineralized calcium carbonate and constitute an interesting bio-based constructive material to be used in the building sector. Previous laboratory research studies (C. Martínez-García, González-Fonteboa, Carro-López, & Martínez-Abella, 2020; C. Martínez-García, González-Fonteboa, Carro-López, & Pérez-Ordóñez, 2020; Carolina Martínez-García et al., 2017, 2019a, 2019b, 2020) applied mussel shells as both loose material and aggregate for concrete and mortars.

The performance of concretes and mortars using mussel shells as aggregate and with different binders, (cement and lime) is conditioned by both the irregular and flaky shape of the mussel particles and their hydrophobic behaviour. These characteristics increase the entrapped air in the mixes and the water demand. Therefore, in fresh state, consistency and porosity are increased, thus decreasing the fresh and hardened densities, as well as the mechanical strength of concretes and mortars (Carolina Martínez-García et al., 2017, 2019a, 2019b). However, due to their particular shape, mussel shell particles act as a water barrier that creates tortuosity water paths, thus strongly reducing the capillary uptake in mortars (C. Martínez-García, González-Fonteboa, Carro-López, & Martínez-Abella, 2020; Carolina Martínez-García et al., 2019b) and the water permeability in concretes (Carolina Martínez-García et al., 2017).

The organic matter content, mainly chitin (a polysaccharide), reacts with some of the clinker components that introduce entrained air into the mixes, delay cement hydration, and increase the setting time of cement mortars (Carolina Martínez-García et al., 2019b). This effect also influences other concrete and mortar properties. The smooth surface area of the mussel particles, together with the presence of chitin, strongly damages the interfacial transition zone (ITZ), thus reducing the paste-aggregate interfacial bond and again the mechanical strength of the mixes (Carolina Martínez-García et al., 2017, 2019a, 2019b). In air lime mortars, the effect of the organic matter is lower than that observed in mixes with hydraulic binders. Moreover, mussel shells could act as a moisture retainer, thus affecting the carbonation process of lime mortars and delaying the rate of carbonation at early ages, although improving that rate after 180 days (Carolina Martínez-García et al., 2020).

The results obtained from the literature indicate that suitable concretes could be designed by replacing conventional aggregates with mussel shells up to 25% (when only the coarse or the fine fraction is replaced) and up to 12.5% (when both fractions are replaced). Mortars with a replacement rate up to 25% (conventional sand replaced by mussel sand) present similar performance to that of the baseline ones. However, the results obtained by using the replacement rate of 50% are acceptable, especially in air lime mortars. Finally, the aesthetic appearance of the mussel shell aggregate in concretes and mortars should be promoted to widespread the use of this by-product.

After analysing the use of mussel shells as loose-fill insulation material, in a previous study (Martínez-García et al., 2020b) it was observed that mussel shells fractions modified their sieve size distribution under compaction process. After testing two different fractions under static loading test, one of them (mussel shell gravel 4-16 mm) was selected for being the least affected by loading. In addition, it was able to maintain its particle size distribution up to 11 MPa, so this material is suitable to be used as a loose-fill material in foundations. The thermal conductivity value of different mussel shell fractions is between 0.12 and 0.20 W/(mK), similarly to the wood or expanded clay (C. Martínez-García, González-Fonteboa, Carro-López, & Pérez-Ordóñez, 2020). In addition, a solution composed by 90 mm of loose-fill mussel shell gravel meets the acoustic standard requirements (CTE-DB-HR, 2009) to be used as a partition wall, as a façade enclosure (for quiet areas) or as a dividing wall between various buildings. The sound reduction index of this solution is analogous to that of other conventional solutions (cellulose, flax and glass wool, among others) with similar width (C. Martínez-García, González-Fonteboa, Carro-López, & Pérez-Ordóñez, 2020). Thanks to its density, a mussel shell gravel shows a very good acoustic behaviour at low frequencies (below 500 Hz). Therefore, loose mussel shells present an appropriate behaviour for insulation applications in different building solutions: floors, walls and roofs.

Finally, the use of mussel shell gravel as insulation material has other advantages: its embodied energy is low (Bordello-Malde et al., 2016b) and is stable against biological attacks and fire as it is a mineral material mainly composed by calcium carbonate (CTE DB SI, UNE 23727-90) . Nevertheless, the lack of real-scale experiences makes it difficult to assess the applicability of mussel shell both as loose-fill material for thermal insulation and as aggregate in both concrete and coating mortars.

3 Materials and methods

This works belongs to a wide research project that was divided into various stages (Figure 1). Stage 1, which consisted in the material characterisation of all mussel shell aggregates, and Stage 2, which included the mix design, the concrete and mortar properties, and the behaviour of mussel shell as loose-fill insulation material, are detailed in previous studies (C. Martínez-García, González-Fonteboa, Carro-López, & Martínez-Abella, 2020; C. Martínez-García, González-Fonteboa, Carro-López, & Pérez-Ordóñez, 2020; Carolina Martínez-García et al., 2017, 2019a, 2019b, 2020).

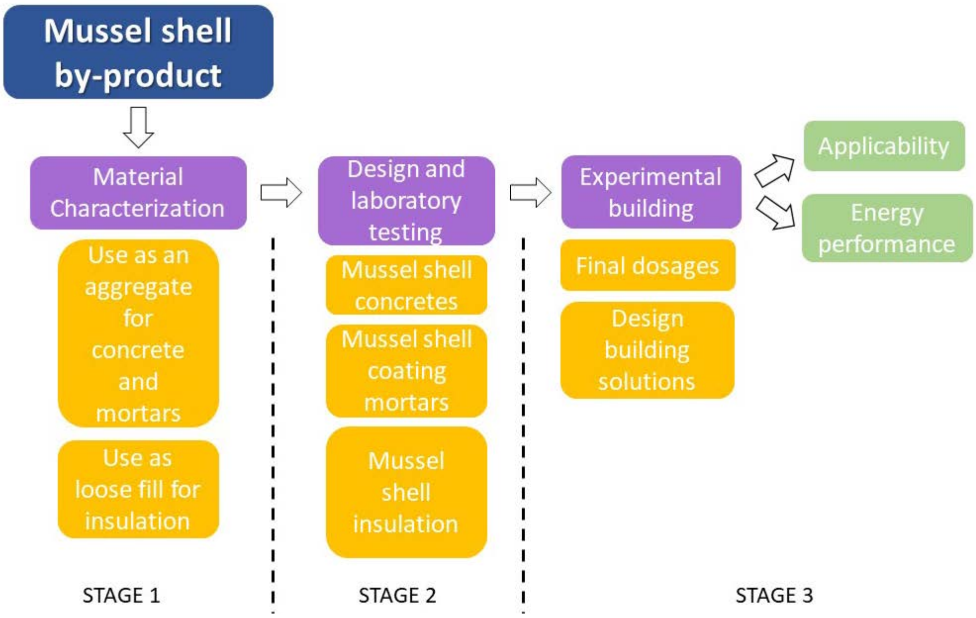


Figure 1. Project stages.

This manuscript is focused on the last stage (i.e., Stage 3) that corresponds to the construction of the experimental building (a real-scale application of all the materials previously tested in the laboratory at a prototype level in real building solutions). This construction allowed the applicability of the new materials in the building solutions to be analysed and the energy performance of the building to be calculated.

3.1 Materials and building solutions

The mussel shells used in the experimental building came from the cannery industry as a by-product named as whole mussel shell (WS). This by-product underwent a heat-treatment (135 °C for 32 minutes in a rotary trommel screen) that resulted in mussel shell gravel (MG). From it, two types of mussel shell sand were obtained by crushing and sieving: coarse sand (CMS) and fine sand (FMS) (Carolina Martínez-García et al., 2017). These fractions of mussel shell were used as aggregate in the concretes and in the coating mortars of the building and as loose-fill insulation material in walls, floor and roof.

The life cycle assessment of the new products incorporating mussel shell as aggregate was carried out within the framework of the project "Assessment of Galician bivalve shell in the construction sector". The assessment was developed using a cradle-to-gate approach and the heat treatment of the by-product was taken into account. The results obtained can be seen in the work of Bordello-Malde et al. (2016a, 2016b, 2015).

In addition, the building solutions were designed with mussel shells following the recommendation of the previous experience (Stage 1 and Stage 2).

The foundation was designed using a concrete strip footing of structural concrete that was cast on a levelling layer of non-structural concrete. Inside the building, there was a concrete slab made of structural concrete that conformed the floor, and outside there was a perimetral sidewalk with the same structural concrete. These concretes were developed using mussel shell gravel and the two mussel shell sands that replaced both fractions of conventional aggregate (limestone gravel and limestone sand). The cement used in all concretes was CEM II/A-M (V-L) 42.5R.

The interior walls were plastered with clay mortars by combining the two mussel shell sands with a conventional siliceous sand. The binder used was a kaolinitic clay from Buño and a kaolin from Vimianzo; these two villages are about 45 km far from the work site. In the exterior walls, two binders were used for coating mortars: a slaked lime putty (EN 459-1 CL90-PL) with 90% minimum content of calcium and magnesium oxides, and a cement CEM II/A-M (V-L) 42.5R (UNE-EN 197-1:2011). Both renders used as aggregate a combination of the two mussel shell sands with a conventional limestone sand. In addition, fibres were added to all coating mortars, so hemp hurds (Cannabric, 2009) with a size of 2-25 mm were used in the different layers of all coating mortars.

The mussel shell gravel was used as loose-fill insulation material in the walls, roof and floor. However, the whole mussel shell was only used as finishing for the roof.

3.2 Methods

Applicability of building solutions

Regarding the assessment of the applicability, various technical control tests of the materials applied to the building solutions were carried out. In situ samples were taken from the two types of mussel shell concretes used in the foundation, and the following control tests were carried out: consistency (slump value UNE-EN 12350-2:2009); fresh and hardened densities (UNE-EN 12350-6:2006); water absorption (UNE 83980:2014); and mechanical strengths (UNE-EN 12390-3:2009; UNE-EN 12390-6:2010) at 7 and 28 days.

Samples of renders made of lime and cement mortars with mussel shell aggregate were tested in the laboratory: consistency (UNE-EN 413-2:2006), fresh and hardened densities (calculated by measuring the volume and the weight of samples), air content (UNE-EN 413-2:2006), water absorption due to capillary action (UNE-EN 1015-18:2003), and compressive strength (UNE-EN 1015-11:2007) at 28 days. Moreover, clay plasters with mussel shell aggregate were studied through in situ tests, and various characteristics were assessed: their surface hardness by durometer (ASTM D2240-15e1) and sclerometer (ASTM C805/C805M-18); their surface cohesion by Martinet-Baronnie (Matias et al., 2020), and their water absorption under low pressure by Karsten tubes (UNE-EN 16302:2016).

The compaction degree of the loose-fill insulation for the whole envelope (roof, floor and walls) was controlled according to the methodology adjusted with the prototypes (C. Martínez-García, González-Fonteboa, Carro-López, & Pérez-Ordóñez, 2020). The material was placed by layers, and each layer was manually compacted until the target compaction degree higher than 35% was achieved to avoid long-term settlements. This degree was fixed in a previous work (C. Martínez-García, González-Fonteboa, Carro-López, & Pérez-Ordóñez, 2020). The initial and final heights of each layer were measured as a reference to define the compaction degree.

Building energy assessment

The energy performance of the building was analysed using the Passive House Planning Package (PHPP) software (Feist et al., 2007) to understand the building performance during cold and hot seasons. The total primary energy demand and heating energy demand was simulated with PHPP in three different phases.

In the first phase, the design process, the thermal conductivity value of mussel shells as insulation was taken from literature (Aagaard and Moller, 2007). The value of building´s air tightness was stablished according to PH standard (0.6 changes per hour (ACH) at a 50 Pa pressure). In the second phase, after an experimental campaign in laboratory, the thermal conductivity value of mussel shell as insulation was measured, and the PHPP simulation was updated.

Finally, in the last phase, after the construction of the building, the air tightness of the building was measured updating the PHPP simulation with this information. The building air tightness was measured by means of the blower door test, according to UNE-EN 13829:2002 and with a single fan placed in one door of the building with a differential pressure of 50 Pa.

4 Experimental building design

The objectives to design the building were as follows: low energy consumption, the application of principles of bioconstruction, and low environmental impact. This implied the selection of local materials with low carbon footprint, and the design of building solutions that minimise heat losses, thus achieving great energy efficiency. To get this objective, most of the building solutions were designed to be built using mussel shells.

The location of the experimental building was in a plot of land ceded by the University of A Coruña (Figure 2). The location (43º 19´ 48.07” N, 8º 24´ 42.54” W) is in the Campus de Elviña, in the city of A Coruña. The specific plot of land is beside the urban orchard-gardens. This location allows the building to be visited for spreading and educational purposes. The purposes of the testing facility were both to impact on society and to develop social awareness about the potential use of mussel shell.

Figure 2. The situation plan. Building under construction (right).

The building was intended to be visited as a demonstrative construction, so it was designed with dimensional characteristics (Table 1). Hence, there is an open space inside to be visited by a small number of people, although both the dimension of the plot and the budget delimited these characteristics.

Table 1. Dimensional characteristics of the building.

Height	4 m
Plot area	1986 m^2
Floor area	49.42 m^2
Built-up area	87.68 m^2

The building was designed with an aesthetical appearance that simulates the shape of a mussel shell in the plant perimeter (Figure 3); moreover, in volume, it seems a big open bivalve shell (Figure 4).

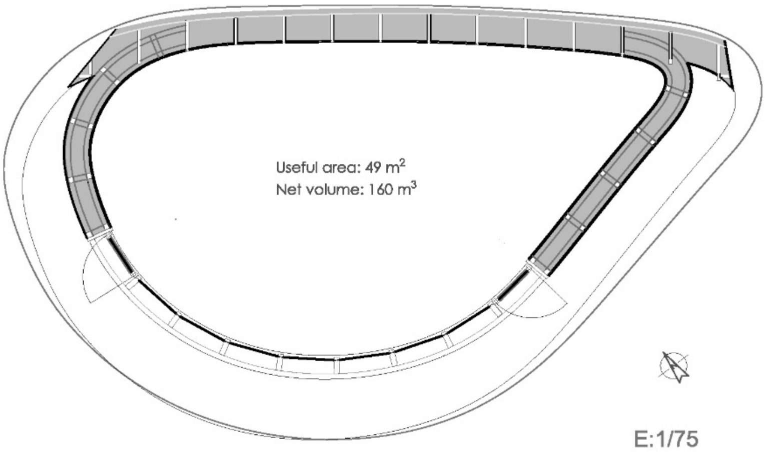
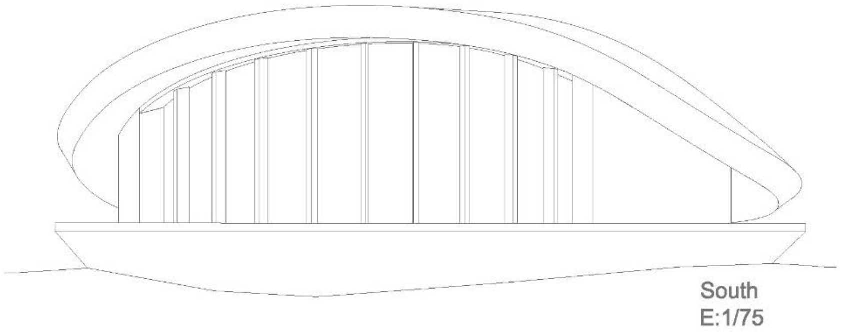


Figure 3. Plant layout.



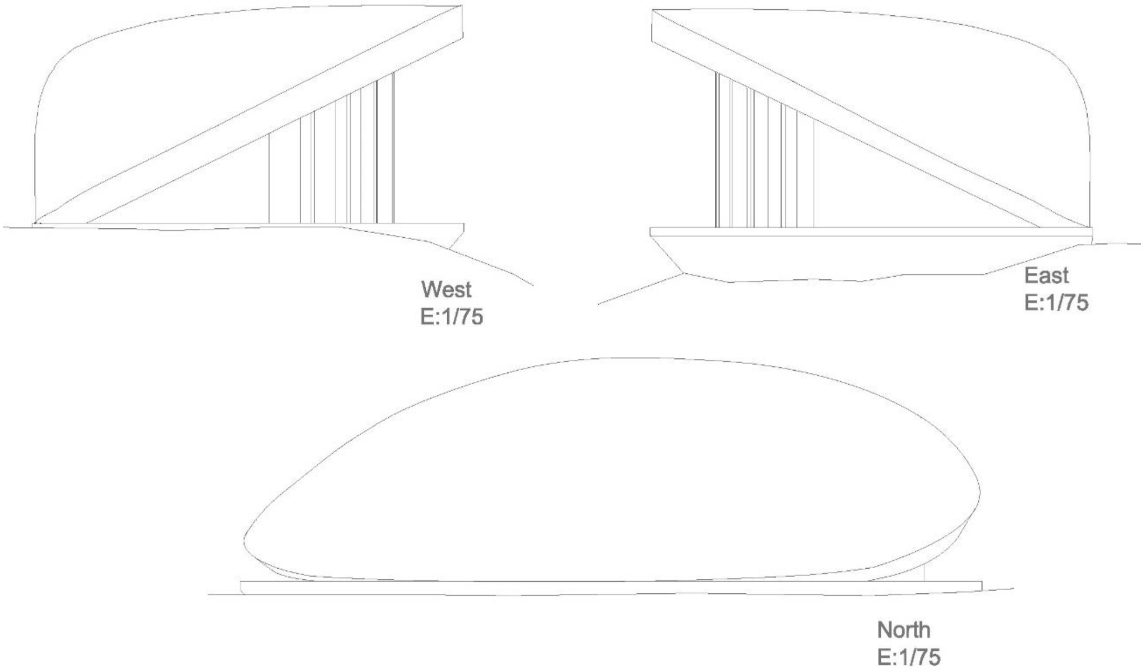
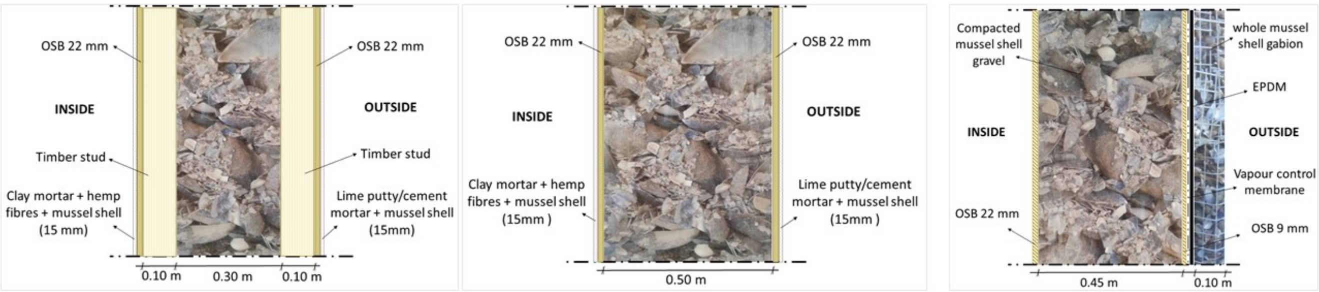


Figure 4. Elevation views of the architecture design simulating the shape of a mussel shell.

The design criteria to get the PH standard in the building included the following energy savings solutions:

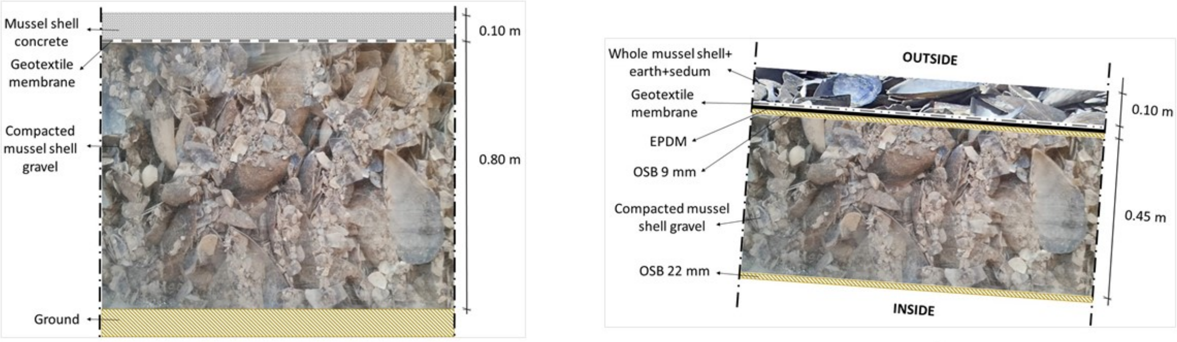
- Bioclimatic design: orientation and natural cross ventilation. For this climate zone, the glazing wall was oriented south to guarantee a passive solar heating. In summer, an eave was designed to shade the windows, thus avoiding overheating. However, due to the plot slope, the glazed façade was not facing the perfect south, but the SW, thus slightly affecting solar gains. Two facing doors guaranteed the cross ventilation; in addition, mechanical ventilation was installed to guarantee energy savings, as well.
- Insulation: the most important principle to save energy and to ensure well-insulated buildings is to create a layer of continuous insulation, without interruptions (thermal bridges). In this case, loose mussel shell gravel (compacted) was used as insulation material with different thicknesses in each building solution, so the envelope could meet the thermal resistance to achieve the building energy efficiency. Thermal bridges, which are caused by the structure, were considered practically non-existent because of both the thickness of the walls and the roof and the use of materials with very similar thermal conductivity values. Therefore, the walls and the roof made up of spruce wood and OSB wooden boards had thermal conductivity values of 0.15 W/(mK) (Spanish Technical Building Code (CTE), 2007) and 0.13 W/(mK) (Spanish Technical Building Code (CTE), 2007), respectively, which were very close to the value measured for the compacted mussel shell making up the insulation filling (0.175 W/(mK) (C. Martínez-García, González-Fonteboa, Carro-López, & Pérez-Ordóñez, 2020)).

- Energy efficient glazing: the triple glazing installed in the building was composed of two laminated safety glass (4+4 mm) and a 16 mm thick glass pane separated by two argon chambers of 16 mm thick: (4+4) + 16 + (16) + 16 (4+4). The argon gas in the chamber and the low emissivity glasses improved the U-value. The glazing in windows and doors offered a U-value of 0.71 W/(m^{2}K) and 0.77 W/(m^{2}K), respectively. In addition, a sun protection glass with a solar factor of 0.33 was selected, thus also providing a high luminous transmittance (TL = 61%).
- Energy efficient opaque elements: each building solution was designed to meet the recommended values of thermal transmittance suggested in the Passive-On study (end-use Efficiency Research Group of Politecnico di Milano, 2007; Fenercom; PEP, 2011). Designed details and characteristics of every opaque element are detailed in Figure 5, and Table 2. The U-values calculations are detailed and discussed in section 5 of Energy performance (Table 9).
- Mechanical ventilation with heat recovery (MVHR): a heat recovery ventilation system was installed to provide a constant supply of fresh filtered air, to maintain the air quality, and to promote energy savings. The central unit installed in this building included a heat exchanger (Figure 6), fans, filters, an air conditioner, an air preheater and a humidifier or air humidity extractor. The interior air was extracted and, before directing it to the outside, the incoming fresh air was prepared by the heat exchanger until the room temperature was reached.



Timber Wall: NW and SE façades
(timber stud section and middle section)

Vertical Wall (NE façade)



Ground floor

Roof

Figure 5. Design detail of all the building solutions.

Table 2. Characteristics of opaque elements.

Building solution	Layer	Thickness (m)	Density (kg/m^3)	Weight (kg/m^2)
Ground floor	Mussel shell concrete	0.10	2200	220
	Compacted mussel shell gravel	0.80	1100	880
	Total	0.90		1100
NW and SE walls	Earth based render	0.015	1800	27
	OSB	0.022	650	14.3
	Compacted mussel shell gravel	0.50	1100	500
	OSB	0.022	650	14.3
	Lime putty plaster	0.015	1700	25.5
	Total	0.574		581.10
NW and SE walls – studs section	Clay mortar	0.015	1700	27
	OSB	0.022	650	14.3
	Wood studs (14 cm) + Comp. mussel shell gravel (36 cm)	0.50	874	437
	OSB	0.022	650	14.3
	Cement plaster	0.015	1700	25.5
	Total	0.574		518.10
NE wall	OSB	0.022	650	14.3
	Compacted MG	0.45	1100	450
	OSB	0.009	650	5.85
	Water proofing membrane	0.02	1150	2.3
	WS gabions	0.10	600	60
	Total	0.583		532.45
Roof	OSB	0.022	650	14.3
	Compacted MG	0.45	1100	450
	OSB	0.009	650	5.85
	Waterproofing membrane	0.002	1150	2.3
	WS with earth and sedum	0.10	600	60
	Total	0.58		532.45

Figure 6. Placement of air ducts for the heat exchanger (left and middle). The heat exchanger installed (right).

5 Applicability of building solutions

Using a loose-fill unconventional material, such as mussel shells, for the whole envelope insulation is something of a challenge, so the building structure should to be a light structure that allows for insulation with a fill-in material. Therefore, the building structure was designed with a bidirectional timber framework made with OSB (Oriented Strand Board), with a double curvature in two directions (Figure 7). OSB boards type four (high performance structural boards for humid environment) with 22 mm of thickness were used for the beams and walls. Beams were made up of both three joined

OSB boards for the vertical and roof pieces (cross beams) and two joined OSB boards for the horizontal pieces (longitudinal beams).

The wood boards were cut in the workshop by gluing the beam planes (with adhesive paper) at real scale (1:1). Then, they were installed on site by gluing and screwing. The glue used was formaldehyde-free polyurethane, specifically suitable for structural wood. The application of the glue required an environmental temperature of 20 °C and very low humidity. For this reason, the structure was assembled and installed under a big tent (Figure 7) that allowed temperature and humidity requirements to be met. The structure of the south glass façade was composed of laminated spruce studs with a section of 12x24 cm.

Figure 7. Timber structure.

The building solutions with mussel shell that were analysed from the applicability point of view were as follows: foundation and floor, roof, façades, and coating mortars.

5.1 Foundation and floor solution

The experimental building foundation was designed as a concrete strip footing where the roof load was transmitted throughout the walls. The strip footing conformed the perimeter of the building and gave the building the mussel shape (Figure 8 and Figure 9). Inside the perimeter of the strip footing foundation, 80 cm of loose mussel shell were placed conforming the insulation and the water barrier. On their top, conforming the floor finish, a concrete slab was casted. There was also an exterior perimetral sidewalk with the same mussel shell concrete (Figure 8, Figure 9 and Figure 10). Concrete properties are shown in Table 4.

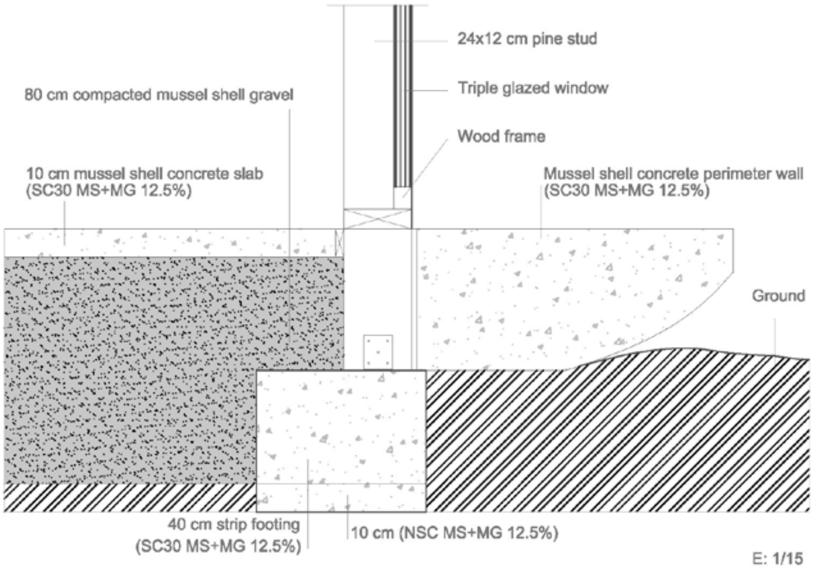


Figure 8. Construction detail of the foundation.

Mussel shell concretes of levelling layer (non-structural), strip footing, floor slab and the exterior sidewalk (structural) were cast and compacted with a vibrator (Figure 9). Both floor and sidewalk were polished to unveil the mussel shells, thus resulting in an interesting aesthetic finishing (Figure 10).

Figure 9. Placement, vibrating and curing of strip footing concretes (non-structural and structural).

Figure 10. Construction process of the concrete slab and the structural piece.

Structural and non-structural concretes employed a replacement rate (conventional aggregate replaced by mussel shell aggregate) of 12.5%, where both coarse and fine conventional fractions were replaced by mussel shell gravel and sand, respectively. Mix proportioning of the two concretes (Table 3) were available for the concrete plant, according to those used in a previous laboratory study (Carolina Martínez-García et al., 2017). The real-scale application implied some adjustments: to maintain the target values of consistency, a 2% superplasticizer was used, and to prevent drying shrinkage cracks, polypropylene fibres were added with a dosage of 0.60 kg/m^3 according to the recommendation provided by the supplier. Various samples were taken from the batches produced at the plant and brought by the truck mixer. The results of the quality control of both non-structural and structural concretes are shown in Table 4.

Table 3. Foundation concretes mixes.

	Structural concrete (strip footing, slab and perimetral sidewalk)		Non-structural concrete (levelling layer)	
	Volume (dm^3)	Weight (kg)	Volume (dm^3)	Weight (kg)
Water	175.61	175.61	186.59	186.59
Cement	116.68	351.22	70.81	219.51
Conventional sand (0–4)	353.32	918.64	455.86	1185.23
Conventional gravel (4–16)	213.28	554.53	141.98	369.15
Conventional gravel (10−20)	52.70	137.01	51.99	135.18
Mussel shell sand (0-4)	50.48	135.70	65.12	175.09
Mussel shell gravel (4-16)	37.93	99.39	27.65	72.44
Total	1000.00	2372.09	1000.00	2343.20
Water-cement ratio		0.50		0.85

Despite the low values of slump, all concretes used on-site in strip footing, slab and perimetral sidewalk were easily placed. Moreover, the mechanical strengths of structural concretes met the requirements of the Spanish standard

(Ministerio de Fomento, 2008) for plain concrete at 28 days. Polypropylene fibres could also be used as there were no drying cracks in the mussel shell concrete elements.

Table 4. Quality control results of on-site concretes.

	Non-structural concrete NSC MS+MG 12.5%	Structural concrete SC30 MS+MG 12.5%
Slump (cm)	1	7
Fresh density (kg/l)	2.14	2.23
Hardened density (kg/l)	2.28	2.27
Water absorption (%)	8.09	8.23
Compressive strength (MPa) 7 days	7.77	18.83
Compressive strength (MPa) 28 days	11.72	23.63
Tensile strength (MPa) 28 days	1.43	2.76

Loose mussel shells were placed, in contact with the ground, under the concrete slab (inside the perimeter of the strip footing foundation), thus conforming the insulation and the water barrier (Figure 11). The loose-fill mussel shell was applied in several layers with a compaction degree greater than 35% to avoid long-term settling; this target value was obtained in a previous work (C. Martínez-García, González-Fonteboa, Carro-López, & Pérez-Ordóñez, 2020). This work showed that mussel shell gravel could maintain its particle size distribution up to 11 MPa (11000 kN/m^2). This figure guarantee that this material bear the service overloads that should be lower than 5 kN/m^2 (CTE DB-SE-AE, 2009), the partitions loads lower than1.2 kN/m^2 (CTE DB-SE-AE, 2009), and the weight of the concrete slab, which should be around 20 kN/m ^{2}.

The mussel shell gravel used as insulation in the ground floor was compacted manually with a hand rammer up to 80 cm thickness. In addition, the material also worked as horizontal waterproofing against capillary rising damp and ground moisture (Aagaard & Moller, 2007). When the mussel gravel was compacted, it became a very stable material, so the easiness of working on it is worth stressing.

This constructive unit worked successfully, with no limitations for other constructions; it is a simple solution that could be used in any foundation. It prevents water intake and provides accurate thermal insulation (see Section 5). Lastly, the finishing of the concrete with mussel shells is an appealing opportunity for this material market.

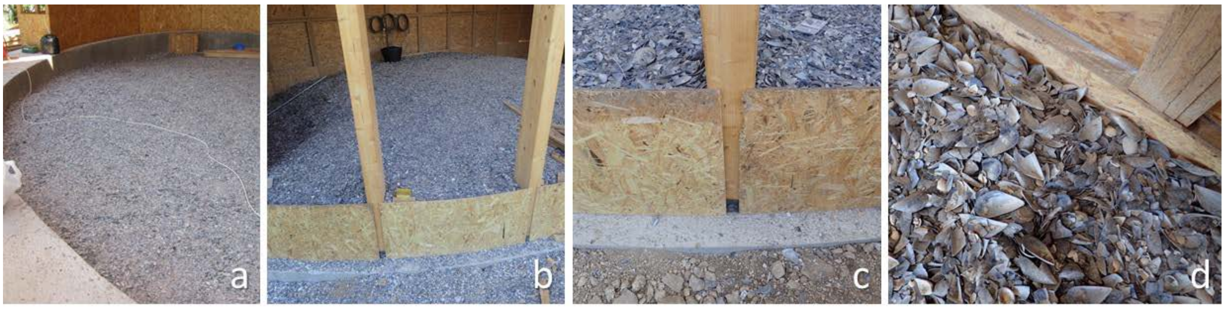


Figure 11. Loose-fill of mussel shell for floor insulation.

5.2 Roof

The basic parameters considered when choosing the roof system were the climactic zone, the degree of permeability and rainwater collection, and the resistance to fire. The finishing of the roof (using whole mussel shells) was chosen from an aesthetic and sustainable perspective. The roof structure presented continuity with the NW facing wall. The wall began in the strip footing and curves until the roof was defined.

The roof section (Figure 12) was composed (from inside to outside) of:

a. OSB board (22 mm) + compacted mussel shell + OSB board (9 mm).
b. A waterproofing layer (EPDM) over two geotextile membrane.
c. Whole mussel shells (WS) mixed with earth and sedum (climate adapted vegetation) that can grow up as a green roof, as exterior finish.

The insulation of the roof was again solved by loose mussel shell gravel, which was manually compacted with hand rammer inside the wood structure (Figure 13). This insulation had a thickness of 45 cm, thus ensuring a suitable thermal and acoustic behaviour (C. Martínez-García, González-Fonteboa, Carro-López, & Pérez-Ordóñez, 2020).

The waterproofing layer was made of a synthetic rubber membrane (EPDM), which guaranteed durability and low maintenance costs. The membrane had 25 cm and 35 cm of overlapping in cross and longitudinal directions, respectively, and it was stapled and glued.

The green roof using WS was selected for aesthetic purposes. As this exterior finishing of the roof ended in a vertical orientation, gabions (wire cages) were used to give continuity to the same finishing. Gabions (Figure 13) were fabricated on site: they were especially designed for this building.

In summary, the roof solution did not present any constructive problem. The only limitation was the thickness, that was greater than that usual for this climate. Also, the execution would have been easier and faster if the geometry of the building had lacked curvatures. Anyway, the constructive solution meets the thermal and acoustic requirements needed for a high insulated roof applicable in multipurpose buildings and green roofs. The final result is high quality roof with interesting aesthetic appearance.

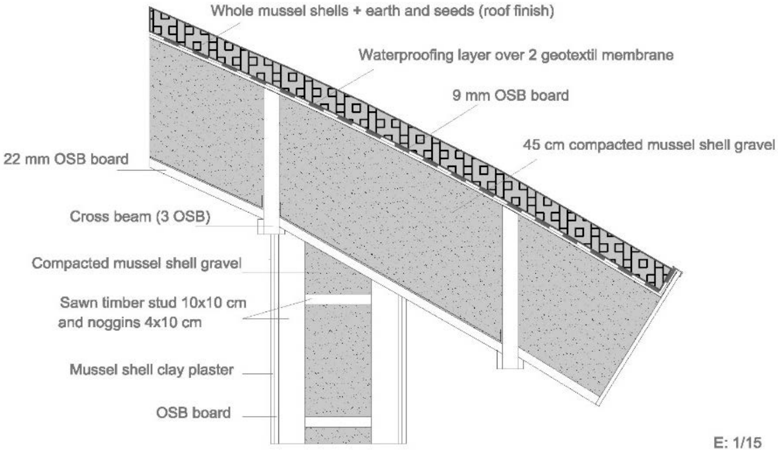


Figure 12. Construction detail of the roof solution.

Figure 13. Constructive process of the roof: a) mussel shells inside roof structure compaction of mussel shells, b).

5.3 Façades and walls

Several façades were distinguished depending on the materials used in the building solution: three types of opaque walls and a glazed façade. The walls could be divided into two types: the north wall was totally different in structure and finishing from north-west (NW) and south-east (SE) walls. These two shared the structure and differed only in the exterior finishing. The composition of the façades is detailed below:

I. Timber walls: NW and SE facing walls were composed of the “OSB-compacted mussel shell-OSB” system (Figure 14), with a sawn timber structure composed of studs of 10x10 cm and noggins of 4x10 cm. In this case, interior and exterior finishes are coating mortars that are defined in the following sub-sections.

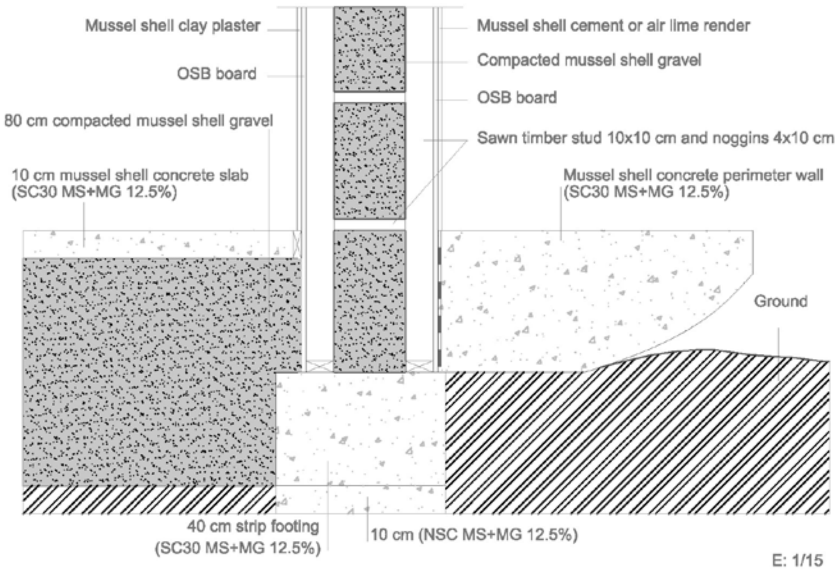


Figure 14. Construction detail of the wall.

II. Vertical roof: this wall was the beginning of the roof and shared with it the same building solution. The structural beams were made of 3-joined-OSB starting from the strip footing foundation, and the wall was composed (from inside to outside) of the following materials:

a. OSB board (22 mm) + compacted mussel shell + OSB board (9 mm).

b. Vapour outward flow regulator membrane.

c. Waterproofing layer.

d. Wire cages (gabions) filled with whole mussel shells as exterior finish.

III. Glazing façade: the SW facing wall was made up by seven fixed windows and two doors (Figure 15). Moreover, a triple-pane glass with argon gas in the chamber was installed. An overhang was placed to prevent overheating due to summer sun radiation. Windows and doors were installed to be airtight, and the spacers in the glass seal edge were thermally separated. Glasses were installed in a thermal bridge free manner in the insulation layer.

Figure 15. Constructive process of façades and walls: a) glazing façade, b) interior view of glazing of windows and doors, c) vertical roof with loose-fill made of compacted mussel shell gravel, d) NW timber wall structure, e) application of loose-fill insulation in wall.

Wall insulation was composed of compacted mussel shell gravel. The compaction was made manually by using a hand rammer. In addition, walls were filled in several layers with a target compaction degree of 40% (C. Martínez-García, González-Fonteboa, Carro-López, & Pérez-Ordóñez, 2020) with good results. Nevertheless, the compaction against the curved beam structure was difficult. Figure 15 shows various images of the wall constructive process.

This constructive unit for walls could be applied in many types of designs. Although, the recommendation would be to prioritize straight and flat surfaces. In these, this solution represents a low-environmental impact solution for insulation that can be erected without specialized workforce, without formworks and using a simple crane. Additionally, it is adaptable to any size and shape, including space for windows and doors.

5.4 Mortars for coatings

Three types of coating mortars were applied to the walls of the experimental building. Cement-based and lime-putty renders were used outside the building, and clay plasters were used inside it.

The earlier laboratory knowledge about tested mussel shell mortars was used to design suitable dosages. First, the application of the mortar coatings to the OSB boards required a surface treatment to ensure a good adhesion. This included sanding the surface with a very coarse grain sandpaper, wetting and finally, applying a primer coat. The different mix proportions of the coating mortar used in the different layers are shown in Table 5.

Table 5. Dosages for coating mortars (by volume).

	Layers	Conventional sand size	Mussel shell sand size	Water/ binder	Binder/ aggregate/ fibre	Mussel shell replacement (%)
Cement	1	0-4 mm	0-4 mm	0.9-1	1:4:0.5	50
	2	0-1 mm	0-1 mm		1:3:0	50
Lime putty	1	0.2 mm	0-4 mm	1 litre water: 40g lime	1:3:1	33
	2	0.2 mm	0-1 mm		1:2:0.5	50
	3	0.08 mm	0-1 mm		1:1.5:0	33
	4	0.06 mm	0-1 mm		1:1:0	50
Clay	1	0.2 mm	0-4 mm	-	1:3:1	33
	2	0.2 mm	0-1 mm		1:2:1	50
	3	0.08 mm	0-1 mm		1:1.5:1	33
	4	0.06 mm	0-1 mm		1:1:0	50

Cement mortars were applied to the SE wall (exterior). The coating was applied in two layers: the base (layer 1) and finish layer (layer 2). The base layer had a dosage with a binder to aggregate of 1:4. The aggregate size was 0-4 mm, and the replacement rate of conventional sand with mussel shell sand was 50%. Hemp hurds (Cannabric, 2009) with a size of 2-25 mm were used to avoid cracks due to drying shrinkage. The finish layer had a different composition, with a higher binder to aggregate ratio (1:3) and a smaller aggregate size of 0-1 mm. Moreover, 50% of the conventional sand was replaced by mussel shell fine sand. Fibres were not used in this layer. Different laboratory tests were carried out before applying the mortars in the experimental building, so the first layer was tested without fibres. The results of the two coating mixes are shown in Table 6.

All renders were easily applied. The various mechanical finishes unveiled the seashells particles in coatings, thus leading to attractive aesthetic qualities that promoted the use of mussel shell as aggregate.

Table 6. Results of previous laboratory tests.

	Cement mortars		Air lime mortars		
	Base layer (50%)	Finish layer (50%)	First layer (50%)	Second layer(50%)	Finish layer(50%)
Slump (cm)	142	147	138	148	146
Fresh density (kg/l)	1.99	1.87	1.89	1.88	1.86
Hardened density (kg/l)	1.77	1.60	1.89	1.88	1.86
Air content (%)	26	25	14	11	10
Compressive strength 28d (MPa)	15.97	13.07	0.79	0.94	0.76
Capillary coefficient (kg/m^2.min$^{0.5}$)	0.18	0.19	1.06	1.20	1.56

A traditional lime stucco was designed according to the results of previous works (C. Martínez-García, González-Fonteboa, Carro-López, & Martínez-Abella, 2020; Carolina Martínez-García et al., 2019b, 2020) (Table 5). It was composed of four thin layers (0.5-1 mm thickness) applied to the NW wall (exterior). The composition of each layer ranged from the lowest to the highest lime content and from the largest to the smallest size of the aggregate, which allowed the layers to be executed from greater to lesser thickness. This made porosity of layers being from the highest to the smallest (from inside to outside), thus guaranteeing that the water went outwards. The fine finishing of the outer layer was applied using a float promoting waterproofing. As in cement mortars, water was adjusted to the lime ratio to have a suitable workability. For the base layer, a mussel shell aggregate size of 0-4 mm was used, but in the other layers, fine mussel shell sand with a maximum size of 1 mm was used. Only marble powder was used as conventional aggregate for the finish layer as it is generally applied to improve the appearance of the floating finish (Figure 16). Except for the finish layer, hemp hurds (2-25 mm) were used to avoid cracks due to drying shrinkage in air lime renders. Different laboratory tests were carried out over three layers of air lime mortars. Results are shown in Table 6.

Clay plasters were applied inside the building (Figure 17), specifically in the inner surface of NW and SE facing walls. Clay mortars were not included in the development of the earlier experimental campaign in the laboratory (developed in Phase 1 and Phase 2). However, we decided to test these kind of coatings in the real scale application as they are a very good solution from an environmental point of view. The design of the mixes and the percentage of replacement used were chosen on site. Clay plasters were composed of four layers, and their dosages are shown in Table 5. Kaolin was used for the finish layers to have white finish. On the SE wall, a rough-looking sponge finish was made, and the mussel particles could be seen. On the NW wall, a trowel and stone burnishing finish were performed, so the finish was softer.

Figure 16. Coating mortars applied in the building: cement mortars (left), lime mortars (middle), and clay mortars (right).

The results of in situ tests over clay plasters are shown in Table 7. Surface hardness both measured by durometer and sclerometer of clay mortars with mussel shell aggregates were similar to other commercial earth plasters (Faria et al., 2014; Santos et al., 2019). In addition, the results of the sphere impact caused by the Martinet-Baronnie ball in the clay plaster of the experimental building were similar to those published focusing on a ready-mixed earth mortar applied to a rubble stone wall, a concrete blocks wall (Santos et al., 2019) or other mineral renders (Flores-Colen et al., 2009). Clay plaster used in the NW wall absorbed 4 ml of water in 20 minutes, and that in the SE wall absorbed it in 15 minutes, taking the average value of three tubes. These values were comparable to those published by other authors (Duarte et al., 2020; Gomes et al., 2018, 2019; Karozou et al., 2019), thus constituting a positive result that promotes the use of mussel shells aggregate in earth-based plasters.

The aesthetic appearance of the mortars is different from the usual finishing of mortars and, in general it has have very good impression on technicians that visited the experimental building. This aesthetic characteristics can make this application one of the most suitable for the mussel shells. This material could be premixed and sold as a ready mix material for mortars.

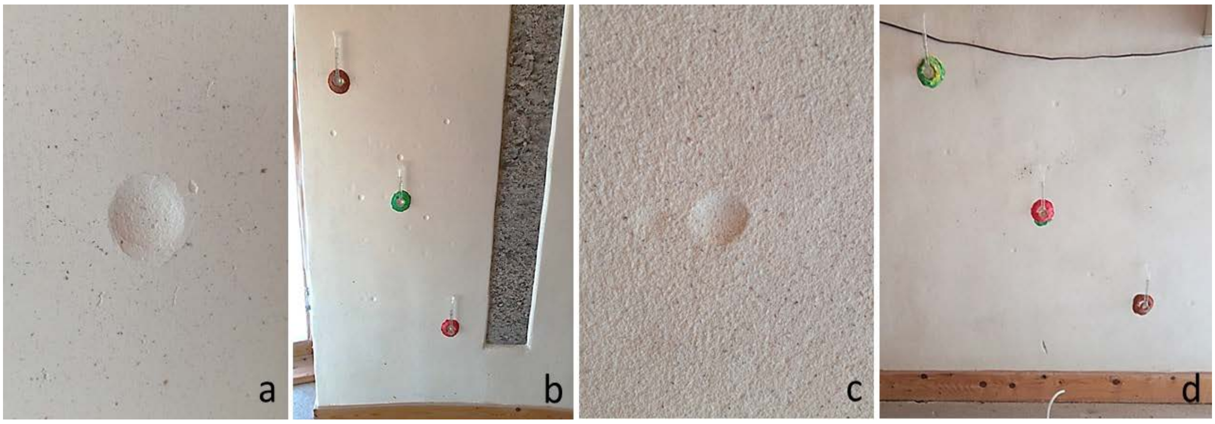


Figure 17. In situ test for clay plasters: a) Impact caused by the Martinet Baronnie ball in the inner surface of the NW wall; b) Karsten tubes in the inner surface of the NW wall; c) impact caused by the Martinet Baronnie ball in the inner surface of the SE wall; and d) Karsten tubes in the inner surface of the SE wall.

Table 7. In situ characterisation of clay plasters.

	Earth-based coating	
	NW wall	SE wall
Durometer (Shore A)	89	85
Sclerometer (Vicker degree)	36	36
Concavity diameter caused by the sphere impact (mm)	21	19
Water absorption at low pressure after 60 min (ml)	8.8	9.8

6 Energy performance

In all phases (design, experimental campaign and constructive process), the energy performance of the building was assessed using the Passive House Planning Package (PHPP) software. After introducing all data, the software obtained the results of both the energy demand for heating and the primary energy consumption.

The PHPP software defines the balance boundary for these calculations in accordance with the external dimensions of the thermal envelope (Table 8), so the external areas of each thermal element should be first extracted from the CAD file. In addition, only one person was considered for the building occupation, considering that the building is going to be empty most of the time.

Table 8. Dimensions of the thermal elements chosen for the calculation.

External volume	281 m^3
Internal volume	167 m^3
Energy reference surface	50 m^2
South windows	17.6 m^2
West windows	13.6 m^2
Exterior walls	39 m^2
Exterior walls – ground	11 m^2
Roof	85 m^2
Ground-floor	69 m^2

The energy consumption depends on the outside temperature, so the PHPP software needs an analysis and integration of climate conditions. Climate is a key factor to design an energy efficient building, affecting not only the building solutions and insulation characteristics but also the orientation and ventilation. An efficient energy building should maintain a comfortable indoor temperature (20 °C ± 2) during winter or summer, with a low energy demand for heating or cooling the space (Mihai et al., 2017). The weather conditions of A Coruña were analysed considering the solar radiation and the ambient temperature. A Coruña a coastal city in NW Spain, with a Mediterranean warm summer climate (Csb in Köppen classification (Kottek et al., 2006)). In this area, there is a limited temperature difference between seasons and the maximum and minimum temperatures of the day. In fact, a temperature lower than 9 °C between average winter and summer temperatures is recorded. Winters are mild (rarely lower than 0 °C) and rainy with rare frosts, and summers are mild (usually lower than 30 °C). It presents an average annual relative humidity of around 77%. The exterior temperature, the dew point, and the different monthly solar radiations collected by the software and considered for the calculation are shown in Figure 18.

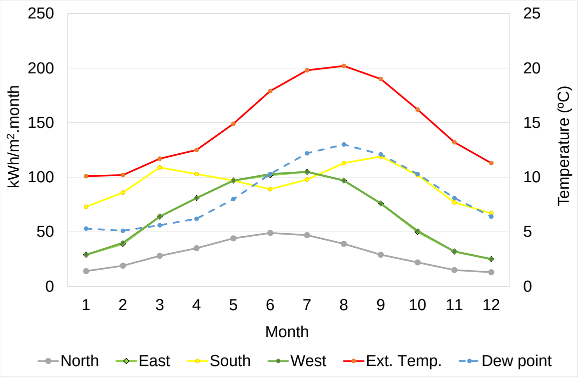


Figure 18. Monthly solar radiation estimated in the building location.

The thermal conductivities of mussel shell concretes and mortars were estimated according to their hardened densities. For these estimations, the compendium of building materials and solutions edited by the Spanish Technical Building Code (Spanish Technical Building Code (CTE), 2007) was taken as a reference. The mussel shell concrete used in floor pavement had a hardened density of 2270 kg/m^3. The value of a range of densities between 2000 and 2300 kg/m^3 should be 1.65 W/(mK). Mussel shell cement and lime mortars with 50% of replacement rate had a hardened density of around 1700 kg/m^3 (Carolina Martínez-García et al., 2019a, 2019b), which implied an estimated thermal conductivity value of 1 W/(mK). The thermal conductivity value of the clay plaster was taken based on the work by Santos et al (Santos et al., 2017).

Firstly, during the design, the available information and references on mussel shells were considered for the building design, and the thermal conductivity value for the mussel shell gravel was.

The thermal conductivity value of the compacted mussel shell gravel considered during the design phase was taken from the literature, 0.11 W/(mK) (Aagaard & Moller, 2007). After an experimental campaign developed in the laboratory (C. Martínez-García, González-Fonteboa, Carro-López, & Pérez-Ordóñez, 2020), this property was measured and a higher value of 0.175 W/(mK) was obtained.

Finally, the structural wood for walls was made of sawn pine studs with a density of around 550 kg/m^3 that implies a thermal conductivity value between 0.15 and 0.18 W/(mK), so a value of 0.165 W/(mK) was taken for the structural wood, thus avoiding thermal bridges in walls. The thermal conductivity of the rest of elements used in the building solutions were based on the Spanish Technical Building Code supporting document (*DA DB-HE/1. Calculation of Characteristic Parameters of the Envelope. Supporting Document.*, 2020).

Table 9 shows all these thermal conductivity values introduced in the software, and the calculated U-values, in both design and experimental laboratory phases.

Table 9. U-values of the building envelope (opaque elements).

		Design phase			Experimental laboratory campaign		
Building solution	Layer	λ [W/(mK)]	R (m^2K/W)	U value [W/(m^2K)]	λ [W/(mK)]	R (m^2K/W)	U value [W/(m^2K)]
Ground floor	Mussel shell concrete	1.65 (2)	0.06	**0.312** (1)	=	=	**0.384** (1)
	Compacted MG	0.11 (3)	7.27		0.175 (4)	4.57	
NW and SE walls	Int. surface resistance	-	0.13	**0.196**	-	=	**0.294**
	Earth based render	0.85 (3)	0.02		=	=	
	OSB	0.13 (2)	0.17		=	=	
	Compacted MG	0.11 (3)	4.55		0.175 (4)	4.57	
	OSB	0.13 (2)	0.17		=	=	
	Lime putty plaster	1.00 (2)	0.02		=	=	
	Ext. surface resistance	-	0.04		-	=	
NW and SE walls – studs section	Int. surface resistance	-	0.13	**0.221**	-	=	**0.290**
	Earth based render	0.85 (3)	0.02		=	=	
	OSB	0.13 (2)	0.17		=	=	
	Wood studs (14 cm) + Comp. MG (36 cm)	0.125	3.98		0.172	4.57	
	OSB	0.13 (2)	0.17		=	=	
	Cement plaster	1.00 (2)	0.02		=	=	
	Ext. surface resistance	-	0.04		-	=	
NE wall	Int. surface resistance	-	0.13	**0.208**	-	=	**0.314**
	OSB	0.13 (2)	0.17		=	=	
	Compacted MG	0.11 (3)	4.09		0.175 (4)	4.57	
	OSB	0.13 (2)	0.17		=	=	
	Water proofing membrane	0.25 (2)	0.01		=	=	
	WS gabions	0.52	0.19		=	=	
	Ext. surface resistance	-	0.04		-	=	
Roof	Int. surface resistance	-	0.13	**0.208**	-	=	**0.317**
	OSB	0.13 (2)	0.17		=	=	
	Compacted MG	0.11 (3)	4.09		0.175 (4)	4.57	
	OSB	0.13 (2)	0.17		=	=	
	Waterproofing membrane	0.25 (2)	0.01		=	=	
	WS with earth and sedum	0.52	0.19		=	=	
	Ext. surface resistance	-	0.04		-	=	

(1) The U-value of the ground floor solution is calculated by extrapolation in Table 3 from the Spanish Technical Building Code supporting document (*DA DB-HE/1. Calculation of Characteristic Parameters of the Envelope. Supporting Document.*, 2020) and according UNE-EN ISO 13370:2017
(2) (Spanish Technical Building Code (CTE), 2007)
(3) (Aagaard & Moller, 2007)
(4) (C. Martínez-García, González-Fonteboa, Carro-López, & Pérez-Ordóñez, 2020)
(5) (Santos et al., 2017)

As it can be seen, results of U-value after the experimental campaign meet recommendation of Passive-On study in NW and SE walls. This study recommends in Spain a U-value of 0.3 W/m^{2}K to achieve the optimum efficiency ratio. In the case of ground floor, vertical wall and roof, the values are slightly higher: 0.384 W/m^{2}K, 0.314 W/m^{2}K and 0.317 W/m^{2}K respectively. Anyway, all the U-values comply with the requirements fixed by Spanish standard (CTE-DB-HE, 2019): 0.49 W/(m^{2}K) for walls and ground floors and 0.40 W/(m^{2}K) for roofs. Taking these values as a reference, we can see an improvement of 36-41% in the case of walls, 22% in the case of ground floor and in a 21% in the case of roof.

Table 10 shows the energy demand results throughout different phases. It includes the passive house requirements of heating energy demand, the total primary energy demand from non-renewable sources for heating, hot water and electricity, and the airtightness value.

Firstly, during the design phase, the available information and references on mussel shells were considered for the building design, and the thermal conductivity value for the mussel shell gravel was 0.11 W/(mK) (Aagaard & Moller, 2007). Moreover, a target leaked air volume of 0.6 $m^3/m^2.h$ was considered. Thanks to these parameters, the building met the PH requirements (Table 10).

Secondly, after the experimental laboratory campaign, the thermal conductivity was further analysed by changing the thermal conductivity value for the mussel shell (0.175 W/(mK)), (Table 10). Changes in the thermal conductivity value of the mussel shell gravel affected all building solutions, thus disturbing the results of the whole energy behaviour of the building. However, even with this new value, the leaked air volume of 0.6 $m^3/m^2.h$ was maintained and the building still met the PH requirements (Table 10).

Finally, the building air tightness is an important factor that affects indoor air quality and building energy consumption (Kim et al., 2013). Moreover, air leakage or infiltration in buildings increase heating and cooling demands. The obtained value of leaked air volume, which was measured by the blower door test (Figure 19), was 9.8 $m^3/m^2.h$ per hour, a very high value for a PH. This result could be related to the lack of a continuous finishing inside the NE-wall and the roof. In addition, the closure of the structure based on OSB board as finishing made the sealing of multiple joints something of a challenge, thus leading to air losses. This high leaked air volume implied that the building surpassed the PH requirements (Table 10).

Table 10. Energy demand results with the PHPP software.

	Design phase	After experimental campaign phase	After constructive process phase	PH standard (max)
λ_{MG} W/(m.K)	0.11	0.175	0.175	
Air leakage (50 Pa, $m^3/m^2.h$)	0.6	0.6	9.8	0.6
Energy demand for heating kWh/(m^2.yr)	2	6	34	15
Heat load (W/m^2)	8	11	36	10
Primary energy consumption (heating, hot water, and electricity) kWh/(m^2.yr)	78	78	84	120
PH requirements met	✓	✓	✗	

Figure 19. Blower door test carried out in the experimental building.

To conclude, the objective of this project was to demonstrate the applicability of mussel shells in a top tier application like a very low-energy consumption building. This was a success, and all the constructive units have demonstrated their applicability in buildings at a real scale. It was misfortune that the complexity of the building geometry (a curve-shaped geometry) made the sealing of the joints of some pieces difficult, and these yielded some cold spots that reduced the energy performance of the building. This prevented the qualification of this global design as a Passive House. Anyway, this experience could serve as useful reference for designers of future low-energy and low-impact buildings.

7 Conclusions

This study aimed to prove the applicability of mussel shells both as aggregate in concretes and coating mortars and as loose-fill material for insulation purposes in various building solutions. This article describes an experimental building that uses mussel shells in all the constructive elements. Additionally, the energy evaluation of each solution is studied, and the results obtained by the Passive House Planning Package software for the whole building are discussed.

This constructive experience is useful to face the use of these new building solutions with mussel shells, so the following conclusions are drawn:

- There are no technical hitches to use mussel shells as aggregate in concretes and coating mortars. Moreover, drying cracks are not observed in mussel shell concretes or in coating mortars. The appearance of the unveiled mussel shell particles is very aesthetic and represents an opportunity to apply this type of aggregate.
- As loose-fill material, the mussel shell gravel is the best option for ground floor insulation as its thermal conductivity value is appropriate. In addition, the waterproofing of the building in contact with the ground is solved. On the other hand, the compaction of mussel shells is something of a challenge in curved or thin spaces, so they should be combined with another type of insulation materials in flexible form (batts or roll). In flat and straight cavities (walls, roofs and slabs), however, it could be a good solution with good thermal and acoustic performance.
- Regarding the energy performance, compacted mussel shells can be used as thermal insulation in a building with low energy consumption. When the geometry of the building allows for suitable air tightness, mussel shell insulation could be used in a designed Passive House building.
- Finally, regarding installation, the mussel shell wall has a simple constructive process: heavy machinery or specialised workers are not required, and the wood structures can be assembled in workshops. All these parameters define an unsophisticated solution to be used in auto-construction; however, it could be sold as a pre-assembled building kit for an easy installation.

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