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Sugarcane Bagasse as Aggregate in Composites for Building Blocks

Patrícia P. L. de Souza [1], Rute Eires [2] and Raphaele Malheiro [2,*]

[1] Department of Civil Engineering, University of Minho, 4800-058 Guimarães, Portugal
[2] Centre for Territory, Environment and Construction (CTAC), Department of Civil Engineering, University of Minho, 4800-058 Guimarães, Portugal
* Correspondence: raphaelemalheiro@civil.uminho.pt

Abstract: Each year, hundreds of millions of tons of processed sugarcane generate, by weight, 25 to 30% of bagasse as waste, whose destination is combustion for energy cogeneration. This research proposes an alternative and more sustainable use for this waste. The use of sugarcane bagasse (SCB) as the single aggregate in composites for building blocks was studied. The raw bagasse was used without any treatment. As the binder, aerial lime and/or soil were used. Both provided enough mechanical strength for non-load-bearing walls. The composite of SCB with soil achieved the best performance in terms of mechanical resistance: 2.6 MPa in compressive strength and 2.1 MPa in bending strength, while the composite of SCB with lime achieved 1.76 MPa and 1.7 MPa, respectively. The higher number of fibers in the SCB/lime mixture provides better thermal insulation than clay brick or conventional concrete, such as "hempcrete". The lime composites obtained greater water resistance and less loss of mechanical strength when saturated. However, the higher water absorption coefficient makes it necessary to apply a waterproof mortar on surfaces exposed to the weather. The replacement of supplied blocks by SCB blocks can offer a better and more economical solution that improves the quality of the built environment and is more ecofriendly.

Keywords: building blocks; sugarcane bagasse; lime; soil; agro-industrial waste

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1. Introduction

As the goals established for sustainable global development, among other measures, the civil construction sector must strive to reduce the consumption of non-renewable materials, the consumption of fossil fuel energy, and the emissions of greenhouse gases.

Finding a destination for the unquantifiable wastes has been a constant task. The sugar and alcohol industry by sugarcane produces a significant amount of natural waste, sugarcane bagasse (SCB). This is the first by-product of this production and has great potential for use as a raw material for the production of other materials.

The sugar and alcohol industries have autonomy, prominence, and influence in several global segments (economic, social, environmental, and agricultural). Brazil is the world's largest producer of sugarcane. The harvest forecast for the period 2022/2023 is 572.9 million tons [1]. Processed sugarcane generates, by weight, 25 to 30% of bagasse [1]. In Brazilian mills, SCB is used for the cogeneration of electrical energy and the surplus, as animal nutritional supplementation and fertilizer for agriculture. Due to the inconsistency of nutrients, this process serves more to discard than to use the material [2].

Thus, this research work aims to contribute to the recovery of this residue (SCB) in a more positive way than combustion for energy cogeneration. In this regard, SCB-based composites and environmentally friendly binders (soil and/or aerial lime) have been developed, which can be used as lightweight and insulating concretes for construction block manufacture, which may be applied in non-load-bearing masonry walls.

As with hemp and under the same arguments, sugarcane is a renewable resource that can be cultivated in annual cycles. In addition, as with other plants, during its development, it extracts carbon dioxide from the atmosphere. Its application in construction materials promotes carbon sequestration during the useful life of the building. Sugarcane bagasse concrete captures more CO_2 in construction than is emitted during its production and any process involved in its disposal at the end of its life. For this reason, it can be considered a "carbon-negative" material [3]; these composites can also be recyclable at the end of the building's life cycle and can be reused, crushed, and mixed with lime binder to make new blocks or recycled in the preparation of plastering mortar. In another hypothesis, the compost crushed and spread over agricultural land can be used to correct soil acidity [4]. As the material is naturally biodegradable, landfilling would also have a minimal environmental impact.

The knowledge presented in the below review focuses on the applications of SCB and the studies that inspired the development of these new light and insolating compositions, especially hemp concrete and other light concrete with agro-industrial residues with lime-based binders and as the only aggregate.

1.1. Applications of SCB

The application of SCB in civil construction has been studied: (i) in addition to cementitious compositions [5]; (ii) with cement and SCB ash (the second by-product of this industry, by the SCB burning to produce energy) [6]; (iii) in composites of SCB with cement and polymers [7]; (iv) in addition to plastic waste [8]; (v) in polymeric tiles of hybrid composites of fiber glass and natural fibers from SCB [9]. In other industries, such as the automotive, a composite of SCB with recycling PET was studied [10] and investigations such as a composite of EPS with SCB [11] seek to prospect innovative applications, based on the study of resistance and new physical characteristics of the resulting materials.

However, in composites of SCB with earth, as in the studies of Bock-Hyeng et al. [12], investigations are scarce and the amount of SCB fiber is very reduced.

The present study sought to develop a material capable of responding in a complementary way to the various contemporary demands in a sustainable context. It is intended to rescue ancient technologies, such as adobe, the use of natural fibers, and lime. The innovation in this work is characterized by the use of a relevant amount of SCB fibers, in the order of 30 to 35%, in the studied composites. Moreover, compositions of SCB fibers with lime as the main binder do not seem to exist at this moment.

1.2. The "Sugar Cane Concrete"

The proposal for the sugarcane bagasse (SCB) and lime mixtures for building blocks is inspired by the existing similar composite based on hemp and lime, briefly presented below. The composite obtained by replacing lime with soil as a natural binder, such as adobe, but with a greater number of fibers as usual was also studied in the search of a more sustainable solution, as it does not use a large quantity of calcined materials in the formulation. Depending on the characteristics of the materials, in a composite with fibers and soil, it is convenient to add a binder capable of improving resistance to water action. Lime has this advantage because reduces water absorption and favors vapor permeability, forming a limestone barrier around the vegetable fiber [13].

In the composite without soil in the matrix, lime is capable of adding and maintaining essential properties for the resistance and durability of the material. As a disadvantage, the long carbonation time impacts the curing time, as verified in studies with hemp [13].

SCB ash has proven a good performance as an efficient pozzolanic material in composites prepared with cement [14]. As long as it can improve or preserve the resistance and durability of the material, it is possible that its addition as a pozzolanic material can bring another environmental benefit, namely through the use of a final residue.

In this work, three composites with sugarcane bagasse were developed, with a view to making building blocks. These are composites with relevant fiber additions, in the order of 30% to 35% of fibers, in formulations with hydrated aerial lime, with lime and soil, and only with soil. Additionally, the addition of SCB ash was also tested in order to compare the pozzolanic effect of this material with the effect of using metakaolin.

The specimens prepared during the study were subjected to laboratory tests with the objective of measuring the mechanical, hygroscopic, and thermal performance of the composites and, thus, verifying the feasibility of applying the product, and also prospecting the potential to act as a structural complement.

1.3. The "Hemp Concrete" and Other Lightweight Concretes with Agroindustry Wastes

The use of hemp fibers in construction goes back a long time. There are hemp/soil mortars in India that are about 1500 years old [15]. The first "hemp/lime concrete" was developed by Charles Rasetti in 1987 in France [16]. The woody core, with a high silica content, interacts with the lime and promotes the hardening of the mixture [16]. Used for the production of hemp concrete (or hempcrete), the construction material is much studied and used in the European Union.

The hemp block walls function as thermal and acoustic insulation and a good compromise between thermal conductivity and thermal inertia [17]. The material is easy to adapt to the climate and easy to produce locally. It prevents the occurrence of condensation due to the wall's breathability and absorption capacity and resistance to water, which impacts the quality of the environment and the health of the inhabitants [16].

In the life cycle assessment, in addition to being biodegradable, it captures CO_2 from the atmosphere, reduces the use of toxic materials and waste production, uses renewable resources, and can be recycled at the end of the useful life of the building, thus reducing the environmental impact [13–16]. Its ductility and ability to adjust to building movements prevent the appearance of cracks. It is a non-flammable material, does not release toxic fumes, and is resistant to insects, fungi, and bacteria [17].

In addition to the hempcrete research, other agroindustry or agri-food wastes have been studied in lightweight concretes, mainly with lime-based binders and replacing the aggregates in full. For example, the study of Chabannes et al. showed the use of rice husk and hemp as aggregates (without and with previously treated aggregates with $Ca(OH)_2$) using a lime-based binder for lightweight concretes, Lime and Hemp Concrete (LHC), and Lime and Rice husk Concrete (LRC) [18]. Chabannes et al. also studied sunflower stem aggregates with eco-friendly binders and their multi-physical properties as insulating concrete [19]. However, there are also studies with cementitious binders and only with a partial replacement of aggregates such as the study of Gradinaru et al. with 50% of sunflower aggregates (treated with sodium silicate solution), with 50% of sand and cement as a binder, and with the addition of superplasticizer to reduce the amount of water and obtain greater resistances [20].

As no lightweight lime-based concrete study has yet been conducted with total aggregate substitution by sugarcane bagasse, the present study was intended to study simple mixtures, without any treatment of the vegetable aggregate and without additives that change its rheology or its binder adhesion. Only in this way will it be possible to determine the material behavior. In addition, it is also intended to obtain an economically accessible construction product; therefore, a minimum of additions and processes is necessary.

2. Materials and Methods

The materials used in the experimental research were sugarcane bagasse (SCB) as an aggregate; aerial lime, SCB ash, Alentejo and Labruge soil, and metakaolin as binders; as an additive, sodium borate or borax.

2.1. Materials

2.1.1. Sugarcane Bagasse—SCB

The SCB used came from Madeira Island, where sugar cane is cultivated for the production of national rum. The preparation of the material used in the mixtures required spreading the wet bagasse over a plastic sheet, where it was turned over twice a week to dry naturally and homogeneously, for 4 weeks, until it was dry. This drying was necessary because, otherwise, fungi would appear, just as it was already appearing in the most humid parts when we received the material. In morphological analysis (Figure 1a,b) of SCB samples, it was found that the SCB length varies between 10 and 30 mm, but most are 15 mm. The pieces of SCB are made up of long fibers [21] with diameters ranging from 0.2 to 0.5 mm below 100 µm and scaly surfaces (Figure 1c).

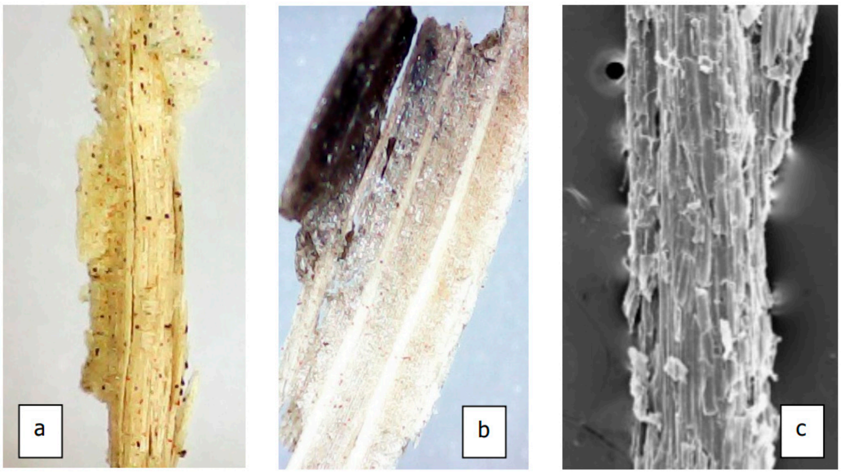

Figure 1. (**a**,**b**) Dried SCB samples were analyzed under an optical microscope (20× magnification) (figures from the authors). (**c**) Bundle of dried fibers analyzed under the microscope (adapted from Oliveira [2]).

SCB is generically composed of cellulose (50%), hemicellulose (25%), and lignin (20%) [2].

2.1.2. Used Soils

Two types of soils were used separately, and Figure 2 shows their particle size distribution curves. The soil used in the first and second trial mixes came from Alentejo, a southern region of Portugal, designated here as Soil 1. It has a good granulometric distribution, with 15.9% of gravel, 47.2% of sand, 17.6% of silt, and 19.4% of clay. The percentage of clay in this soil is considered sufficient for construction, as it reaches just over 20% of the analyzed volume. Soil sifting is necessary to adjust the amount of gravel and obtain 4 mm as the maximum dimension. In the third trial mix, soil from Labruge, Vila do Conde, designated here as Soil 2, was used. This soil presented 65% of fine material (silt + clay), with the clay fraction equivalent to 15%. The type of aggregate present is fine sand, with a maximum diameter of 2 mm and with a well-graded granulometry distribution. The percentage of sand present in this soil is small.

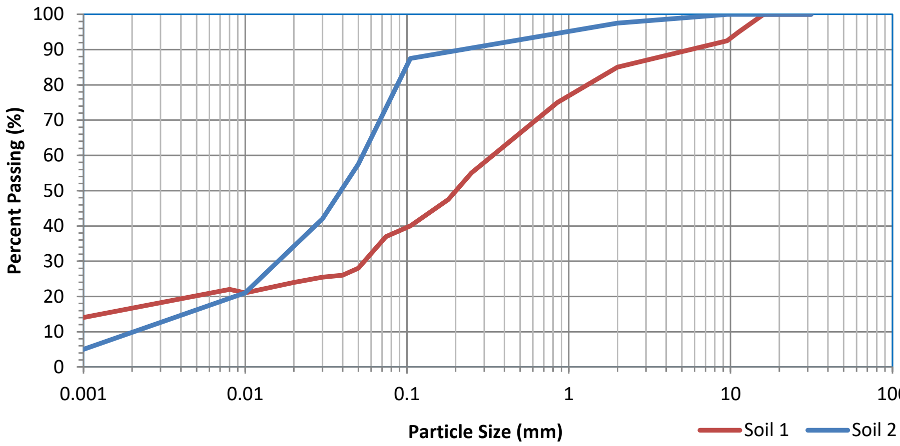

Figure 2. Particle size distribution of the soils used.

2.1.3. Hydrated Lime

Hydrated aerial lime (calcium hydroxide), manufactured in Portugal, was used. It is calcium lime, classified as CL90-S according to the EN 459-1:2015 [22] standard, which has an apparent density of 0.46 g/cm^3.

2.1.4. Metakaolin

Metakaolin is obtained from the calcination (at temperatures between 700 and 800 °C) of kaolinitic materials, which is a mineral clay with a high content of silicon dioxide. The reaction of metakaolin with lime produces hydrated calcium silicate (CSH) and aluminum hydrates. Processed with less energy than cement, metakaolin is used as a pozzolana to improve the mechanical strength of mixtures with lime or cement. The metakaolin used in this study was produced in Portugal and is characterized by a light orange color, which influences the final composite color. The main components of its chemical composition are the silica (60.7%) and alumina (34.3%) according to the producer's datasheet, mentioned by Kropidłowska [13].

2.1.5. Ashes of SCB (ASCB)

For the use of SCB ashes in this research, a portion of SCB, 800 g, was placed into the muffle furnace at 600 °C. The process was carried out in 3 cycles: heating (1 h), burning (4 h), and cooling slowly, obtaining 106 g of ash. It was observed that this process did not produce calcination identical to that of the industrially obtained process, as the reference studies indicate that the ASCB corresponds to 0.6% of the initial weight of the SCB [23], and was obtained here in the proportion of 13.25% of the initial weight of the SCB.

2.2. Methods

2.2.1. Mixtures

An outline of all the steps carried out in the methodology can be seen in Figure 3.

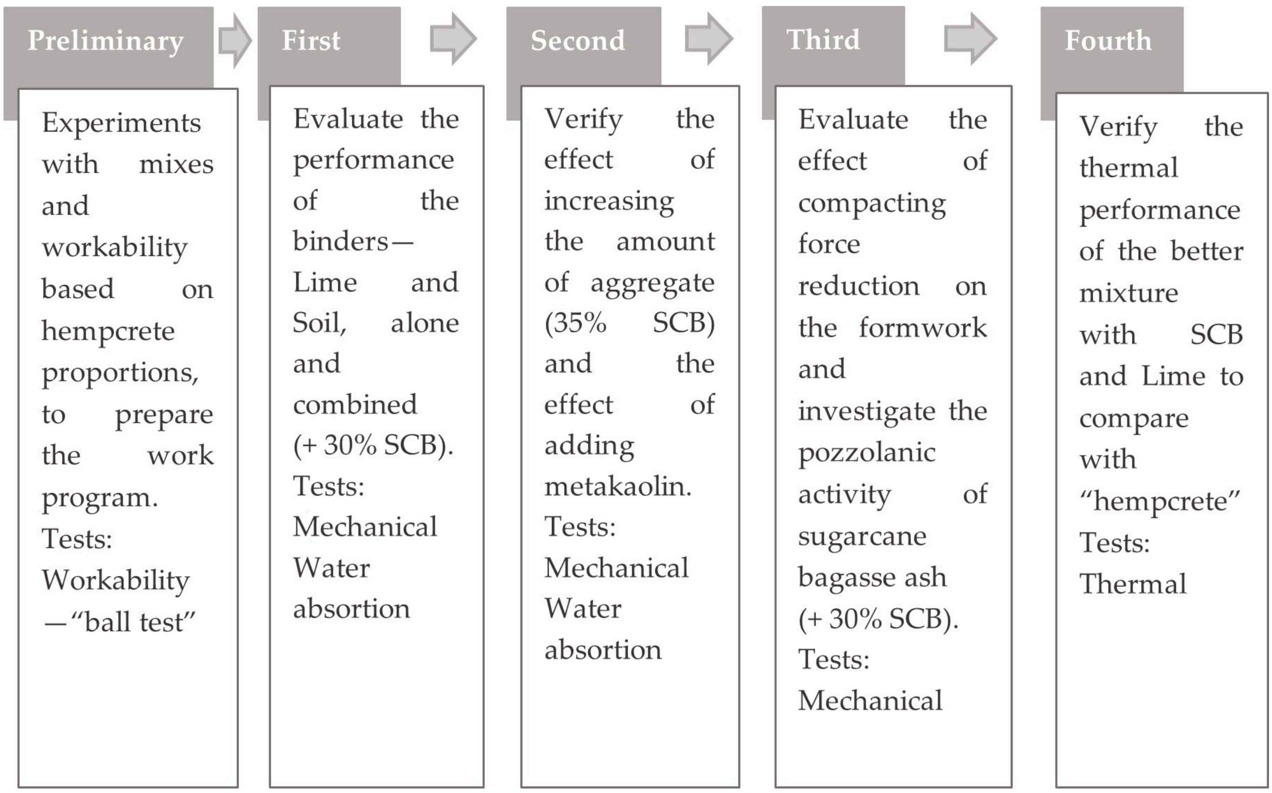

Figure 3. Stages of the study and the purpose of each.

To prospect the material, potential preliminary mixes were prepared to evaluate the binder amount of water necessary to form a composite with adequate workability and minimum resistance for the manufacture of the blocks, to establish a plan in line with the intended results. The results obtained in this preliminary stage were guidelines for the planning of the 1st trial mix of the work. Three different trial mixes were then carried out, as shown in Table 1:

- The first is to evaluate the performance of the main binders (lime and soil) and the combination of both, with 30% of SCB.
- The second is to seek the maximum sustainability potential by increasing the fiber content and further reducing the weight of the material to improve the thermal behavior. For this, we tried to verify the effect of increasing the amount of SCB fibers in the mixtures to 35%. Furthermore, to reduce the amount of lime, it was decided to add metakaolin and evaluate its pozzolanic effect, using the proportions tested by Kropidłowska [13] with hemp concrete mixes, including the use of borax as an additive.
- The third is to evaluate the addition of SCB ash as a pozzolanic material, readjusting the number of fibers to the content of the first trial, but slightly reducing the compaction force in the formwork, to not interfere with the thermal behavior. The MR3 reference mixture is an adobe without the addition of fibers and was prepared with the purpose of comparing the results and evaluating the resistance of the soil used.

Table 1. Studied compositions and used symbols.

Studied Compositions									
	Symbol	Solid Materials						Binder %	Water %
		Aggregate %	Binder %						
		SCB	Lime	Soil	MKL	Ash	BX		
1st trial mix	S.L-1	30	70	-	-	-	-	46	54
	S.So1-1	30	-	70 *	-	-	-	70	30
	S.L.So1-1	30	10	60 *	-	-	-	48	52
2nd trial mix	S.L-2	35	65	-	-	-	-	36	64
	S.So1-2	35	-	65 *	-	-	-	41	59
	S.L.Mk.B-2	32	40.6	-	27	-	0.4	44	56
3rd trial mix	S.L-3	30	70	-	-	-	-	36	64
	S.So2-3	22	-	78 **	-	-	-	49	51
	S.L.So2-3	20	60	20 **	-	-	-	47	53
	S.L.A-3	26	68	-	-	6	-	38	62
	So-2	-	-	100 **	-	-	-	77	23

* Soil 1, ** Soil 2.

To verify the workability of the composites obtained, an empirical test known as the “ball method” was carried out, which consists of taking a sample of the mixture and making a ball by hand. If the ball remains well formed and with good consistency, it means that the workability of the material is suitable to produce specimens, as was used by Martins in soil mixtures for compressed earth [24], and, in this case, its procedure helps to verify the adhesion of the materials.

2.2.2. Manufacture and Curing Conditions of Samples

Specimens measuring 40 × 40 × 160 mm (Figure 4a) were used for mechanical resistances and water absorption by immersion test, while specimens measuring 150 × 150 × 59 mm (Figure 4b), dimensions compatible with the hot box, were only used for the thermal conductivity test.

Figure 4. (**a**,**b**). Specimens for general tests (**a**) and sample for thermal conductivity (**b**).

The mixing process was carried out in a pan mixer with a rotating drum. The procedure is based on the methods used to produce hemp concrete, such as those used by Kropidłowska [13]. Water was added partially before and after the binder ($^1/_3$ of the amount before and the rest after). Each sample was manually compacted in three layers, using a stone block and a rubber mallet to compact evenly. The formwork took place after 2 h of rest and the specimens were stored in a dry, semi-closed cupboard, at room temperature and humidity for the curing process (around 20 °C and relative humidity of approximately 50%).

2.2.3. Performed Tests

The mixtures made were tested for their mechanical performance: concerning resistance to compression and bending, at 28, 60, and 90 days, with the exception of the mixtures from the second trial mix, which, due to the COVID-19 pandemic, were only tested at 28 and 90 days.

The flexural strength tests were carried out in accordance with EN 1015-11:1999 [25]. Tests were conducted on Lloyds Instruments (universal test hydraulic press with a maximum capacity of 50 kN), with an applied load of 10 N/s. Three to six specimens were used per lot.

The compressive strength tests were carried out in accordance with the EN 1015-11:1999 [25] standard, using the parts left after the rupture of the specimens used in the bending test. A force of 10 N/s was applied in the most unfavorable direction, perpendicular to the compaction of the fibrous material.

With regard to the performance against the water action, tests of water absorption by capillarity and by immersion were carried out. The fibrous nature of the SCB and the porous nature of the raw soil demanded an adaptation of the measurement process of the capillary water absorption test, commonly presented by EN 1015-18:2002 [26]. The method used was described by Hall and Djerbib [27] and this was applied to obtain a good indication of the performance of compacted earth blocks, which is an adaptation of the British Standard BS3921 (IRS) test [28]. Called IRS Oasis, the method was very useful, due to the special vulnerability of earth and fiber when in contact with water. For the test, specimens of 40 × 40 × 160 mm were used, one of each mixture from the first and second trials (213 and 107 days, respectively), cured at room temperature and humidity. The specimens were cut in half, measured, weighed, and arranged on a spongy block (known as Oasis) immersed in a box with water until its maximum absorption capacity stabilized. The Oasis was kept saturated, with 2 cm out of the water, as seen in Figure 5. The contact times began to be measured and the samples were weighed after 5, 10, 15, and 30 min and then 1, 2, 3, 4, 5, 7, 9, and 24 h.

Figure 5. Specimens cut and accommodated over the saturated Oasis.

Regarding water absorption by immersion, specimens measuring 40 × 40 × 160 mm were used. One from the first trial mix at 210 days of curing and two from the second, at 105 days, always under the same conditions of ambient temperature and humidity. After drying in an oven at 60 °C, they were immersed in water at room temperature. After the first hour, the specimens were removed from the water and excess water was removed with absorbent paper. Then, they were weighed and returned to the water, where they remained for 24 h, calculating the water absorption after this time. At the end of the absorption period, the specimens were subjected to the compressive strength test, according to the procedure described above, to measure the loss of strength due to exposure to water. However, only the SCB with lime and SCB with lime and soil specimens were subjected to the test, as the specimens without hydraulic binders were very fragile and would not withstand the immersion test.

As it is possible that the SCB composite has a thermal performance similar to that of hempcrete, a specimen of the BC1 mixture (150 × 150 × 59 mm) was prepared to be evaluated. The thermal performance of SCB composites was evaluated by considering their thermal resistance (Re) and thermal conductivity (λ). These parameters were determined using a calibrated hot box designed and built at the Department of Civil Engineering of the University of Minho [29], based on ASTM specifications ASTM C1363-19 [30].

The hot box is composed of two chambers, the cold and the hot one, and one mounting ring is placed between the two chambers (Figure 6). The SCB composites were placed in the center of the mounting ring.

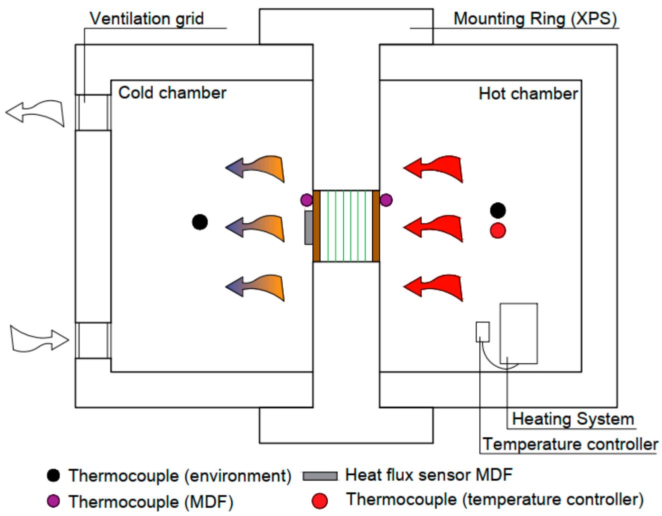

Figure 6. Schematic representation of the hot box used [31].

The tests were carried out considering the heat flow meter method, defined in ISO 9869-1 [32]. The heat flux was measured through a heat flux sensor installed in the SCB composites' central part, and thermocouples measured the temperatures. With the values of the heat flux (q) and the surface temperatures (T), it was possible to determine the thermal resistance (Re) of the material, using Equation (1). ΔT is the difference between the surface temperature of the SCB composites in the hot and cold chambers. The thermal resistance of the SCB composites was determined using Equation (2). The SCB composites' thermal conductivity (λ) was assessed using Equation (2), where e is the SCB composites' thickness.

$$\mathrm{Re}\ [(\mathrm{m2.^{\circ}C})/\mathrm{W}] = \Delta\mathrm{T}/\mathrm{q} \quad (1)$$

$$\lambda\ [\mathrm{W/m.\ ^{\circ}C}] = \mathrm{e}/\mathrm{Re} \quad (2)$$

3. Results and Discussions

Considering that there are still no standards for this type of lightweight composite material with fibers and lime-based binders, considerations are made considering the aforementioned studies on hempcrete and the technical guides about this construction product.

3.1. Mechanical Resistance Performance

As seen in Figures 7 and 8, the adobe without fibers So-2 had better compressive strength than the mixtures with SCB, which was expected considering the large volume of fibers added. Among the mixtures with SCB, the S.So1-1 (30% SCB and soil) obtained the best values, followed by the S.L.So1-1 (30% SCB with soil and lime) and the S.L-1 (30% SCB with lime). This means that the addition of lime seemed to reduce the resistance, alone or combined with soil. Other authors noted a reduction in resistance in mixes of soil and lime as binder material [33]. However, what happens with the isolated use of lime as a binder with SCB should be tested further. Microscopy tests would help to understand better the adhesion between these fibers and the aerial calcic lime. In terms of flexural strength, a similar behavior can be seen, and in general, the following considerations can be made:

- The increase in the proportion of fibers from 30% to 35% of SCB reduced the mechanical performance of mixtures (comparing the better results in the first trial mix with the other trials);
- In addition, the compaction force positively affected the mixtures, as the best performances were registered in the first trial, in which all specimens presented higher density;
- The addition of SCB ash did not show efficacy in the composite's behavior, S.L.A-3;
- Comparing the mixtures of soil/lime with the mixtures only with soil, it was observed that mixtures only with soil presented a greater magnitude of resistance, both to compression and flexion, seeming to have no advantages in terms of mechanical resistance in lime addition. It should be noted that the results were inconsistent at some ages, but this can be considered normal as the study was carried out with natural materials and subject to a greater dispersion of results.

Comparing the obtained results with standards or guidelines, the following may be considered:

- Considering the minimum compressive strength performance values required by a French hempcrete technical guide (>0.2 MPa for walls) [34] and the results obtained in the sample tests, the composites fell within the range of materials with sufficient strength for non-structural walls.
- The strengths of the S.So1-1 mixture were higher than the minimum 1.5 MPa, established for adobe blocks, by NBR 16814:2020 [35], in compression. However, its density, very close to that of adobe, eliminated the virtue of lightness, compared with the mixtures without soil. Among SCB composites with lime and soil, only S.L.So1-1 showed recommendable mechanical efficiency.
- The mechanical performance tests of the SCB blocks, in the various mixtures studied in this investigation, showed resistances lower than the 3 MPa established by

NBR 15.270-2 [36] for ceramic blocks and conventional hydraulic concrete blocks, established by NBR 6136: 2016 [37].

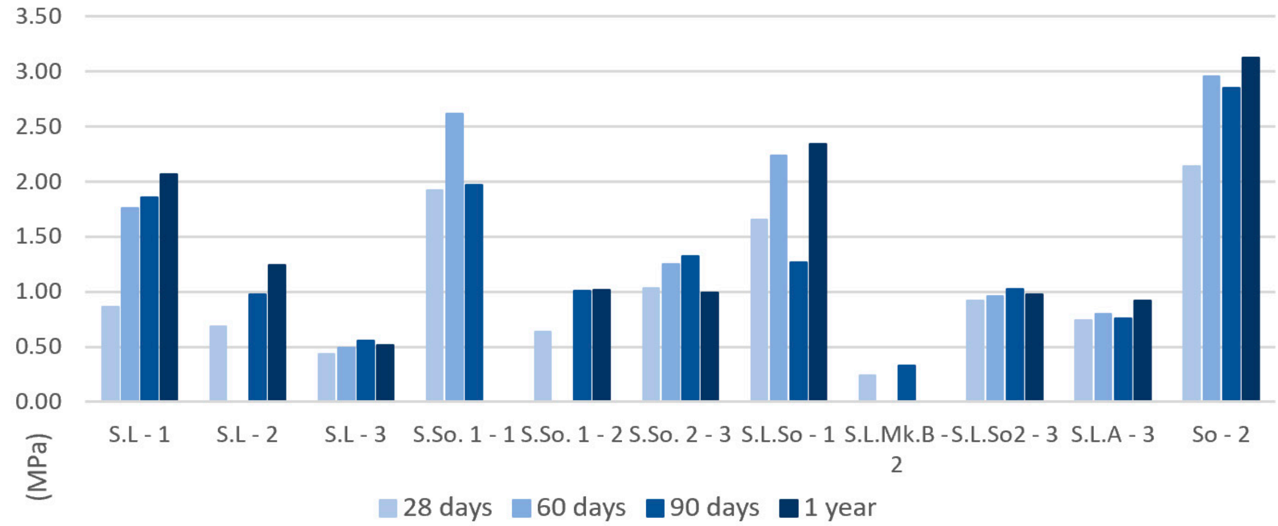

Figure 7. Compressive strength performance of all mixes.

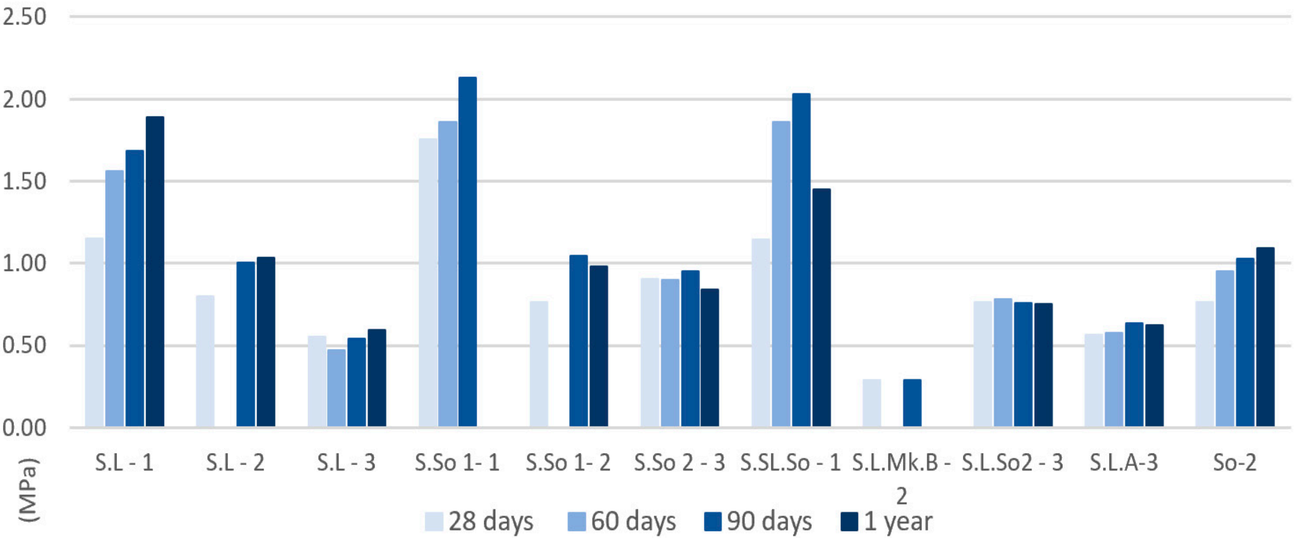

Figure 8. Bending performance of all mixtures.

In this way, the results seem to be good, even considering the lower obtained values by the increase in the number of fibers and reduced compaction. However, for better conclusions, it should be interesting to develop more research, with more variation in the number of fibers and greater control of compaction through sample density.

For a better analysis of the results obtained, it is important to remember that the sugarcane bagasse is a unique aggregate, it is not a mineral and rigid material, and no cement is used, so the resistances are very low when compared to conventional concrete or even with concrete reinforced with vegetable fibers for hollow building blocks. Some studies noted a compressive strength between 13 and 33 MPa in cement-based composites to produce hollow blocks [38,39].

However, it can be compared with identical composites, such as adobe (for soil-based mixtures) and lightweight concretes of industrial hemp and lime binders, also without sand or cement.

Comparison of Compressive Strength Performance of SCB Composites with "Hempcrete" and Other Agro-Wastes Lime-Based Composites

For the reasons mentioned above, a comparison of the obtained results (considering the average values of the three phases for each mixture) and the results of other researchers was made. Table 2 shows the main methods used in the research, as mixtures, specimens, and curing conditions, and Figure 9 shows the results of the compressive strength and density for a better interpretation of the results.

Table 2. Comparison with other authors—mixtures and their methods used.

Mixtures	Binders	Aggregate % (Mass)	Specimens (Dimensions-mm^3)	Curing Conditions	References
Light Rice Lime Concrete	NHL3.5 and CL90-S at 50/50 wt.%	33.33%	Ø110 × 220 cylindrical	climate-controlled room at 20 °C and 50% RH	Chabannes et al. [18]
Light Hemp Lime Concrete					
Light Hemp Lime Concrete	CL90	30%	100 × 100 × 100	room temperature and humidity (18 to 22 °C) in formwork 5 days	Araújo [40]
Light Sunflower Lime 10% Poz Concrete	75% CL, 15% NHL 10% pozzolanic binder	33.33%	Ø110 × 220 cylindrical	room temperature 20 °C and35 ± 5% RH	Chabannes et al. [19]
Light Hemp Lime 27% Mk Concrete	77% CL90 27% Metakaolin	32–35%	100 × 100 × 100	humidity chamber 7days (87%RH) room temperature (21 °C) and humidity (65–75%)	Kropidłowska [13]
SCB Lime Concrete	CL90	30–35%	40 × 40 × 160 Load area-40 × 40	semi-closed cupboard, room temperature 20 °C and 50 ± 5% RH	Present study
SCB Soil	Soil	22–35%			
SCB Soil Lime Concrete	Soil CL90	20–30%			
SCB Lime 27% Mk Concrete	CL90 Metakaolin	32%			
SCB Lime 6% SCBA Concrete	CL90	26%			

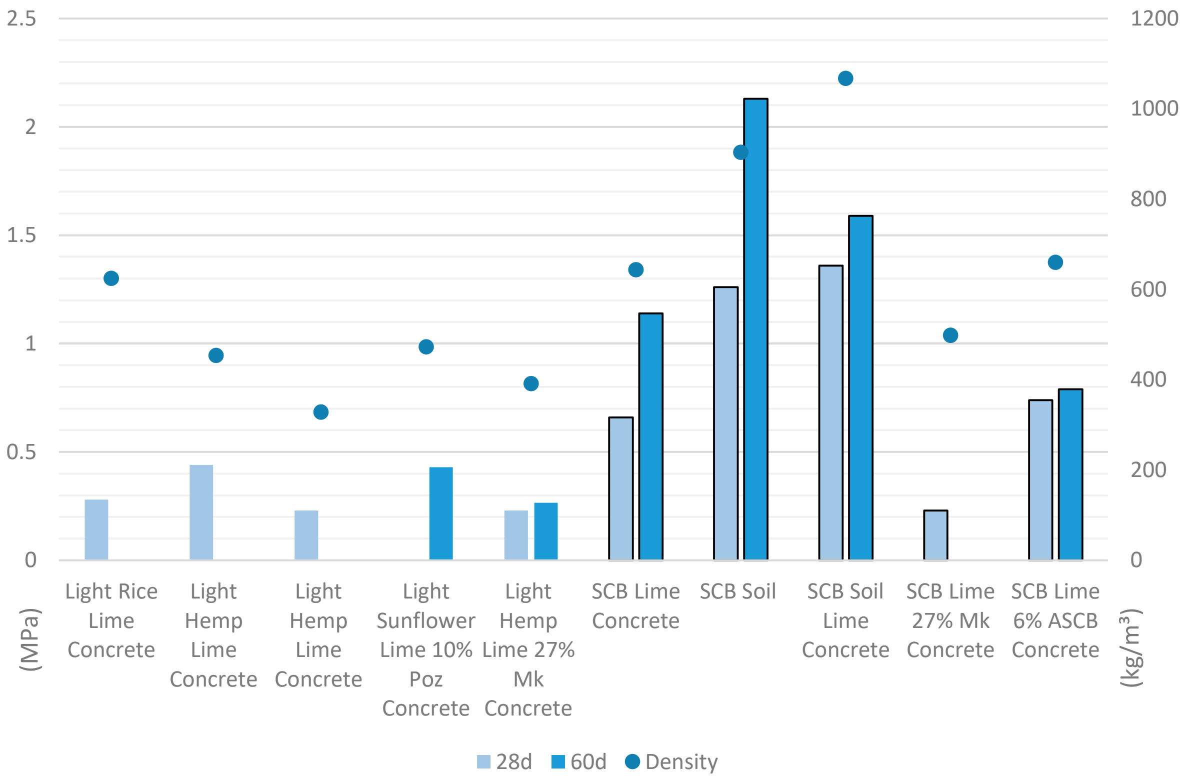

Figure 9. Comparison of compressive strength results with other authors.

Considering the methods presented in Table 2, it was verified that the percentage of plant aggregates varied between 20 and 35%. The curing conditions were somewhat similar to the air, at an approximate temperature of 20 °C, and the difference in humidity in most of the curing time was not very significant. The shape and size of the samples in the different studies presented differences compared to the size used in this study. In this case, the size used was smaller.

Comparing the values, the following may be considered:

- Regarding density versus resistance, there is a general trend of increased resistance as the density increases, as expected. However, there is the exception of Light Rice Concrete, which, even with reduced resistance, achieves values above the average of concrete with hemp. This value is most likely justified by the use of hydraulic lime together with the aerial lime (50% of each) as this type of lime usually leads to greater resistance.
- Regarding the values obtained from resistance, considering a smaller sample size used in this study, it can be considered that the size of the specimens does not seem to have much influence on the resistance increase, because the mixture SCB Lime 27% Mk Concrete, performed with the same proportion of aggregate and binders as Kropidłowska [13], had an identical resistance. Moreover, in the literature, there also does not seem to be certainty in the true influence of the size and shape of the specimens, and there are many contradictory results [40];
- The preformed mixtures with sugarcane bagasse (SCB) generally have higher resistances, except for the mixture with referred metakaolin. These values seem to be related to the higher density of mixtures with SCB. In reverse, the mixture with metakaolin has a lower density and also lower resistance compared to the other mixtures with SCB.
- For the use of pozzolanic material, there tends to be better results with a lower percentage added to the aerial lime according to the results of mixing sunflower concrete with 10% of pozzolanic material and the mixture of SCB with 6% Ash of SCB (or ASCB). However, this difference may also be related to the type of pozzolans added. In addition, concerning the use of the Ash, it is possible to make some relationships with another study of [41] where this Ash was used with lime in soil stabilization for other uses. These authors obtained, with a lower amount of lime, higher resistance values with the increase in Ash amount, between 8% and 16% of Ash. This indicates that the results are consistent and probably, with a higher percentage of gray, the result would be even better.
- It is also observed that the mixture of SCB with soil, without lime, also presents better results than "hemp concrete". This higher strength is justified by the higher density of the mixtures once the soil is used.

In general, is important to note that, for a precise conclusion, the use of a similar density is usually obtained with hemp. However, as the SCB aggregate has a smaller dimension than hemp hurds, for the cohesion of the mixture, it requires a greater amount of binder material in volume, and this leads to a higher density.

3.2. Thermal Performance

Figure 10 represents the temperatures and heat flow reached for the 72 h test [32] in the hot box for the SCB composite studied. From Figure 10, it is possible to see that the temperature in the chambers (hot and cold) and heat flow remained very stable during the test period.

The outputs from the hot box were used to calculate the thermal parameters considering Equations (1) and (2).

Table 3 shows the value of the thermal conductivity coefficient (λ) obtained by the SCB/lime composite (S.L-1 mixture) in comparison with the typical values of several conventional construction materials and some studies of hemp concrete.

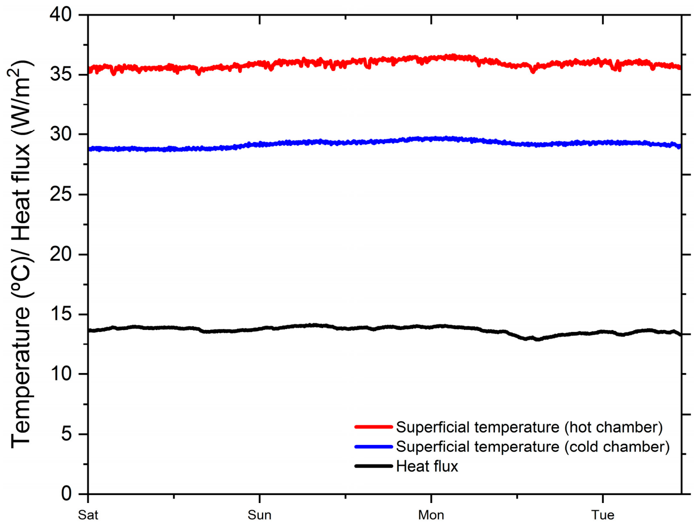

Figure 10. S.L-1 mixture: temperatures and heat flux.

Table 3. Thermal conductivity coefficient of SCB composite and other building materials.

Building Materials	Thermal Conductivity Coefficient (λ) (W/m. °C)	References
Hard limestone	1.7	Nunes [42]
Adobe	1.1	Nunes [42]
Brick	0.41	Carvalho [43]
S.L-1 mixture (70% lime, 30% SCB; 842 kg/m^3)	0.12	This study
"Hempcrete" (65% de hydrated lime, 30% de hemp)	0.11	Araújo [40]
Hemp concrete (220–627 kg/m^3)	0.06–0.14	Abdellatef and Kavgic [17]

The results show a satisfactory thermal performance for the SCB composite. Its thermal conductivity, 0.12 W/m. °C, is less than those of hard limestone, adobe, and brick. Considering the hempcrete, the SCB composite studied shows a very similar performance to hempcrete studied by Araújo [40], 0.11 W/m. °C. Furthermore, the value achieved is in between the values shown by Abdellatef and Kavgic [17] for different hemp concrete compositions. However, for a more assertive conclusion of the results, a more detailed investigation would be important, such as testing different variations of binder material and mixtures with different densities.

3.3. Water Absorption and Resistance

3.3.1. Water Absorption by Capillarity and Immersion

As vegetable materials and soil binder, the water absorptions values are, in general, very high. As can be seen in Figure 11, the study of water absorption by capillarity showed reduced tolerance to water, requiring the application of waterproof mortar and the preparation of a base with conventional masonry or stonework, to keep the material away from contact with water, which is essential to guarantee the durability of the building.

The results obtained in capillary absorption, considering the values in kg/m^2. $min^{0.5}$, also reveal that:

- Mixtures only with SCB and lime have a smaller water absorption and the replacement of lime by metakaolin does not present an advantage at this level, on the contrary;
- In general, mixtures with soil have higher water absorption, except the mixture with lime and metakaolin, probably due to its reduced compaction and mass;
- The addition of lime to the soil does not seem to have an advantage; on the contrary, water absorption is lower than expected.

During the capillary test, fungal growth was also observed in the mixtures with soil and without lime. Thus, it can be considered that lime offers the advantage of not facilitating the development of living matter. In those where lime was mixed with soil, contamination was delayed and greatly reduced.

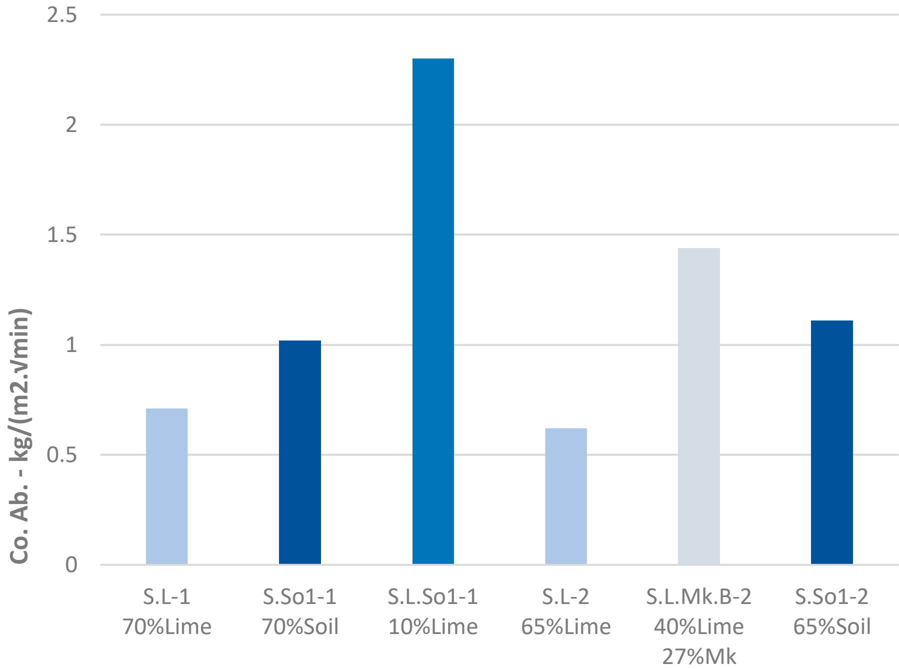

Figure 11. Coefficient of absorption by capillarity.

The water immersion test results presented some differences in relation to the capillarity test. In this case, the addition of lime seemed to favor the reduction in water absorption, as shown in Table 4, comparing S.L-1 with S.L-2 (with less than 5% of lime) and S.So1-1 with S.L.So1-1 (10% lime). In addition, a lower absorption in two mixtures with soil (S.So1-1 and S.L.So1-1 (with 10% lime)) can be seen, contrary to what would be expected for soil mixtures. This lower absorption may be justified by the greater mass of the specimens compared to the others, which indicates that the higher compaction of the mixtures will have fewer voids and reduce the absorption.

Table 4. Percentage of water absorption by immersion after 24 h and nominal value per m^3.

Mixes	Dry Weight (g)	24 h (g)	Absorption (%)	Water (kg)/m^3
S.L-1 (70% Lime)	155	268.9	73.5	445
S.So1-1	255.7	393.9	54	539
S.L.So1-1 (10% Lime)	254	362.1	42.5	421
S.L-2 (65% Lime)	125	229.7	83.8	409
S.So1-2	119	283	137.81	640

Figure 12 presents a comparison of the results obtained in this study with the values of research on hempcrete [13], ceramic masonry blocks, and concrete blocks [44]. The relationship between the density and the absorption coefficient of the tested compositions was examined.

As expected, there was less absorption in brick and ordinary concrete. It was observed that denser materials seemed to have less absorption in general, but in the SCB's studied mixtures or in hempcrete, this was not always true. The obtained results showed that the hempcrete based on hydrated lime [13–17] presented a lower density and a lower absorption than the composites with SCB and also the mixture S.L-2.

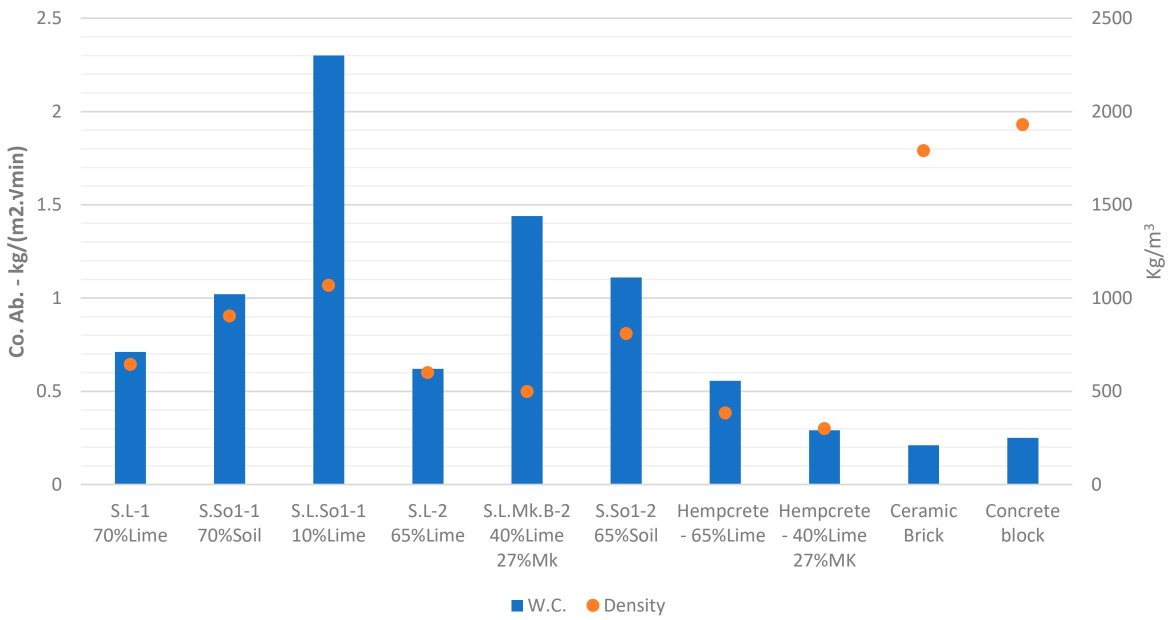

Figure 12. Comparison between densities and absorption coefficients of studied compositions and other materials.

3.3.2. Compressive Strength in Saturated Specimens

The results of the compression test on specimens subjected to the absorption test by immersion are presented in Table 5, where it can be seen that the water absorption did not affect the compressive strength of S.L-1 and S.L.So1-1. On the contrary, there was a slight increase in resistance. However, there was a small loss of resistance in S.L-2. As stated by Pinto [45], when saturated, the tensile strength of lignocellulosic fibers is also slightly higher, which could justify this increase. It was also registered that the composite with only soil could not be tested, due to the lack of cohesion of the material after absorption. As such, it is not water-resistant.

Table 5. Compressive strength in specimens subjected to the immersion absorption test.

Mixes	Compressive Strength (MPa) 90 d, Dry	Compressive Strength (MPa), Saturated
S.L-1	1.60	1.65
S.L.So1-1	1.26	1.38
S.L-2	0.98	0.82

4. Conclusions

The main conclusions that can be reached about this study are the following.

Considering the minimum performance values required by the hempcrete technical guide and the results obtained in the sample tests, the composites fall within the range of materials with sufficient strength for non-structural walls.

Aerial lime and/or soil used as binder provide enough mechanical strength for this application. The composite of SCB with soil achieves the best performance in terms of mechanical resistance: 2.6 MPa in compressive strength and 2.1 MPa in bending strength, while the composite of SCB with lime achieves 1.76 MPa and 1.7 MPa, respectively.

The lime composites obtain greater water resistance and less loss of mechanical strength when saturated. However, the higher water absorption coefficient makes it necessary to apply a waterproof mortar on surfaces exposed to the weather.

Concerning the thermal properties, it is verified that the composition reaches low values of thermal conductivity; therefore, it presents good behavior, far superior to conventional materials used in masonry construction.

Alongside the results, it is concluded that the researched composites can have several applications as a non-structural material (Figure 13a,b).

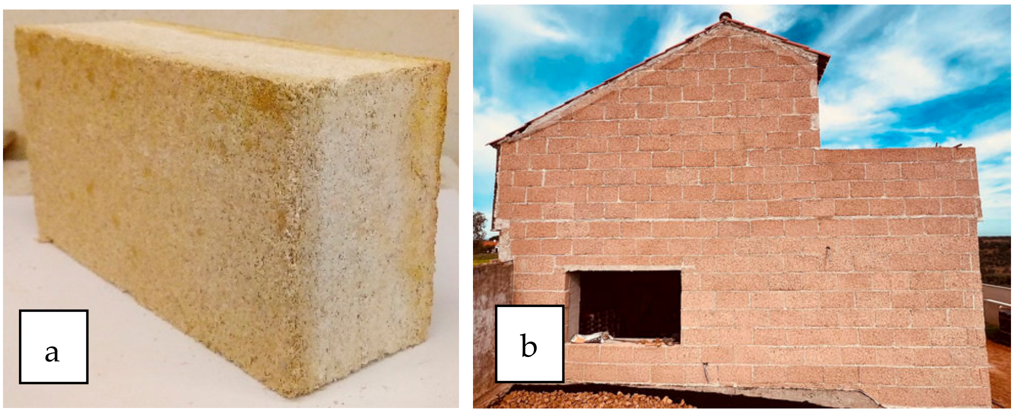

Figure 13. (**a**) Block with SCB and lime (credits: Souza [46]); (**b**) house with hemp concrete blocks (credits: Cânhamor [47]).

Regarding the sustainability of the studied composites, it can be considered that the mixtures with only SCB and soil will be the most sustainable, as they do not contain a binder and, as such, will have a lower energy expenditure. For the same reason, the compositions of SCB with soil and lime will follow, and finally, the composite of SCB with lime. However, due to the lower density, the mixture with lime may have better thermal behavior, which will lead to benefits in the sustainability of construction in general. In addition, due to its lightness, the composite with SCB and lime contributes significantly to lightening the structure.

Furthermore, the products in this study show a potential for a differentiated finish, with comfort, durability, and economy that compensate for the difficulties. The fact that this can be manufactured in a simple way means that it would be constructed at an affordable cost. As such, the intensive sugarcane industry could easily sponsor the construction of houses for local communities to partially compensate them for the inconvenience caused.

All waste produces discontent. Far from agreeing with the monoculture of sugar cane, while the agroindustry does not find solutions with lesser environmental, social, and economic impact, this type of composite for building blocks can be a viable solution for increasing the value of sugarcane bagasse.

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