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Performance Assessment of Giant Reed-Based Building Components

Rosa Caponetto [1], Massimo Cuomo [1], Maurizio Detommaso [1], Giada Giuffrida [1,2,*], Antonio Lo Presti [3] and Francesco Nocera [1,*]

[1] Department of Civil Engineering and Architecture, University of Catania, Viale Andrea Doria 6, 95125 Catania, Italy
[2] CERTES, Université Paris Est-Créteil, 61 Av. du General de Gaulle, 94010 Créteil, France
[3] L.A.P.I.S. Laboratorio Analisi Petrografiche e Indagini Strumentali, 101/B, Via della Regione, 95037 Catania, Italy
* Correspondence: giada.giuffrida@u-pec.fr (G.G.); francesco.nocera@unict.it (F.N.)

Abstract: The growing concern for the reduction of energy needs and the environmental impact of the building sector has placed emphasis on the possibilities offered by natural materials. The adoption of agricultural by-products seems to be promising and in line with the circular economy paradigm. Materials such as hemp and straw have been extensively adopted in contemporary construction, but nevertheless, the potential use of giant reed has not been sufficiently investigated despite being a common infesting plant abundantly available all over the planet. This work focuses on the performances assessment of lime/cement–reeds mixtures as base materials to design a new line of building components (bricks, blocks, panels and loose insulation) that can be used both in new bio-based construction and in existing buildings for energy-efficiency retrofit. The main materials used in the experimental campaign are giant reed by-products, lime, cement and local and recycled aggregates. The evaluation of the physical, mechanical and thermal properties of lime–reed and cement–reed composites are presented. The results of thermal conductivities (between 0.245 and 0.191 W/m K) and mechanical properties (compressive strengths between 0.848 and 1.509 MPa, and flexural strengths between 0.483 and 0.829 MPa) allow meeting the requirements for non-bearing and thermal building blocks. The outcomes show how blocks made with the abovementioned lime–reed mixture have good mechanical performance and thermo-physical behavior when compared to conventional building materials such as hollow clay or hemp blocks with the same thickness.

Keywords: giant reed; cement–reed composites; lime–reed composites; performances assessment

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1. Introduction

The rapid growth of urban, industrial and agricultural wastes has encouraged interest in the research on their possible reuse as well as on economically harnessing them. Among the many alternatives sought to face the problem, the use of materials derived from various end-of-waste processes to develop innovative products for the construction industry is one of the most promising fields.

Agricultural by-products such as bagasse, rice husk, jute fibers, reeds, cattail, rice and wheat straw, groundnut shell, banana bunch, corn peel and cob, coconut coir, kenaf, cotton stalk, date palm fibers, durian, oil palm fibers, pineapple leaves, sansevieria fibers, sunflower and olive waste have been used to develop new sustainable building materials [1].

The main advantages associated with the use of natural fibers are the improvement of thermal properties of the building components, mainly to reduce thermal transmission and to increase the envelope's permeability to moisture, which helps to control the internal hygrothermal conditions of a building [2]. Moreover, the use of natural fibers has a fundamental role in the improvement of the mechanical properties of composites [3].

The use of agro-waste, biomass products and local materials is a careful choice to improve the sustainability of the construction sector and produces several benefits. Concerning environmental issues, the use of natural materials or agro-waste reduces resource consumption as well as the production of potentially dangerous by-products and carbon dioxide emissions in a circular economy scheme. Moreover, as the usual application for these materials is thermal insulations, their use leads to a reduction in energy consumption during the operating phase. Concerning economic issues, using local materials and by-products means cutting down production costs and, therefore, selling costs. Finally, concerning social issues, the use of local and recycled materials bolsters the territorial production system.

The purpose of this research is to evaluate the performance of a thermal block made by combining lime and/or cement with mineral aggregates and fibers obtained from a local indigenous reed's (Arundo Donax) waste, which is abundant and infesting many parts of the world. Such a newly developed block must simultaneously meet two requirements: have a better thermal performance compared to other blocks used for non-load-bearing external vertical closures (e.g., Poroton blocks) and, at the same time, have a higher mechanical resistance than the natural thermal blocks (as lime–hemp blocks) found on the market. For this reason, in the design of the mixtures, in addition to lime (or cement) and natural fibers, mineral aggregates capable of improving the mechanical performance of the mixture have also been included. These aggregates also help to increase the thermal inertia of the mixture, with direct consequences on the improvement of the indoor thermal comfort of buildings.

It is worth highlighting that the Arundo Donax used in this research is the waste product of a manufacturer that provides mats and wattles for roofs and fences. Hence, the waste product of these processes is not currently implemented in a new production line, and it represents a cost for the manufacturer. Following the approach of circular economy, this giant reed waste may become a new value chain. The research involves several types of mixtures for bricks and/or blocks that will be shortly addressed as cement–reed and lime–reed mixtures. Reed by-products are shredded and mixed with different aggregates and binders and tested concerning their physical, mechanical and thermal properties. Moreover, thermal dynamic parameters performance (Time Lag, Decrement Factor, etc.) of an external wall made up of lime–reed blocks have been investigated and compared with external walls made up of hollow clay blocks (Poroton) and a bio-based material like lime–hemp block in three different climatic conditions.

2. State of the Art and Relevance

There are many studies that evaluate the latest developments of agro-waste-based and biomass-based composites and their corresponding performances [1]. The most significant ones for our research are presented herein.

One of the most famous biomass-based products is lime–hemp concrete (LHC), hemp concrete or hempcrete, which is currently used for non-load-bearing purposes in new construction (mainly as a base material for blocks for walling systems, but also for roof insulation) and energy retrofit of the existing building stock. The use of hemp shivs as aggregate in concretes leads to a considerable lowering of the density, which ranges from 270 kg/m^3 to 850 kg/m^3, with a consequent reduction in thermal conductivity values, with values ranging from 0.06 W/m K to 0.18 W/m K [4]. This wide density variability is reflected in the different compressive strength performances achieved by the composites, which go from 0.10 MPa to almost 4 MPa [4]. These composites also have good acoustic properties, fire resistance and durability to salt exposure and biological deterioration [4–6]. Hemp concrete can also be prefabricated through vibro-compaction by using hemp shiv with lime–metakaolin binders [7]. Alternative binders such as silica and polysaccharide can be used to confer to this hemp-material water resistance, vapor permeability and superior moisture buffering capacity [8]. Nevertheless, other agro-waste and natural by-products, currently disposed of as waste, have been tested in the literature.

Date palm fibers have been used, together with cement and sand, to produce cement composites [9]. Excellent hygrothermal properties were assessed, including dry-state thermal conductivity (0.19 W/m K–0.22 W/m K) and moist-state thermal conductivity (0.25 W/m K–0.30 W/m K).

In [10], composites made of hemp shiv, alkali-treated corn cob and green binders are investigated. The compressive strengths of the lightweight composites range from 0.03 MPa to 0.695 MPa [11]. The dry-state thermal conductivities range from 0.067 W/m K to 0.148 W/m K, while at 50% RH, the values range from 0.08 W/m K to 0.172 W/m K [11].

Lightweight concretes, with partial replacement of the conventional aggregates (sand, gravel) by sunflower stem aggregates, were studied in [12]. The sunflower aggregates are left untreated or treated with a sodium silicate solution to reduce water absorption. Results show a reduction in density values (from 2191 kg/m^3 of the reference concrete to 1553.57 kg/m^3 of the lightened one) and mechanical ones (average values of compressive and flexural strengths of the best sample are, respectively, 13.61 MPa and 2.43 MPa).

Hemp and wood cellulose were used together with hydrated lime, cement, zeolite and magnesium oxide in [13]; the hemp fiber and MgO–cement composites had higher densities (1040–1160 kg/m^3) and compressive strengths (1.73–2.73 MPa) compared to the lime–hemp composites (for which densities ranged between 540–790 kg/m^3 and compressive strengths between 0.23 and 0.83 MPa). Wood cellulose composites had higher densities (940–1260 kg/m^3), good thermal conductivities (0.12–0.24 W/mK) and compressive strengths (1.42–5.44 MPa).

Crop residues such as banana fibers and peanut shells were used in [14] for the design of insulating panels. In this case, the crushed banana and peanut agricultural waste were used within a polyester resin binder. The measured thermal conductivity of the composite was 0.059 W/mK, while the compressive strength was 0.177 MPa.

In Charai et al. [15], concretes with partial substitution of sand by Alfa fibers (from now on: AF) are tested. The addition of 10% wt of 3 cm-long AF in the concrete matrix allows for density reduction, with a consequent decrease in thermal conductivity from 0.591 (0% of Alfa fibers) to 0.193 W/mK (10% of AF). The addition of fibers also causes a drop in compressive and flexural strengths, which pass, respectively, from 19.14 MPa and 4.16 MPa for the unfibered concrete to 0.66 and 0.54 MPa for the 10% AF percentage.

Portland cement mortars incorporating 10 mm long rock wool and rice straw fibers in percentages ranging from 0 to 50% in weight were tested in [16]. It was observed that mortars with rock wool and rice straw fibers yielded a significant drop in the mortar's thermal conductivity, from the 1.004 W/mK of the unfibered mortar to the 0.246 W/mK of the most insulating mixture using both. In this work, the addition of fibers did not seem to induce a significant decrease in mechanical performance, with a flexural strength passing from 1.38 MPa to 0.7 MPa, and a compressive strength decreasing from 9.3 MPa to 6.4 MPa.

The technical feasibility of concretes with partial replacement of sand by giant reed aggregates has been previously evaluated by [17,18], thus obtaining good mechanical performances but poor thermal ones.

A study on the properties of cement composites with the addition of common reed fillers in two different sizes (2–10 mm and 10–20 mm) was carried out in [19]. It was found that the fillers allow for obtaining ecological, durable and lightweight cement composites when subjected to mineralization processes. As the findings and SEM observations show, the mineralization of the organic fillers with solutions of aluminum sulfate and calcium hydroxide (ratio 1:2) significantly affected the contact zones tightness and improved adhesion between the filler and the paste.

Natural hydraulic lime-based mortars, mixed with growing percentages (0%, 1% and 2% by weight) of common reed fibers at three different lengths (4 cm, 8 cm and 12 cm), have been tested in [20]. Three types of samples are manufactured, in which reed fibers are, respectively, left untreated, treated with linseed oil or treated with polyethylene glycol (PEG) to reduce their moisture hydrophilic nature. The apparent densities of the samples are near the value of 1800 kg/m^3. The compressive strengths of these composites are comprised in the range 5.01–7.32 MPa, while first and post-fractural flexural strengths are, respectively, in the ranges 1.49–2.41 MPa and 0.13–2.97 MPa. The water absorption coefficient reduces more in the linseed oil-treated samples than in the PEG-treated ones. Cement-based mortar mixtures containing different amounts of common reed fibers were also tested [21], finding mechanical properties which met the criteria for lightweight structural concrete and a reduction in thermal conductivities (compared to plain concrete) between 30–40%.

As can be seen from the literature review, natural fibers are often used either in lightweight mixtures for insulation purposes or as aggregates in concretes. There are no studies that foresee the design of giant reed mixtures which could, at the same time, guarantee good thermal properties (by reaching low thermal conductivities but also good inertial properties) and adequate mechanical performances (blocks made of this mixture are meant for non-loadbearing purposes, but they can guarantee containment of damages in case of seismic events). In this work, this end is sought through the formulation of mixtures using both giant reed fibers (to decrease the density and thermal conductivity of the composite) but also aggregates (sand, recycled clay aggregate), which allows for the increase in the mechanical resistance and inertial properties of the final product.

3. Materials and Methods

As anticipated, the objective of the research is to evaluate the performance of a non-load-bearing thermal block made with a new mixture that combines binders (lime or cement) with the natural fibers of Arundo Donax (to improve thermal performance) and mineral aggregates (to improve mechanical performance). There are no references in the literature to such mixtures. Usually, insulating mixtures use binders and natural fibers (without aggregates), thus obtaining low mechanical strengths [6,7,15]; other works analyze concretes with natural fibers added as partial replacements for sands, with poor thermal performance [15,16,20].

Consecutive research iterations were used to determine the composition of the mixtures to be tested, following the trial and error approach of research by design methodology [22]. In the first phase of the research (which will not be herein reported for brevity), tests have been carried out to detect the best mix designs in terms of physical and mechanical performances (both for lime–reed and cement–reed solutions). Once the best mixtures were identified, further mechanical and thermal tests were performed. For this second phase of the research, four different types of composites (the best ones from the first step) were selected and tested.

- One is a mixture of lime and cement, with a predominance of cement, sand and reeds (cement–reed).
- Two of them are a mixture of different limes, sand and reeds (Lime–reed White Calix NHL and lime–reed Villaga NHL)
- One is a mixture of lime and cement, with a predominance of lime, sand and reeds (lime–reed Calce Fiore + Cement)

The materials used are specified in more detail in Section 3.1, the mix design is in Section 3.2 and the tests performed are shown in Section 3.3.

Finally, a wall-scale comparison of the thermal behavior of blocks composed of the best lime–reed mixture (Calce Fiore + cement) was compared to hollow clay (Poroton 700) and lime–hemp blocks for the purpose of assessing their effectiveness for future commercial development (see 4.3).

3.1. Raw Materials

3.1.1. Natural By-Products: Giant Reed (Arundo Donax)

Arundo Donax has been employed as a natural component in the composite. It is a rhizomatous grass [23], copiously and spontaneously growing in all temperate areas, and it is very common in Mediterranean regions such as Sicily, easily adapting to different climatic conditions. As a matter of fact, because of its rapid and abundant growth, it is often qualified as an invasive species, hard to vanquish. Reeds are traditionally used for creating fences, suspended ceilings and insulating layers made of whole reeds juxtaposed and assembled, etc.

In this research, the disposal of the industrial processes undergone by the reeds was used. Only the cut-out stems of the plants were used, without the leaves. The fibers were cut with a length of 3 cm. The material employed is mainly composed of cellulose (around 65%), and it contains about 20% of lignin, plus other minor components such as sugars [24,25]. The percentage of lignin content is higher than in other natural fibers such as linen or jute. A similar composition has been found for giant reed experimentally grown in Sicilian farms [26,27], with a reported percentage of lignin slightly higher than 20%.

As in almost all vegetable fibers, cellulose is the primary component; the mechanical properties and structural stability of the plant depend on it. For instance, the tensile strength of the fibers increases as the cellulose content increases. Lignin is the substance that gives stiffness to the cell walls and allows the connection between the different cells, creating a structure resistant to shocks, compressions and bending. However, the presence of lignin makes the use of natural fibers in combination with lime difficult since it reduces its adherence to the matrix.

3.1.2. Binders

In this investigation, two types of binders have been used: lime and cement. Three types of natural lime were employed for preparing the lime–reed samples.

White Lime Calix NHL 3.5. This is a natural hydraulic lime, as defined in [28], produced from natural materials (mainly marly limestones derived from deposits located in the Pyrenees region) by calcination in vertical ovens. After 28 days of curing, its compressive strength reaches 5.17 MPa.

Villaga Lime NHL 3.5. This is a natural hydraulic lime, as defined in [28], produced by the calcination of marly limestone from the Berici Mountains in traditional stratified ovens. Its compressive strength after 28 days of curing is greater than 3.5 MPa, and it increases to greater than 4.5 MPa after 56 days.

Calce Fiore (Calcium Lime). It is a powder-hydrated lime CL90 S as defined in [28], produced by Calce Casertana enterprise, obtained from the calcination of calcareous stones from the Dolomites Mountains. Calce Fiore is obtained by the controlled slaking of quicklime. Its fineness has a beneficial effect on the plasticity and workability of all the composites, allowing them to lower the amount of water used in the mix and improving the strength of the hardened lime.

For the cement–reed block, Portland white cement was used. It is a CEM 32.5 R, type II/B-LL (according to [29]) with a compressive strength at least equal to 10 MPa after two days and a compressive strength between 32.5 e 52.5 MPa after 28 days of curing.

3.1.3. Aggregates

A local type of sand (called "azolo") was used as aggregates. Azolo is a fine volcanic sand, dark grey colored, obtained from the crushing of volcanic stones produced by the eruptions of the Etna volcano. It is mainly composed of silica (45.9%), aluminum oxide (20.43%), ferric oxide (9.99%), calcium oxide (10.22%), magnesium and sodium oxide (respectively, 4.71 and 4.02%) and other components in smaller percentages [30]. A maximum particle size of 3 mm was used in the samples after removing the fraction with a diameter size between 0 and 0.5 mm, sieving the raw sand with a metallic sieve as indicated in [31]. Its main function is to compensate for the shrinkage of the binder due to water loss during curing [32,33] but also to increase the thermal inertia of the produced mixture, with positive consequences on indoor comfort.

A recycled clay aggregate (cocciopesto) was used, which is obtained from crashed iron-rich clay block fired at temperatures lower than 800 °C. Such material usually consists of silicon oxide (60%), aluminum oxide (20%), calcium oxide (about 10%), iron oxide (7%) and other components in smaller percentages [34]. The particles size of the recycled clay aggregate used in the research ranged between 1 and 4 mm. Cocciopesto gives pozzolanic characteristics to mortars [34].

3.1.4. Additives

An air-entraining agent (type Hostapur) has been used as an additive in all the mixtures to favor the development of air bubbles. Air bubbles are able to reduce the stresses produced by thaw cycles and prevent the penetration of water and moisture. Figure 1 shows some of the base materials used in the research.

Figure 1. Main components of the cement–reed mixture. From the top, rotating clockwise: Arundo Donax, white cement, Azolo sand, Recycled clay aggregate.

3.2. Mix Design and Sample Manufacturing

As indicated above, several types of composites were tested: three lime–reed mixes and a cement–reed mix.

3.2.1. Lime–Reed Mixtures

Before establishing the composition of the lime–reed mixtures, several mixes have been compared, all including the same constituents but with different proportions. The three mixtures that showed the best mechanical performance in the first phase of the research were selected:

1. A mix using hydraulic natural lime White Calix NHL 3.5 (from now on, “Lime–reed, White Calix NHL”);
2. A mix using hydraulic natural lime Villaga NHL 3.5 (from now on, “Lime–reed, Villaga NHL”);
3. A mix using powder hydrated lime made hydraulic by the addition of cement, in a percentage lower than 50% of lime (from now on, “Lime–reed, Calce Fiore + Cement”). This kind of lime is classified as EL by [28].

The composition of the mixtures used in the research is reported in Table 1, expressed as volume and weight fractions. The density of the raw materials was determined as the average of three samples taken from the furnisher.

Table 1. Mix design for lime–reed mixtures.

		Lime–Reed (White Calix NHL)		**Lime–Reed (Villaga NHL)**		**Lime–Reed (Calce Fiore + Cement)**	
Materials	Density (kg/m^3)	Volume ratio (%)	Dose per 30 lt (g)	Volume ratio (%)	Dose per 30 lt (g)	Volume ratio (%)	Dose per 30 lt (g)
Saturated reeds	357.00	50	5355	50	5355	54.55	5840
NHL Villaga Lime	809.00	-	-	25	6070	-	-
NHL Calix Lime	643.53	25	4830	-	-	-	-
Calce Fiore	520.00	4.17	650	4.17	650	16.36	2550
Cement	1193.39	-	-	-	-	8.18	2930
Azolo (0.5–3 mm)	1494.14	16.67	7470	16.67	7470	16.36	7335
Recycled clay aggregate (1–4 mm)	1338.04	4.17	16.70	4.17	16.70	4.55	1825
Air-entraining agent	-	-	22.5	-	22.5	-	22.5
Water	-	-	5000	-	5000	-	3100
Water/binder ratio	-	0.57	-	0.57	-	0.41	-
Air-entraining/binder ratio	-	0.004	-	0.004	-	0.004	-

3.2.2. Cement–Reed Mixture

The adopted mix design (from now on, "Cement-reed" mix) is specified in Table 2, in a relative volume of parts and in weight. Notice that in the mixtures, the percentage of reeds used in weight ranges between 38% for lime–reed composites and 26% for cement–reed composites. As observed in [18], the large presence of reed reduces the mechanical performance of the mix, but as will be shown in the next section, it allows the optimization of thermal properties.

Table 2. Mix design for cement–reed mixture.

Materials	**Density (kg/m^3)**	**Volume Ratio (%)**	**Dose Per 30 lt (g)**
Saturated reeds	357.00	52.17	5590
Calce Fiore	520.88	4.35	680
White Cement	1125.23	21.74	7340
Azolo (0.5–3 mm)	1494.14	17.40	7800
Recycled clay aggregate (1–4 mm)	1338.04	4.35	1745
Air-entraining agent	-	-	22
Water	-	-	4600
Water/binder ratio	-	0.51	-
Air-entraining/binder ratio	-	0.003	-

3.2.3. Samples Manufacturing

The Arundo Donax reeds were received as a waste product, so a series of preliminary treatments was adopted:

- Shredding. The residuals of the industrial treatment of the reeds were first cleaned by removing the leaves (with an industrial sugarcane leaf remover/stripper machine). Then, they were reduced to fragments of length smaller than 3 cm using bio-grinders.
- Treatments for reducing the lignin content (mercerization). The lignin contained in the reeds reduces adherence between the fibers and the binders. Therefore, before preparing the composite, the shredded reeds were pre-treated by immersion into a watery solution with additives. The treatment is called mercerization [35] and develops a rough texture on the surface of the reed that improves the adhesion fiber matrix.

In addition, the treatment of the reed with alkali determines a variation in the degree of polymerization and enhances the percentage of crystal cellulose, causing an improvement in the fiber's stiffness. Two different solutions for the treatment of the reeds were tested to carry out the mercerization:

- Solution of water and quicklime.
- Solution of water and caustic soda (NaOH).

The proportions of the solutions and the duration of the treatment are indicated in Table 3. The solutions with caustic soda and quicklime had a final pH between 13 and 14 (the initial pH of pure water was 8). Notice that the treatment with quicklime took approximately twice the time required for the treatment with caustic soda. The caustic soda solution produced the best effects on the crystallization of the reeds. After the treatment, the reeds were washed several times and left in pure water to saturate before being mixed in the composite.

- Preparation of the composite. The consistency of the mixtures was determined by means of a shaking table, according to the procedure indicated in [36].
- Filling of the formworks. Several formworks were filled by the lime–reed and the cement–reed mixtures by means of a trowel and a hand tamper.
- Curing. The samples were cured for 28 days. In the first seven days, they were placed in an environment with almost 100% relative humidity; after that, once hardened, they were removed from the formworks. In the case of the cement–reed composites, the samples were removed from the formwork after 14 days.

Table 3. Treatments used for mercerization of shredded reed.

Type of Solution	Reed (kg)	Active Component (kg)	Water (l)	Duration of Immersion
Caustic soda	1	0.23	25	8 days
Quicklime	1	2.0	25	13 days

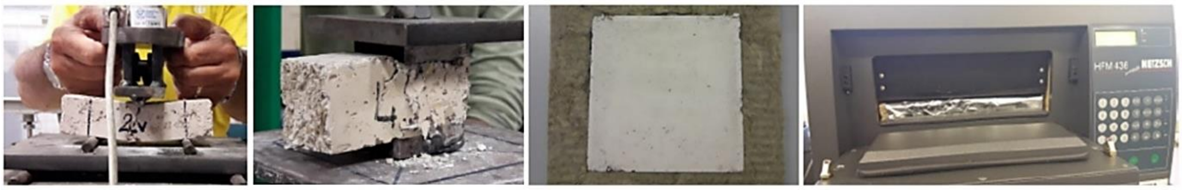
3.3. Experimental Procedure

All tests were performed after 28 days of curing for the cement–reed mixture and at 28 and 90 days of curing for the lime–reed mixtures. The following properties were measured on the lime–reed and cement–reed samples:

- Apparent volumetric mass, capillary water absorption and porosity, according to [37,38] (Figure 2b);
- Compressive strength according to [39] (Figure 2f);
- Thermal conductivity coefficient, by means of a heat flow meter conformal to [40], which induces a thermal gradient between the faces of the specimen (Figure 2g,h).

Apparent volumetric mass and capillary water absorption test were performed on 6 prisms 160 × 40 × 40 mm per mixture. For the flexural and compressive strength tests, 6 prisms 160 × 40 × 40 mm were used, and particularly, the prisms were tested at 28 days of curing concerning their bending properties. Once broken, a compressive strength test was performed on each half of the samples. Additionally, a second compressive strength test was performed after 90 days of curing on lime-based composites. The will to repeat compressive strength measurements at 90 days for the lime–reed mixtures is a peculiarity of this experimental campaign, which allowed for the observation of a difference in assessed mechanical performances. Thermal properties were measured only for the mixtures which registered better mechanical properties. Four plates 200 × 200 × 40 mm were tested for each best mixture inside HFM 436 Netzsch equipment: during the test, the specimen was placed between a hot and a cold plate, and the heat flow created by the well-defined temperature difference was measured with a heat flux sensor. Synthetically, the tests performed on the mixtures are reported in Table 4. Some images of the performed test are reported in Figure 2.

(a) Oven-drying of the samples (b) Porosity test (c, d) Capillary water absorption test



(e, f) Flexural and compressive strength test (g, h) Plates samples and equipment for thermal conductivity test

Figure 2. Test performed on reed composites (**a**–**h**).

Table 4. Test performed on reed-composites.

Mix	Apparent Mass and Porosity	Capillary Water Absorption	Compressive Strength	Flexural Strength	Thermal Conductivity
Cement–reed	X	X	X	X	X
Lime–reed (White Calix NHL)	X	X	X	X	-
Lime–reed (Villaga NHL)	X	X	X	X	-
Lime–reed (Calce Fiore + Cement)	X	X	X	X	X

Note: all tests were performed after 28 days of curing, except for the reed composites containing lime, for which the compressive and flexural strength tests were repeated at 28 days and 90 days of curing.

3.4. Thermal Performance Assessment on a Wall Scale

The thermo-physical performance of the best mixtures of lime–reed (Calce Fiore + cement) blocks was calculated and compared to materials possessing the same thickness that were already present in the construction market and widely used in contemporary buildings. For this purpose, hollow clay aerated blocks and lime and hemp blocks were considered. Therefore, three different wall configurations made up of hollow clay aerated block (Bs), lime and hemp (LHs) and lime and reed blocks (LRs) were investigated. The comparison was carried out on the basis of steady-state parameters (U-values), Surface Mass (SM) and thermal dynamic parameters such as periodic thermal transmittance (Y_{ie}), Time Lag (TL) and Decrement Factor (DF) [41]. Thermal inertia parameters were calculated considering the warmest day in summer as the reference period. Three Italian cities, Catania (Lat. 37.47), Rome (Lat. 41.54) and Milan (Lat. 45.41), were considered to evaluate the influence of different climate conditions on the thermal dynamic parameters of the investigated wall configurations. Localities were selected on the basis of their Heating Degree Days (HDD), as provided by the Italian Presidential Decree [42]. U values were calculated according to [43], while the thermal inertia parameters were calculated by means of a dynamic calculation model that complies with [44]. In order to verify that the thermo-physical parameters (U-values, Surface Mass and Periodical Thermal Transmittance) of the analyzed wall configurations comply with the principles of energy savings for buildings, the Italian Minister Decree 25/06/2015 was adopted [45]. This latter transposes the fundamental principles of the European Directive 2010/31/UE about the calculation of primary energy and the energy efficiency of buildings. To this end, the Minister Decree 26/06/2015 implemented the limit values of thermal transmittance for building envelope components of new and existing buildings in order to limit the heat dispersion through walls and roofs and implemented the minimum requirements of air conditioning systems.

4. Results and Discussion

4.1. Physical, Mechanical and Thermal Characterization of the Composites

The results of the tests for all the types of investigated mixtures are summarized in Table 5.

Table 5. Summary of the measured properties for the reed composites tested.

Properties	Unit	Cement–Reed	Lime–Reed (White Calix NHL)	Lime–Reed (Villaga NHL)	Lime–Reed (Calce Fiore + Cement)
Apparent mass per unit volume	kg/m^3	872.81	870.85	1134.34	1152.31
Apparent porosity	%	31.02	44.40	47.21	44.74
Thermal conductivity	W/m K	0.245	-	-	0.191
Compressive strength	MPa	28 days 0.849	28 days 0.073 90 days 0.168	28 days 0.256 90 days 0.440	28 days 1.029 90 days 1.510
Flexural strength	MPa	28 days 0.483	28 days 0.075	28 days 0.256	28 days 0.829
Water absorption	kg/m^2 min $^{0.5}$	0.0013	0.0014	0.0006	0.0011

The diagram of Figure 3 allows a more direct comparison of the properties of the tested composites. The diagram presents a group of histograms for each mixture, representing the main material properties assessed (apparent mass, water absorption coefficient, compressive strength, flexural strength and thermal conductivity). Each of these values was normalized with respect to the maximum value assessed for the corresponding property (the minimum value was adopted for the normalization of water absorption coefficient and thermal conductivity) so that 1 stands for the "best" result obtained.

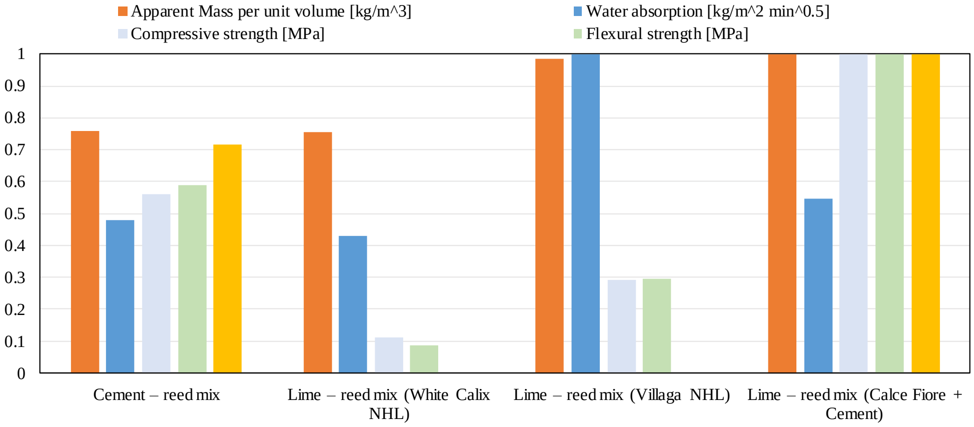


Figure 3. Comparison of physical, thermal and mechanical properties of the tested reed composites.

Finally, the last part of the research consisted of the prototyping of blocks for vertical envelopes made with the best composites tested (the cement–reed and the lime–reed cement-enhanced mixtures). The blocks' dimensions are comparable to those of conventional concrete blocks, hollow clay aerated blocks or non-structural lime–hemp blocks. By manufacturing the prototypes, it was possible to verify the phases of the block production process and of the mixture behavior and performances at a different scale, thus enabling a comparison of the compressive strengths of the blocks with the average values obtained from the smaller samples. The compressive strength results obtained on the blocks showed good consistency with the average values assessed on the specimens. Figure 4 shows some production phases of the cement–reed prototype block.

Figure 4. Prototyping of the cement–reed block.

4.2. Discussion of the Results and Comparison with Previous Studies

A direct examination of the results of the experimentation allows observing that concerning the mechanical properties, the cement–reed mix has a greater compressive strength (0.849 MPa) with respect to the lime–reed mixes (all below 0.500 MPa, even after 90 days), with the exception of the lime–reed (Calce Fiore + cement) mix that, at 90 days of curing, presents a compressive strength nearly twice (1.510 MPa) as strong as the cement–reed mixture.

Similar results were found for the bending resistance. In this case, the lime–reed mixes without cement presented very low flexural strength values; it is remarkable that for these mixes, compressive and flexural strength values are near, a fact that can be explained by the combined effects of incomplete curing of lime (which worsen compressive behavior of the composite) and bridging effect provided by the reeds (which improved the flexural behavior of the composite). Flexural strengths of cement–reed and lime–reed (Calce Fiore + cement) mixtures are, respectively, 0.483 MPa and 0.826 MPa. The ratio between compressive and flexural strength for these mixes is, respectively, equal to 1.76 and 1.82; in the literature, ratios around 1.83 were found [6] for lightweight lime–hemp mixtures, while higher ratios were found for denser hemp materials (around 4.95 in [6]), for reed reinforced lime mortars (around 3.10 in [20]) and for reinforced cement mortars (5.35 in [15] and 6.42 in [16].

It is worth noting that, given their insufficient mechanical performances, the thermal conductivity of the two lime–reed mixes without cement was not measured. The thermal conductivity coefficients measured for the cement–reed and lime–reed (Calce Fiore + cement) mixtures appear satisfactory and, respectively, equal to 0.245 W/mK and 0.191 W/mK, close to those of other lightened materials as [9,13,15,16].

Previous considerations can also be confirmed through the comparison with other studies on natural fiber-based composites using lime or cement as binders (Table 6).

Table 6. Reed composites' average properties compared to lightweight composites found in the literature.

Composite	Apparent Mass Per Unit Volume (kg/m³)	Compressive Strength (MPa)	Flexural Strength (MPa)	Thermal Conductivity (W/m K)
Lime–hemp [6,7,13]	510	1.040	0.230	0.06–0.18

Date Palm–cement [9]	954	-	-	0.185
Corn cob-binder [11]	488	0.3625	-	0.126
Lime–reed mortar [20]	1802	6.069	1.954	-
Hemp and MgO–cement [13]	1100	2.230	-	-
Wood cellulose–cement [13]	1100	3.430	-	0.18
Alfa fiber concrete [15]	1463	6.335	1.185	0.392
Rock wool and rice straw mortar [16]	1974	7.700	1.200	0.298
Cement–reed (present study)	872.8	0.849	0.483	0.245
Lime–reed (present study)	1152.3	28 days 1.029 90 days 1.510	0.826	0.191

Presently, the most widely adopted bio-based product for wall elements is the lime–hemp block. The lime–hemp block is characterized by a wide variability of mechanical and thermal properties depending on the manufacturer. In Table 6, we reported the common density values (around 500 kg/m^3), usual compressive strengths (around 1.00 MPa) and thermal conductivities (around 0.12 W/mK) [6,7,13].

The good mechanical performances of the investigated reed composites are mainly due to the presence of sand aggregates in the mix. At the same time, these aggregates determine a greater volumetric mass (872.81 and 1152.31 kg/m^3, respectively, against the average 500 kg/m^3 of the lime–hemp composites values, as taken from the literature).

The greater volumetric mass has some negative implications since it prevents obtaining very low values for thermal conductivity and also limits the maximum allowable dimensions of the blocks that can be easily handled in the construction process. Nonetheless, the relatively high value of the volumetric mass can give the blocks a good thermal inertia, which is a very desirable property in hot climates such as the Mediterranean's, for which these reed mixtures were designed.

4.3. Wall-Scale Behavior of Lime–Reed Blocks and Comparison with Competitors' Products

In this paragraph, the lime–reed block's thermal behavior, manufactured with the innovative lime–reed (Calce Fiore + cement) mixture, is compared with two materials that are commonly used in contemporary buildings evaluating their behavior in stationary and dynamic thermal conditions. This comparison demonstrates the thermal performance effectiveness of the lime–reed mixture external walls when they are used as vertical closures.

To this purpose, the best lime–reed mixture (Calce Fiore + cement) was compared to hollow clay (Poroton 700) and lime–hemp blocks. In particular, Poroton 700 block was chosen because it is a widely used solution for the construction of building envelopes in Italian new construction. The lime–hemp block was selected because it is an already established solution for bio-based walling systems.

The compressive strength of the investigated lime–reed mixture can be observed as lower than conventional hollow clay blocks by examining the data reported in Table 7. At the same time, the thermal conductivity of the lime–reed mixture is higher than that of the lime–hemp block, but it is lower if compared to that of hollow clay aerated blocks.

Table 7. Reed composite properties compared with hollow clay aerated block and lime hemp product.

Type	Density (kg/m^3)	Thermal Conductivity (W/mK)	Compressive Strength (MPa)
Hollow clay aerated block (Poroton 700)	700	0.23	> 3.5
Lime–hemp	450	0.10	1.040

Lime–reed (Calce Fiore + Cement) composite	1152	0.19	1.510

The thermal parameters of walls built with lime–reed blocks, lime–hemp blocks and hollow clay blocks, respectively, were investigated in three different Italian climate zone: Catania, Rome and Milan. In Table 8, the main geographic and climatic data of Catania, Rome and Milan are reported.

Table 8. Geographic and climatic data of Catania, Rome and Milan.

Parameters			**Catania**	**Rome**	**Milan**
Climate zone	-	-	B	D	E
Winter degree—days	GG	-	833	1415	2404
Latitude	-	-	37,47	41,54	45,27
Longitude	-	-	15,05	12,29	9,11
Height above sea level	H	m	7	20	122
Average irradiance in the month of maximum insolation	I	W/m^2	298.1	321	269.6

Three wall configurations with the same thickness (30 cm) were investigated: the baseline wall (Bs) was realized with hollow clay aerated block (Poroton 700 block) coated with plaster of lime and cement both on the inner and outer side, respectively; the LHs wall was realized with lime and hemp block and plaster of lime and sand on the inner and outer side of the wall; the LRs wall was built up with lime and reed blocks with a mixture of lime reed (Calce Fiore + cement).

The layers and thermo-physical properties of all investigated wall scenarios are reported in Tables 9–11, respectively.

Table 9. Stratigraphy and thermal features of the wall made up of Poroton block (Baseline scenario, Bs).

Layers	**s (m)**	**k (W/m K)**	**ϱ (kg/m^3)**	**C_p (J/kg K)**
Lime and cement mortar (Outer plaster)	0.03	0.900	1800	1000
Hollow clay aerated block–POROTON 700	0.30	0.212	700	1000
Lime and cement mortar (Inner plaster)	0.03	0.900	1800	1000

Table 10. Stratigraphy and thermal features of the wall made up of lime and hemp block (Lime hemp scenario, LHs).

Layers	**s (m)**	**k (W/m K)**	**ϱ (kg/m^3)**	**Cp (J/kg K)**
Lime and sand plaster (Outer plaster)	0.03	0.800	1600	1000
Lime–hemp block	0.30	0.100	450	850
Lime and sand plaster (Inner plaster)	0.03	0.800	1600	1000

Table 11. Stratigraphy and thermal features of the wall made up of lime and hemp block (Lime Reed scenario, LRs).

Layers	s (m)	k (W/m K)	ϱ (kg/m^3)	Cp (J/kg K)
Lime and sand plaster (Outer plaster)	0.03	0.800	1600	1000
Lime–reed block	0.30	0.191	1152	850
Lime and sand plaster (Inner plaster)	0.03	0.800	1600	1000

The U-values of each investigated wall configuration are reported in Table 12. The table also shows the limit U-values (U_{lim}) that the same wall has to comply with according to Italian regulation [45] in the case of the building located in Catania (CT), Rome (RO) and Milan (MI), respectively.

Table 12. U-values of the investigated wall configurations and Italian limit U-values in Catania (CT), Rome (RO) and Milan (MI).

Wall Configuration	U (W/m^{2}K)	U_{lim}-CT (W/m^{2}K)	U_{lim}-RO (W/m^{2}K)	U_{lim}-MI (W/m^{2}K)
Hollow clay aerated block (Bs)	0.65	≤ 0.43	≤ 0.29	≤ 0.26
Lime–hemp block (LHs)	0.30	≤ 0.43	≤ 0.29	≤ 0.26
Lime–reed block (LRs)	0.55	≤ 0.43	≤ 0.29	≤ 0.26

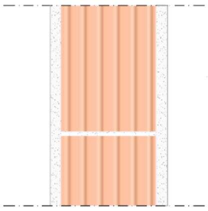
It is worth highlighting that the bio-based materials (LHs and LRs) are characterized by U-values lower than Poroton 700 block (Bs), while only the LRs have higher SM than Poroton 700 block (Bs), as reported in Table 13.

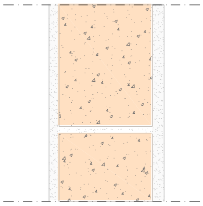
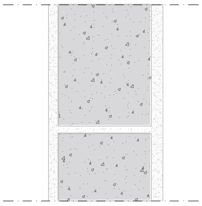
Table 13. Surface Mass (SM) values of the investigated wall configurations and Italian limit values.

Wall configuration	SM (kg/m^2)	SM_{lim} (kg/m^2)
Hollow clay aerated block (Bs)	300	≥ 230
Lime–hemp block (LHs)	135	≥230
Lime–reed block (LRs)	345	≥ 230

Table 14 summarizes the thermal dynamic parameters of all investigated wall scenarios in all selected cities. The values of internal heat capacity (C), Periodic thermal transmittance (Y_{ie}), Decrement Factor (DF) and Time Lag (TL) are reported for each stratigraphy and location.

Table 14. Heat capacity (C), Periodic thermal transmittance (Y_{ie}), Decrement Factor (DF) and Time Lag (TL) values of wall scenarios for the investigated cities.

Scenario	Thermal Dynamic Features	Localities		
		Catania	Rome	Milan
BS	s (m)	0.36	0.36	0.36
	C (J/kgK)	57.95	57.95	57.95
	Y_{ie} (W/m^{2}K)	0.024	0.026	0.028
	DF (-)	0.037	0.040	0.043
	TL (h)	11 h	10 h	10 h

LHs	s (m)	0.36	0.36	0.36
	C (J/kgK)	49.04	49.04	49.04
	Y_{ie} (W/m^{2}K)	0.0132	0.0135	0.141
	DF (-)	0.044	0.045	0.047
	TL (h)	9 h	8 h	8 h
LRs	s (m)	0.36	0.36	0.36
	C (J/kgK)	54.53	54.53	54.53
	Y_{ie} (W/m^{2}K)	0.0165	0.0220	0.0231
	DF (-)	0.030	0.040	0.042
	TL (h)	10 h	9 h	8 h

The analysis of dynamic parameters highlighted the optimal performance of bio-based blocks (LHs and LRs), which are comparable to the Poroton 700 blocks in any configuration because the periodic thermal Transmittance (Y_{ie}) is lower than 0.10 as well as the Decrement Factor (DF). All wall scenarios have a value of Time Lag higher than 8 h which is a typical value of traditional masonries with double block walls which are able to reduce and shift the thermal heat wave. In particular, the wall made up with lime–reed blocks is able to delay the peak of heat wave of 10 h as well as Poroton blocks, thanks to density value of the lime–reed mixture.

5. Conclusions

In this work, several types of reed composites for building purposes, produced with end-of-waste natural reed material, natural and recycled aggregates and binders, were proposed. The methodology used for the manufacturing of these innovative mixtures for building components with thermal and non-load-bearing purposes (bricks, blocks and insulating panels) was described. Four different mixtures, three making use of lime and one of white cement, were designed and tested concerning their physical, mechanical and thermal properties.

Among the mixtures tested:

- The lime–reed (Calce Fiore + cement) mixture presents the best results concerning mechanical (with a flexural strength of 0.826 MPa and a compressive strength of 1.510 MPa) and thermal properties (k = 0.191 W/mk), but it also has the highest density value (1152 kg/m^3).
- The cement–reed mixture presents slightly lower mechanical (a compressive strength of 0.849 MPa and a flexural strength of 0.483 MPa) and thermal performances (thermal conductivity is equal to 0.245 W/mK) but also a lower density value (872.8 kg/m^3).
- The lime–reed (White Calix NHL) and lime–reed (Villaga NHL) mixtures present low compressive and flexural strengths, which were deemed to be insufficient even for non-load-bearing applications.

In this study, the presence of a limited amount of cement appears necessary to improve the compactness and the resistance of the composites (as mixtures using lime have far lower compressive and flexural strengths).

The density of the composites is in the range of 900–1150 kg/m^3. The value is higher than for other bio-based building materials used for walling but is still acceptable and can be useful for improving the thermal inertia of the building's envelope Indeed, this was verified through the assessment of the effectiveness of lime–reed composite's energetic performance when compared with other established building materials such as lime–hemp blocks and hollow clay blocks (Poroton 700). The analysis demonstrated that the thermophysical performances of lime–reed blocks realized with the innovative lime–reed mixture (Calce Fiore + cement) are comparable and, in some cases (as concerning SM and U-values), better than those of the others cases. In particular:

- The Surface Mass of lime–reed blocks is 345 kg/m^2, which is higher than that of hollow clay blocks (300 kg/m^2) and of lime–hemp blocks (135 kg/m^2), making it the best scenario among the analyzed ones in warmer climates for the direct effect of moderating the magnitude of the thermal excursion.
- The U-values of the 30 cm-thick lime–reed wall is 0.55 W/m^{2}K, in an intermediate position between that of hollow clay block wall (0.65 W/m^{2}K) and that of lime–hemp blocks (0.30 W/m^{2}K).
- The periodic thermal Transmittance (Y_{ie}) is lower than 0.10 W/m^{2}K for all the examined scenarios.
- The Decrement Factor (DF) of the lime–reed wall is the lowest among all the wall configurations in all the examined scenarios.
- The Time lag of lime–reed blocks wall for Italian Climate zone B and D is, respectively, 10 h and 9 h, similar to that of Poroton blocks (respectively, 11 h and 10 h) and better than that of lime–hemp blocks (respectively, 9 h and 8 h), thanks to the higher density value of the lime–reed mixture.

It can be stated that even when compared with lime–hemp materials, the lime–reed blocks have competitive dynamic thermal performances in different climatic conditions.

The proposed composites appear to be suitable for practical use, given the obtained results and their economical convenience provided by the wide availability of the reed material. Further studies will provide more in-depth investigations of the hygrothermal performance of the mixtures and will consider the use of the composites for other building components, particularly insulating panels.

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