

Mechanical properties and durability of compressed earth blocks incorporating natural materials

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ABSTRACT

The construction industry urgently needs engineering solutions that reduce embodied carbon and promote circular material flows. Compressed earth blocks (CEBs) represent a promising low-carbon alternative, but their large-scale use is challenged by issues of mechanical strength and durability, particularly when natural materials are incorporated to improve thermal performance. Due to the inherent variability of natural products, their interactions within mixtures are still poorly understood, and quality control of the resulting materials is lacking. This study provides a comprehensive investigation of CEBs incorporating two agro-industrial by-products, wheat straw (WS) and cork granules (CGs), sourced locally from Portuguese production chains. The experimental program evaluates mechanical properties (compressive strength, tangent stiffness, flexural strength, fracture energy) and water absorption behaviour (capillary absorption, total immersion), and integrates non-destructive testing (NDT) techniques, including ultrasonic pulse velocity (UPV) and electrical resistivity, to outline practical guidelines for optimising additive content while ensuring mechanical performance and durability. Results indicate that the lowest 5% volumetric addition of WS yields the best balance between enhanced mechanical performance and acceptable water resistance. In contrast, CG additions must be limited to 3–5% by volume to avoid significant losses in strength and water resistance. The study demonstrates the diagnostic and predictive capacity of NDTs for the materials tested, with UPV correlating well with strength and stiffness, and electrical resistivity effectively reflecting capillarity. NDTs offer scalable, field-applicable tools for quality control, supporting a broader and more confident use of bio-based materials in modern construction.

1. Introduction

The construction sector plays a crucial role in society but has a significant environmental impact due to high levels of emissions, energy consumption, raw material depletion, and waste generation [1,2]. Within the European Union (EU), the built environment is the largest consumer of energy, accounting for 40% of total energy use, and a major contributor to greenhouse gases emissions, responsible for 36% of the total [3]. Additionally, it drives the extraction of 50% of all raw materials and generates 35% of the EU's total waste production [4]. Despite this awareness, anthropogenic activities continue to drive climate change, posing serious and potentially irreversible environmental, social, and economic consequences. In response, urgent mitigation strategies are required, one

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the most impactful being the responsible selection and use of building materials.

Environmentally conscious building materials prioritise locally sourced raw materials, low processing requirements, non-toxicity and recyclability. As a result, such materials tend to have low embodied carbon and energy content. Featuring these characteristics, earth as a building material is experiencing a revival, further supported by its natural hygroscopic qualities and ability to self-regulate indoor temperature and humidity [5]. Estimates suggest that 8–10% of global households live in earthen dwellings [7], and scientific interest in earthen materials and methods has increased exponentially in recent decades [8], both in developed and developing countries. Traditionally associated with vernacular and low-cost housing, earth is now gaining traction in modern construction as a sustainable alternative to high-impact cement-based materials [6].

Among the various earthen construction techniques, compressed earth blocks (CEBs) represent a technological advancement over traditional adobe. Unlike manual ramming (rammed earth), CEBs are compacted using a mechanical or hydraulic press, resulting in denser, stronger units that enhance production efficiency and construction quality. Notably, CEBs do not require firing, significantly reducing their embodied energy and global warming potential [9,10]. However, they exhibit relatively high thermal conductivity (0.6–1.2 W/mK) [11], which often necessitates the thicker wall assemblies to meet modern energy efficiency standards. This requirement, along with other socio-economic barriers [12], is considered a key factor limiting their widespread adoption in contemporary architecture [13,14]. To address this challenge, numerous studies propose incorporating lightweight and porous natural materials into CEB mixtures [15]. Given economic incentives, environmental concerns, and resource scarcity, agricultural crop residues are among the most used additives [16].

Research indicates that integrating agricultural and industrial by-products into earthen materials can reduce the demand for virgin soil, divert waste from landfills, and enhance material performance [15,17–20]. However, depending on their shape, composition, and microstructure, these natural additives serve different functions [15]. For example, plant fibres and straw reinforce earth-based materials by mimicking root-like stabilising mechanisms [21], improving ductility but sometimes reducing compressive or tensile strength. Nonetheless, significant enhancements in thermal and moisture regulation can be achieved [19]. Similarly, powders derived from fruit shells or stones act as lightweight fillers, reducing density and improving thermal performance due to their porous, lignocellulosic structure [22]. Despite these benefits, the inherent variability of such materials makes their response unpredictable. As a consequence, their interaction within the earthen matrix remains poorly understood, and the experimental assessment becomes essential to assess the properties of materials.

This paper presents an experimental study conducted in Portugal, where two readily available by-products were incorporated into CEBs to mitigate the material's limitations. These are: (i) wheat straw (WS), a residue from wheat harvesting, and (ii) cork granules (CGs), recycled from wine bottle corks. The blocks were produced by a company in the south of the country, with all raw materials sourced locally. While the thermophysical properties of these blocks have already been examined [22], this study focuses on their mechanical and durability aspects, addressing the challenges associated with the heterogeneity of natural waste materials and agro-industrial by-products.

Comparative analyses were conducted between modified and conventional CEBs through mechanical tests (compression and bending), durability assessments (water absorption by capillarity and total immersion), and non-destructive testing (NDT) techniques, including ultrasonic pulse velocity (UPV) and electrical resistivity, explored for their diagnostic and predictive potential. Microstructural analyses provided insights into material interactions within the matrix. In line with the principles of sustainability and the circular economy, and given the global challenges related to waste disposal, this study supports current research trends using agro-industrial by-products as sustainable additives [15].

2. Materials and methods

2.1. Raw materials

2.1.1. Soil

The soil used in this study was sourced from the Beja district in the Alentejo region of southern Portugal. Key characteristics are presented in Table 1, alongside the corresponding adhered standards followed for their assessment.

According to these characteristics, the soil is classified as sandy and silty. The liquid limit ($w_L = 29.5\%$), and plasticity index ($IP = 11\%$) indicate moderate plasticity. The particle density of 2.71 g/cm^3 aligns with typical values for mineral soils [29] with limited organic content (3.5%). The Proctor test results indicate a relatively high dry density (2.01 g/cm^3), sufficient for load-bearing capacity, with a moderate water content (12%). The moderate activity of clay minerals (0.67 mg/g), and sand content (18.8%) ensures adequate

Table 1
Physical and geotechnical characteristics of the soil used.

	Characteristics	Test methods	Standards
Consistency limits	$w_L = 29.5\%$, $IP = 11\%$	Atterberg limits	NP-143 [23]
Particle density	2.71 g/cm^3	Pycnometer test	NP-83 [24]
Maximum dry density	2.01 g/cm^3	Proctor test	E 197 [25]
Optimum water content	12%		
Sand content	18.8%	Sand equivalent test	NP EN933-8 [26]
Activity of clay minerals	0.67 mg/g	Blue methylene test	NP EN933-9 [27]
Organic content	3.5%	Loss on ignition	ASTM D2974 [28]

binding properties without the occurrence of adverse effects such as swelling and shrinkage. Furthermore, in a previous study [22], the mineralogical fraction of the soil used was characterised by XRD, identifying the presence of quartz and non-swelling kaolinitic clay minerals such as muscovite and clinochlore.

Fig. 1 illustrates the particle size distribution, showing a well-graded soil, with a clay content near 10%, deemed suitable to produce CEBs [30].

2.1.2. Wheat straw

Wheat straw (WS), an agricultural by-product of wheat cultivation, was used as a natural fibre for reinforcing the earthen matrix. WS consists of the wheat residual stalks, including stems and leaves, and is valued for its fibrous structure and lightweight properties. For this study, the WS was supplied by a local farmer and chopped into pieces measuring 30–50 mm in length, with a diameter of approximately 0.85 mm [31], resulting in a low aspect ratio ranging between 35 and 60. No surface treatments or modifications were applied.

2.1.3. Cork granules

Cork granules (CGs), a by-product from cork wine bottle stoppers production, were incorporated as a filler material. Cork was selected for its unique properties of low density, elasticity, thermal insulation, and resistance to chemical and biological degradation [22]. Unlike WS, which were added for reinforcement, the CGs replaced a portion of the raw soil in the mixtures to investigate their influence on mechanical and durability properties, alongside their established thermal benefits. For this study, granules were supplied by the Portuguese company Amorim. Particle size is 2 mm.

2.1.4. Other materials

The investigation also involved the use of lime and water. Natural hydraulic lime (NHL) type NHL5, eminently hydraulic lime, was used for soil stabilisation. Tap water was used for mixing.

2.2. Mix design and sample preparation

The CEBs were produced at the company’s site according to their established procedures. To allow comparisons, this study included a control sample (referred to as ‘REF’) consisting of plain, commercial CEBs made from soil, water, and 5% hydraulic lime (by volume, v.%). All mixtures were prepared on a volumetric basis, and the mix designs for both the control and modified samples are detailed in Table 2.

Initially, the raw materials were mixed in their dry state to ensure uniform distribution. Water was then added gradually until the mixture met the criteria of the dropping ball test [32–34]. This field test consists of observing the behaviour of a ball of moist mix

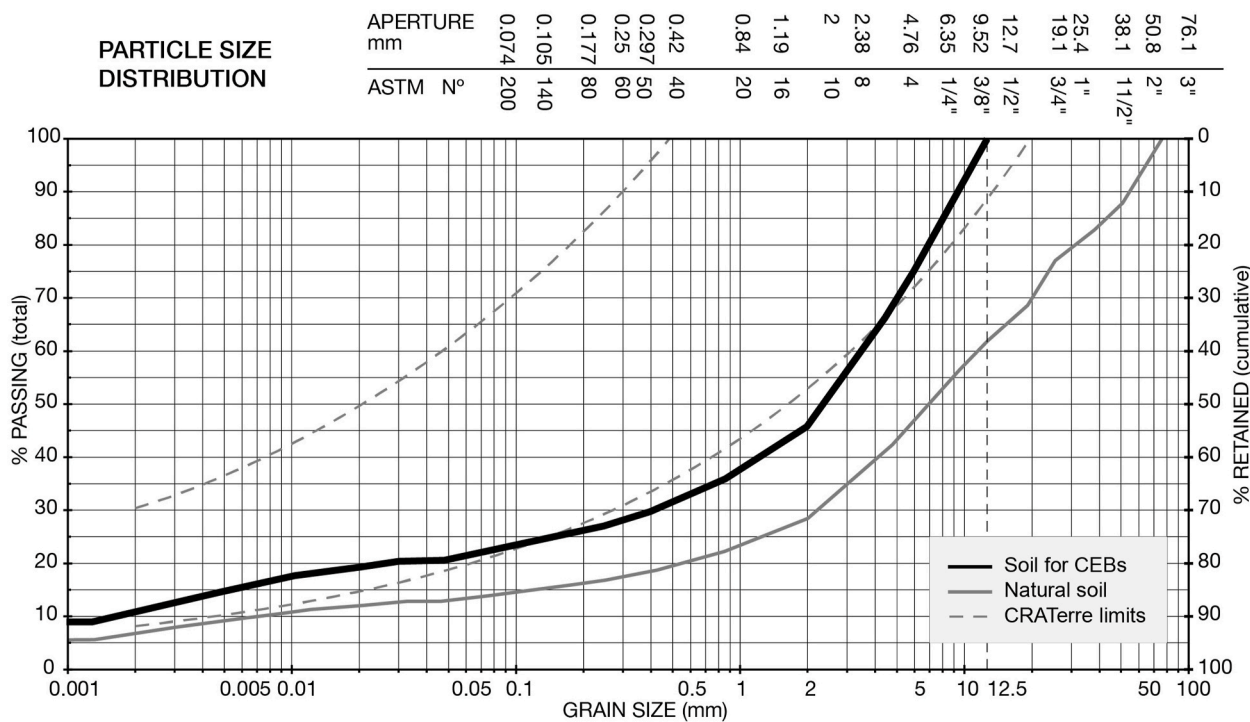


Fig. 1. Particle size distribution of the natural and sieved soil used.

Table 2
Designed mixtures.

Mixture type	Id	Soil [v.%]	Hydraulic Lime [v.%]	Natural Material [v.%]	Mixing Water [v.%]
Reference mixture—REF	REF	100%	5%	—	10%
Mixtures with addition of 5, 10 and 15v.% WS	WS5	100%	5%	5%	13%
	WS10	100%	5%	10%	12%
	WS15	100%	5%	15%	11%
Mixtures with substitution of 1, 3 and 5v.% CGs	CG1	99%	5%	1%	16%
	CG3	97%	5%	3%	15%
	CG5	95%	5%	5%	14%

dropped from a height of 1 m and is considered adequate for non-plastic earth techniques [11]. It should be noted that on a full production scale, oven-drying of the raw soil prior mixing is often impractical. Therefore, based on the manufacturer's experience, the mixing water shown in Table 2 differs from the optimal level suggested by the Proctor test.

The blocks were compressed using a hydraulic press (Eco Máquinas, São Domingos, Brazil – Eco Master 7000 Turbo II) at a pressure of 10 MPa. The steps of the production are shown in Fig. 2 with (a) showing the sieving process, (b) the soil preparation, (c) the mixing and wetting process, (d) the compaction process, finally (e) and (f) details of WS-blocks and CG-blocks.

The blocks have standard dimensions of 300 mm × 150 mm × 80 mm (length × width × average height), with slight variations in height depending on the mixture composition. After compression, the blocks were cured in a sheltered environment. During the first week, they were water-sprayed twice daily and covered with a plastic sheet to prevent rapid drying and ensure adequate curing.

2.3. Experimental methods

2.3.1. Mechanical characterisation

2.3.1.1. Compression tests. Compression tests on the blocks followed adapted protocols from EN 772-1 [35]. Blocks were laid flat, and the load was applied in displacement control mode at a rate of 0.5 mm/min. To reduce confinement effects due to the blocks' aspect ratio and reduce the friction with the load plate, a rubber sheet was placed between the blocks' top face and the load plate [36,37]. Axial deformation (ϵ) [%] was calculated as the ratio of height change (ΔL) [mm] to the initial height (L) [mm], assuming the displacement recorded by the transducer represented the height change. Stress (σ) [MPa] was determined by dividing the load (F) [N] by the contact area (A) [mm²]. The peak compressive strength (σ_c) in MPa was calculated as:

$$\sigma_c = \frac{F_{max}}{A} \quad (1)$$

where F_{max} is the maximum load [N], and A the contact area [mm²]. The apparent elastic modulus (E_0) was derived from the tangent slope of the stress–strain ($\sigma - \epsilon$) curve within the elastic range 0.5–1.0 MPa to exclude initial effects such as stresses or plastic deformations [38]. This range differed from previous studies (e.g., 0.2–0.3 MPa by Kouakou and Morel [39]), which did not align with our data. Given approximations in the method, results are best interpreted relatively, focusing on how natural materials influence performance compared to controls. Six blocks per mixture were tested, and average values for compressive strength and stiffness are reported.

2.3.1.2. Three-point bending tests. For the three-point bending test, blocks were placed on a two-point support with a 200 mm span. A central load was applied in displacement control mode at 0.005 mm/s. To avoid damaging the blocks, no notching was performed. However, as for the comparative framework adopted, the test was useful to study variations in bending strength and fracture energy (work). The maximum bending stress (σ_f) in MPa was calculated as:



Fig. 2. Main steps of the production process of the CEBs involved in this study.

$$\sigma_f = \frac{3F_{max}L}{2bd^2} \quad (2)$$

where F_{max} is the peak load [N], L is the support span [mm], and b and d are the blocks' width and height [mm], respectively.

Fracture energy (W_f) [J] was determined from the force-displacement curve area up to the peak load using the trapezoidal integration method in MATLAB®. Blocks were inspected post-test to examine fracture planes, particularly for WS fibre presence. Three blocks per mixture were tested, and average values of maximum flexural strength and fracture energy were reported.

2.3.2. Microstructural investigations

Microstructural investigations were conducted to gain insights into the internal structure and to characterise the interactions of raw materials within the soil matrix. Both analyses were performed on raw materials and block samples (after mechanical testing) to compare patterns.

2.3.2.1. Infrared spectroscopy. Attenuated Total Reflectance-Fourier Transform Infrared (ATR-FTIR) spectroscopy measured the absorption of infrared radiation, revealing functional groups and chemical structures. An IRAffinity-1S SHIMADZU spectrophotometer (Kyoto, Japan) with an ATR diamond crystal accessory was used, performing 45 scans per sample with a spectral resolution of 16 cm^{-1} over a wave number range of $4000\text{--}400 \text{ cm}^{-1}$. Each analysis was repeated three times, and for clarity, only one representative pattern is shown.

2.3.2.2. Thermogravimetric analysis. Thermogravimetric Analysis (TGA) measured weight changes as a function of temperature to evaluate decomposition, oxidation, and thermal stability. An SDT Q600 V20.9 Build 20 instrument was used with a heating rate of $10.0 \text{ }^\circ\text{C}/\text{min}$ up to $1100.0 \text{ }^\circ\text{C}$. Samples weighing $20\text{--}30 \text{ mg}$ was analysed in triplicate for each block type and a representative pattern is shown.

2.3.3. Durability characterisation

2.3.3.1. Water absorption by capillarity. Capillarity coefficients were determined adapting test protocol from LNEC E 393 [40]. Oven-dried blocks were placed sideways in contact with a $5 \pm 1 \text{ mm}$ water layer. At intervals (0, 5, 10, 15, 30, 45 min, and 1, 1.5, 2, 3, 4, 5, 6, and 24 h), weight changes and water rise heights were recorded. The capillarity coefficient (c_b), in $\text{g}/\text{cm}^2\text{min}^{0.5}$, was calculated using:

$$c_b = \frac{m_1 - m_0}{A\sqrt{t}} \quad (3)$$

where m_0 is the dry block mass [g], m_1 is the mass after immersion [g], A is the contact area [cm^2], and t is the immersion time [min]. The angular coefficient of the straight line between 10-min and 5-h values, denoted as C_b , represents capillary absorption over time [41,42]. Three blocks per sample were tested.

2.3.3.2. Water absorption by total immersion. For total immersion testing, adapted from LNEC E 394 [43], oven-dried blocks were submerged in water at $20 \pm 3 \text{ }^\circ\text{C}$. Mass changes were used to calculate water absorption (W) as:

$$W = \frac{m_1 - m_0}{m_1 - m_2} \times 100 \quad (4)$$

where m_0 is the dry mass, m_1 is the wet mass in air, and m_2 is the hydrostatic mass of the wet specimen.

2.3.4. Non-destructive testing

2.3.4.1. Ultrasound pulse velocity. Adapting from NP EN 12504-4 [48], UPV measurements were taken using a Proceq PUNDIT Lab tester with a 54 kHz frequency [49,50]. Coupling gel was applied to eliminate air gaps at the interface with the transducers. To reduce interference from the environment, an XPS board was used to place the blocks while recording measurements. The UPV, in m/s , was calculated as:

$$UPV = \frac{L}{t} \quad (5)$$

where L is the distance between the transducers [mm], and t is the wave travel time [s]. Measurements were taken on the major length of the block, spanning 300 mm. Five readings were taken per sample.

2.3.4.2. Electrical resistivity. The electrical resistivity (ρ), in $\text{k}\Omega\text{cm}$, was measured at ambient temperature ($20 \pm 1 \text{ }^\circ\text{C}$), on water-saturated blocks using a ResipodProceq device with 38 mm distance among the electrodes. Five readings were taken per sample.

3. Results and discussion

3.1. Mechanical properties

3.1.1. Compressive strength and stiffness

The stress-strain curves in Fig. 3 illustrate the results of compression tests for (a) control sample blocks (REF), (b) blocks with 1v.% CGs (CG1), (c) blocks with 3v.% CGs (CG3), (d) blocks with 5v.% CGs (CG5), (e) blocks with 5v.% WS (WS5), (f) blocks with 10v.% WS (WS10), (g) blocks with 15v.% WS (WS15).

The stress-strain curves of the reference blocks (REF) exhibit near-linear elastic behaviour, with minimal initial deformations attributed to settlements (Fig. 3(a)). In WS-blocks, the initial deformations are more pronounced, and the stresses achieved generally surpass those of the REF blocks (Fig. 3(b–d)). Conversely, CG-blocks display significantly higher deformations, characterised by a more nonlinear, plastic behaviour with distinct patterns at low and high strain levels (Fig. 3(e–g)). Despite these differences, the stress levels in CG-blocks remain comparable to that of the control sample REF. Overall, increasing natural by-products content leads to a progressive reduction in stiffness and peak strength.

Fig. 4 presents the average (a) peak compressive strength, and (b) tangent stiffness (apparent elastic modulus) for each batch of CEBs tested.

The addition of WS enhances the compressive strength of the blocks at all concentrations compared to the REF sample (2 MPa) and the stiffness up to WS10. However, the most notable improvement occurs for WS5 (5v.% WS addition), with the strength increasing to 2.4 MPa (16.7%) and the stiffness to 49.6 MPa (7.4%). Further increases in WS content reduce the reinforcement effect. In contrast, CG-blocks demonstrate either similar or reduced compressive strength and stiffness compared to the control. At 1v.% CGs (CG1), the strength remains nearly unchanged (2.1 MPa, ~1 % increase). Higher concentrations of CG lead to a progressive degradation of mechanical properties: in the case of the CG5 mixture, 5% less strength and 21% less stiffness. These results indicate that while WS effectively improves compressive strength and stiffness, CG negatively impacts these properties and is better suited as a filler material,

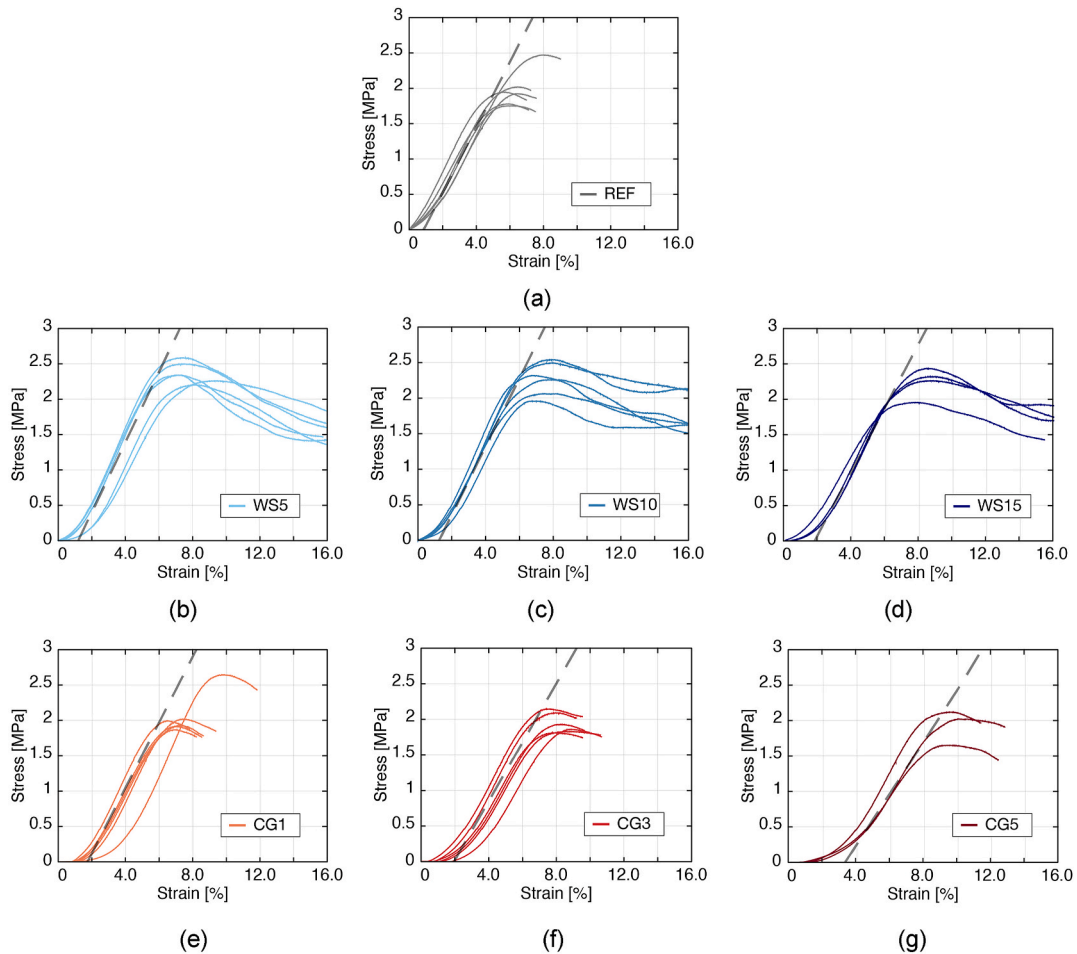


Fig. 3. Stress-strain curves derived from compression tests.

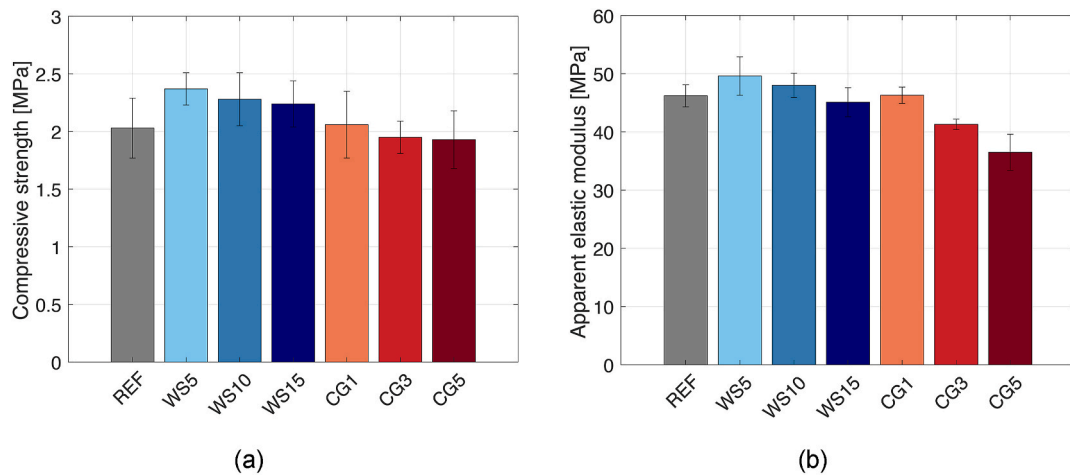


Fig. 4. Compression test results: (a) compressive strength at the peak, and (b) tangent stiffness.

and in limited quantities.

In relation to damage and failure modes, most blocks showed vertical fractures along the load axis, often preceded by thin cracks on the upper and lower surfaces (Fig. 5(a–c), REF, WS5, and CG3 blocks' specimen respectively). In some cases, diagonal shear planes formed, indicating an internal imbalance in stress distribution. These mechanisms are usually followed by edge crushing and disintegration (Fig. 5(d) and (e), WS-blocks details) or fragmentation (Fig. 5(f) and (g), CG-blocks details). Blocks containing the highest WS content showed a more gradual failure, suggesting that fibres helped to fill the cracks and delay total disintegration (Fig. 5(h), WS15 blocks at the end of the test). In contrast, blocks with no or low natural material content showed a more sudden failure.

3.1.2. Flexural strength and fracture energy

The force-displacement curves in Fig. 6 illustrate the results of the three-point bending tests for (a) REF, (b) CG1, (c) CG3, (d) CG5, (e) WS5, (f) WS10, and (g) WS15.

The curves highlight the peak load (black dot), and the segment (identified by the thickest portion of the lines) used to calculate the fracture energy up to failure. The flat initial portion observed in some curves, where displacement increases at low loads, arises from adjustments of the specimen on the load supports. This behaviour is attributed to imperfections in the blocks, such as gaps and misalignments.

The curves exhibit quasi-brittle behaviour with no plastic deformation. The recorded force-displacement responses are predominantly associated with crack propagation and fracture. Compared to the control sample REF (Fig. 6(a)), the inclusion of WS increases the load-bearing capacity and toughness, particularly in the WS5 and WS10 cases (Fig. 6(b) and (c)). For WS15 (Fig. 6(d)), higher

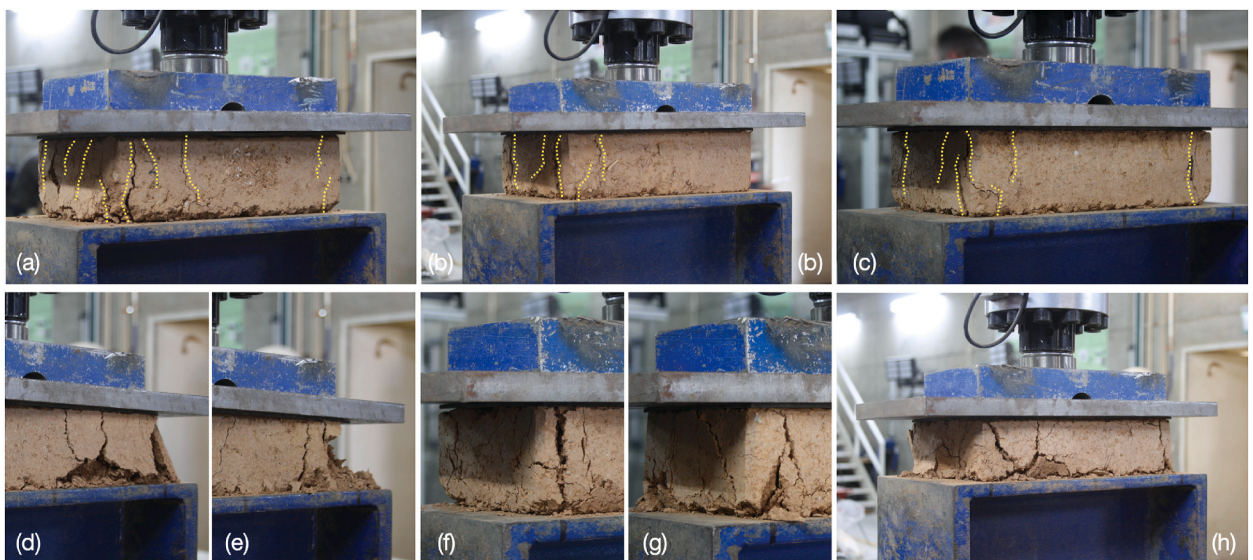


Fig. 5. Damage patterns and failure modes of CEBs subjected to compression tests.

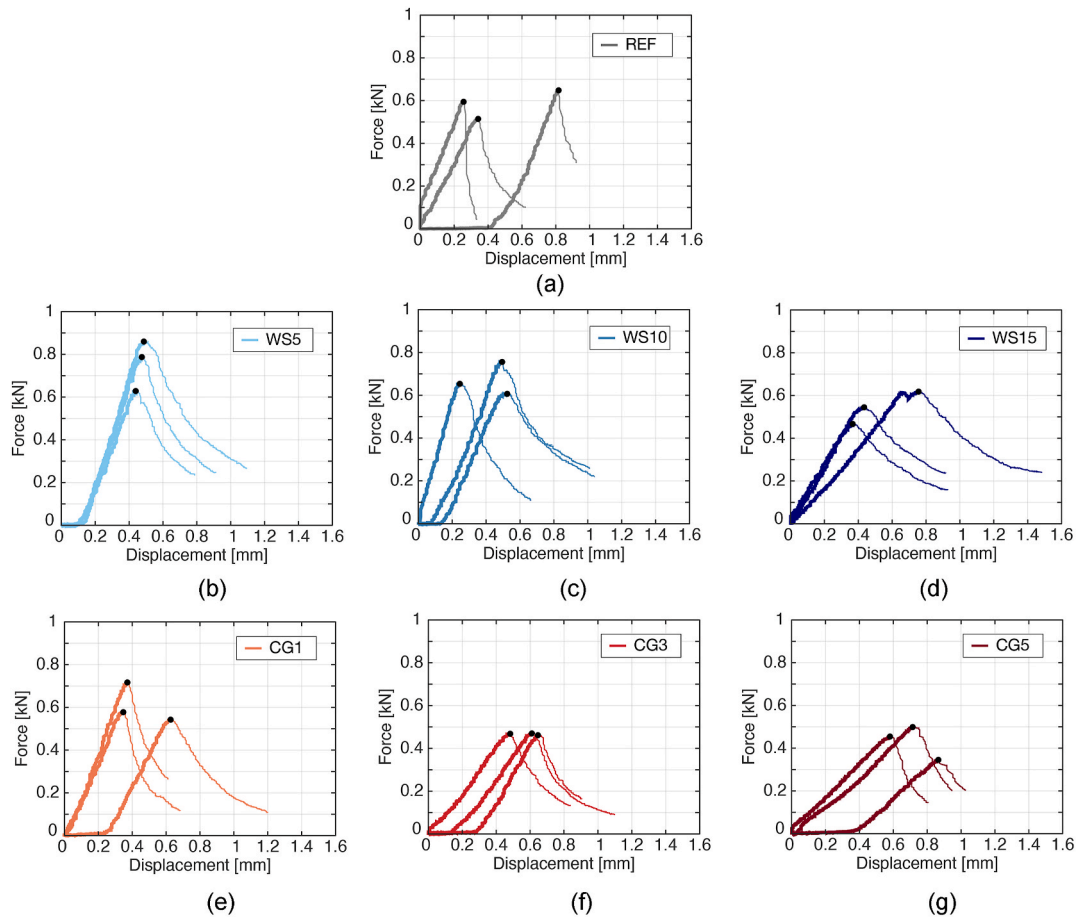


Fig. 6. Stress-strain curves derived from three-point bending tests.

deformations occur at lower loads. The double-hump feature in one of these curves is ascribed to the fibres' role in resisting fracture. While the CGs do not enhance toughness, the curves show higher residual strength compared to the control REF-blocks. In terms of toughness, the curves of CG1 (Fig. 6(e)) resemble the control sample; CG3 and CG5 (Fig. 6(f) and (g)) show more elastic behaviour. Overall, the results suggest that the presence of both natural materials influence post-fracture behaviour by improving ductility and energy dissipation, consistent with prior studies [21,52].

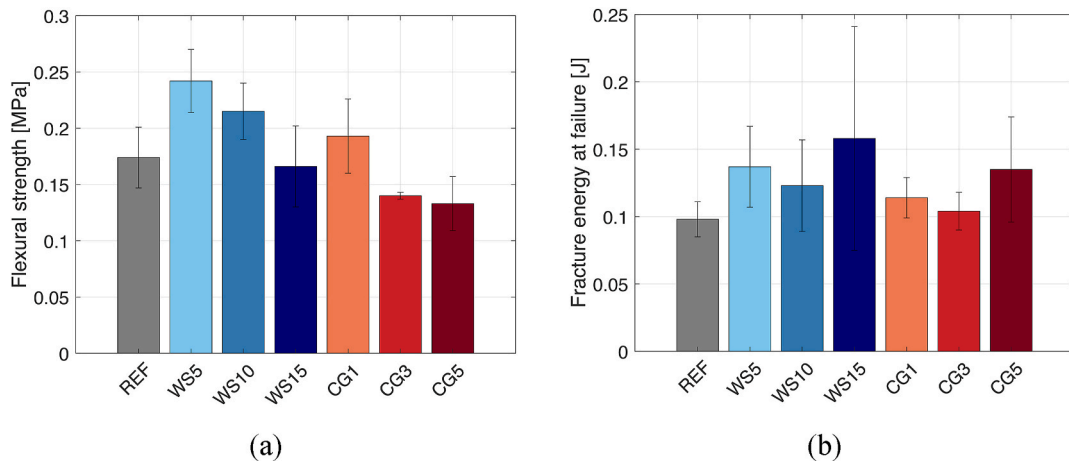


Fig. 7. Three-point bending test results: (a) flexural strength at the peak, and (b) fracture energy at failure.

Fig. 7 presents the average flexural strength and fracture energy at failure for each batch of CEB tested.

The control sample REF blocks exhibited a peak flexural strength of 0.174 MPa (Fig. 7(a)). Adding 5 and 10v.% WS increases this strength by 39% (0.242 MPa) and 23.7% (0.215 MPa), respectively. However, at 15v.% WS, the strength decreases by 4.5%, indicating a threshold where excess fibre content negatively affects the material. For CGs, the inclusion of 1v.% granules result in an 11% increase in flexural strength (0.193 MPa), but higher concentrations lead to reductions of 19.5% and 23.4%, with strength dropping to 0.133 MPa.

Fig. 7(b) shows that all blocks with natural materials exhibit higher fracture energy than the control sample. The bending behaviour of the analysed CEBs changes with the addition of WS and CG, as discussed earlier. For WS, up to a 10v.% content, the blocks demonstrate increased strength and toughness. Beyond this threshold, higher fibre percentages increase ductility, allowing for greater displacement. Though the absence of notching may have slightly overestimated the fracture energy, the presence of WS still influences the work required to propagate cracks and cause failure. Despite this, the low fibre content prevents true plastic deformation or ductility. Short fibres like straw, with a low aspect ratio (35–60), primarily enhance stiffness and toughness at low concentrations [53].

Bouhicha et al. [54] highlighted that, in earthen blocks, straw reduces shrinkage, shortens curing time, and improves compressive strength when used at optimal reinforcement ratios. However, studies suggest that an ideal fibres amount threshold exist, beyond which the benefits associated with their presence diminish due to accumulation and overlap [21]. While fibres improve ductility, if overload occurs, they may lead to excessive deformations deemed unacceptable for practical applications.

Fig. 8 shows an example of a three-point bending test on a block from the WS10 batch. The images include (a) the test setup, (b) the broken sample after testing, and (c) a detail of the perpendicular orientation of fibres to the fracture plane [54].

In contrast to WS, CG incorporation at concentrations > 1v.% reduces the blocks' strength and stiffness. The addition of CGs increases deformability at lower loads, justifying the high fracture energy observed in the CG5 batch. However, the granules do not provide any strengthening effect.

3.1.3. Microstructural insights

3.1.3.1. Infrared spectroscopy. Microstructural investigations performed on samples taken from the tested blocks provide information on the characteristics of the materials present and the nature of the bonds. Fig. 9 shows the results of the infrared spectroscopy.

Fig. 9(a) shows the ATR-FTIR spectra of the raw materials providing insights into the structures present. The soil spectrum shows peaks in the 3700–3400 cm^{-1} range, attributed to O–H stretching in clay hydroxyl groups, and in the 1100–1000 cm^{-1} range, corresponding to Si–O and Al–O stretching in aluminosilicates (e.g., kaolinite and other clay minerals) [55]. Peaks in the 2500–2000 cm^{-1} region suggest the presence of nitrile impurities ($\text{C} \equiv \text{N}$) [56]. The NHL spectrum is dominated by a peak near 1410 cm^{-1} , indicative of carbonate ions (CO_3^{2-}), with additional peaks at 871.82 and 709.80 cm^{-1} associated with calcite (CaCO_3) [57]. O–H stretching peaks in the 3700–3400 cm^{-1} range are also observed, likely due to clays and impurities naturally present in hydraulic lime. The WS spectrum features a broad peak around 3340 cm^{-1} , attributed to O–H stretching in cellulose and hemicellulose, and another peak at 1035 cm^{-1} corresponding to C–O stretching in cellulose [58,59]. The CGs spectrum exhibits a broad peak between 3410 and 3460 cm^{-1} , attributed to O–H stretching in lignin, alongside bands at 2919 and 2852 cm^{-1} , indicative of C–H stretching in CH_2 groups [60,61]. Additional bands confirm the presence of suberin, lignin, and polysaccharides [61].

The block spectra (Fig. 9(b)) are characterised by prominent peaks in the 1100–900 cm^{-1} range, corresponding to the hydration products of calcium silicate (C–S–H) and aluminate (C–A–H) phases derived from the NHL used to stabilise the soil [55,62]. Additionally, peaks near 1420 cm^{-1} indicate the presence of carbonates [62,63], formed as a secondary product from the carbonation of residual free lime.

3.1.3.2. Thermogravimetric analysis. Fig. 10 shows the results of the TGA.

Fig. 10(a) shows the TGA of the raw materials. The soil thermogram shows mass losses near 300°C, attributed to the decomposition of organic matter, at 470°C and above 800°C attributed to the decomposition of clay minerals compatible with those detected by XRD (muscovite and clinocllore) [64]. The NHL thermogram displays two characteristic peaks: one near 410°C, corresponding to the dehydroxylation of calcium hydroxide, and another around 760°C, attributed to the decomposition of calcite [65]. The thermograms of WS and CGs show mass losses near 300°C attributable to the decomposition of hemicellulose and cellulose. Beyond 400°C, more evident in the thermogram of cork, the loss is attributed to the decomposition of more stable aromatic structures such as lignin and



Fig. 8. Three-point bending test on a WS10 block.

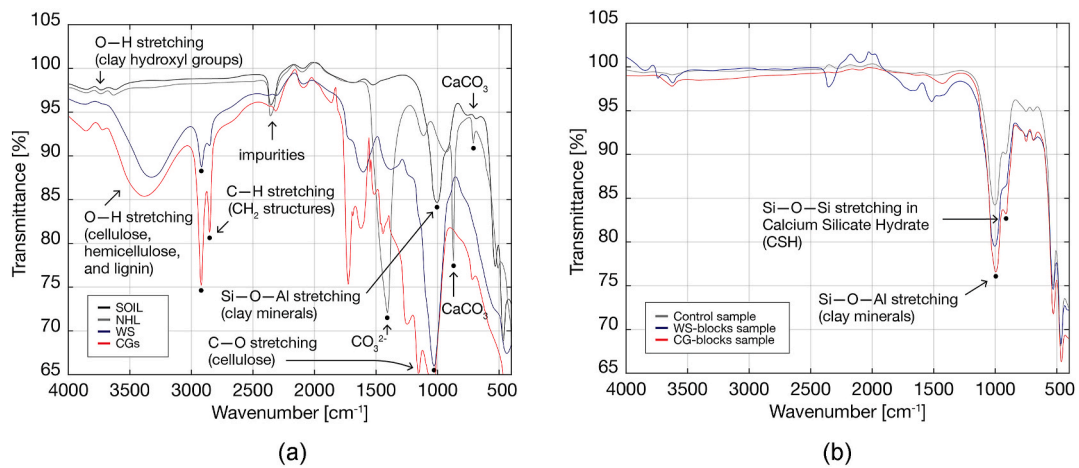


Fig. 9. ATR-FTIR spectra of (a) raw materials, and (b) blocks.

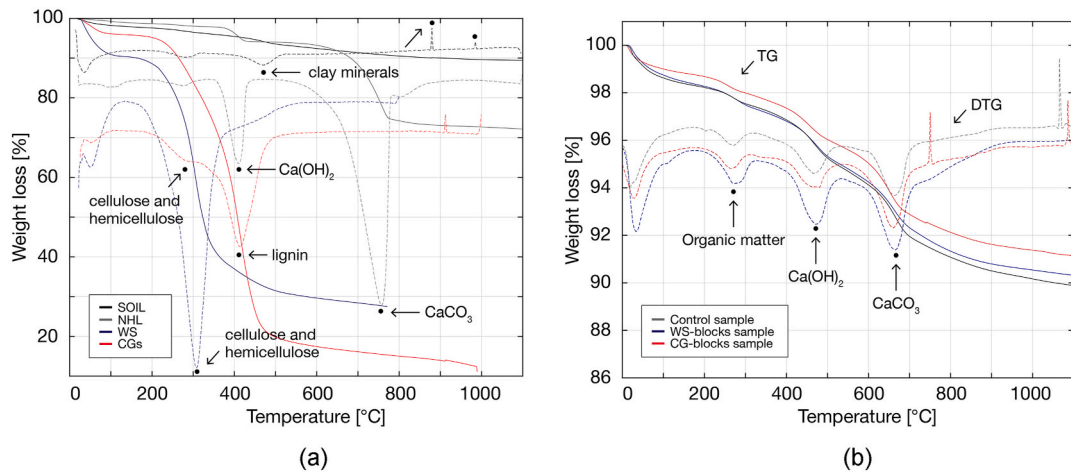


Fig. 10. Thermograms of CEBs incorporating natural materials. The solid line indicates the thermogravimetric curve; the dashed line is the first derivative.

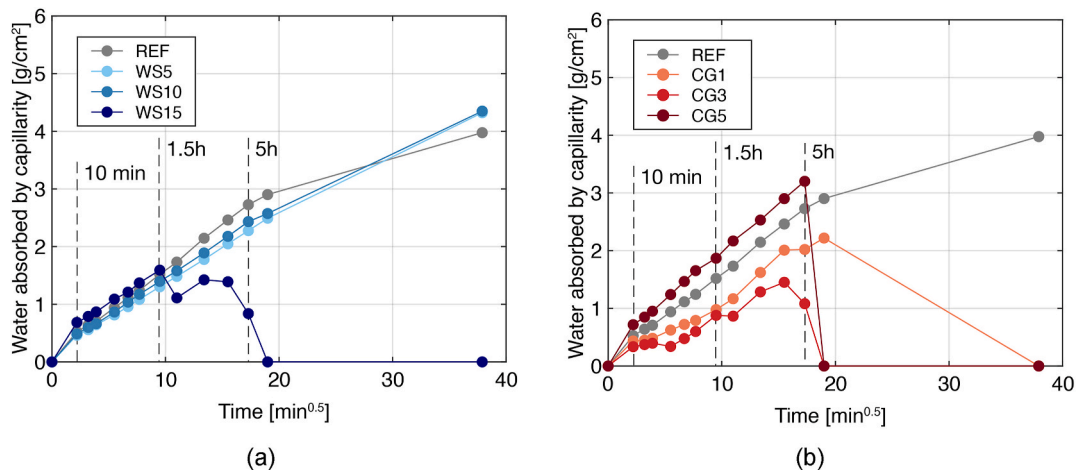


Fig. 11. Capillarity curves: (a) WS-blocks, and (b) CG-blocks.

suberin [66,67].

The TGA conducted on block samples (Fig. 10(b)) from the three batches reveals a consistent pattern with four main mass loss events. Analysis of the first derivative curves identifies events as follows: peaks below 150°C correspond to the loss of water; peaks near 280°C are attributed to the decomposition of organic matter; peaks around 470°C are associated with the dehydroxylation of $\text{Ca}(\text{OH})_2$; and peaks above 600°C indicate the decomposition of CaCO_3 [68,69]. These results reflect the interaction between the soil and lime, with no significant microstructural interference observed from the presence of natural materials.

3.2. Durability properties

3.2.1. Capillarity coefficient

Fig. 11 presents the results of the capillarity test.

The curves illustrate the water absorption behaviour of the CEBs over 24 h, with Fig. 11(a) showing data for WS-blocks and Fig. 11(b) for CG-blocks. In all mixtures, the initial water absorption rate is higher during the initial 10 min, indicated by the steep slope of the initial segment [70]. After this period, the absorption rate decreased, resulting in a gentler slope in subsequent segments.

All blocks withstood water contact for up to 5 h, after which severe deterioration occurred, and measurements were discontinued. Notably, only the REF-blocks and those containing 5v.% and 10v.% WS resisted until the end of the test and showed capillary water rise with linear trend. In contrast, for WS15, two out of three blocks failed after 1.5 and 3 h, confirming the detrimental effect of fibre overloading already observed for the mechanical characterisation, compounded by the hydrophilic nature of the fibres [71].

For CG-blocks, although the CG1 and CG3 mixtures exhibited lower absorption rates compared to the other CG batches, the curves displayed pronounced non-linear behaviour. Measurements for CG1 extended up to 6 h, while for the other CG-blocks, testing was discontinued after 4–5 h. The behaviour of CG-blocks in contact with water proved challenging due to the combined influence of cork's inherent hydrophobicity and the disrupted soil matrix structure caused by the heterogeneity at the soil-cork interface [72].

At low concentrations, the earthen matrix benefits from the presence of WS and CGs in improving the pore network. The reduction in pore connectivity and surface wettability at low additive levels delays the onset and rate of water absorption. At higher dosages, however, the opposite may occur, with more open porosity and poor cohesion, which can increase water absorption.

3.2.2. Water absorption by total immersion

The results of the total immersion water absorption test are shown in Fig. 12.

Compared to the control sample, blocks WS5 and WS10 absorbed 3.8% and 11.2% more water, respectively. For WS15, one block failed within a few minutes, while the remaining two exhibited water absorption increases of 6% and 20% after 15 min, resulting in a high coefficient of variation (74.6%). Conversely, the CG1 and CG3 mixtures absorbed significantly less water, with reductions of 80.7% and 64%, respectively. In the case of CG5, only one block remained intact after 15 min, precluding the calculation of a standard deviation.

The water absorption mechanisms observed differ between WS- and CG-blocks. WS fibres act as pathways for water to infiltrate the soil matrix, thereby facilitating absorption. The results suggest that low fibre concentrations enhance block strength without significantly affecting water absorption, while higher concentrations may lead to adverse effects. In contrast, CGs reduce water absorption due to their granular structure and intrinsic hydrophobicity [72]. However, exceeding the threshold concentration of CGs (3v.%) appears to induce internal micro-cracks, which enable water ingress and compromise block integrity. Blocks incorporating CGs demonstrated inconsistent and unpredictable responses to water exposure, indicating they are unsuitable for prolonged water contact. These findings also underscore the limitations of this testing method, which is overly severe for unstabilised [73,74] or moderately

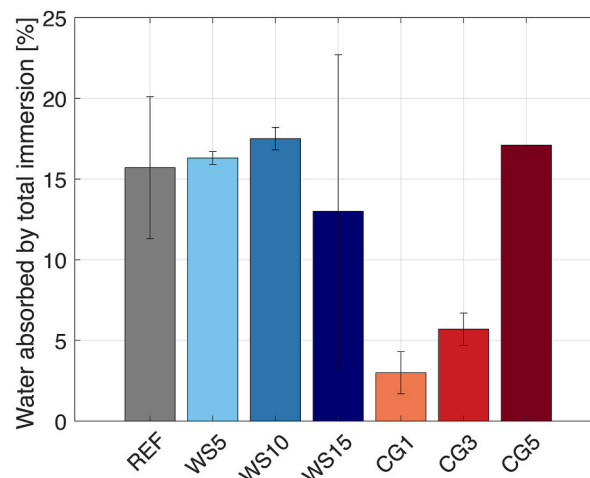


Fig. 12. Percentage of water absorption after 15 min of total immersion.

stabilised CEBs, as is the case of this study. The method is best suited, at best, on cement-stabilised blocks, as shown by the more consistent results reported in Ref. [75].

3.3. Non-destructive testing

3.3.1. Ultrasound pulse velocity

The ultrasonic pulse velocity (UPV) test consists of measuring the velocity of longitudinal stress waves transmitted through a material. In denser and more cohesive materials, the wave front propagates more quickly due to greater rigidity and better bonding at the microstructural level [44–47]. This makes UPV a commonly used surrogate for compressive strength and stiffness in cementitious composites.

Fig. 13 illustrates the UPV measured on the CEBs before the compression tests, and its relationship with their results.

The control and WS-blocks show wave velocities within a narrow range (1100–1200 m/s), while CG-blocks exhibited slower wave propagation, dropping to 780 m/s (Fig. 13(a)). As the speed of ultrasonic waves, propagating through the medium via mechanical vibrations, depends on the elastic properties and density of the material, the presence of voids, cracks, and other imperfections can scatter or attenuate the waves, thereby affecting their speed or amplitude.

A moderate positive correlation was observed between UPV and compressive strength, with a coefficient of determination $R^2 = 0.64$, while a stronger correlation ($R^2 = 0.96$) was observed with the tangent stiffness (Fig. 13(b)). These correlations suggest that the relationship between variables is influenced by internal heterogeneity introduced by natural aggregates, including variations in density, elasticity, and microcracks. Discontinuities affecting UPV measurements as well as mechanical integrity.

The lower UPV of the CG-blocks, particularly for CG5, combined with a high coefficient of variation (37.3%), indicates an underlying discomfort in the blocks tested [76]. Concentrations exceeding 5v.% led to blocks with poor cohesion, often crumbling immediately after fabrication, as observed in Ref. [22]. Therefore, 5v.% represents the upper limit. However, to ensure quality and safety, 3v.% is recommended. In contrast, WS-blocks exhibited more consistent UPV values and maintained structural integrity, aligning with literature data [46,47]. Overall, UPV proved to be a quick and cost-effective tool for assessing the quality and integrity of CEBs, particularly when soil remains the dominant component in the mix.

3.3.2. Electrical resistivity

The electrical resistivity test quantifies the material's opposition to ionic conduction. In concrete, resistivity is mainly controlled by porosity, pore connectivity, moisture content and degree of saturation [51]. It is therefore used as an indicator of durability, especially in relation to moisture ingress and permeability. In the case of CEBs, studies have found a correlation with capillary rise [46], thus it was measured to get additional insights into water absorption and porous structure.

Fig. 14 presents the electrical resistivity measured on water-saturated blocks after the capillarity tests, and its relationship with their results.

Recorded values fall between 1.4 and 1.8 kΩcm (Fig. 14(a)). These data are consistent with typical ranges reported in the literature for similar materials under saturated conditions [77]. In saturated media, electrical conduction occurs mainly through ions dissolved in the fluid filling the pores. In this study, tap water. With due approximation, from a theoretical point of view, according to Archie's law [78], for the same degree of saturation and resistivity of the pore-filling fluid, electrical resistivity is directly proportional to tortuosity and porosity. Both tortuosity and porosity, however, are difficult to quantify accurately in these materials due to the complex composition and heterogeneity.

A very strong correlation was observed between resistivity and the capillarity coefficient, with a coefficient of determination $R^2 = 0.90$ (Fig. 9(b)). Blocks with the highest resistivity, such as CG3, corresponded to the lowest water absorption rates, while those with the lowest resistivity, such as CG5, absorbed water more readily. This strong correlation reinforces the hypothesis that resistivity can provide information on durability performance (water absorption properties) within heterogeneous media. Although further studies are needed to confirm these preliminary results, these findings provide insight into the porous structure of complex materials with difficult-to-predict properties, such as those analysed in this study.

3.3.3. Statistical correlation analysis

To quantify interdependencies across macro-scale properties, a Pearson correlation matrix was constructed for the five core parameters: UPV, compressive strength, tangent stiffness, electrical resistivity, and capillarity coefficient. The results are presented in the heatmap of Fig. 15.

The heatmap visually confirms the results presented above, with dark red indicating strong positive correlation (e.g., UPV–stiffness) and deep blue signifying strong inverse relationships (e.g., resistivity–capillarity). These dependencies emphasise the diagnostic and predictive power of NDT techniques and validate their use in evaluating the mechanical behaviour and durability-related pore structure and moisture transport phenomena in CEBs incorporating natural materials.

Table 3 synthesise the coefficients of determination, Pearson and Spearman defining the relation between key variables.

UPV, while moderately reliable for estimating strength, more accurately reflects stiffness-related elastic behaviour. Electrical resistivity shows strong inverse dependency with capillary absorption and offers a reliable indicator of pore continuity and permeability. These findings highlight the potential for integrating UPV and resistivity into quality control protocols and durability assessments in heterogeneous systems, such as those studied.

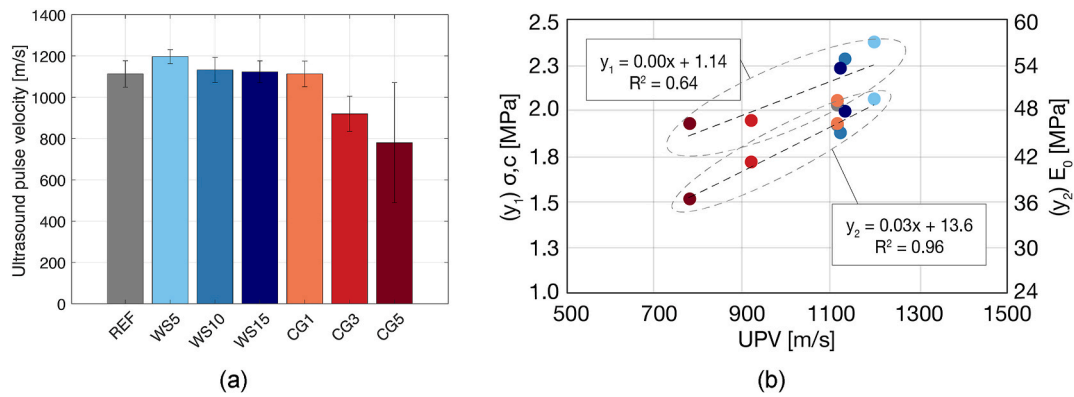


Fig. 13. Ultrasound pulse velocity: (a) UPV measurements on the batches tested, and (b) relationship between UPV, compressive strength and tangent stiffness.

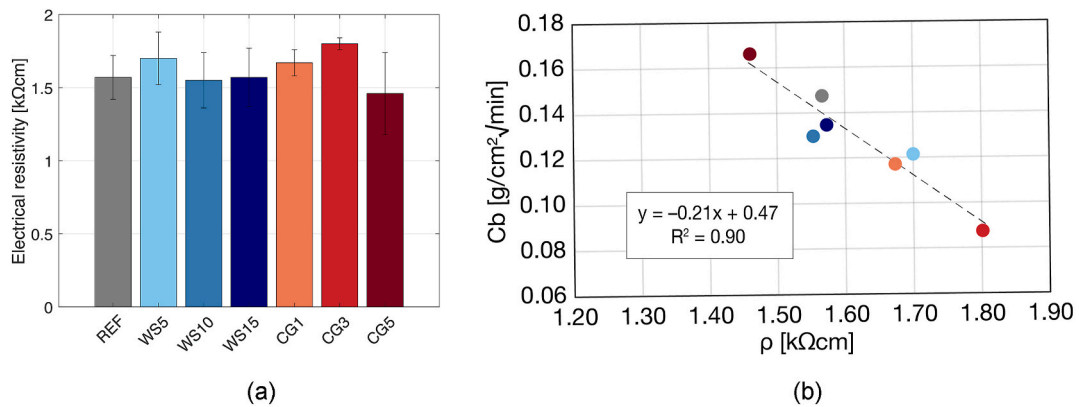


Fig. 14. Electrical resistivity: (a) measurements on the batches tested, and (b) relationship with capillarity coefficients.

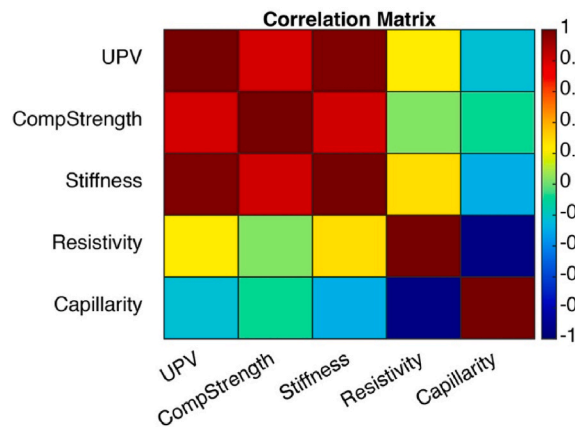


Fig. 15. Heat map of Pearson correlation matrix.

4. Conclusions

This paper presents the results of an experimental campaign on compressed earth blocks (CEBs) incorporating natural materials produced by a Portuguese company. These are wheat straw (WS) and cork granules (CGs), two agro-industrial by-products sourced from the local production context. The presence of these materials served to reduce the high density and thermal conductivity of the blocks [20], but the implications for mechanical properties and durability remain poorly explored and inconsistent.

Table 3Coefficient of determination (R^2), Pearson (R), and Spearman (p-value) among key parameters.

Parameter Pair	R^2	R	p-value
UPV – Compressive strength	0.64	0.80	0.031
UPV – Tangent stiffness	0.96	0.98	0
Electrical resistivity – Capillarity coefficient	0.90	−0.95	0.001

For the study, CEBs made with natural materials in various proportions were characterised through mechanical tests (compression and bending), durability tests (water absorption by capillarity and total immersion), non-destructive tests (ultrasound pulse velocity and electrical resistivity), and microstructural analyses (infrared spectroscopy and thermogravimetric analysis). The results demonstrated that:

- WS can enhance mechanical performance and reduce water vulnerability if incorporated within optimal thresholds. The best results were obtained with a WS content of 5% by volume (v.%), which improved compressive strength, flexural strength, and fracture energy while maintaining acceptable water absorption levels. However, increasing WS content beyond this threshold led to a progressive decline in these properties.
- Conversely, the incorporation of CGs reduced both compressive and flexural strength while slightly increasing fracture energy. The blocks exhibited non-linear behaviour in capillarity tests and unreliable performance under immersion, indicating that they are unsuitable for prolonged water exposure.
- Non-destructive testing (NDT) results aligned with mechanical and durability trends. Higher WS or CGs content correlated with lower UPV values, suggesting increased internal micro-cracking or reduced material homogeneity due to excessive lignocellulosic material (overload). Electrical resistivity, on the other hand, showed a strong inverse correlation with capillarity coefficients, with higher resistivity values observed in blocks that absorbed less water.
- Microstructural observations confirmed no interference in the earth-lime matrix from the presence of natural materials.
- Recommendations: In terms of thermal performance, previous investigations indicated that a low WS amount (5v.%) has a negligible impact on the thermal conductivity [22]. Though, given the low aspect ratio of WS fibres, a minimal yet controlled concentration can improve the overall integrity of CEBs, making 5v.% the recommended dosage for quality improvement. In the case of CGs instead, a 19.5% reduction in thermal conductivity was obtained for 5v.%. Based on these findings, the incorporation of CGs is recommended for indoor applications, with an optimal dosage of 3v.% and an upper limit of 5v.%.

Overall, the experimental results confirm the viability of this approach, provided the optimal material thresholds are maintained. Findings from this study are particularly relevant given the uncertainties associated with using waste and by-products in construction materials. Agro-industrial waste and by-products often lack standardisation and exhibit variability depending on local production processes. The possibility of performing rapid, systematic quality control using NDT represents a significant step toward increasing confidence in bio-based building solutions at an industrial scale.

CEBs offer a valid alternative to conventional masonry materials, particularly for interior partition walls, where vulnerability to water is less critical. From a broader perspective, the development of such solutions is of paramount importance in addressing the challenge of making earthen building materials more suitable to meet modern building standards, while addressing challenges such as reducing waste disposal and conserving natural resources. By involving local suppliers and contractors, utilising regional resources and leveraging traditional techniques, this study also supports promoting more sustainable and low-carbon building practices.

Future studies should quantify the potential environmental and economic impact of using agro-industrial waste and by-products in a life cycle assessment perspective. In particular, the avoided environmental burden related to the use of residues, waste, by-products or co-products in construction remains an open question.

CRediT authorship contribution statement

Chiara Turco: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Marta O. Teixeira:** Investigation. **Elisabete Teixeira:** Writing – review & editing, Supervision, Methodology, Investigation, Conceptualization. **Ricardo Mateus:** Writing – review & editing, Supervision, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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