Exploration of Thermal and Structural Performance of Bio-Stabilised Cob Mixes

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Abstract. This study evaluates bio-stabilised cob's structural and thermal performance for sustainable buildings. Thirty-three cob mixes were analysed: subsoil, water, and natural fibres—hemp shiv and barley straw—with fibre contents ranging from 1% to 10% and water contents ranging from 20% to 30% by volume. Unstabilised samples of subsoil and water served as baselines.

X-ray diffraction revealed the subsoil contained 70% quartz, while the fibres were predominantly cellulose. Scanning electron microscopy showed the subsoil had a compact structure with 20% porosity, whereas hemp shiv and barley straw were more porous, with 30% and 43%, respectively.

Adding fibres significantly reduced thermal conductivity compared to unstabilised mixes. The lowest thermal conductivity was 0.132 W/m·K for a mix with 7% barley straw and 30% water, while the highest was 0.378 W/m·K for the unstabilised mix with 20% water. Higher densities correlated with higher thermal conductivity.

Compressive strength decreased with increased fibre content, with hemp shiv causing a smaller reduction than barley straw. The highest compressive strength was 1.719 MPa for a mix with 5% hemp shiv and 25% water; the lowest was 0.785 MPa for a mix with 7% barley straw and 25% water. Volumetric shrinkage increased with higher fibre and lower water contents.

The mix with 3% hemp shiv and 30% water content demonstrated optimal performance: thermal conductivity of 0.163 W/m·K, compressive strength of 1.454 MPa, density of 1,676 kg/m³, and volumetric shrinkage of 16.4%.

This research highlights the importance of analysing cob's constituents to optimise its properties, supporting cob's potential as a sustainable construction material for decarbonising the built environment.

Keywords: Earthen materials, cob, bio-based, thermal performance, structural integrity.

1 Introduction

The International Energy Agency (IEA) 'Tracking Clean Energy Progress' 2023 report reported that buildings contributed to 34% of global energy demand and 37% of global emissions [1]. Research indicates that approximately 60% of the materials used in building construction consist of concrete, and concrete waste accounts for 42% of the total waste generated by the construction industry [2]. These figures significantly impact climate change and global warming. Therefore, adopting more eco-friendly materials and construction methods that reduce energy usage and carbon emissions is essential.

Earthen materials are demonstrated to have evidential proof to offer the basis of a more sustainable, circular, and resilient built environment that is adapted to mitigate the projected impact of climate change and global warming [3-5]. This is attributed to earthen materials' hygrothermal and environmental benefits which lower operational energy consumption, maintaining user comfort [5], their capacity to absorb carbon dioxide [3], and their minimal environmental impact [6-8].

This research focuses on cob construction, a classified wet method of earthen construction. While some research has explored key structural and hygrothermal properties of cob as a building material [9-15], previous research has highlighted some gaps in the exploration of the material and the impact of cob's constituents on its overall performance [16, 17].

Initially, the research studies the different constituents of cob, such as hemp shiv, barley straw, and subsoil. Then, after analysing the results and previous literature, it explores cob at the material level. This is performed systematically by proposing different cob mixes and testing their structural and thermal properties to identify the best-performing cob mixes.

2 Literature Review

Exploring existing literature and identifying gaps was crucial to developing the cob mixes for testing. Accordingly, this section discusses the key insights from the literature on the constituents of cob and the design of cob mixes, the thermal performance of cob, and the structural performance of the material. Previously published research detailed the systematic literature review on cob and its performance [16-18].

2.1 Cob Constituents and Mix Design

Cob Constituents
Cob is a natural construction material made mainly from soil, water, and plant-based fibrous additives. Recently, the material has been investigated due to its environmentally friendly attributes and its potential as a structural element, with research increasingly focusing on its thermal and environmental performance [9-13, 18]. The subsoil typically utilised in cob mixtures contains around 15–25% clay and 75–85% aggregate or sand, derived from loam, clay, silt, or clayey-silt textures [19, 20]. Such well-graded soils enhance the density and strength of cob, while topsoil, which decomposes quickly and weakens the wall structurally, is generally deemed unsuitable [19]. The careful selection of subsoil ensures improved durability and mechanical performance.

Beyond soil selection, the water content and initial moisture level are paramount in achieving cob mixtures' desired strength and workability [20, 21]. Reinforcement with fibrous materials has also been recognised to provide multiple benefits, including reduced cracking, accelerated drying, improved cohesion, and enhanced weathering resistance. [21-25]Various fibres, from cereal straw and wood aggregates to bast fibres, leaf fibres, aquatic plants, and wool, have been explored in cob construction. Their thermal properties and influence on mechanical behaviour vary depending on their type and proportion [26].

Mix Design

The overall mix design of cob construction materials involves carefully balancing the proportions of soil, water, and fibres to achieve desired mechanical and thermal characteristics. Although most studies have focused on optimising structural integrity, there has also been growing interest in improving hygrothermal properties [5, 7, 9, 12, 15, 19, 22]. Each constituent's ratio can be adjusted according to specific performance targets, such as increased load-bearing capacity [15], better insulation [10, 13], or suitability for emerging construction methods like 3D printing [27].

A critical aspect of this design lies in selecting and preparing the subsoil and any supplementary additives. The subsoil commonly includes a blend of clay, silt, and sand, with clay percentages ranging from around 15–25% and the remainder composed of sand and aggregates [13, 22, 27]. Some mixtures incorporate a small fraction of gravel or introduce stabilisers like lime or cement to improve durability and handling. This is particularly important when creating more uniform or extrudable mixtures for advanced manufacturing techniques [20, 27]. Adjusting these inorganic components allows for fine-tuning compressive strength, shrinkage resistance, and overall density.

The initial water content is also significant, influencing workability and final performance. Mixtures designed primarily for structural purposes may have initial water contents ranging from 19% to 40%, while those aiming to enhance hygrothermal efficiency can surpass 60% [12, 13]. For applications involving 3D printing, precise control of water concentration is critical, with some mixtures optimised at around 22–28% to maintain suitable viscosity and extrudability without compromising final mechanical stability [27].

Nonetheless, fibre content ratios and fibre types significantly influence the structural, hygrothermal, and environmental performance. Research has identified various fiber types, and aggregates such as coconut coir, hemp shives, reeds, and straw have been added to cob mixes to improve their performance [10, 12, 13, 23, 28]. Fibre content in cob mixtures typically ranges from 0.6% to 3% for instance, Alassaad et al. used 2.5% flax straw by dry soil mass [28]. Meanwhile, in a study by Ben-Alon et al., the data inventory for a Life Cycle Analysis (LCA) discussed a soil/fibre proportional factor of 0.039, achieved by adding 10.1 kg of wheat straw to 256 kg of clay-rich soil. [4]. Goodhew et al. explored higher fibre proportions to optimise cob for improved thermal insulation [10]. Zeghari et al. developed eight structural mixes using hemp, flax, wheat straw, and reed, along with two additional mixes for insulation using hemp shiv and reed [12]. Fibre lengths across reviewed studies ranged from 20 mm to 300 mm, with shorter fibres proving more effective for achieving a homogeneous cob mix.

2.2 Thermal Performance of Cob

The thermal conductivity of cob has been evaluated across numerous studies as a key indicator of the overall thermal performance of the material, each highlighting the impact of material composition, density, and aggregate type. Tchiotsop et al. investigated the effects of plant-based aggregates on cob's thermal conductivity, finding values ranging from 0.12 W/m.K to 1.06 W/m.K depending on the mix design [12]. Mixtures with lightweight aggregates, such as hemp shives and straw, consistently showed lower thermal conductivity, indicating superior insulation properties. For example, mixtures incorporating 3% hemp shives significantly reduced thermal conductivity compared to denser cob formulations [12].

Zeghari et al. highlighted the role of fibre and aggregate type in enhancing cob's insulation properties. Their findings demonstrated that cob walls intended for structural use had higher thermal conductivity due to their denser composition. In contrast, walls explicitly designed for insulation exhibited significantly lower values, achieving superior thermal regulation [16]. This research supports using composite materials like straw or hemp to reduce thermal conductivity, enhancing cob's application as an energy-efficient building material.

Additionally, studies by Goodhew et al. focused on integrating higher fibre content into cob and light earth dual walls to improve insulation. Increasing fibre proportions further reduced thermal conductivity, reinforcing cob's suitability for passive temperature regulation in buildings [14].

The relationship between cob density and thermal conductivity is a key determinant of its performance as a construction material. Research consistently demonstrates that lower-density cob mixtures exhibit improved insulation due to reduced thermal conductivity. For instance, Zeghari et al. reported that cob mixtures designed for insulation, with densities below 700 kg/m^3, achieved thermal conductivity as low as 0.19 W/m.K, whereas structural cob mixtures with densities ranging between 1107 kg/m^3 and 1583 kg/m^3 had higher conductivity values, reducing their insulation potential [12]. Similarly, Tchiotsop et al. observed that cob mixtures without fibres had thermal conductivity as low as 0.062 W/m.K, while the inclusion of 3% hemp shiv raised the conductivity to 0.079 W/m.K due to an increase in density [13].

2.3 Structural Performance of Cob

Cob's structural performance has been widely studied, with emphasis on its relatively low compressive strength compared to other earthen materials but notable shear properties. [29]. The material gains compressive strength as it dries, while adding organic fibres provides tensional strength, preserving structural integrity [30]. Cob can endure stress beyond its elastic range with a gradual decline in capacity, a quality that supports its use in resilient construction [15, 20]. Various laboratory tests have assessed cob's compressive and tensile strength, elastic modulus, Poisson's ratio, shrinkage, and cracking levels to align with global building regulations [14, 15, 21, 23]. These tests underscore the potential of cob as a sustainable construction material with enhanced performance characteristics through optimised fibre and binder content.

Compressive strength tests have revealed various results depending on mixture composition, testing protocols, and fibre content. Vinceslas et al., using Brittany's vernacular cob process, found compressive strengths between 0.50 MPa and 0.76 MPa, correlating higher density with increased strength but reduced stiffness [31]. Miccoli et al., employing EN 1052-1 standards [32], reported an average strength of 1.59 MPa [29]. Studies such as Saxton and Weismann's studies have shown that moisture content significantly affects compressive strength, varying from 0.35 MPa to 1.75 MPa depending on water content and soil-clay ratios [22, 33]. Other researchers, including Sangma and Tripura, demonstrated that adding coconut coir or cement stabilisers could enhance compressive strengths, achieving values up to 2.98 MPa [21, 23]. Similarly, tensile strength tests indicated coir's superior performance, ranging from 0.48 MPa to 0.75 MPa, compared to straw fibres [23].

Shrinkage and density are critical factors affecting cob's structural stability and insulation potential. During drying, water loss leads to shrinkage, which can cause cracking and compromise structural integrity. Studies by Saxton and Sangma showed that fibre content and drying temperature significantly influenced shrinkage levels, with coir and straw additions reducing shrinkage effectively [21]. For instance, adding 3% coir reduced shrinkage to 1.07% at 30°C, compared to 3.18% for unstabilised cob under similar conditions.

Bulk density, influenced by material composition, ranged from 1107 kg/m³ to 1583 kg/m³ for structural walls, with lower densities observed in insulation walls [12]. Zeghari et al. reported densities aligning with this range, while Miccoli et al. noted consistent results around 1475 kg/m³ [14]. These findings highlight the role of material composition and processing techniques in enhancing cob's performance for modern construction.

The relationship between compressive strength and density in cob materials highlights a direct correlation, where higher-density mixtures generally exhibit increased compressive strength. Vinceslas et al. found that cob specimens with higher densities, manufactured following traditional processes, achieved compressive strengths ranging from 0.50 MPa to 0.76 MPa, demonstrating that increased density enhances the load-bearing capacity [31]. Similarly, Sangma and Tripura observed compressive strength values between 1.35 MPa and 2.98 MPa for cement-stabilized cob mixtures with densities varying from 1710 kg/m³ to 1780 kg/m³, further confirming this trend [23].

3 Material and Methods

This section discusses the different methods applied in this research. This can be divided into two main segments; the first examines the methods applied at the constituent level. The constituent-level investigation includes the X-ray Diffraction Test (XRD) and the Scanning Electron Microscopy (SEM) applied to the subsoil, barley straw, and hemp shiv samples. Meanwhile, the second segment discusses the characterisation of the design cob mixes at the material level for their thermal and structural performance using experimental tests. The tests involve thermal conductivity, compressive strength testing, and density and volumetric shrinkage measurements.

3.1 Constituent-Level Exploration

Previous literature has discussed the different properties of cob's constituents, including subsoil, barley straw, and hemp shiv; it was evident that a variation in cob performance is present. Due to these inconsistencies and variations, examining the specific subsoil and fibrous materials used in this research was critical. The study utilises subsoil excavated from a farm in Cardiff, South Wales. Additionally, the research investigates two distinct fibres, hemp shiv and barley straw, which have demonstrated good thermal and structural potential in previous literature. [34, 35]. The fibre length of barley straw fibres was cut manually to range between 20 mm and 50 mm to maintain a relatively short fibre, allowing a better blend within the cob mix [10, 28, 31, 36]. Hemp shiv fibres, on the other hand, are naturally shorter, ranging between 1 mm and 40 mm [37].

A sieve test was performed on subsoil to determine its composition based on the granular sizes of soil particles. Hence. A total of 3080 grams of soil was used in this sieving test based on the ASTM 6913 standard [38]. The sieves ranged between 6mm and 90µm and were placed on a vibration table to run the test. However, the soil was creating masses that gave false granularity due to the presence of clay, which would lead to inaccurate characterisation results. Therefore, there was a need to examine the subsoil's particle structure at a more detailed level. Hence, an XRD test was performed.

Accordingly, Bulk analysis was carried out on the powdered sample. Following ASTM E3294 [39], a scan was run using the Philips PW1710 Automated Powder Diffractometer using Cu Ka radiation at 35kV and 40mA, between 2 and 75 °2θ at a scan speed of 0.02 °θ/s.

The XRD test was essential in determining the accurate composition of the used subsoil and fibrous materials. This was crucial in the mix design process and in analysing the applied test results. On the other hand, understanding the constituents' surface textures and pore sizes required an SEM test. This is crucial to evaluate the material's hygrothermal performance and ability to blend homogeneously in the mix, affecting its structural integrity.

Before the SEM imaging, the samples were placed in an argon gas vacuum for three minutes to eliminate air and particulates that could interfere with the results. The samples were then coated with a gold-palladium alloy for approximately 15 minutes to enhance electrical conductivity and prevent charging under the electron beam. After the sample preparation, the SEM chamber was purged with nitrogen to remove residual contaminants. The imaging was conducted using a Sigma 300 VP SEM machine at an accelerating voltage of 10 kV. The magnification of the three samples varied based on the requirements and needs of understanding the constituents, which ranged between 30X and 3000X. To analyse the produced images, a threshold analysis was performed using ImageJ by calculating the porous area and, therefore, determining the porosity of the constituents. An iterative process was employed to determine the optimal threshold value: the threshold was adjusted until the dark regions corresponding to the pores were accurately isolated from the surrounding material. Once established, this threshold value was uniformly applied to all images, enabling a consistent measurement of the porous area and, by extension, the porosity of the constituents.

3.2 Material-Level Exploration

After the cob mixes were designed based on previous literature analysis and the constituent level's investigation findings, the material was mixed and cased in timber-based moulds. The proposed variations of cob mixes were designed by exploring the impact of adding different fibrous content between hemp shiv and barley straw. The fibre concentrations were 1%, 3%, 5%, 7%, and 10% by volume. On the other hand, the study aimed to explore the impact of water content on structural and thermal performance by exploring water content of 20%, 25% and 30% by volume. The required volume of each constituent was considered by considering its densities as stated in previous literature, followed by calculating the mass of that specific volume.

The mixes were cast in timber-based moulds prepared for this purpose, each 0.001 m^3 in volume, to align with the requirements of the relevant standards for thermal conductivity and compressive strength. The cubic samples accordingly was 10 x 10 x 10 cm. Each mix was cast into three moulds to more precisely determine the structural and thermal performance, ensuring statistical accuracy. After casting, the moulds were kept in an unconditioned indoor space to dry naturally for 48 days. The samples were weighed regularly and considered dry, with the mass difference close to zero. The storing space was monitored constantly for the entire period using a HOBO U12-013 Temperature/Relative Humidity. The temperature in the space varied between 17.1 and 22.8 degrees Celsius, while the relative humidity fluctuated more, ranging between 35% and 65%.

When the samples were dry, their dimensions were measured, and their mass was recorded. This was essential for calculating the sample's density and volumetric shrinkage. The volume of the cubic dry samples was calculated. By comparing the dry volume with the wet volume, which was the volume of the mould, which was 0.001 m^3, the volumetric shrinkage of the samples was calculated. Additionally, by dividing the mass of the dry samples by the dry volume, the density of each sample was found. While the literature has used various measurement approaches for shrinkage, the volumetric shrinkage of the material was used as it implies the overall structure.

The transient plane source (TPS) method is used for thermal conductivity testing. A thermal conductivity sensor with a surface probe with a circular cross sectional are aof 50 cm diameter was selected for its cost-effectiveness and ease of rapid testing. Following calibration, each dry specimen was placed on a clean, flat, horizontal surface free of contaminants and moisture. The probe was then positioned in the centre of the specimen's top surface, with a 1 kg weight applied to ensure proper contact.

The TPS instrument introduced heat pulses into the specimen for 5 to 15 minutes per reading. Each specimen underwent 3 to 6 measurements on different surfaces to enhance the accuracy of the thermal conductivity readings. Surface temperatures were recorded to ensure that all thermal conductivity measurements corresponded to similar conditions across specimens.

To conduct a compressive strength test on cubic samples, the samples were first prepared according to EN 206 – 2013 [40]. The cubes' surfaces were inspected to ensure they were smooth and free of irregularities or damage.

After preparation, the testing apparatus was set up, ensuring a 45-degree sample rotation angle. The uniaxial compression testing machine was calibrated to guarantee accurate and reliable results.

The cube specimen was placed between two plates of the compression testing machine during the testing procedure. As suggested by Gomaa et al., a gradually increasing compressive force was applied to the specimen at a loading rate of 0.0013 cm/s. The force was continuously applied until the specimen was fractured, and the maximum load applied was recorded.

The compressive strength of the specimen was then calculated by dividing the maximum load by the cross-sectional area of the cube. The cross-sectional area was determined by measuring the dimensions of the cube specimen.

4 Results

4.1 Constituent-Level Exploration Results

Sieve Tests

The sieve analysis reveals a complex texture in the subsoil, combining sandy and clay-like particles, which points to a loamy composition ideal for cob construction. The composition of the soil was determined based on the specified granular size defined in the standard [38]. Some larger particles appear incompletely crushed, showing clay-like properties when broken down, which enhances the subsoil's cohesion and structural integrity. This composition is favourable for cob, as the mix of sand and clay particles provides the necessary balance for both strength and flexibility. ***Figure 1*** presents the sieve test results, showing the percentage of retained substance in each sieve.

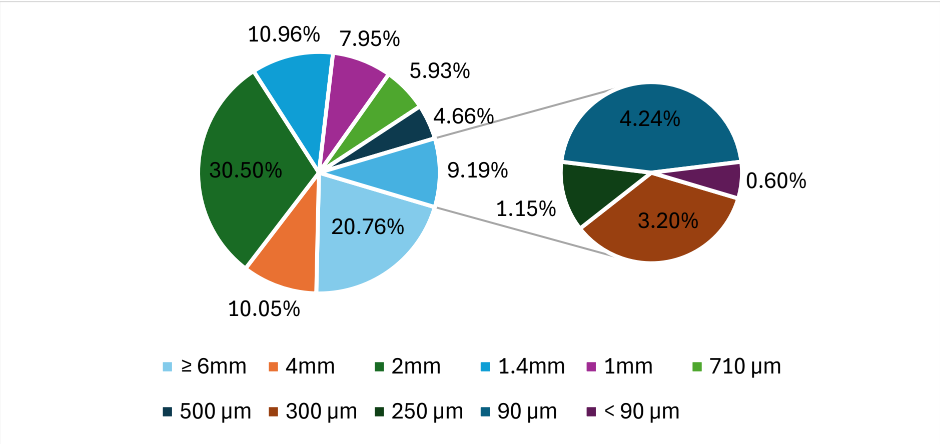

Figure 1 Percentage of retained subsoil based on sieve test

X-ray Diffraction (XRD) Test

The phases were identified using Philips PC Identify software for all samples of the cob constituents (i.e., Soil, barley straw, and hemp shiv). After performing a semi-quantitative analysis, the peaks of the graphs were used to identify the composition.

Based on the analysis of the subsoil XRD testing peaks presented in **Figure 2**, the subsoil sample predominantly consisted of quartz and 70% illite, 8% dolomite, 6% albite, and 4% kaolinite. The significant peak at 2θ ≈ 26.6° represents quartz, indicating the subsoil's high quartz content. Peaks corresponding to illite and kaolinite, observed in the 8–10° and 12° ranges, respectively, confirm the presence of clay minerals. Additionally, the XRD analysis revealed the presence of dolomite (8%), as indicated by peaks at 2θ ≈ 30° and 41°, and albite (6%), evident from peaks near 2θ ≈ 27° and 40°.

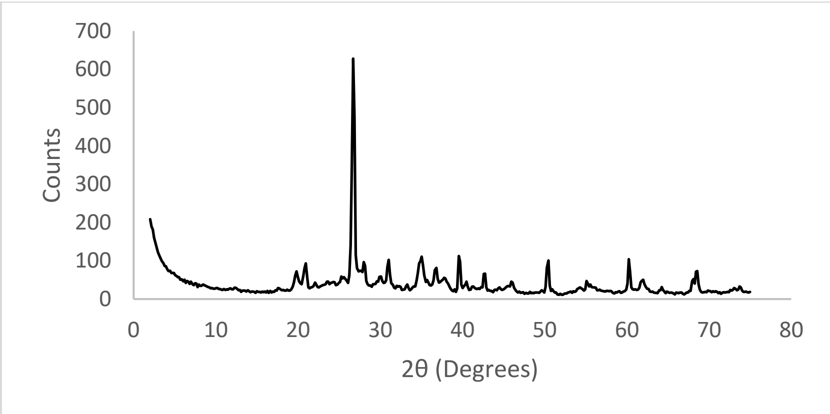

Figure 2. The XRD testing results of the subsoil sample.

The XRD tests on both fibres have demonstrated a different chemical characterisation due to the biological nature of the materials. The XRD test revealed several vital features indicative of the sample's structural composition for barley straw presented in **Figure 3** A prominent peak was observed at 2θ = 22.06°, with an intensity of 399.625 counts. This peak corresponds to the (002) plane of cellulose I, confirming a significant presence of crystalline cellulose within the barley straw fibre. Additionally, smaller peaks appeared between 2θ values of approximately 15° and 17°, likely corresponding to the (101) and (10Ī) planes of cellulose I, further supporting the existence of crystalline cellulose structures in the sample.

The XRD graph of hemp shiv, presented in **Figure 4**, shows an evident peak at approximately 2θ=22∘, representing the characteristic of the (002) plane in cellulose I. This indicates a significant crystalline cellulose component within the tested hemp shiv. On the other hand, smaller peaks are observed at 2θ values between 15° and 17°, which translates to (101) and (101¯) planes in cellulose I, mirroring the results of barley straw in that regard.

Regarding the amorphous background analysis of the hemp shiv fibre, a broad baseline spanning 2θ values of approximately 10° to 25° indicates amorphous content.

This background signal arises from hemicellulose and lignin, which also mirrors the general trends of barley straw.

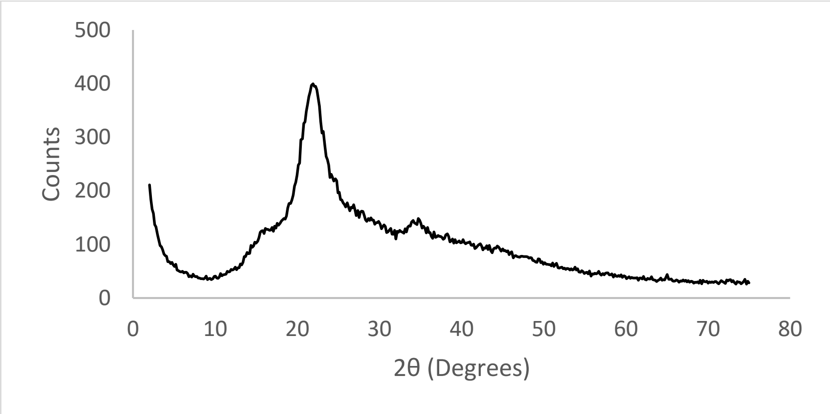

Figure 3 The XRD testing results of the barley straw sample.

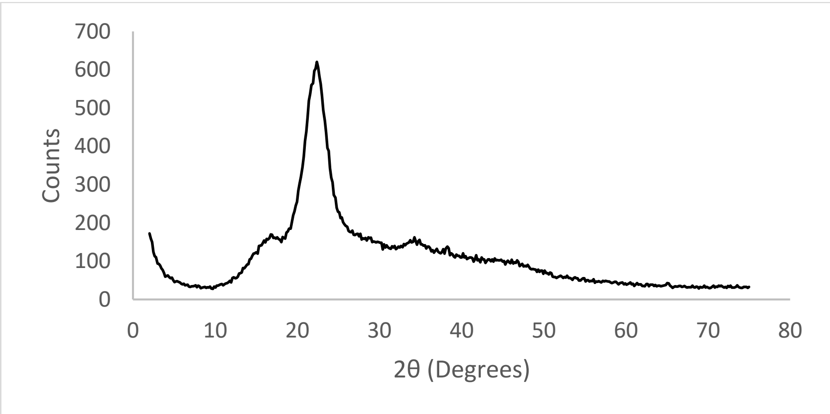

Figure 4 The XRD testing results of the hemp shiv sample

Scanning Electron Microscopy (SEM) Test

As discussed, SEM testing is essential in understanding the material's porosity and surface texture, which impact its hygrothermal and structural properties. The SEM image of the subsoil demonstrated in **Figure 5** and its threshold image present the compact nature of the subsoil and the rough texture of its sample due to the presence of quartz and clay in the sample, as indicated in the XRD testing. The subsoil's porosity averaged 20 ± 1%, calculated based on the pores area of the soil sample at three magnification levels.

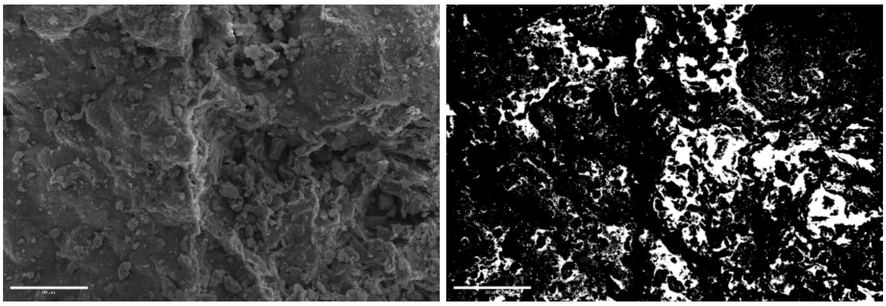

Figure 5 (Left) Produced SEM image of subsoil sample at 300X magnification, (Right) Processed image used in porosity determination.

When the fibrous materials were analysed, it was evident that larger pores and a more uniform surface texture were present. The barley straw sample was more extensive and uniform than the hemp shiv. The average pore diameter for barley straw ranged between 3.5 µm and 40.5 µm, with an average porosity of 43± 1%. On the other hand, the diameter of the pores for the hemp shiv sample ranged between 1.5 µm and 24.5 µm with an average porosity of 30 ± 1%. **Figure *6*** presents the SEM image of the barley straw sample and its associated pores analysis image, while **Figure *7*** shows SEM image for the hemp shiv.

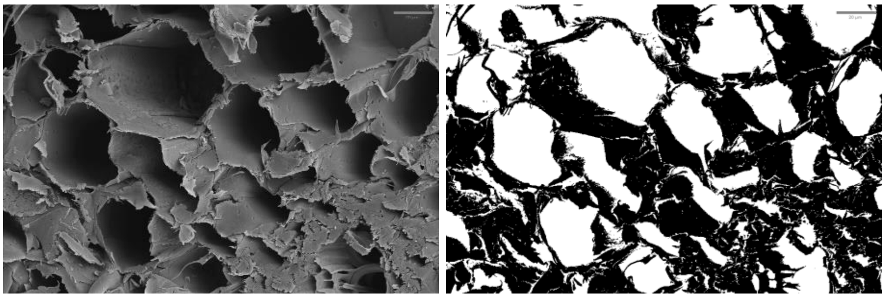

Figure 6 (Left) Produced SEM image of barley straw sample at 500X magnification, (Right) Processed image used in porosity determination.

Figure 7 (Left) Produced SEM image of hemp shiv sample at 1000X magnification, (Right) Processed image used in porosity determination.

4.2 Material-Level Exploration Results

After investigating the constituents of cob, it was essential to identify the impact of adding water and fibrous content to the cob mixes at the material level on its structural and thermal properties. Hence, different cob mixes are developed and tested. **Table** presents the non-fibred cob mixes, which were critical to understanding the impact of water content along with having a baseline for the effect of adding fibrous materials. **Table** presents the overall results of the various cob mixes under investigation, which consist of barley straw as the stabilisation fibre. In contrast, **Table** presents the overall results of mixes that used hemp shiv as the primary fibre for stabilisation.

Non-Fibred Mixes

These non-fibred mixes consist of subsoil combined with water content only, which was tested at different concentrations as presented in **Table 1** The interplay between these components directly influences cob's thermal, mechanical, and volumetric properties.

Table 1. The result of Non-Fibred Mixes at different water contents

Mix ID	Initial Water Content (%)	Thermal Conductivity (W/m.K)	Density (kg/m^3)	Compressive Strength (MPa)	Volumetric Shrinkage (%)
NF20W	20	0.378	1633	0.860	20.9
NF25W	25	0.241	1664	1.04	18.1
NF30W	30	0.177	1606	0.933	22.2

As the initial water content increases from 20% to 30%, the thermal conductivity shows a notable decline from 0.378 W/m.K to 0.177 W/m.K. This trend suggests that higher water content leads to a more porous mix as the subsoil is partially replaced by water, reducing the ability of the mix to conduct heat. These characteristics highlight the potential for mixes with higher water content to perform better in thermal insulation applications. However, the density and compressive strength exhibit different trends. Density peaks at 25% water content at 1664 kg/m^3 and drops slightly at 30%, while compressive strength also reaches its highest value of 1.04 MPa at 25% water content before decreasing at 30%, causing larger voids that impact the structural integrity.

Volumetric shrinkage, another critical property, decreases at 25% water content to 18.1% but rises to 22.2% at 30%. This indicates that moderate water content enables better cohesion and reduces drying shrinkage, whereas excessive water results in higher evaporation and void formation during drying, resulting in higher volumetric changes. Overall, the mix with 25% water content achieves the most balanced performance, providing optimal compressive strength, moderate shrinkage, and relatively low thermal conductivity.

Barley Straw Stabilised Mixes

Barley straw mixes incorporate varying fibre and water content levels, significantly influencing their thermal, mechanical, and volumetric properties (See **Table**). Including straw fibres alongside subsoil and water introduces additional complexity to the mix's behaviour, with notable trends observed across the measured parameters.

Table 2 The results of barley straw stabilised cob mixes at different fibre and water contents.

Mix ID	Fibre Content (%)	Initial Water Content (%)	Thermal Conductivity (W/m.K)	Density (kg/m^3)	Compressive Strength (MPa)	Volumetric Shrinkage (%)
1S20W	1	20	0.209	1698	1.02	22.1
1S25W		25	0.272	1557	1.12	18
1S30W		30	0.236	1677	1.368	16.6
3S20W	3	20	0.217	1620	0.915	17.2
3S25W		25	0.241	1666	1.094	18.5
3S30W		30	0.305	1691	1	16.9
5S20W	5	20	0.225	1605	0.886	18.7
5S25W		25	0.206	1631	1.172	18.4
5S30W		30	0.191	1717	1.173	16.1
7S20W	7	20	0.142	1715	0.962	21.3
7S25W		25	0.237	1558	0.785	16.7
7S30W		30	0.132	1763	0.948	13.7
10S20W	10	20	0.188	1669	0.809	21.6
10S25W		25	0.202	1661	0.789	18.7
10S30W		30	0.204	1736	1.01	16.6

Thermal Conductivity

Thermal conductivity across barley straw mixes shows a broad range of values, with lower values generally observed at higher fibre contents. For instance, at 7% fibre content and 30% water content, the mix achieves the lowest thermal conductivity of 0.132 W/m.K, while mixes with lower fibre contents, such as 3S30W, show higher values like 0.305 W/m.K. The variability in thermal conductivity reflects the influence of fibre and water content on the thermal performance of the cob mixes.

Density

Density in barley straw mixes reflects the interplay between fibre and water content, which affects the overall compactness and material structure. Higher water content typically increases density due to improved cohesion and compaction during curing. For instance, 7S30W achieves a high density of 1763 kg/m^3, the highest among the tested mixes. However, the presence of fibres introduces variability in this trend.

While fibres enhance stability and reduce shrinkage, their inclusion also creates voids within the matrix, which can minimise density in some mixes. For example, 5S30W has a slightly lower density of 1717 kg/m³ despite similar water content.

Compressive Strength
By analysing the compressive strength results of barley straw-stabilised cob mixes, an inverse relationship appears between fibre content and the material's ability to resist compression force. The highest strength was observed at moderate water content and lower fibre levels. For instance, the mix consisting of 1% barley straw and 30% initial water content has achieved a compressive strength of 1.368 MPa, the highest among the tested mixes. Higher fibre levels, such as 10%, can decrease strength, as seen in the mix10S25W, which consists of 10% barley straw and 25% initial water content, with a value of 0.789 MPa. This may be attributed to the lack of cohesion and blend within the cob mix due to the larger sizes of the straw fibres.

Volumetric Shrinkage
Volumetric shrinkage decreases as fibre content increases, demonstrating the stabilising influence of the barley straw fibres in counteracting drying-induced volume shrinkages. The lowest shrinkage of 13.7% was recorded for the cob mix with 7% barley straw and 30% initial water content. On the contrary, mixes with a lower fibre content of 1% and 20% initial water content exhibited higher shrinkage rates of 22.1%. This trend highlights the role of straw in reducing volumetric shrinkage while drying.

Hemp Shiv Stabilised Mixes
As presented in **Table** , hemp shiv-stabilised cob mixes were tested at fibre concentrations between 1% and 10% and 20% to 30% of initial water content. The results present the various mixes' thermal conductivity, density, compressive strength, and volumetric shrinkage performance.

Table 3 The results of hemp shiv stabilised cob mixes at different fibre and water contents.

Mix ID	Fibre Content (%)	Initial Water Content (%)	Thermal Conductivity (W/m.K)	Density (kg/m^3)	Compressive Strength (MPa)	Volumetric Shrinkage (%)
1H20W	1	20	0.19	1891	1.512	21.4
1H25W		25	0.288	1831	1.66	21.2
1H30W		30	0.204	1690	1.116	19
3H20W	3	20	0.218	1653	1.634	17.5
3H25W		25	0.331	1870	1.508	21.9
3H30W		30	0.163	1676	1.454	16.4
5H20W		20	0.185	1693	1.444	15.8

5H25W	5	25	0.207	1743	1.719	20.5
5H30W		30	0.317	1687	0.961	18.2
7H20W	7	20	0.236	1796	1.352	22.5
7H25W		25	0.194	1630	1.393	17.8
7H30W		30	0.207	1603	1.272	19.3
10H20W	10	20	0.212	1710	1.155	19.9
10H25W		25	0.142	1606	1.322	17
10H30W		30	0.158	1663	1.114	18.8

Thermal Conductivity

Thermal conductivity varies widely depending on the fibre and water contents, with the lowest values observed in mixes with higher fibre content and moderate water content of 25%. For instance, the mix 10H25W achieves a conductivity of 0.142 W/m.K, showcasing the excellent insulating properties of hemp shiv fibres. Conversely, mixes with lower fibre levels, such as 1H25W, which consists of 1% hemp shiv and the same water content, exhibit higher conductivity at 0.288 W/m.K, reflecting a denser, less porous structure that allows more efficient heat transfer.

Density

The density in these mixes is influenced by both water and fibre content. Higher fibre content was demonstrated to reduce the density due to the increased porosity introduced by the hemp shiv, reflecting the SEM image analysis. The mixes with 7% hemp shiv and 30% water content, along with the mix consisting of 10% hemp shiv and 25% water content, show densities of 1603 kg/m³ and 1606 kg/m³, respectively, among the lowest in the dataset. On the other hand, mixes with lower fibre content, such as the mix with 1% hemp shiv and 20% initial water content, achieve much higher densities, with the highest value being 1891 kg/m³. Water content was also observed to impact the hemp shiv-stabilised mixes density, with mixes at 25% water content often achieving the highest compaction levels, as seen in the mix 3H25W with a density of 1870 kg/m³.

Compressive Strength

The compressive strength of hemp shiv stabilised mixes reaches its highest levels in mixes that effectively balance fibre and water content. The highest compressive strength of the mix, 5H25W, which contains 5% fibre and 25% initial water content, achieves a compressive strength of 1.719 MPa, benefitting from sufficient compaction and reinforcement from the hemp fibres. However, high fibre or water content was demonstrated to negatively impact the compressive strength, as seen in 10H30W with 10% fibre and 30% water content, which has a strength of just 1.114 MPa, likely due to insufficient cohesion and blending between the mix's constituents.

Volumetric Shrinkage

Like barley straw, the volumetric shrinkage tends to decrease with higher fibre content, as the hemp stabilises the matrix during drying, preventing excessive contraction. Mixes with 5% fibre and 20% initial water content, 7% hemp shiv and 25% initial water content show reduced shrinkage at 15.8% and 17.8%, respectively. In contrast, mixes with lower fibre content, such as the mix consisting of 1% hemp show and 20% initial water content, experience higher shrinkage of 21.4%, as the mix lacks sufficient reinforcement to counteract drying stresses.

5 Overall Discussion

The research investigated various cob mixes incorporating different fibre types and contents alongside three distinct water contents. A constituent-level analysis revealed a direct correlation between the type of fibre used and its impact on the material's performance.

Comparing the mixes' results while considering the XRD and SEM tests conducted on cob's constituents highlighted distinct trends, underscoring the importance of exploring this material at both levels. Previous sections examined the effects of adding barley straw, hemp shiv fibres, and varying water concentrations on cob's thermal and structural performance. This section builds on those findings by analysing the overall trends in constituent concentrations and their influence on the material's performance and exploring interconnections and relationships between various factors.

Material density emerged as the most significant variable across all mix types, demonstrating strong correlations with thermal conductivity, compressive strength, and volumetric shrinkage. Density was critical as a baseline for characterising thermal and structural performance.

This section also compares the results of the different mixes to determine which combinations optimise performance, achieving low thermal conductivity and volumetric shrinkage while ensuring high compressive strength and moderate density.

5.1 Discussion on Barley Straw Stabilised Mixes

In barley straw stabilised mixes, density shows transparent relationships with thermal conductivity, compressive strength, and volumetric shrinkage. Higher-density mixes often exhibit better thermal conductivity due to reduced porosity, although straw fibres can alter this trend by acting as insulators. For example, the mix 7S30 with 7% barley straw and 30% initial water content achieves a high density of 1763 kg/m^3. Still, as the SEM test results suggested, it maintains a low thermal conductivity of 0.132 W/m.K due to the influence of fibres.

The general trend also presents that mixes with higher densities are often associated with higher compressive strength, as seen in the mix with 1% barley stew and 30% initial water content, which has a density of 1677 kg/m^3 and compressive strength of 1.368 MPa. However, mixes with excessive fibre content, such as 10S25W, which contains 10% barley straw, deviate from this trend as the void content increases, impacting the material's binding. The relationship between density and volumetric shrinkage shows that denser mixes, such as 7S30W, tend to shrink less, with a recorded value of 13.7%. In contrast, lower-density mixes, such as 1S20W, show higher levels of volumetric shrinkage of 22.1%. This suggests the significance of adding fibres to the overall structural integrity of the material.

Furthermore, an inverse relationship is evident when exploring the trends between compressive strength and volumetric shrinkage. Mixes with higher compressive strength tend to have lower shrinkage rates. For instance, the mix with 1% barley straw and 30% initial water content presented the highest compressive strength of 1.368 MPa and a relatively low volumetric shrinkage of 16.63%. Similarly, 7S30W demonstrates low shrinkage of 13.7%, consisting of 7% fibre and 30% of water content, although its compressive strength is lower at 0.948 MPa. In contrast, mixes with higher shrinkage, such as 1S20W at 22.1%, tend to have lower compressive strength values of 1.02 MPa. This relationship suggests that as shrinkage reduces, the structural matrix of the material becomes more stable, enhancing compressive strength aligning with previous research findings [21].

Barley straw mixes show apparent differences from non-fibred mixes in thermal, mechanical, and volumetric behaviour. Including straw fibres in barley mixes significantly lowers thermal conductivity, with values as low as 0.132 W/m.K for 7S30W, compared to 0.177 W/m.K for the best-performing non-fibred mix (NF30W). Volumetric shrinkage is also notably lower in barley straw mixes, particularly at higher fibre content, as demonstrated by 7S30W's shrinkage of 13.7% compared to 22.2% in NF30W. However, non-fibred mixes typically achieve higher compressive strength at moderate water content, with NF25W reaching 1.04 MPa, while most barley straw mixes, except 1S30W, fall below this value. These distinctions suggest that barley straw mixes are better suited for applications requiring thermal insulation and shrinkage resistance. Additionally, this implies that adding higher amounts of barley straw can negatively affect the compressive strength of the cob.

5.2 Discussion on Hemp Shiv Stabilised Mixes

When analysing cob mixes with hemp-shiv stabilisation, similar trends appear between density and the three other aspects under investigation, highlighting these mixes' complex interplay. Higher-density mixes typically show increased thermal conductivity, as their denser structure facilitates heat transfer. For instance, the mix with 3% hemp shiv and water content of 25% presented a density of 1870 kg/m³ and the highest recorded thermal conductivity across all mixes with 0.331 W/m.K. However, adding hemp fibres often disrupts this trend, as their insulating properties reduce conductivity even in denser mixes, as seen in 10H25W, which consists of 10% hemp shiv and 25% water content with a density of 1606 kg/m³ and a conductivity of 0.142 W/m.K.

In terms of compressive strength, denser mixes often exhibit stronger performance. For instance, 1H25W, with a density of 1831 kg/m³, achieves a compressive strength of 1.66 MPa. However, the effect of density on strength diminishes at higher fibre content, where porosity increases despite similar water levels. Density also correlates inversely with shrinkage, as higher-density mixes tend to contract less during drying. For instance, 3H25W, with a high density of 1870 kg/m³, has a shrinkage value of 21.9%, compared to lower-density mixes like 7H25W with 17.8%.

These mixes show a trend of lower volumetric shrinkage rates aligning with higher compressive strength. Mixes like 5H25W, with a compressive strength of 1.719 MPa, exhibit relatively low shrinkage at 20.47%. Conversely, mixes with lower compressive strength, such as 10H30W, are also associated with higher shrinkage at 18.8%.

Hemp shiv composites exhibit several advantages over non-fibred and barley straw composites. In terms of compressive strength, hemp-based mixtures demonstrate superior performance, with values such as 1.719 MPa for 5H25W exceeding the maximum strengths observed in barley straw composites, which is 1.368 MPa for 1S30W, and non-fibred composites, which is 1.04 MPa for NF25W. Additionally, hemp mixtures provide enhanced thermal insulation properties, as exemplified by 10H25W, which achieves a thermal conductivity of 0.142 W/m·K, surpassing both barley straw and non-fibred counterparts. However, hemp shiv composites exhibit higher shrinkage than barley straw mixtures, which display superior dimensional stability. These distinctions underscore the suitability of hemp shiv composites for applications requiring higher compressive strength and improved insulation. In contrast, barley straw and non-fibred composites may be more appropriate for contexts prioritising reduced shrinkage and enhanced stability.

5.3 Overall analysis and recommendations for cob mix optimisation

The study reveals that incorporating fibrous materials such as barley straw and hemp shiv into cob mixes significantly influences their thermal, mechanical, and volumetric properties. Hemp shiv-stabilised mixes demonstrate superior compressive strength and thermal insulation compared to barley straw-stabilized and non-fibred mixes, making them preferable for applications requiring enhanced structural performance and energy efficiency. Barley straw-stabilized mixes while offering reduced thermal conductivity and volumetric shrinkage compared to non-fibred mixes, generally exhibit lower compressive strength. An optimal balance between fibre content and water content is crucial; higher fibre contents tend to reduce thermal conductivity and shrinkage but may decrease compressive strength if excessive. Constituent-level exploration is essential, as understanding the specific properties of the materials used is critical for predicting and optimising the overall performance of the cob mixes. Accordingly, the following points summarise the key findings and recommendations that can be relevant for future research and the optimisation of cob as a building material:

- A detailed examination of cob’s constituents is essential for evaluating and enhancing the overall performance of cob mixes.
- Hemp shiv-stabilised cob achieved the highest compressive strength of 1.719 MPa and a thermal conductivity of 0.142 W/m·K when using 5% fibre and 25% initial water content.
- Barley straw-stabilised cob reduced volumetric shrinkage to 13.7% and achieved a thermal conductivity of 0.132 W/m·K when incorporating 7%

fibre and 30% initial water content. However, the compressive strength of barley straw mixes is generally lower than that of hemp shiv mixes.
- A 5-7% fibre content and an initial 25-30% water content achieved the most effective balance between thermal insulation, compressive strength, and volumetric stability.
- Moderate material density is critical for optimising and evaluating cob mixes' thermal conductivity, compressive strength, and volumetric shrinkage, as it directly correlates with these properties.

6 Conclusion

This research highlights the importance of a comprehensive approach to evaluating cob materials by examining both constituent- and material-level performance metrics. By analysing the composition and microstructure of subsoil, barley straw, and hemp shiv through advanced techniques such as XRD and SEM, the study effectively characterises the individual components of cob, which significantly influence the performance of the final mix. Thermal and structural tests further emphasise how variations in fibre content and water ratios impact critical parameters such as thermal conductivity, compressive strength, and volumetric shrinkage, offering insights into optimising cob for modern construction needs.

The findings reveal a direct relationship between the mix composition and performance. Hemp shiv-stabilized cob demonstrated superior compressive strength, achieving up to 1.719 MPa, and low thermal conductivity at 0.142 W/m·K with a 5% fibre and 25% initial water content. These properties make hemp shiv composites ideal for structural resilience and energy efficiency applications. Conversely, barley straw-stabilized cob mixes excel in minimising shrinkage and enhancing thermal insulation, with a thermal conductivity as low as 0.132 W/m·K and shrinkage reduced to 13.7% at 7% fibre and 30% initial water content. Non-fibred mixes, while achieving higher compressive strength at moderate water content, lag in thermal and volumetric performance compared to fibrous mixes.

The research underscores that an optimal balance between fibre and water content is crucial to achieving desired performance characteristics. Moderately dense mixes with 5-7% fibre and 25-30% initial water content consistently demonstrated the most effective balance and stability across thermal, mechanical, and shrinkage properties. Furthermore, constituent-level analysis proves essential, as understanding the mineralogical and physical properties of materials like subsoil and fibres supports the predictability and optimisation of cob mixes.

The researchers advocate further investigation of cob materials to optimise their thermal and structural properties. By refining mixture ratios and incorporating innovative bio-based additives, there is significant potential to enhance cob structures' insulation and load-bearing capacities. This optimisation could improve energy efficiency and greater durability of earthen constructions across diverse climatic conditions.

Furthermore, the researchers emphasise the importance of examining the hygroscopic behaviour of cob. A comprehensive understanding of moisture interactions is crucial for regulating indoor humidity and preventing structural degradation. Explorations on moisture absorption and desorption cycles, Moisture Buffer Value, and water vapour permeability may enable the development of bio-stabilised earthen materials with superior moisture management properties. These advancements would enhance the sustainability of cob as a building material and expand its applicability in modern construction practices, thereby supporting global sustainability objectives and promoting environmentally responsible building techniques.

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