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Thermophysical Properties of Compressed Earth Blocks Incorporating Natural Materials

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Abstract: Building materials are responsible for significant CO_2 emissions and energy consumption, both during production and operational phases. Earth as a building material offers a valuable alternative to conventional materials, as it naturally provides high hygrothermal comfort and air quality even with passive conditioning systems. However, disadvantages related to high density, conductivity, and wall thickness prevent its effective inclusion in the mainstream. This research explores enhancing the thermophysical properties of compressed earth blocks (CEBs) by using locally sourced natural materials. The study is framed in the Portuguese context and the natural materials involved are wheat straw (WS) as a by-product of wheat harvesting, cork granules (CGs) from bottle caps, and ground olive stone (GOSs) residues from olive oil production. Blocks were produced with different mixtures of these materials and the thermal response was examined in a hot box apparatus. Best results include a 20 and 26% reduction in thermal conductivity for mixtures with 5v.% CG and 10v.% GOS, respectively, and an associated reduction in bulk density of 3.8 and 5.4%. The proposed approach therefore proves to be effective in improving the key thermophysical characteristics of CEBs. The article includes a comparative analysis of the experimental data from this study with those from the literature. The study contributes to the growing knowledge of sustainable materials, providing insights for researchers and practitioners looking for innovative solutions for low-carbon and energy-efficient materials.

Keywords: compressed earth blocks; natural materials; thermal properties; hot box testing; sustainable construction

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1. Introduction

The construction sector has a significant impact on the planet. To deliver infrastructure and buildings, it consumes a large amount of natural resources and non-renewable energy [1]. According to the European Commission, accounting for materials and operations, buildings are responsible for 40% of energy consumption and 36% of greenhouse gas emissions [2]. Furthermore, it is estimated that this industry produces more than 35% of the total waste in Europe [3]. Therefore, the quest for energy-efficient and environmentally conscious building materials and methods has become paramount. In the ever-evolving landscape of sustainable construction, a crucial aspect is the integration of technologies that facilitate thermal energy storage and passive cooling systems [4]. Traditional building materials often struggle to adapt to external temperature fluctuations, leading to an increased reliance on energy-intensive climate control systems. In this context, earth as a building material is experiencing a renaissance as it naturally guarantees high hygrothermal comfort and indoor air quality with low or no energy requirements for conditioning [5–7].

Compressed earth blocks (CEBs) are unfired masonry blocks made from locally sourced earth and compressed with a manual or hydraulic press. The stages of raw material extraction, transportation, and production are characterised by minimal energy consumption, making them highly environmentally sustainable building materials. In a 2020 study, Dabaieh et al. [8] found that eliminating the firing process (in favour of sun-drying) leads to the reduction of about 6 tonnes of CO_2 and over 5000 MJ of embodied energy to produce 1000 clay bricks. Fernandes et al. [9] quantified 0.39 kg of CO_2 emissions and 3.94 MJ of total embodied energy per CEB. In the cradle-to-gate analysis of walls, the authors found that the use of earth-based materials (CEBs and rammed earth) reduced the environmental impact by 50% compared to the use of conventional materials (fired clay bricks and concrete blocks). According to Ben-Alon et al. [10], earthen wall assemblies reduce environmental impact by 62–99% compared to conventional assemblies such as timber frame and concrete blocks. At the end of their life cycle, CEBs can be reused, recycled [11], or possibly disaggregated and returned to the natural environment. These characteristics are critical for the assessment of the environmental performance of the product, positioning CEBs as promising candidates to contribute to the decarbonisation of the construction sector and the promotion of a circular economy in the building materials cycle [12].

In addition to their environmental advantages, from a technical point of view CEBs have high thermal mass, meaning they can store and release heat slowly, acting as a natural reservoir of heat. According to [13], for different moisture levels, the capacity of earth to absorb it is fifteen and ten times higher than that of concrete blocks and fired clay, respectively. These properties help to stabilise indoor temperatures and reduce fluctuations and the need for active cooling systems [14]. Nevertheless, the regulatory frameworks geared towards conventional building materials and the physical limitations associated with the material itself (high thermal conductivity, heaviness, and wall thickness, among others) prevent it from being effectively included in the mainstream [15,16].

The thermal conductivity of earthen building elements lies in the range of 0.60–1.20 W/mK [17], with corresponding bulk density values typically between 1700 and 2000 kg/m^3. These values are higher than those of insulation materials, which are characterised by very low densities and thermal conductivity of less than 0.10 W/mK. At the same time, they are superior to or comparable with conventional building materials such as concrete blocks, fired clay bricks, and stones, yet stronger. Therefore, to achieve a satisfactory level of thermal insulation, the earthen building envelope can reach significant thicknesses. On the other hand, from a mechanical point of view, typical compressive strength values in the 1.0–2.0 MPa range (unstabilised or slightly stabilised mixtures) allow the safe use of CEBs for one- or two-storey constructions (maximum two in seismic areas) [18], or higher if combined with other load-bearing structures. Though, such cases are still rare.

However, in light of the environmental, economic, hygrometric, and non-toxicity advantages, the wide availability of the material, and considering the pressing demand for housing due to the growing population, complying with the EU 2050 climate neutrality target [19], the scientific effort pursued aims to mitigate the described limitations by modifying the basic mixtures with other materials.

This study responds to a very specific research question: is it possible to improve the thermophysical properties of CEBs without compromising their quality and keeping environmental impact and costs low? To answer this question, the proposed experimental strategy is to use local natural materials with low density and low thermal conductivity in the mixture. In this category, residues and by-products are prime candidates.

In a previous study [20], we reviewed the research published from 2015 to 2021 on the use of materials of natural origin for the optimisation of CEBs. The abundant quantities of natural residues generated daily by agricultural, textile, and food industry processes are routinely dumped in landfills or, at best, used as biofuels. However, depending on their form and composition, their potential can be better exploited. Fibres and straws improve the ductility of the blocks, mitigate cracking and shrinkage, and elevate the thermal properties. Nevertheless, their hydrophilic nature entails disadvantages such as increased water absorption rate, which compromises the mechanical and adhesion properties between the fibre and the matrix, and hence the durability [21]. To counter this, surface chemical treatment of fibres can be implemented [21,22], albeit at the expense of sustainability. Examining the studies, the fibres and straws involved ranged from bamboo, hemp, date palm, banana, kenaf, and jute fibres to fonio, lavender, barley, wheat, and rice straw. In general, plant fibres exhibit low density and lightweight properties. Overall, the studies reveal that, when introduced into the soil mixture, intrinsic properties and constituents, aspect ratio, concentration, orientation, and bonding capacity must be considered as key factors in achieving effective composite behaviour. Natural aggregates, such as argan nutshell, olive stone, shea butter residue, and sawdust, share a composition with fibres, consisting of natural polymers (cellulose, hemicellulose, and lignin). They exhibit high porosity and lightweight properties, making them ideal for enhancing thermal characteristics. Powders or ashes of natural origin, with distinct purposes, often contribute to stabilisation. Examples are eggshell or mussel powders [23,24], and sawdust, wood, rice husk, and sugarcane bagasse ashes. While aggregates are usually derived by simple grinding, powders and ashes derive from more complex processes such as thermal treatments (e.g., calcination). The presence of oxides such as CaO, SiO_2, and Al_2O_3 confers them a certain degree of reactivity allowing for pozzolanic reaction in the presence of water and over time [25,26]. Therefore, their use could improve the compressive strength, durability, and overall quality of the blocks.

Considering the above, the use of local waste and by-products to enhance the properties of earthen building materials fosters a virtuous chain of values in terms of environmental regeneration and the circular economy. The use of local resources is now necessary to counter the environmental and social problems of our time, as advocated by the 17 Sustainable Development Goals claimed by the United Nations [27]. The proposed solution also contributes to mitigating their accumulation and reducing the extraction of raw soil. However, the inherent diversity of the materials involved makes the response of new products very difficult to predict [28]. Uncertainties in the interaction between soil and different natural materials represent one of the main limitations of this research topic. Furthermore, the literature review revealed a lack of data on thermal properties, with only one-third of the research addressing these aspects, compared to more than 80% of the research addressing mechanical aspects [20]. Other limitations are related to the wide variability of the available data, which makes it difficult to compare results. The limited data available and the multiple methods of measuring thermal properties adopted (stationary and non-stationary methods) result in an overall fragmented and heterogeneous picture. Therefore, to be fully understood, the topic must still be investigated. As this approach helps mitigate the thermophysical limitations of CEBs and has the advantage of proposing new local waste streams, this type of research has recently been strongly encouraged in the literature [13,20,29–31]. It is believed that feeding the literature with more data can provide a less heterogeneous picture and clarify the extent to which these differences should be adequately considered. In addition, procedures and criteria for the reference mix design are outlined that can support the setting of standards, government policies, and social acceptance, all of which are essential factors to support the true dissemination of materials incorporating waste [32].

This study provides experimental data on CEBs incorporating separately and in various percentages three different natural materials. It is framed in the Portuguese context and the natural materials to modify the mixtures were selected according to local availability. These are wheat straw (WS), cork granules (CGs) and ground olive stones (GOSs). While straw is more widely used in soil-based mixtures, even traditionally [33], little data have been found in the literature on the use of cork granules [34,35] and olive oil residues [36]. Therefore, this study could be seen as confirmatory research.

The blocks used as reference for this study are produced by a company in the south of the country and are commercially available. Their properties were analysed in a previous work [35], in which another variable that largely governs thermophysical behaviour, the particle size of the soil, was studied. The key attributes are: bulk density—1850 kg/m^3;

open porosity—32%; natural moisture content—0.60%; thermal resistance—0.23 m^2K/W; thermal conductivity—0.65 W/mK; thermal diffusivity—3.99×10^{-7} m^2/s; compressive strength—2.03 MPa; E-Modulus—46.21 MPa; ultrasound pulse velocity—1079.09 m/s; flexural strength—0.21 MPa; coefficient of capillarity absorption—0.15 $g/(cm^2\sqrt{min})$; electrical resistivity—1.57 kΩcm and; water absorption by total immersion—16% (refer to the R2-180D mixture).

Based on this reference, the objective of this research is to improve the thermophysical properties of these CEBs by using locally sourced natural materials. By selecting WS, CGs, and GOSs, a new waste stream management is proposed for southern Portugal. The experimental results presented here are part of a comprehensive study, including analyses of mechanical strength and durability, the results of which will be presented in future studies.

2. Materials and Methods

This section introduces and characterises the raw materials used and describes sample preparation. Subsequently, the experimental methods for investigating the blocks are presented.

2.1. Raw Materials and Sample Preparation

CEBs used as reference for this study consist of a mixture of soil, hydraulic lime as stabiliser, and water. The blocks were produced by a company in the south of Portugal with long experience in earthen construction, Betão e Taipa. The company supplied these materials.

Natural materials used for the experimentation are wheat straw (from wheat harvesting), cork granules (from recycling bottle stoppers) and ground olive stones (from olive oil production). These materials were selected according to local availability and the producers who supplied them. As the aim is to keep raw materials minimally processed, they were not subjected to any treatment aimed at changing their surface or microstructural attributes.

2.1.1. Soil Characteristics

The soil was quarried in the region of Serpa, Alentejo, Portugal. The main characteristics were deduced from common physical and geotechnical testing methods. Complementary analyses such as X-ray diffraction (XRD) and thermogravimetric analysis (TGA) provided microstructural insights.

The primary characteristics are given in Table 1, along with the standards followed.

Table 1. Physical and geotechnical characteristics of the soil used.

	Characteristics	Test Methods	Standards
Consistency limits [1]	w_L = 29.5%, w_P = 18.5%, IP = 11%	Atterberg limits	NP-143 [37]
Particle density [1]	2.71 g/cm^3	Pycnometer test	NP-83 [38]
Specific heat (at 26.85 °C) [1,2]	883.93 J/kg°C	DSC	ASTM E1269 [39]
Maximum dry density	2.01 g/cm^3	Proctor test	E 197 [40]
Optimum water content	12.0%		
Sand content	18.80%	Sand equivalent test	NP EN933-8 [41]
Activity of clay minerals	0.67 mg/g	Blue methylene test	NP EN933-9 [42]
Organic content	3.50%	Loss on ignition	ASTM D2974 [43]

[1] This test is standardised for a maximum particle size of 4.75 mm. [2] Due to the apparatus's calibration, it was impossible to obtain reliable measurements at 20 °C.

Based on this characterisation, the soil is classified as 'sandy'. Figure 1 illustrates the particle size distribution, showing adequate clay content to produce CEBs (~10%) [44].

XRD analysis, used for mineral identification, was conducted using a Locked Coupled configuration on a Bruker AXS D8 Discover diffractometer (Bruker, Billerica, MA, USA) equipped with Cu-Kα radiation (λ = 1.54060 Å) at 40 kV and 40 mA. Scanning was performed between 5° and 82° with a step size of $0.04°s^{-1}$ and a step time of 3 s. Phase identification was performed using EVA analytical software (v. 4.2.2). Crystalline phases were indexed in the International Centre for Diffraction Data (ICDD) database. Quantitative phase analysis was attained employing Rietveld refinements with TOPAS software (v. 3).

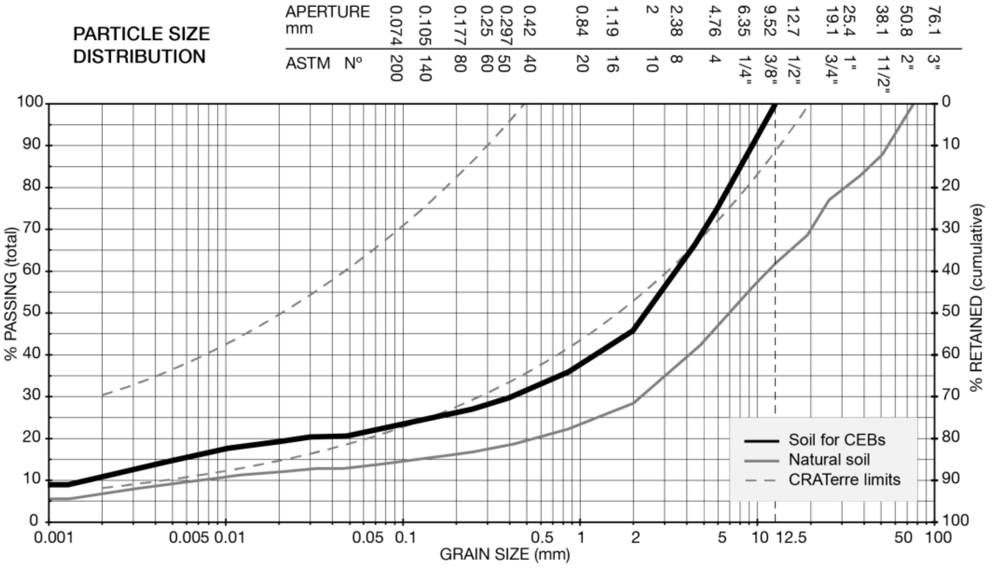


Figure 1. Particle size distribution curve of the soil used.

The obtained XRD pattern is presented in Figure 2. Peak-matching analysis reveals the presence of three plausible main crystalline phases: quartz (13%), muscovite (55%), and clinochlore (32%).

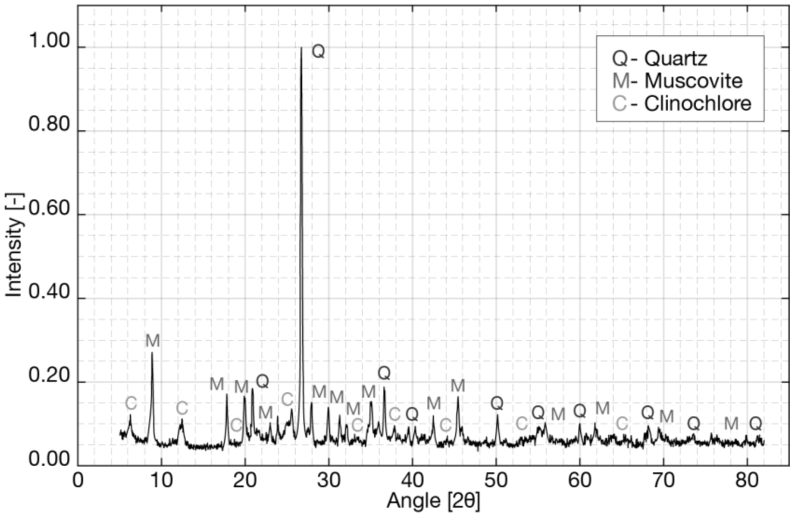


Figure 2. X-ray diffraction pattern of the soil sample analysed.

Quartz (SiO_2) belongs to one of the most significant and common classes of minerals, and its presence is expected in sandy soils. This element suggests a significant granitic and metamorphic influence on the soil. Muscovite and clinochlore are phyllosilicates, minerals consisting of parallel sheets of hydrated silicate tetrahedra with water or hydroxyl groups attached. Muscovite ($KAl_2[(AlSi_3O_{10})(OH)_2]$) is the most common dioctahedral mica characterised by perfect basal cleavage [45]. Clinochlore ($Mg_5Al[(AlSi_3O_{10})(OH)_2]$) is a Mg-dominant species belonging to the chlorite group (clay mineral group). Generally green, with a pearly to glassy lustre, it is relatively soft and has a scaly, platy appearance [45]. On visual examination and touch, the presence of such soft and relatively soft minerals as muscovite and clinochlore is evident.

Soil characterisation is finally completed with TGA. The analysis was performed by an SDT Q600 V20.9 Build 20 apparatus (TA Instruments, New Castle, DE, USA). The temperature program set was a linear ramp with an increase of 10.0 °C/min up to 1100.0 °C. The mass loss of each analysed sample is recorded against the increase in temperature. The first derivative of the gravimetric curve is then plotted to identify the peaks corresponding to the reactions in the sample. The soil gravimetric curve and its first derivative are shown in Figure 3.

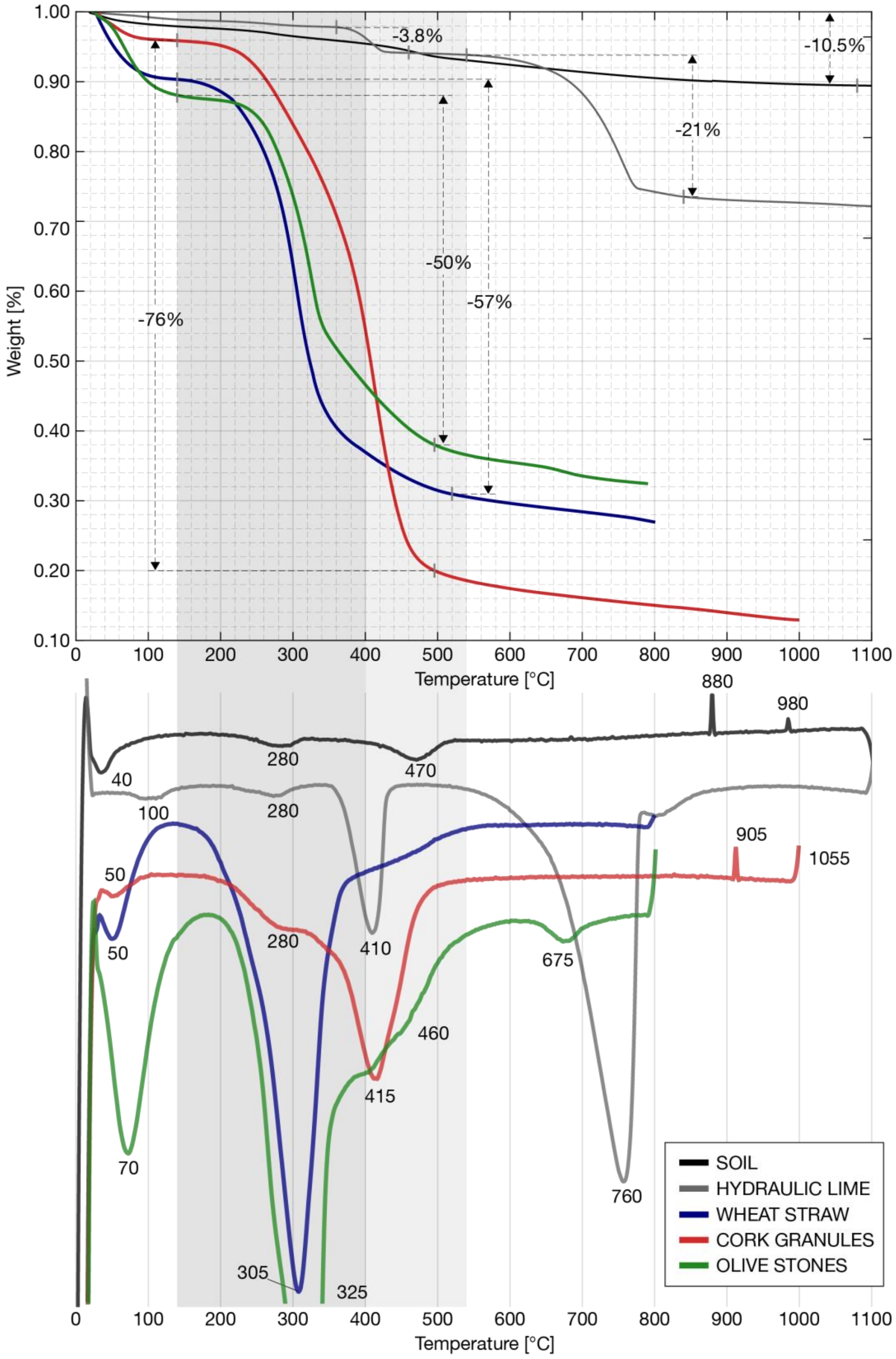


Figure 3. Thermograms of the raw materials involved: at the top the thermogravimetric curves (TG), at the bottom their first derivative (DTG) for peak identification.

It is anticipated that, for a more direct comparison, Figure 3 shows the thermograms of all the raw materials involved in this study. Please refer to the specific sections (Sections 2.1.2 and 2.1.3) for the discussion about these results.

The first derivative (DTG) of the soil thermogravimetric (TG) curve revealed five distinctive peaks. The initial weight loss below 100–140 °C corresponds to hygroscopic water loss (free water between clay particles). This loss continues to increase at higher temperatures due to water being bound to exchangeable cations in the minerals. In the temperature range 200–400 °C (low), decomposition of organic matter occurs first, followed by oxidation of the carbon content. Therefore, the peak identified at 280 °C possibly represents the dehydroxylation or decarboxylation of organic compounds. However, it could also represent the loss of hydroxyl groups from gibbsite ($Al(OH)_3$) or the dehydroxylation of goethite ($FeO(OH)$), which occurs in the 290–330 °C range and whose possible presence is based on visual inspection of the soil sample (characteristic iron-red colour). In the temperature range of 400–500 °C (moderate), a peak at 470 °C suggests the decomposition of more complex organic compounds or the presence of clay minerals (most likely the presence of the latter, as the same peak was detected in the analysis of soil samples free of organics). Finally, carbon thermal degradation occurs in the high-temperature range above 600 °C. Peaks at 880 °C and 980 °C may correspond to mineral decomposition and oxidation processes, respectively. It is reported in the literature that phyllosilicates detected by XRD (muscovite and clinochlore), for example, show a simple dehydroxylation reaction in the temperature range 820–920 °C, compatible with the peak found [46]. The presence of quartz, with its characteristic peak at 573 °C corresponding to phase transition α-β, was not found [47,48].

2.1.2. Natural Hydraulic Lime

As sandy soils may lack of cohesion, 5% by volume (5v.%) of Natural Hydraulic Lime (NHL5) was used for stabilisation. The grey TG and DTG curves in Figure 3 form the fingerprint of hydraulic lime with the two main peaks at 410 °C and 760 °C. The first one is associated with the dehydroxylation of $Ca(OH)_2$, while the second indicates the thermal decomposition of $CaCO_3$ to form CaO and CO_2 [49].

2.1.3. Natural Materials

This study defines 'natural materials' as all raw materials of plant or animal origin, such as fibres, straw, leaves and any aggregate, powder or ash derived from fruit stones, shells, and wood. To be considered residues and by-products, these materials must derive from other processes and not be extracted directly. In this study, three were selected on the basis of their local availability. These are wheat straw, cork granules, and ground olive stones.

Wheat straw (WS) is an agricultural by-product of wheat cultivation represented by the residual stalk, which includes stems and leaves. Cellulose, hemicellulose, and lignin are the main components of its fibrous structure. Observing Figure 3, the weight loss in the 140–540 °C range and the peak at 305 °C in the DTG curve are indeed related to the release of condensable vapours (acetic acid, methanol, and wood tar) and incondensable gas (CO, CO_2, CH_4, H_2, and H_2O) deriving from their decomposition (pyrolysis) [50]. The lightweight and porosity characteristics of straw fibres make them suitable for inclusion in composite materials designed for construction purposes. In this study, the WS was chopped into pieces 3 to 5 cm long.

Cork granules (CGs) are a recycled product from bottle stoppers. Along with Spain, Algeria, and California, Portugal is one of the leading countries producing commercial cork. For its ease of availability in the local market and outstanding properties (low density and permeability, elasticity, resiliency, acoustic and thermal insulation, chemical and biological inertia, and fire resistance [51–53]), this material emerges as a valuable candidate for enhancing the thermal performance of CEBs. As a natural aggregate, unlike fibres, CGs are used as a partial substitute for soil. The TGA (Figure 3) shows that, like straw, the most prominent mass loss occurs in the 140–540 °C range. In this region, a smaller peak around 280 °C corresponding to the degradation of polysaccharides composed of cellulose and hemicellulose can be noticed. However, a second, more important reaction is noticeable at 415 °C, corresponding to more stable aromatic structures, such as lignin and suberin. Above 540 °C, the mass loss rate is slow until the cork reduces to ash [54].

Ground olive stones (GOSs) are the residual by-products of olive oil production. GOSs are composed mainly of the hard, inner seeds crushed during olive oil processing and exhibit a durable and granular structure, rich in lignin and cellulose, also confirmed by TG analysis. Figure 3 shows that the most significant mass loss occurs in the 140–540 °C range. Identified peaks at about 325 °C and 460 °C are due to the cellulose. The long tail corresponds to the thermal decomposition of lignin, which indeed decomposes, overlapping the cellulose [55]. The physical properties of GOSs include a low density and high porosity, making them ideal candidates for enhancing materials' thermal and structural characteristics.

Table 2 provides the main characteristics of selected natural materials.

Table 2. Characteristics of the natural materials involved in this study.

	Thermal Conductivity [W/mK]	Moisture Content [%]	Bulk Density [g/cm^3]	Porosity [%]	Absorption [%]
Wheat straw (WS)	0.041–0.049 [1] [56]	5.02–7.79% [57]	0.98–1.77 [57]; 0.104 [29]	–	–
Cork granules (CGs)	0.036 [35]	–	0.70 [35]	51% [35]	2.40 [35]
Olive stones (GOSs)	–	–	0.65; 0.70 [36]	83% [36]	4.60 [36]

[1] This range was calculated on wheat straw bales. Note: If not calculated, data in the table were taken from the specific literature referenced. Due to the highly variable composition, materials' properties do not have an unambiguous value but fall within a range of values.

Pictures in Figure 4 show their appearance.

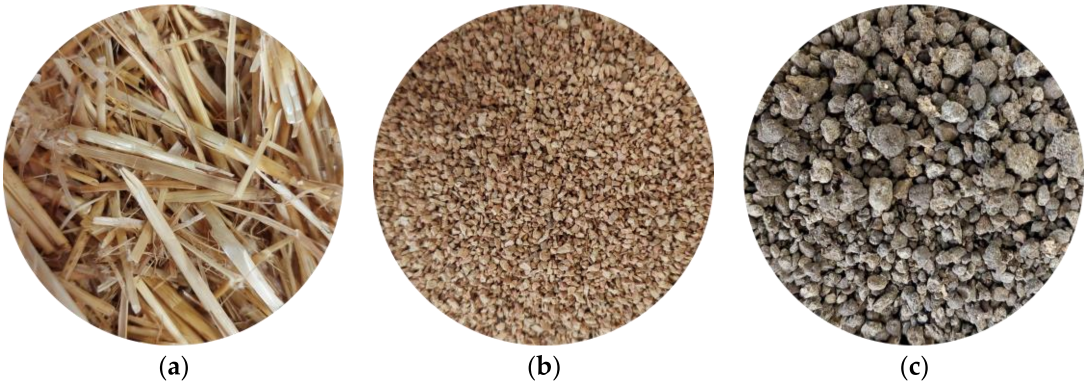


Figure 4. Appearance of the natural materials selected: (**a**) WS—wheat straw (WS); (**b**) CGs—cork granules; (**c**) GOSs—ground olive stones.

2.1.4. Preparation of the Samples

The block samples were prepared at the company's premises, following company practice. Regarding preparation conditions, some important information about the production process should be highlighted: (i) at the company scale, it was not possible to oven-dry the raw soil before mixing; therefore, the water content was defined for each mixture based on the producer's experience and may not reflect the optimal content deduced from the Proctor test; (ii) as for company uses, all mixtures were prepared on a volumetric basis; (iii) the blocks produced do not have the same volume (block height varies slightly depending on the mixture).

To produce CEBs, raw materials were mixed 'dry' first to ensure an even distribution. Water was added gradually until the dropping ball test conditions were satisfied [33,58,59].

This field test, which consists of dropping a ball of moist earth from a height of 1 metre and observing how it breaks, is considered adequate for non-plastic earthen techniques [17].

In this study, the reference blocks are CEBs consisting of soil, 5% by volume (v.%) hydraulic lime addition, and water. This basic mixture is identified here as 'REF'. The designed mixtures covered by this study are those shown in Table 3.

Table 3. Designed mixtures.

		Soil	Hydraulic Lime [v.%]	Natural Material [v.%]	Mixing Water [v.%]
Reference mixture—REF [1]	REF	100%	5%	-	10%
Mixtures with addition of wheat straw—WS	WS5	100%	5%	5%	13%
	WS10	100%	5%	10%	12%
	WS15	100%	5%	15%	11%
Mixtures with replacement of soil with cork granules—CGs	CG1	99%	5%	1%	16%
	CG3	97%	5%	3%	15%
	CG5	95%	5%	5%	14%
Mixtures with replacement of soil with ground olive stones—GOSs	GOS10	90%	5%	10%	15%
	GOS15	85%	5%	15%	14%

[1] The blocks used as reference for this study were characterised in their main thermophysical, mechanical and durability attributes in a previous study [60], see batch 'R2-180D'.

According to the above-presented mixes, CEBs were produced using a hydraulic press machine (Eco Máquinas, São Domingos, Brazil—Eco Master 7000 Turbo II) at 10 MPa (Figure 5a). Blocks have standard dimensions of 300 mm × 150 mm × 80 mm (length × width × average height). After compression, the blocks were stored in a sheltered area, sprayed with water twice a day for the first week and covered with a plastic sheet. They were cured for 180 days before testing (Figure 5b).


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

Figure 5. (**a**) Freshly manufactured blocks and (**b**) batch of blocks (mixture WS15) ready for curing.

2.2. Experimental Methods

The experimental investigation consisted of characterising the physical–geometric and thermal attributes of the CEBs. For each mixture, the batch of blocks produced comprises at least eighteen blocks. Due to the inherent variability of the material, to provide the best representative value, the physical and geometric attributes refer to the average measurement of the entire batch. Thermal tests were instead performed on a sample of three blocks.

2.2.1. Physical Characterisation of the Blocks

The volume and mass of each block was measured at natural moisture content. The bulk density, expressed in kg/m^3, is estimated according to Equation (1):

$$\gamma = m/V, \tag{1}$$

where m and V are the measured mass and volume of the block, respectively. The dry bulk density (γ_d) is estimated through Equation (1), by replacing the mass m with the dry mass (m_d). The blocks were considered dry when their mass stabilised after several days in the oven at 40 °C. An estimation of the percentage of open porosity (φ) and natural moisture content (ω) can be then obtained through equations:

$$\varphi = 1 - (\gamma_d/\gamma_s), \text{ and} \tag{2}$$

$$\omega = (\gamma - \gamma_d)/\gamma \tag{3}$$

where γ_s is the soil particle density (see Table 1).

2.2.2. Thermal Characterisation of the Blocks

The thermal characterisation of the blocks was performed in a hot box apparatus. The primary output of the hot box is the thermal resistance. The thermal resistance was measured under steady-state conditions according to ASTM C1363-11:2011 [61] and ISO 9869-1:2014 [62]. Each block was placed between two sensors in a temperature-controlled enclosure while a known temperature difference was applied. The sensors measured the heat flux. Steady-state conditions are assumed to occur when the percentage change in heat flux throughout the sample is ≤5% at 24 h intervals and after a minimum of 72 h of testing. For a detailed description of the apparatus, please refer to [63].

The thermal resistance, expressed in m^{2}K/W, is defined by Equation (4):

$$R = \Delta T/q, \tag{4}$$

where ΔT is the applied temperature difference, and q is the heat flux across the sample. From it, thermal conductivity (W/mK) can be deduced according to Equation (5):

$$\lambda = d/R, \tag{5}$$

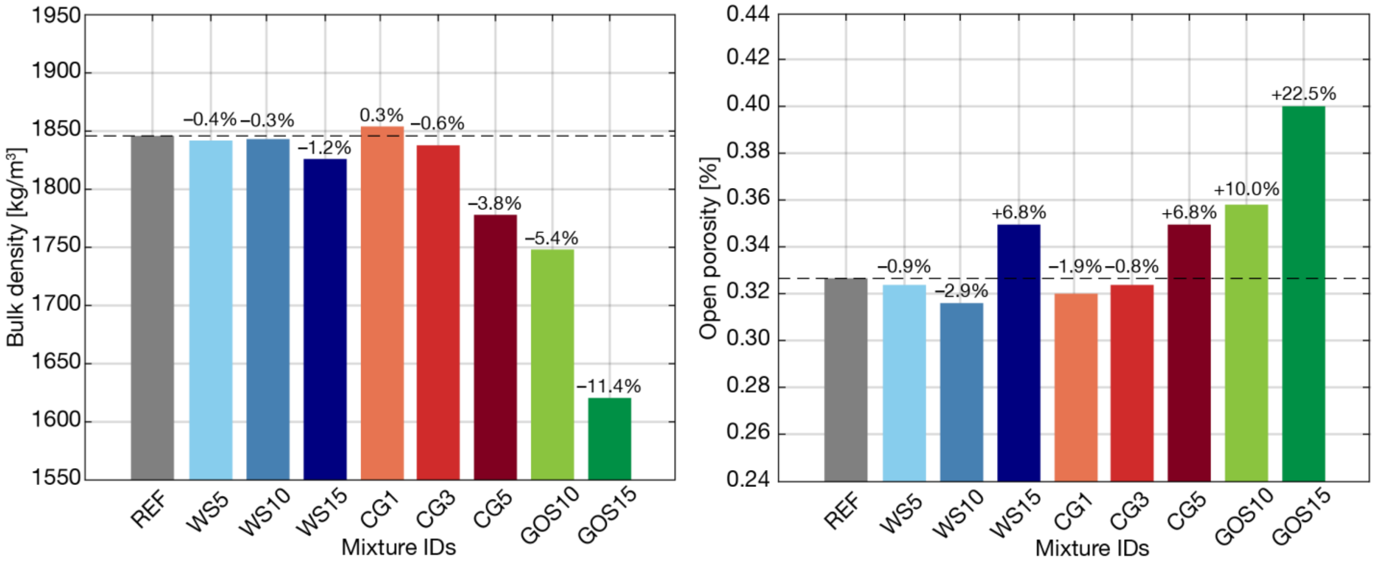
where d is the thickness of the product (wall thickness), and R is the thermal resistance.

3. Results and Discussion

3.1. Physical Properties of the Blocks

The average bulk density values calculated for the entire batch of CEBs produced for each mixture are presented in Figure 6a. The graph of Figure 6b shows the estimated open porosity associated with each mixture.

The reference CEBs (REF) are characterised by a bulk density of 1848.0 kg/m^3 and an estimated open porosity of 32.6%. In the histograms, the dashed line indicates these reference values, while the percentages on each bar represent the variation from the reference. As a general tendency, the incorporation of natural materials reduces the bulk density as their concentration increases. In the case of WS, the effect is less pronounced as the fibres were added to the mixture rather than replacing a portion of soil. In fact, mixtures containing 5 and 10v.% WS only marginally reduced bulk density to 1841.2 and 1842.5 kg/m^3, respectively—less than 1% of the reference. Porosity is estimated to be 32.4% for WS5 and 31.7% for WS10. The mixture with 15v.% WS recorded a slightly lower bulk density (1825.5 kg/m^3), and higher porosity (34.9%).



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

Figure 6. Bulk density (**a**) and open porosity (**b**) of CEBs incorporating different natural materials.

The replacement of 1 and 3v.% of soil with CGs had an almost negligible impact on the bulk density, with values of 1853.3 and 1837.1 kg/m^3 respectively—both still varying within 1%. Porosity is estimated to be 32.0% for CG1 and 32.4% for CG3. Incorporating 5v.% CG resulted instead in 4% lower bulk density (1777.5 kg/m^3), and higher porosity (34.9%). These results, particularly those for CG1 and CG3, are due to the minimum substitution rate examined. Unfortunately, it was not possible to go any further as, for concentrations above 5v.%, a degradation of the blocks' quality was observed during production. As shown in Figure 7, beyond this threshold, the blocks exhibited poor quality and a lack of cohesion that made them prone to crumbling immediately after compaction. It can be said that 5v.% represents the upper limit for effective soil replacement with CGs.

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

Figure 7. CEBs incorporating 10v.% CG broke down (**a**) and cracks (**b**) immediately after compaction.

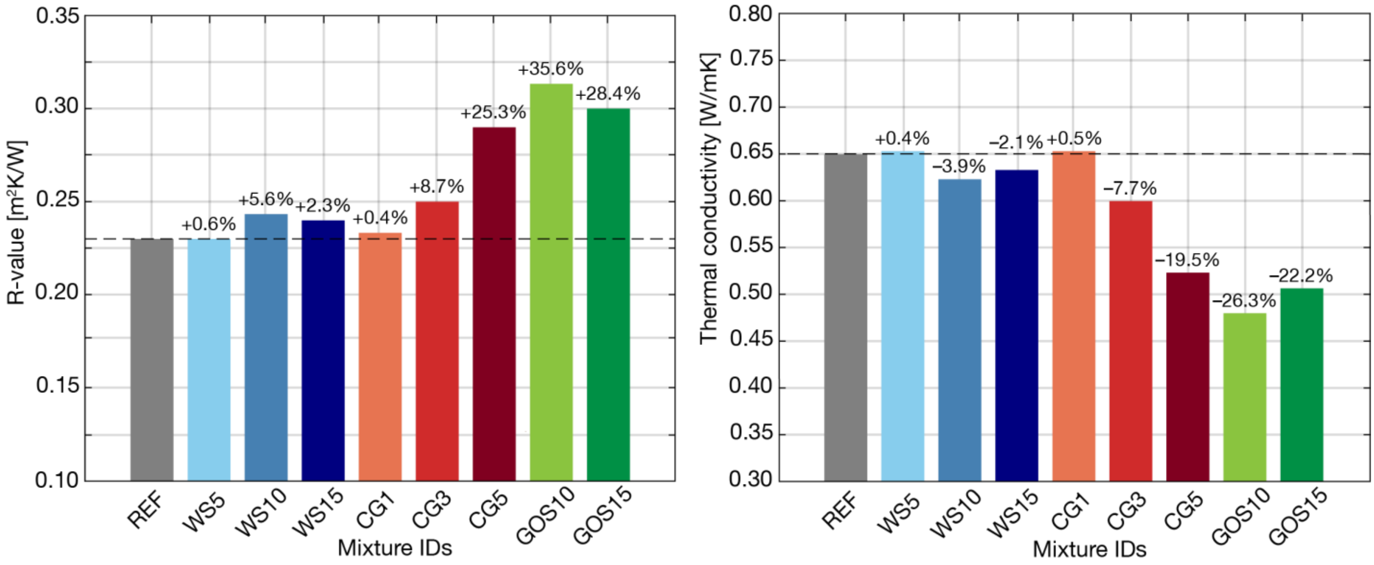
Mixtures incorporating GOSs exhibited more remarkable results. Replacing 10 and 15v.% of soil with GOSs reduced the bulk density to 1747.8 and 1636.7 kg/m^3: in percentage, 5.4 and 11%, respectively. The estimated porosity raised up to 35.9% for GOS10 and 40% for GOS15. Unlike CG, even at higher concentrations, GOS mixtures encountered no significant issues during the production process. This disparity may be attributed to the differences between the two natural aggregates. Although both are characterised by considerable lightness and porosity, the hardness of the olive kernel and the surface's roughness prove to be more akin to soil particles compared to the soft and resilient honeycomb structure of cork. Therefore, GOSs exhibit a superior affinity than CGs for replacing a portion of the soil in mixtures intended for CEBs.

With the exception of GOS15 blocks, the bulk density of the CEBs examined falls within the typical range disclosed in the literature—from 1700 to 2000 kg/m^3 [20]. It should be noted that there are no regulatory requirements on this aspect in most parts of the world. Only Indian and Sri Lankan standards have set a minimum bulk density of 1750 kg/m^3 [30,64,65]. This notwithstanding, despite lower density values in the range 1600–1650 kg/m^3, blocks with 15v.% GOS showed no discernible problems during the production process (as in the case of blocks with >5v.% CG).

Finally, in the reference CEBs as in those with natural materials, the natural moisture content at 180 days was always around 0.6%.

3.2. Thermal Properties of the Blocks

The average results of thermal tests performed in the hot box apparatus are presented in Figure 8. As in the previous graphs, the dashed lines indicate the reference values, while the percentages on each bar represent the variation from this reference.



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

Figure 8. Thermal resistance (**a**) and conductivity (**b**) of CEBs incorporating different natural materials.

Reference CEBs are characterised by a thermal resistance of 0.23 m^{2}K/W. The incorporation of WS did not lead to any significant alterations of the thermal response: in the case of 5v.% addition, the increase in resistance is below 1%; in the case of 15v.%, it is slightly above 2%. A modest increase of 5.6% can be noted for a concentration of 10v.% (WS10: R-0.24 m^{2}K/W). However, it would be premature to attribute this result to the presence of fibres for two reasons: the first is that the relatively low percentages considered can make the soil thermal response dominant over the presence of straw; the second is that mixing on a volumetric basis and producing blocks on a large scale (company scale) increases data scattering. Similar to the WS5 blocks, the CG1 blocks include an extremely small percentage of CGs (1v.%), essentially incapable of modifying the thermal resistance. On the other hand, the other CG mixtures exhibit a sharper response. Replacing 3 and 5v.% of the soil with CGs brings the thermal resistance of the blocks to 0.25 and 0.29 m^{2}K/W, corresponding to an increase of 8.7 and 25.3% for CG3 and CG5, respectively. However, the best results are obtained for CEBs incorporating GOSs. The R-value increases by 35.6%, reaching 0.31 m^2K/W in the case of a 10v.% GOS concentration (GOS10), and by 28.4%, reaching 0.30 m^2K/W, in the case of a 15v.% GOS concentration (GOS15). Overall, the incorporation of natural materials increases the thermal resistance of the blocks, enhancing their insulating potential. Note that, according to the actual laying in masonry walls, the blocks were measured in flat position and, therefore, the R-values correspond to a wall-thickness of 15 cm. Regardless of the thickness, Figure 8b represents the thermal conductivity of each mixture experimented.

As in the case of thermal resistance, the same non-linear trend is observed for the reciprocal thermal conductivity in blocks with WS and GOS mixtures (Figure 8b). In fact, in the case of these mixtures, the results show an initial improvement in the thermal properties (see WS10 and GOS10) followed by their decay (see WS15 and GOS15), in line with the literature findings suggesting a maximum concentration threshold limiting the benefits related to the presence of natural materials [20]. Interestingly, the CG mixtures exhibit a more linear trend: the thermal conductivity, as well as the bulk density (Figure 6a), decrease steadily as the concentration of CGs increases. This response may be attributed to the presence of non-hygroscopic water associated with the microstructure of the natural materials involved. In fact, for dry soils, relatively small increases in water content can substantially increase the thermal contact between soil particles, resulting in a non-linear increase in thermal conductivity [66]. As evidenced by the thermograms in Figure 3, the water content (mass lost below 140 °C) exceeds 10% in the case of WS and GOSs, while for CGs it remains below 4%. Experimental data are provided in Table 4.

Table 4. Thermophysical properties of CEBs incorporating natural materials [1].

	γ_d [kg/m^3] [2]	**R-Value [m^{2}K/W]**	**λ [W/mK]**
REF	1831.53 ± 4.72 (0.26%)	0.231 ± 0.01 (4.13%)	0.650 ± 0.03 (4.11%)
WS5	1835.31 ± 13.14 (0.72%)	0.232 ± 0.03 (12.28%)	0.653 ± 0.09 (13.08%)
WS10	1805.36 ± 68.06 (3.77%)	0.243 ± 0.04 (14.45%)	0.625 ± 0.08 (13.60%)
WS15	1816.43 ± 32.24 (1.77%)	0.236 ± 0.02 (6.35%)	0.636 ± 0.04 (6.59%)
CG1	1771.21 ± 41.65 (2.35%)	0.232 ± 0.03 (12.85%)	0.653 ± 0.08 (12.32%)
CG3	1848.86 ± 76.02 (4.11%)	0.251 ± 0.02 (7.94%)	0.600 ± 0.05 (8.32%)
CG5	1748.36 ± 7.21 (0.41%)	0.289 ± 0.04 (12.15%)	0.523 ± 0.06 (11.54%)
GOS10	1737.31 ± 16.21 (0.93%)	0.313 ± 0.01 (4.17%)	0.479 ± 0.02 (4.14%)
GOS15	1626.84 ± 50.87 (3.13%)	0.297 ± 0.01 (3.24%)	0.506 ± 0.02 (3.21%)

[1] This table shows the average data with their standard deviation and, in brackets, the coefficient of variation.
[2] These data refer to the average dry bulk density of only the CEBs used for the thermal tests (three). Therefore, they may differ from the values shown in the histogram of Figure 6a, as those values were calculated by averaging the entire batch of blocks produced (eighteen per mixture) to obtain a more robust measurement.

3.3. Comparison and Analysis

In the graph of Figure 9, the experimental data are presented along with data from the literature. As the compression process entails some substantial changes in soil particle packing and heat transfer, it is worth mentioning that these data were collected within the context of a previous study [20] focusing exclusively on the case of CEBs incorporating natural materials. These materials are indicated in the legend.

Experimental data of this study fit well into the broader framework collected, being in the range of both conventional density and thermal conductivity values. Although one cannot speak of a linear dependency relationship between the two variables—statistical analyses have estimated very low coefficients of determination (in the range 0.2–0.4, see Figure 9, top left-hand corner)—a certain increase in the thermal conductivity as the bulk density increases is noticeable. It is legitimate to query whether more data availability could support this hypothesis which remains an open issue [45].

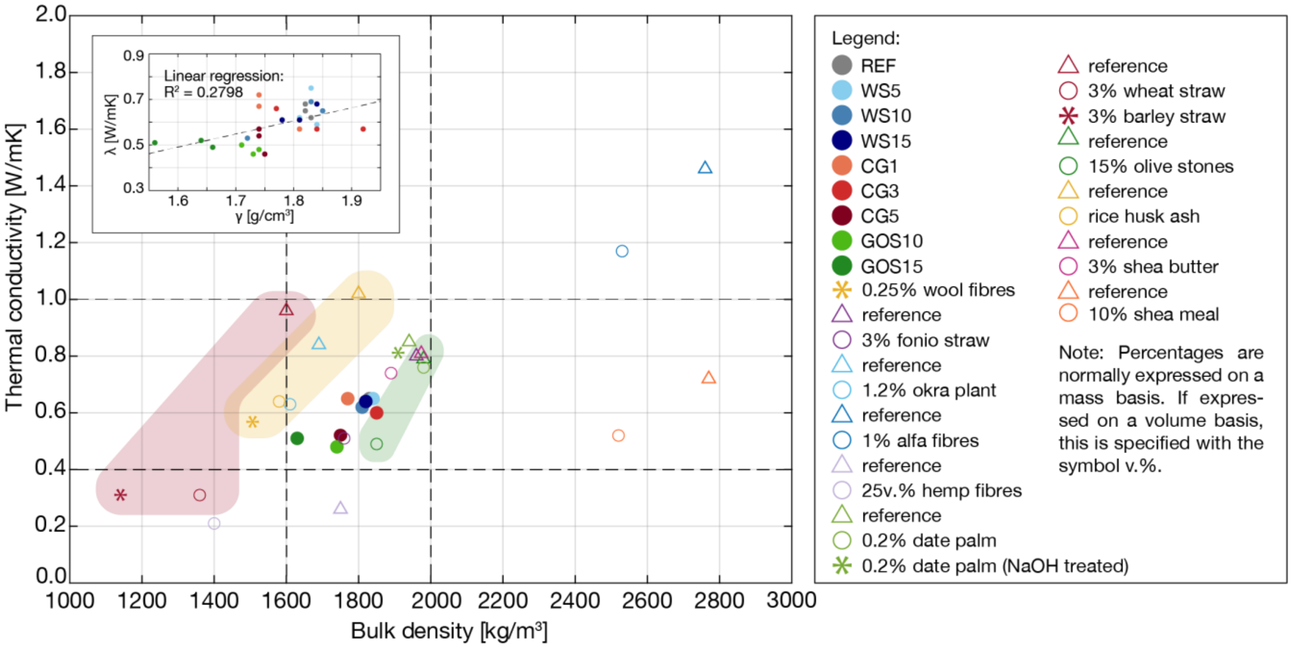


Figure 9. Comparison of the experimental data with the literature data. The main graph shows average values, while the zoom in the top left-hand corner presents the raw data and the linear regression.

However, data reassure on the effectiveness of the natural materials considered in improving thermal properties of CEBs. Observing the graph and the highlighted cases, the consistent reduction in thermal conductivity of mixtures modified with natural materials compared to those unmodified can be noted. The most significant reduction in thermal conductivity, exceeding 50%, was observed in mixtures containing 3% by mass of wheat and barley straw [67] (highlighted in red). This notable achievement can be attributed to the significant amount of fibres used (calculated on a mass basis), fairly above the concentrations considered in this study (calculated on a volumetric basis). Without compromising the essential mechanical strength and durability of the blocks, these results suggest the possibility of exploring even higher proportions.

Other noteworthy examples showcased reductions in thermal conductivity exceeding 35%, particularly in mixtures incorporating rice husk ash [25] (highlighted in yellow) and olive stones (highlighted in green) [36]. In this regard, the results of the present study concerning GOS mixtures align consistently with those reported by [36] and other studies not included in the review article [68,69].

In the case of CGs, the results of this study still find consensus with the literature, but outside of that included in the review article [34,35]. The thermal conductivity as well as the bulk density of mixtures incorporating CGs decreased with a linear trend. The authors agree on attributing this result to the low density and low thermal conductivity of this natural aggregate. However, within the scope of this study, production problems were observed for concentrations above 5v.% CG. Above this threshold, in fact, the blocks crumbled and broke immediately after demoulding.

In conclusion, continuing to explore the potential of natural materials to improve the thermal characteristics of CEBs has proven beneficial. The increase in thermal resistance improves the insulation potential of the material, allowing a reduction in the thickness of the building envelope. Many natural materials inherently exhibit a lightweight and porous structure, making them particularly well suited for achieving this purpose. When sourced from production processes, such as those in the agro-food industry, the utilization of these materials not only presents a substantial opportunity for improving thermal behaviour but also contributes significantly to waste reduction. The findings underscore the feasibility of simultaneously attaining diverse objectives that could generate a positive environmental and economic impact for the building industry [70].

4. Conclusions

This study investigates enhancing the thermophysical properties of compressed earth blocks (CEBs) by incorporating locally sourced natural materials. The experimental design involved formulating eight different mixtures with varying volume concentrations (v.%) of wheat straw (WS—5, 10 and 15v.%), cork granules (CGs—1, 3, and 5v.%), and ground olive stones (GOSs—10 and 15v.%). The resulting blocks were tested using a hot box apparatus and characterised in their thermophysical attributes. The findings reflect the distinct impact of adding natural fibres (as seen with WS) or substituting soil with natural aggregates (the case observed with CGs and GOSs) on the mixtures' properties. Notably, the variations in properties were more pronounced with natural aggregates. Certain mixtures showed superior thermal properties compared to standard blocks (REF: R—0.23 m^2K/W and λ—0.65 W/mK). The best mixture incorporating WS, albeit with modest improvements, achieved a 4% decrease in thermal conductivity at a 10v.% concentration (WS10: R—0.24 m^2K/W and λ—0.63 W/mK). In contrast, mixtures with 5v.% CG and 10v.% GOS reduced conductivity by approximately 20 and 26%, respectively (CG5: R—0.29 m^2K/W and λ—0.52 W/mK; GOS10: R—0.31 m^2K/W and λ—0.48 W/mK). These findings underscore the potential of these materials to enhance the thermal properties of earth-based mixtures while also contributing to waste reduction and minimising raw material extraction.

Some observations:

- Further research is warranted to refine the material ratios and manufacturing processes to achieve optimal thermal performance in mixtures incorporating WS. Contrary to the existing literature [67], this study did not observe an improvement in thermal properties.
- Utilising CGs from bottle stoppers showcases the recycling and reusing potential of this natural material. However, concentrations exceeding 5v.% were found to compromise block quality, as evidenced by immediate block crumbling post compaction.
- The inclusion of GOSs in mixtures is a promising alternative for enhancing earth's insulating properties and overall energy efficiency, while also proposing a sustainable waste management technique. Positive results from their use align with the existing literature [36], marking a significant milestone. Further experimentation in other producing countries would be beneficial.
- The investigation did not reveal a linear correlation between density reduction and thermal conductivity reduction. Two considerations: the introduction of natural materials into the soil matrix, whose properties diverge from those of the soil grains, lead to non-linearities in the heat flux paths. Accurately describing this problem using analytical models is difficult without significant simplifications. On the other hand, numerical approaches employing random discrete-element modelling could simulate the behaviour of the mixed granular medium, albeit with computational cost. Despite low coefficients of determination indicating weak correlations, a certain pattern is still decipherable. Consequently, while more data can increase confidence in navigating the survey space, the creation of a comprehensive database could make it easier to exploit the potential of artificial intelligence.

Enhancing our understanding and refining the thermophysical properties of earth-based building materials incorporating natural elements is an essential prerequisite for their advancement. Therefore, continued research in this area is strongly encouraged.

In the comprehensive evaluation of the proposed new products, following studies will present the analysis of mechanical and durability aspects as well as the life cycle assessment in terms of environmental impact and cost. Further investigations will focus on the possibility of using materials of natural origin for soil stabilisation, thus eliminating traditional binders (cement or lime, as in the case of this study).

Future prospects should encompass conducting experimental thermo-hygrometric investigations on walls and simulations to evaluate their performance across different climate zones, thus enabling the transition from product to building scale.

This study represents a foundational yet indispensable step towards the implementation of a closed-loop approach that positions earth as a central component of sustainable and regenerative building solutions. The integration of residues and by-products of natural origin not only enhances thermal performance, but also sets the stage for a transformative shift in the use of unconventional materials in the construction industry.

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