Journal of Building Engineering 87 (2024) 108959

Contents lists available at ScienceDirect

Journal of Building Engineering

journal homepage: www.elsevier.com/locate/jobe

# Investigation of Cob construction: Review of mix designs, structural characteristics, and hygrothermal behaviour

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ARTICLE INFO

*Keywords:*
Earthen construction
Mixing ratio
Structural testing
Hygrothermal testing
Cob

ABSTRACT

Earthen construction systems have potential hygrothermal, and environmental benefits over conventional building materials such as concrete. However, such systems are not yet fully optimised to be part of an energy-efficient building. To further optimise the material, this review explores peer-reviewed research articles that relate to distinct constituents used in cob mixes and the different testing methods used to assess the produced specimen's hygrothermal and structural performance. For data collection, a systematic keyword search was carried out on ScienceDirect, Scopus and Google Scholar search engines, and relevant books were also consulted. The filtering of journal articles was based on studying the abstracts followed by analysing their content within the scope of the review. The results show that the soil's constituents and the added fibre ratios critically affect the percentages of clay and water added to the mixture. Fibres' impact on the mix was experimentally assessed by multiple researchers using distinct types of plant aggregates. The percentage of fibre addition ranged between 0.9% and 3% for structural specimens and reached 25% for non-structural specimens with optimised insulation properties. The investigation of cob's structural performance highlights that the compressive strength of cob has ranged between 0.1 MPa and 2.02 MPa, in contrast, the tensile strengths were between 0.01 MPa and 0.75 MPa. The shear strength was found to range between 0.37 MPa and 0.63 MPa. Furthermore, the hygrothermal exploration of cob demonstrated that the thermal conductivity was ranging between 0.12 W/m.K and 1.06 W/m.K. The review has also reviled that the moisture buffering value (MBV) of different mixtures ranged between 1.06 g $m^{-2}$ $\%RH^{-1}$ and 1.74 g $m^{-2}$ $\%RH^{-1}$. The review finds that there is no consensus and robust collated data available about the ratios of the mixes concerning the hygrothermal and structural performance of the specimens. This paper collected the tests results from the literature and highlights the missing results that needs to be considered in further research work.

## 1. Introduction

Since the industrial revolution, the use of conventional materials such as concrete has gained momentum for showing great potential and offering more flexibility in design because of their structural performance. Conversely, cement, which is one of the main constituents of concrete, contributes to over 8% to the worldwide total of $CO_2$ emissions [1]. The International Energy Agency (IEA) have reported that such materials are responsible for over 30% of total global final energy consumption as well as contributing to 27% of total energy sector emissions [2].

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https://doi.org/10.1016/j.jobe.2024.108959
Received 5 December 2023; Received in revised form 16 February 2024; Accepted 28 February 2024

Over one-third of the world's population lives in earthen dwellings [3]. Earthen construction has been defined as the construction system that uses building materials in which clay is a binder [4]. Many developed and developing countries have adopted this system due to its affordability and environmental benefits [3].

The use of earth in construction has gained momentum due to the increased interest in applying green building practices in current and future buildings [5]. Recognised as a natural alternative to concrete, earth offers reduced embodied carbon and lower energy demands for both production and operation compared to conventional materials [6]. Furthermore, Earth-based construction materials exhibit considerable diversity in their inherent characteristics, composition, and physicochemical properties, which is manifested in their hygroscopic attributes [7]. In contrast, despite its potential, there remains a lack of comprehensive understanding regarding its structural performance and response to environmental factors. This research aims to address this gap by investigating the structural, hygroscopic, and thermal performance of earth-based construction, particularly focusing on cob as a representative material. Through systematic analysis of cob's constituents, mixing ratios, and environmental conditions, this study seeks to provide insights for enhancing its suitability for sustainable building practices by formulating the most suitable optimisation protocol.

Hamard et al. classified earthen construction into two groups based on the construction methods: wet methods and dry methods. Rammed earth, and masonry units such as compressed earth blocks fall under the dry construction methods. Wet earthen construction methods, on the other hand, include adobe, wattle and daub, earthen-based plaster, and cob as a monolithic wall [8].

This review aims to bridge this gap by comprehensively investigating the structural, hygroscopic, and thermal performance of cob construction. The study will analyse its constituents, mixing ratios, and response to various environmental conditions. By synthesising existing literature and conducting empirical investigations, this study seeks to enhance our understanding of cob's suitability for sustainable building practices. Consequently, this study can contribute to the standardisation of cob as building material.

Building upon previous research, this study will provide insights into cob's structural integrity and hygrothermal performance. By identifying key factors influencing cob construction, this research aims to contribute to the development of eco-friendly construction methods and promote the adoption of sustainable building practices.

In summary, while prior research has explored cob's potential, a comprehensive understanding of its long-term structural and hygrothermal performance under diverse environmental conditions and mixing ratios remains limited. This study surpasses simply bridging this gap by systematically analysing cob's constituents, mixing ratios, and environmental response, to unlock its full potential as a sustainable building material. This research collates and builds upon existing knowledge to develop reliable and optimised cob construction methods, promoting its wider adoption for creating sustainable, energy-efficient, and comfortable built environments. This paper serves as a crucial step towards standardising and advocating for cob as a structurally sound and hygrothermally efficient material.

## 2. Material and methods

The literature review included all cob materials that were investigated by researchers around the world. The research methodology consisted of 5 main steps: (i) defining the aim and scope of the review, (ii) conducting systematic research using online search engines and books, (iii) selection of relevant research aligning with the aim and scope of the review, (iv) building the literature review and categorising the outcomes under three main sections; cob mixes in literature, structural performance of cob, and the hygrothermal performance of cob. Fig. 1 below presents a detailed flow chart of this review exploring the different stages of research and results representation.

Accordingly, a comprehensive and systematic keyword search was carried out on the database of ScienceDirect, Google Scholar, and Scopus between 1990 and 2023 in addition to searching relevant books. Such databases were selected in the review because they cover more publications and citations and includes publications produced by researchers in developing countries that cannot afford the ISI's or Elsevier's subscription.

The search algorithms consisted of the terms: "earthen construction", "cob", "structural testing of cob", "hygroscopic testing of cob", "thermal testing of cob", "hygrothermal testing of cob." The titles of the studies were screened and analysed to filter relevant studies. A large number of the papers that appeared in the search were out of the scope of the study which resulted in eliminating the studies from the analysis. For instance, the largest number of eliminated studies were presenting research work on corn cob rather than cob in the context of earthen construction. Afterwards, relevant work was evaluated, and their abstracts were systematically analysed and studied which resulted in finding 25 studies that align with the scope of this research (see Fig. 2).

## 3. Discussion of cob as a building material

Cob is defined as a lump of rounded shape [10]. Specifically, within the field of earthen construction, cob is defined as an environmentally friendly material that consists of soil, water, and fibrous materials as described in the following sections. The construction of cob walls has been investigated as a structural element which explains the large research on its structural properties [11]. Due to its potential, researchers have started investigating its hygrothermal and environmental aspects [12–16].

### 3.1. Sub-soil

Loam, clay, silt, and clayey-silt soil were designated as the four ubiquitous cob earth textures. The typical composition of sub-soil that is used in cob mixtures was suggested to be 15–25% clay to 75–85% of aggregates and sand.

Vernacular cob earth textures were defined as loam, clay, silt, and clayey-silt soil [8]. According to Gomaa et al., the recommended composition of earth that is used in cob mixtures was suggested to be 15–25% clay to 75–85% aggregate/sand [17]. To increase cob's density, well-graded soils were preferred since they had good space-filling properties that improved cob strength. Since topsoil

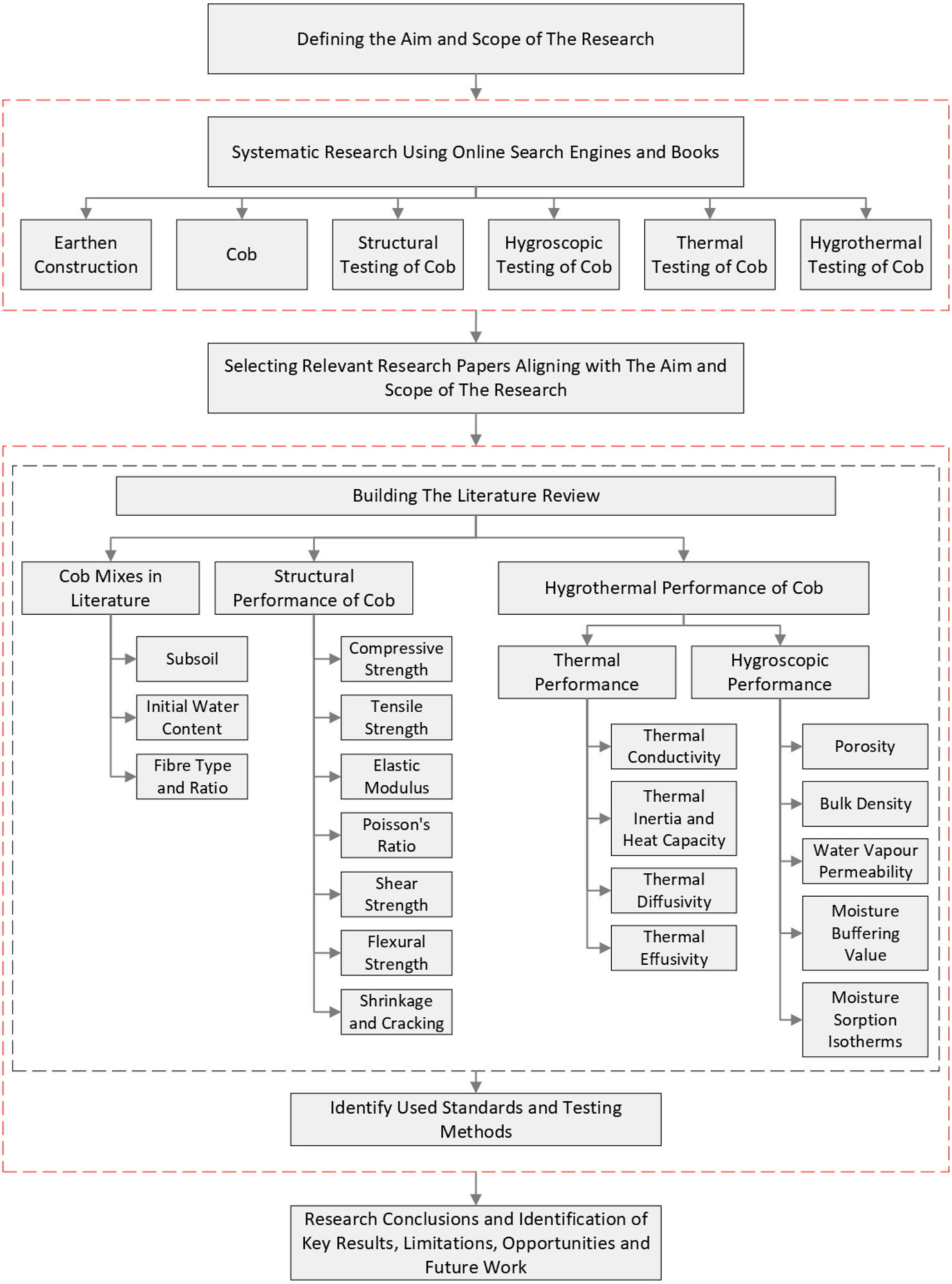

**Fig. 1.** Literature review framework flow chart.

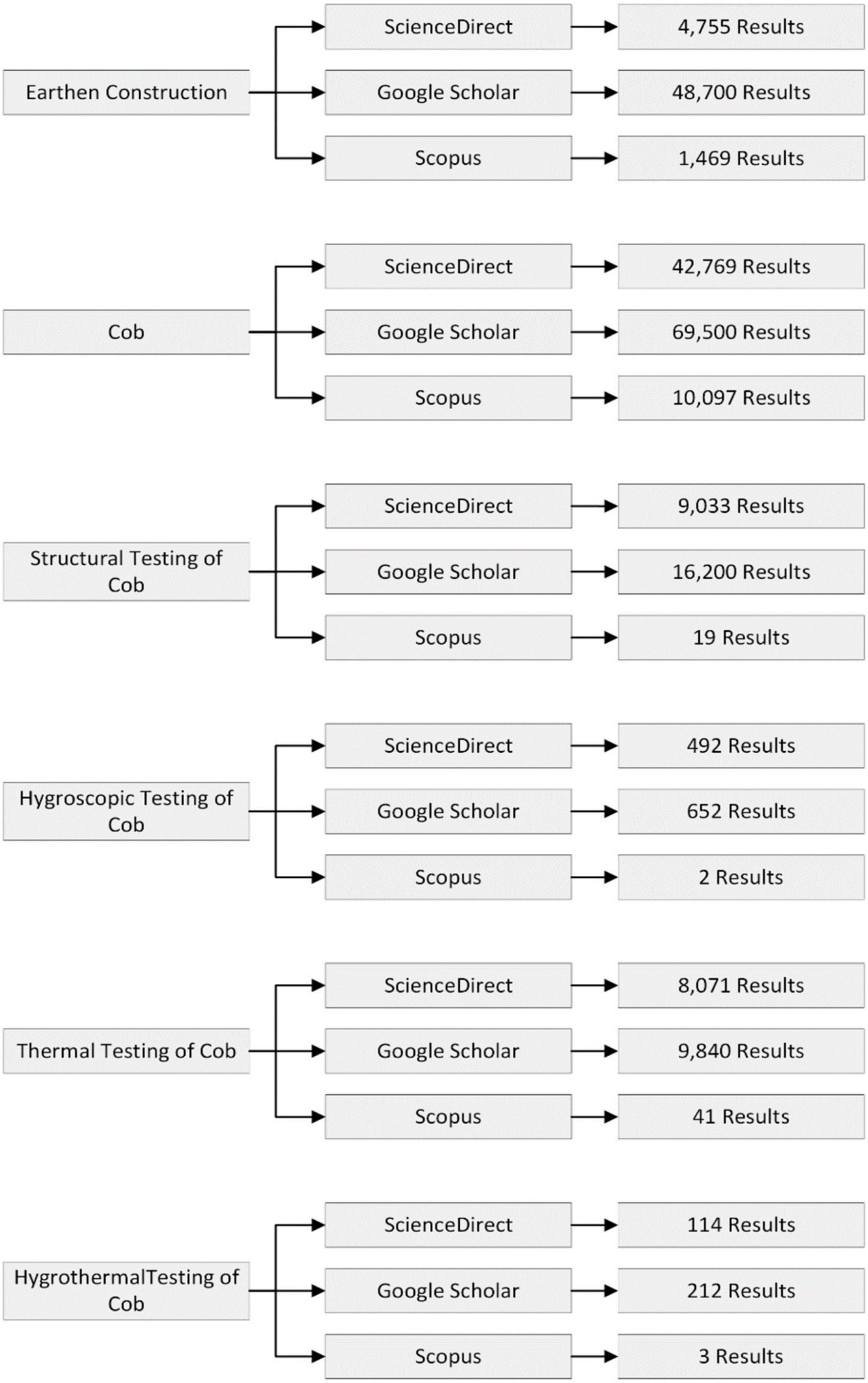

**Fig. 2.** The Methodological framework that was undertaken for the review paper.

decomposes rapidly after application and leaves a mechanical weakening in earth walls, it has been considered not suitable for cob construction. Therefore, it has been found that the most suitable soil for cob mixtures is just under topsoil [8].

### 3.2. Water content

Water content and the initial moisture level of a cob mixture have a significant effect on the strength of the material [17].

Furthermore, mixtures that are reinforced with fibres have the tendency to require more water content in the mixture [9].

### 3.3. Fibres

Even though the tensile strength and bonding of straw help in the reduction of cracking [3] some studies found that adding large amounts would increase the strain at failure when subjected to loads. Currently, many researchers are experimenting with distinct types of fibres that are considered green and mostly biodegradable such as cereal, straw, corn stalk, bagasse, rice straw, sunflower hulls and stalks, banana stalks, coconut coir, bamboo, durian peel, and palm leaves oil [10].

It is observed that the fibre content has several advantages to assure the success of cob mixtures. For instance, it facilitates the mixing of cob, assists handling, accelerates the drying process, works on distributing shrinkage cracks throughout the wall mass, enhances cohesion and shear-resistance of the wall, and helps improving weathering resistance. The impact of fibres on thermal insulation was discussed in some studies, whereas Keefe et al. discussed that fibres' effect on thermal conductivity would be noticeable when the content of fibres in the fabric is about 25% by mass [18]. Gomaa et al., discussed that the use of a wall with a gap that is filled with straw had a thermal conductivity of 0.32 W/m.K in comparison with 0.48 W/m.K for a solid wall section [19].

Distinct types of plant fibres and aggregates were studied in earthen construction literature and were categorised by Laborel-Preneron et al. into eight main categories as discussed in an inclusive review on plants aggregates and fibres in earthen construction materials [20]: (i) cereal straw; Wheat straw, barely straw, and oat straw (ii) wood aggregates; Wood shavings and wood fibres (iii) bast fibres; hemp fibre, hemp hurds, jute fibre, kenaf fibre, and diss fibre (iv) waste and residues: Cassava peel, millet residue, cotton residue, tea residue, tobacco residue and grass (v) leaf fibres; Sisal fibre, banana fibre, and pineapple fibre (vi) aquatic plant; Phragmite, Typha, and seaweed fibre (vii) wool; Sheep wool.

## 4. Discussion of cob mixes in literature

Several researchers have initiated investigations into the implications of utilising cob as a construction material [3,4,8,16,21,22]. Most of the studies have focused on improving the material's structural performance, while a limited number have concentrated on enhancing its hygrothermal performance. In this section, we will delve into these studies at the component level, examining the various ratios of cob's constituents that have been reported in the literature. A comprehensive analysis of the mixing ratios employed in previous research is presented in Table 1.

### 4.1. Sub-soil and binder ratios and granulometric characterisation

In studies [13,14,23,26,31], the structural and hygrothermal characteristics of the material are significantly influenced by the choice and preparation conditions of the soil used in the mixture. To minimise the carbon emissions produced during transportation, it is recommended that the soil be sourced locally.

Saxton's early paper on cob revealed that typical soil usually comprises 30% gravel, 35% sand, and 35% silt and clay [3]. Meanwhile, Alassaad et al. employed two types of soil in their research, with the first being categorised as low plasticity silt (ML) based on its Unified Soil Classification (UCS). It had a plasticity of 24% and a plasticity index of 3.6%. The second type of soil was classified as silty sand with gravel (SM), with a plasticity of 21% and a plasticity index of 2.7%. Both types of soil shared similar mineral components, including quartz, mica, feldspar, iron oxyhydroxides, and limonite, as reported in the same study [23].

Quagliarini et al. examined a historic cob structure and found that it comprised 34% clay, 17% sand, and 49% silt, with a plastic index of 19% and a liquid index of 38% [24]. The researchers also attempted to create a mixture with a similar composition, consisting of 36% clay, 13.5% sand, and 50.5% silt, with a plastic index of 21% and a liquid index of 42%. They subsequently used 3 kg of the newly formed soil in their cob mixture. In a separate study, Alhumayani et al. used 80 kg of subsoil [25].

Miccoli et al. employed a combination of materials consisting of 18% sand and gravel, 61% silt, and 21% clay [31,26,30]. Ben-Alon et al. utilized 257 kg of soil rich in clay, containing 50% clay for one square metre of cob with a thickness of 457 mm [4]. Medero et al. experimented with soil comprising 24.4% gravel, 19.7% coarse sand, and 32.5% fine sand [27]. Sangma and Tripura have conducted multiple studies to enhance the structural performance of cob, using a soil mix with 60.5% sand, 22.25% silt, and 14.25% clay and a plastic index of 11.43% [9,32].

Alqenaee and Memari have focused on creating a mixture that is optimised for stability and efficiency in 3D printing. In their study, they developed 36 different mixtures, out of which nine are described in Table 1. The mixtures varied in their clay content, which ranged from 38.53% to 52.63%, sand content between 11.11% and 17.73%, and lime content between 7.08% and 11.63%. Two of the mixtures, M30 and M31, contained cement to work as binders with values of 2.40% and 2.48%, respectively. Their final mixture, M36, consisted of 49% clay, 15.31% sand, and 10.00% lime [29]. Similarly, Gomaa et al. focused on developing a 3D printable mixture using soil that contained 19–20% clay and 80–81% aggregate/sand of the total mixture, which made up 73% of the final mixture [21].

Several standards have been employed in previous studies to determine soil properties and characteristics, which could also be used for future research. For instance, ISO 13320:2009 [44] and IS 2720 Parts 4, 5, and 7 [45] are commonly used. Additionally, Vinceslas et al. have described the methods they used to characterise the soil in their study, including the use of NF P 94-056 to assess particle size distribution [46], NF P 94-068 to determine absorption capacity [47], NF P 94-051 to determine plastic limit, liquid limit, and plastic index [48], NF P 94-093 to determine normal proportional water content and density of the main materials [49], NF P 94-050 to determine the specific gravity of the produced specimens [50], and ASTM D2487-11 to test soil characterisation [51].

### 4.2. Water content in mixes

Akinkurolere et al. have suggested that incorporating fibres into a cob mixture with high initial moisture content can improve its

**Table 1**
Matrix of mixes and ratios of studied cob mixtures.

| Test | | Soil | | | | Total Soil content | Additives | | | Water content | Fibres | Ref |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| # | Mix ID | Clay (%) | Silt (%) | Sand (%) | Gravel (%) | | Cement (%) | PCM kg/m$^3$ | Lime (%) | | | |
| 1 | Soil 0 | 15–25 | | 75–85 | | 78 % | – | – | – | 20% | 2% | [8] |
| 2 | Soil 0 | 35 | | 35 | 30 | – | – | – | – | 17–29% | 0%–3% | [3] |
| | Soil 1 | 4 | 76 | 17 | 3 | – | | | | | | |
| | Soil 2 | 1 | 13 | 51 | 35 | | | | | | | |
| 3 | Cob 0 | – | – | – | – | 1500 kg/m$^3$ | – | 0 | – | 375 kg/m$^3$ | 37.5 kg/m$^3$ | [23] |
| | Cob 2 | | | | | 1475 kg/m$^3$ | | 30.2 | | 368 kg/m$^3$ | 36.9 kg/m$^3$ | |
| | Cob 5 | | | | | 1450 kg/m$^3$ | | 74.3 | | 362 kg/m$^3$ | 36.3 kg/m$^3$ | |
| | Cob 10 | | | | | 1390 kg/m$^3$ | | 142.5 | | 347 kg/m$^3$ | 34.8 kg/m$^3$ | |
| 4 | Original soil | 34 | 49 | 17 | – | – | – | – | – | | | [24] |
| | Yellow soil | 36 | 50.5 | 13.5 | | 3 kg | | | | 28% | 0.02 kg | |
| 5 | Conventional Cob | | | | – | 78% | – | – | – | 20% | 2.0% Straw | [25] |
| | 3DP Cob | | | | | 73% | | | | 25% | 2.0% Straw | |
| 6 | Soil 0 | 21 | 61 | 18 | | | – | – | – | | 20–30 kg/m$^3$ | [26] |
| 7 | Soil 0 | | | | | 256 kg | – | – | – | 185 kg | 10.1 kg | [4] |
| 8 | Soil 0 | 20.6 | | 52.2 | 24.4 | 79.2% | – | – | – | 1.55% | 1.25% Straw | [27] |
| 9 | All Mixes Average | 14.25 | 22.25 | 60.5 | | | 3–10 | – | | 31.7–40 | 3–10% Straw 3–10% Coir | [9] |
| 10 | UK3 Soil | 12.83 | 68.93 | 17.8 | 0.44 | – | | | | | | [14] |
| | UK4 Soil | 5.59 | 58.64 | 16.74 | 19.03 | | | | | | | |
| | FR3 Soil | 12.85 | 65.43 | 12.36 | 9.36 | | | | | | | |
| | Soil 0 | UK3 | | | | | – | – | – | 65.6 | Hemp shiv: 50% | |
| | Soil 1 | UK3 | | | | | | | | 107.3 | Hemp shiv: 50% | |
| | Soil 2 | UK3 | | | | | | | | 107.3 | Hemp shiv: 25% | |
| | Soil 3 | UK3 | | | | | | | | 107.3 | Reed: 25% | |
| | Soil 4 | FR3 | | | | | | | | 131.3 | Reed: 25% | |
| | Soil 5 | FR3 | | | | | | | | 131.3 | Hemp shiv: 25% | |
| | Soil 6 | UK4 | | | | | | | | 62.1 | Reed: 25% | |
| | Soil 7 | UK4 | | | | | | | | 62.1 | Reed: 50% | |
| 11 | S1 | Three different French soils were used | | | | | – | – | – | 25 | Hemp straw: 5% | [16] |
| | S2 | | | | | | | | | 28 | Hemp straw: 5% | |
| | S3 | | | | | | | | | 28 | Hemp straw: 2.5% | |
| | S4 | | | | | | | | | 28 | Flax straw: 2.5% | |

(*continued on next page*)

**Table 1** (*continued*)

| Test | | Soil | | | | Total Soil content | Additives | | | Water content | Fibres | Ref |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| # | Mix ID | Clay (%) | Silt (%) | Sand (%) | Gravel (%) | | Cement (%) | PCM kg/m$^3$ | Lime (%) | | | |
| | S5 | | | | | | | | | 31 | Flax straw: 2.5% | |
| | S6 | | | | | | | | | 31 | Wheat straw: 2.5% | |
| | S7 | | | | | | | | | 31 | Reed: 2.5% | |
| | S8 | | | | | | | | | 31 | Wheat straw: 5% | |
| | I1 | | | | | | | | | 131 | Reed: 25% | |
| | I2 | | | | | | | | | 131 | Hemp shiv:25% | |
| 12 | Soil 0 | 3 | 18 | 42 | 37 | – | – | – | – | – | 0.9% Straw (by mass) | [28] |
| 13 | Soil 0 | – | – | – | – | – | – | – | – | 33–47 | Rice straw that varies from 0.6% to 3% | [22] |
| 14 | S3 | FR2 soil | | | | | – | – | – | 28.5 | 2.5% hemp straw | [15] |
| | T1 | UK 3 soil | | | | | | | | 107.3 | 25% hemp shiv | |
| 15 | WF | 8 | 47 | 45 | | 100 kg | – | – | – | 19 | 0% | [12] |
| | FL-1% | | | | | 100 kg | | | | 23 | 1% Flax yarn | |
| | HA-1% | | | | | 100 kg | | | | 24 | 1% Hay stalk | |
| | HE-1% | | | | | 100 kg | | | | 25 | 1% Hemp shiv | |
| | FL-3% | | | | | 100 kg | | | | 24 | 3% Flax yarn | |
| | HA-3% | | | | | 101 kg | | | | 23 | 3% Hay stalk | |
| | HE-3% | | | | | 100 kg | | | | 23 | 3% Hemp shiv | |
| 16 | Soil 0 | 19–20 | | 80–81 | | 73 | – | – | – | 22, 24, 26, and 28 | 2% Straw | [17] |
| 17 | Soil 0 | 19–20 | | 80–81 | | 73 | – | – | – | 25 | 2% Straw | [21] |
| 18 | M23 | 50.51 | | 11.11 | | | | | 10.1 | 28.28 | – | [29] |
| | M25 | 52.63 | | 11.58 | | | | | 7.37 | 28.42 | | |
| | M26 | 46.51 | | 12.79 | | | | | 11.63 | 29.07 | | |
| | M27 | 49.78 | | 14.6 | | | | | 7.08 | 28.54 | | |
| | M28 | 48.39 | | 14.19 | | | | | 9.68 | 27.74 | | |
| | M30 | 38.53 | | 17.12 | | | 2.40% | | 7.71 | 34.25 | | |
| | M31 | 39.89 | | 17.73 | | | 2.48% | | 7.98 | 31.91 | | |
| | M34 | 51.23 | | 16.01 | | | | | 7.47 | 25.29 | | |
| | M34 w/straws | 50.69 | | 15.84 | | | | | 7.39 | 25.03 | 1.06% | |
| | M36 | 49 | | 15.31 | | | | | 10 | 24.19 | 1.50% | |
| 19 | Soil 0 | 21 | 61 | 18 | | | | | | 24 | 1.7% Wheat straw | [30] |

strength by promoting better bonding and homogeneity among the mixture's constituents [22].

Table 1 demonstrates that mixtures that are designed for structural purposes have a significantly lower water content compared to mixtures that are designed to be hygrothermally efficient. Hence, the initial water content for structural mixtures ranges between 19% and 40%. Whereas the mixtures optimised for hygrothermal testing had an initial water content with a range between 62.1% and 131.3%. This variation in ratios is yet to be fully studied and researched to understand the precise implications on water addition for the mixture on its performance [14,16].

Alassaad et al. have specified the proportional factor of water to soil as 0.3 [23]. Similarly, Alhumayani et al. used 20 kg of water, resulting in a ratio of 1:4 for soil content in the mixture [25]. This is consistent with Weismann and Bryce's recommendation of a water-to-subsoil ratio of 1:4 [35]. To determine the water content in cob specimens, researchers such as Vinceslas et al. used the French standard NF P 94-050 [50], after drying the specimens at 105 °C [28].

While most papers have focused on casting cob, others have worked on investigating the feasibility of 3D printing the material. The amount of water in the mixture is a key consideration for 3D printing, as it must be consistent and stable while also being viscous enough to be extruded through the nozzle. In 2021, Gomaa et al. worked on developing an extrusion system for 3D printing cob. The authors experimented with different water content concentrations in the mixture (22%, 24%, 26%, and 28%), and concluded that the optimal water content was 25% [17]. Similarly, Alqenaee and Memari also experimented with water contents ranging from 24.19% to 34.25% [29]. Gomaa et al. observed that the extrusion process slightly reduced the moisture content of the final printed cob due to pressurization of the mixture inside the extrusion system, which caused moisture release in the form of leakage around the cartridge connections [17,21].

### 4.3. *Fibres and aggregates in cob mixtures*

In analysing a material such as cob, it is crucial to consider both the fibre content ratios and fibre type, as they play a vital role in affecting the structural, hygrothermal, and environmental performance. A variety of fibre types have been studied in the current literature, including seaweed fibre, sheep wool, and tobacco residue grass [52–54]. Researchers in different studies have utilized distinct types of straw, including hemp straw, flax straw, wheat straw, paddy straw, and rice straw. Additionally, some studies have used other aggregates in their mixes, such as coconut coir [9,32], hemp shives [12,14–16], and reed [14,16].

The use of fibres and added aggregates in cob mixtures has been extensively researched due to their impact on the mix's performance. In many studies, the fibre content ranged from 0.6% to 3%. For example, Alassaad et al. used 2.5% flax straw of the dry soil mass [23], while Ben-Alon et al. added 10.1 kg of wheat straw to 256 kg of clay-rich soil, resulting in a calculated soil/fibre proportional factor of 0.039 [4]. In a study that focused on optimising cob for better insulation and thermal performance, Goodhew et al. added a higher amount of fibre within different mixes in aim to improve the thermal performance of the wall section [14].

Zeghari et al. created eight mixtures using hemp straw, flax straw, wheat straw, and reed, which were optimised to improve structural performance [16]. Additionally, two mixes were developed for the insulation part of the dual-system wall, using hemp shiv and reed.

Within reviewed studies, it has been observed that fibre lengths have varied from 20 mm to 300 mm, with shorter fibres showing better performance as they tend to blend in the mix more easily, resulting in a homogeneous cob mixture. Sangma and Tripura conducted a systematic comparative analysis to evaluate the structural performance of cob mixtures containing coconut coir and straw fibres, and they concluded that coconut coir outperforms straw fibres in enhancing the structural performance [9,32].

## 5. Discussion of structural performance of cob

Although cob has a lower compressive strength than other earthen materials, it has relatively good shear properties [30]. During the drying process, cob gains compressive strength while its tensional strength comes from the presence of organic fibres, which help to maintain its structural integrity [55]. Moreover, cob has the ability to withstand stress even after the peak stress has passed, and it can deform beyond the elastic range with a gradual reduction in capacity [17,26].

Numerous studies have extensively explored the structural capabilities of cob to adapt this construction material to the current global building regulations. Various laboratory tests that were conducted on cob specimens assessed the specimens' compressive strength, tensile strength, elastic modulus and Poisson's ratio, shear and flexural strengths, shrinkage, and cracking levels. This section of the review will describe the various testing methods and their outcomes in the analysed studies. Table 2 presents the different structural tests of analysed research.

### 5.1. *Compressive & tensile strength tests*

#### 5.1.1. *Compressive strength test*

As cob known for being a compressive material several studies have investigated the compressive strength of the material for multiple mixtures. Vinceslas et al. worked on four fibred cob wall elements that were manufactured in accordance with Brittany's vernacular cob process case (a) of the classification proposed by Hamard et al. [56]. The study demonstrated that the compressive strength from UCS test of the cob wall elements were higher than the ones of the other types. Besides, the study showed a correlation between having a high specimen density and receiving higher UCS values and therefore lower stiffness values. The compressive strength results of this study were between 0.50 MPa and 0.76 MPa [28].

A study by Miccoli et al. who performed compressive tests on four mixtures by following EN 1052-1 (CEN 1998) [57] with a test speed of 0.25 mm/min to reach the failure after 15–30 min. The results varied between 1.55 MPa and 1.63 MPa and an average of 1.59 MPa [26,30]. Saxton have studied the compressive strength of cob mixtures and their moisture content where mixtures that had a water content of 15% recorded 0.35 MPa and 1.75 MPa. Weismann and Bryce obtained a value of 0.77 MPa [3].

Sangma and Tripura have followed IS 4332 Part 5 [58] and performed the compressive strength test on a number of mixtures that

**Table 2**
A matrix of the structural tests of analysed research.

| Test | | Compression Strength Test (MPa) | Test Type | Tensile Strength Test (MPa) | Shear Strength Test | | | Elastic Modulus (MPa) | Vertical Strain | Poisson's Ratio | Shrinkage | Ref. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| # | Mix ID | | | | Shear Strength (MPa) | Shear Modulus (MPa) | Shear Strain | | | | | |
| 1 | CDA | 0.67 | Uniaxial | – | – | – | – | 100 | – | – | 0.92 | [28] |
| | SRO | 0.5 | Uniaxial | – | – | – | – | 345 | – | – | 1.7 | |
| | SDA | 0.64 | Uniaxial | – | – | – | – | 320 | – | – | 1.15 | |
| | SDO | 0.6 | Uniaxial | – | – | – | – | 320 | – | – | 1.2 | |
| | Wall | 0.76 | Uniaxial | – | – | – | – | 260 | – | – | 2.1 | |
| 2 | CWUC_1 | 1.6 | Axial | – | – | – | – | 988 | – | 0.13 | – | [30] |
| | CWUC_2 | 1.63 | Axial | – | – | – | – | 1084 | – | 0.11 | – | |
| | CWUC_3 | 1.58 | Axial | – | – | – | – | 1036 | – | 0.23 | – | |
| | CWUC_4 | 1.55 | Axial | – | – | – | – | 977 | – | 0.09 | – | |
| | DWUC_1 | – | – | – | 0.37 | 311 | 2.04 | – | – | – | – | |
| | DWUC_2 | – | – | – | 0.46 | 343 | 1.07 | – | – | – | – | |
| | DWUC_3 | – | – | – | 0.47 | 375 | 0.8 | – | – | – | – | |
| | DWUC_4 | – | – | – | 0.56 | 462 | 0.87 | – | – | – | – | |
| | DWUC_5 | – | – | – | 0.63 | 634 | 0.74 | – | – | – | – | |
| | DWUC_6 | – | – | – | 0.37 | 455 | 0.56 | – | – | – | – | |
| | DWUC_7 | – | – | – | 0.64 | 421 | 0.98 | – | – | – | – | |
| 3 | 0 | 1.59 | Uniaxial | – | 0.5 | 420 | 0.041 | 651 | 0.12 | 0.15 | – | [31] |
| 4 | 0 | 0.52–2.2 | – | – | – | – | – | – | – | – | – | [22] |
| 5 | USCEB | 1.31 (D) 0.00(W) | Axial | 0.11 | – | – | – | – | 0.012 | – | 1.23 | |
| | 3CSCEB | 1.40 (D) 0.55 (W) | Axial | 0.13 | – | – | – | – | – | – | 0.83 | |
| | 5CSCEB | 1.47 (D) 0.85 (W) | Axial | 0.14 | – | – | – | – | – | – | 0.63 | |
| | 7CSCEB | 1.78 (D) 1.05 (W) | Axial | 0.19 | – | – | – | – | – | – | 0.56 | |
| | 10CSCEB | 3.18 (D) 1.99 (W) | Axial | 0.31 | – | – | – | – | 0.028 | – | 0.48 | |
| | 3CFRCEB | 1.35 (D) 0.00 (W) | Axial | 0.48 | – | – | – | – | – | – | 0.93 | |
| | 5CFRCEB | 1.74 (D) 0.18 (W) | Axial | 0.75 | – | – | – | – | 0.08 | – | 0.75 | |
| | 7CFRCEB | 1.7 (D) 0.00 (W) | Axial | 0.72 | – | – | – | – | – | – | 0.52 | |
| | 10CFRCEB | 1.60 (D) 0.12 (W) | Axial | 0.7 | – | – | – | – | – | – | 0.4 | [32] |
| | 3SFRCEB | 1.30 (D) 0.00 (W) | Axial | 0.29 | – | – | – | – | – | – | 0.81 | |
| | 5SFRCEB | 1.38 (D) 0.11 (W) | Axial | 0.35 | – | – | – | – | 0.056 | – | 0.71 | |
| | 7SFRCEB | 1.28 (D) 0.00 (W) | Axial | 0.32 | – | – | – | – | – | – | 0.56 | |

(*continued on next page*)

**Table 2** (*continued*)

| Test | | Compression Strength Test (MPa) | Test Type | Tensile Strength Test (MPa) | Shear Strength Test | | | Elastic Modulus (MPa) | Vertical Strain | Poisson's Ratio | Shrinkage | Ref. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| # | Mix ID | | | | Shear Strength (MPa) | Shear Modulus (MPa) | Shear Strain | | | | | |
| | 10SFRCEB | 1.25 0.00 (W) | Axial | 0.3 | – | – | – | – | – | – | 0.43 | |
| 6 | 1 | 0.88 | Axial | – | – | – | – | 22.7 | 0.04 | 0.16 | – | [21] |
| | 2 | 0.83 | Axial | – | – | – | – | 25.3 | 0.05 | 0.28 | – | |
| | 3 | 0.89 | Axial | – | – | – | – | 20.6 | 0.061 | 0.21 | – | |
| 7 | 3DP4C8D | 0.3994 | – | 0.08 | – | – | – | – | – | – | – | [29] |
| | 3DP3C14D | 0.5958 | – | 0.12 | – | – | – | – | – | – | – | |
| | 3DP3C21D | 0.7297 | – | 0.14 | – | – | – | – | – | – | – | |
| | 3DP3C28D | 0.8125 | – | 0.14 | – | – | – | – | – | – | – | |
| | C3C14D | 0.0625 | – | 0.01 | – | – | – | – | – | – | – | |
| | C3C21D | 0.3072 | – | 0.07 | – | – | – | – | – | – | – | |
| | C3C28D | 0.4116 | – | 0.09 | – | – | – | – | – | – | – | |
| 8 | 0 | 0.1 | – | – | – | – | – | – | – | – | – | [33] |
| 9 | 0 | 0.35–1.75 (mc < 15%)<br>0–0.2 (mc > 15%) | – | – | – | – | – | – | – | – | – | [3] |
| 10 | 0 | 0.48–1.24 | – | – | – | – | – | 0.33–1.25 | – | – | – | [34] |
| 11 | 0 | 0.6–1.4 | – | – | – | – | – | – | – | – | – | [18] |
| 12 | 0 | 0.77 | – | – | – | – | – | – | – | – | – | [35] |
| 13 | 0 | 0.24–0.40 (mc > 15%) | – | – | – | – | – | 4.0–40 | – | – | – | [24] |
| 14 | 0 | 0.45–0.89 (22%) | – | – | – | – | – | 11–69 | 0.03 | – | – | [36] |
| 15 | 0 | 0.5–5.0 | – | – | – | – | – | 60–850 | – | – | – | [37] |
| 16 | 0 | 0.60 (13%) | – | – | – | – | – | 71.5 | – | – | – | [38] |
| 17 | 0 | 0.71–0.87 (8%–15%) | – | – | – | – | – | | – | – | – | [39] |
| 18 | 0 | 1.12 (5%) | – | – | – | – | – | 16.9 | – | 0.12 | – | [40] |
| 19 | 0 | 1.22–1.53 (18%–21%) | – | – | – | – | – | – | – | – | – | [41] |
| 20 | 0 | 0.70 (12%) | | | | | | 143 (23%) | | | | [42] |

varied in fibre and binder type and content. For cement stabilised samples, the values ranged between 1.35 MPa and 2.98 MPa [32]. Specimens with coconut coir fibre were 1.25 MPa–1.63 MPa while the ones with straw fibre varied between 1.18 MPa and 1.34 MPa [9]. Akinkurolere et al. have received values between 0.6 MPa and 2.2 MPa which is slightly higher than the results of Keefe with 0.6 MPa and 1.4 MPa [22]. Wright has retrieved values between 1.22 MPa and 1.53 MPa for mixtures that varies in straw content and 0.77 MPa and 2.45 MPa for samples with varied soil-clay content [41]. Meanwhile Guillaud and Houben (1994) and Quagliarini et al. (2010) have received lower compressive strength results of 0.10 MPa and 0.24 MPa–0.40 MPa [24,33]. Miccoli et al. by following DIN 18945 [59] have received a mean compressive strength of 1.59 MPa with a standard deviation of 0.03 MPa [30].

Sangma and Tripura have examined the specimens by following IS 5816 standards. Accordingly, for cement stabilised units the tensile strength was between 0.13 MPa and 0.31 MPa. For specimens that had coir, the results ranged between 0.48 MPa and 0.75 MPa, meanwhile, for specimens with straw fibre the results were in the range of 0.29 MPa and 0.35 MPa [32].

Gomaa et al. performed the compressive strength test on three samples that were 3D printed using a robotic arm where the results were between 0.83 MPa and 0.89 MPa where the test specimens were subjected to uniform axial load in a universal testing machine and a rate of applied load equals to 0.08 MPa/min [21].

#### 5.1.2. Tensile strength tests

A study by Alqenaee and Memari following the ASTM-C496/C496 M [60] on cylindrical specimens have resulted in values ranging between 0.083 MPa and 0.145 MPa for 3D printed specimens compared to 0.014 MPa and 0.090 MPa for casted specimens. The authors have assumed the lower values of cast as the result of the insufficiency of drying time of 14 days in moulds [29].

### 5.2. Elastic modulus and poison's ratio

#### 5.2.1. Elastic modulus

Several papers have determined the values of the elastic moduli where it was ranging between 0.33 MPa and has reached high values up to 850 MPa. Ziegert obtained values between 170 MPa and 335 MPa. Coventry obtained values between 0.48 MPa and 1.24 MPa with CoV 3% TO 10% [34].

Quagliarini et al. determined values between 4.0 MPa and 40 MPa [24] while Pullen and Scholz's results varied between 11 MPa and 69 MPa [36] and Minke's study recorded results varying between 60 MPa and reached a high value of 850 MPa [37]. Miccoli et al. study resulted in an elastic modulus value of 651 MPa with CoV of 68% [30]. A distinct study by Rizza and Bottger recorded a value of 71 MPa [38]. Quagliarini and Maracchini values were 16.9 MPa with CoV of 4% whereas Vinceslas et al. specimen's results were between 110 MPa and 350 MPa [40]. Gomaa et al. with their investigation with 3D printed specimens have reported a mean value of 22.9 MPa with CoV 10% where the highest value was 25.3 MPa [21].

#### 5.2.2. Poisson's ratio

An extremely limited data was found on Poisson's ratio within current literature. Miccoli et al. using video recording analysis by a photogrammetric camera system reported a mean value of 0.15 with a standard deviation of 0.04 [26]. Miccoli et al. determined the Poisson's ratio for 4 samples where the values varied between 0.09 and 0.23 [31]. Another study by Quagliarini and Maracchini found a value of 0.12 [40]. Gomaa et al. study recorded values between 0.16 and 0.28 with a mean of 0.22 [21].

### 5.3. Shear and flexural strength tests

#### 5.3.1. Shear strength tests

Miccoli et al. have investigated shear strengths, shear modulus, and shear strain of different earthen materials. The mean result of shear strength of cob was 0.50 MPa with a standard deviation of 0.10 MPa, the mean shear modulus $G_{1/3}$ was found to be 420 MPa with a standard deviation of 137 MPa, and the test resulted in a mean shear strain $\gamma_{1/3}$ of 0.041% with a standard deviation of 0.006% [30]. These results were obtained by following ASTM E 519-10 [61] where to induce shear forces, the specimens were rotated 45° about the centre axis with one sample being diagonal parallel to the loading direction and the other perpendicular. Loading shoes were used to apply stress on the testing specimens, and they were positioned between the jack and the specimen's corner. Additionally, a photogrammetric camera system (ARAMIS) was used to measure the two-dimensional deformation of a few chosen specimens during the test.

#### 5.3.2. Flexural strength tests

Alqenaee and Memari, by following the procedure of ASTM-C293/C293 M [62], to determine the modulus of rupture for a 3D printed and casted cob beam. The results of a 3D printed curved cob beams were 0.359 MPa 21 days after printing and 0.407 MPa after 28 days after printing the beam. The results for 3D printed straight cob beams were 0.124 MPa, 0.552 MPa, 0.786 MPa, and 0.903 MPa measured 7, 14, 21, and 28 days after of printing, respectively. On the other hand, cast cob beams have recorded lower results of 0.014 MPa, 0.041 MPa, 0.159 MPa, and 0.269 MPa measured 7, 14, 21, and 28 days of casting, respectively due to the insufficiency of drying time in moulds [29].

### 5.4. Shrinkage and cracking in cob

Due to the water loss during the drying process, the soil experiences a volumetric contraction or shrinkage that results in cracking which might affect the structural stability and the structural performance of the cob structure. Typically, fibre and water content are the most influential factors that would affect the severity of the shrinkage levels. Saxton has discussed that the mixes that contained the most straw and required the most water to provide a suitable mix tended to shrink the most [3]. Besides, the size of soil particles also has a significant effect on controlling the shrinkage levels [30].

Sangma and Tripura have thoroughly explored the effect that fibre content and drying temperature would have on the shrinkage levels while considering the moulding water content [9] (see Figs. 3-6). For their study, the authors have used IS 2720 Part 20 [45], in order to assess the linear shrinkage of the tested specimens. The study has concluded that unstabilised cob the average linear shrinkage

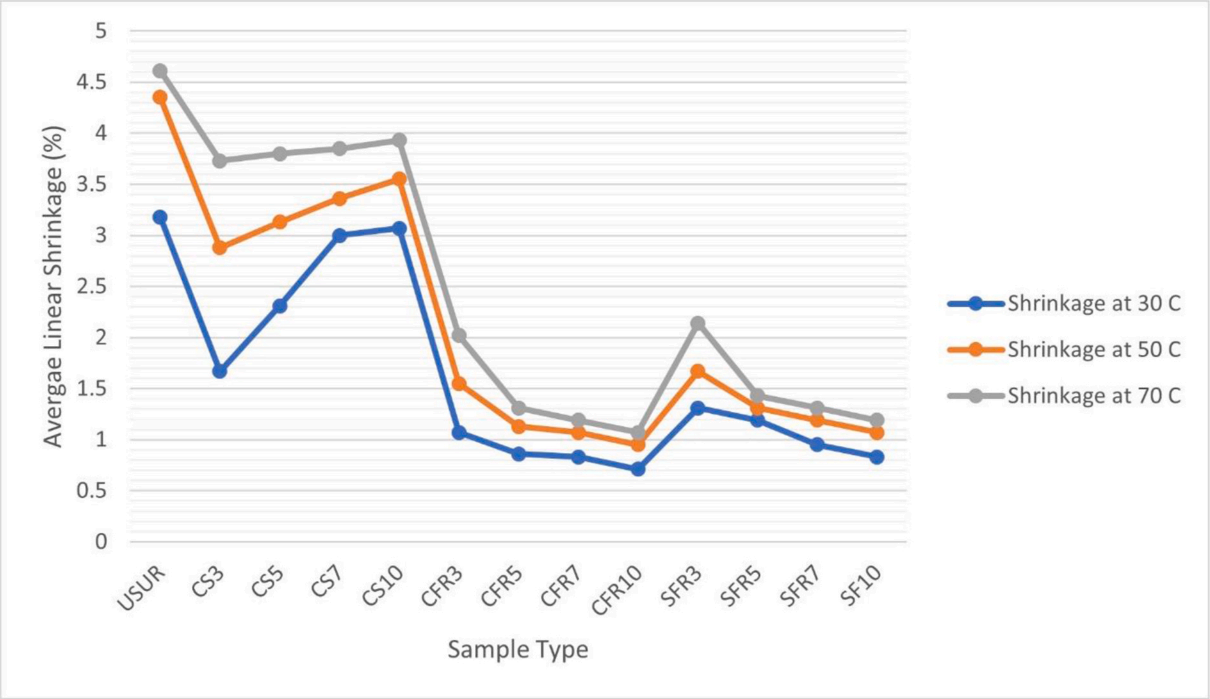

**Fig. 3.** The calculated average linear shrinkage for cob mixtures with different types and proportions of aggregates at different drying temperature at initial water content of 31.7% based on [9].

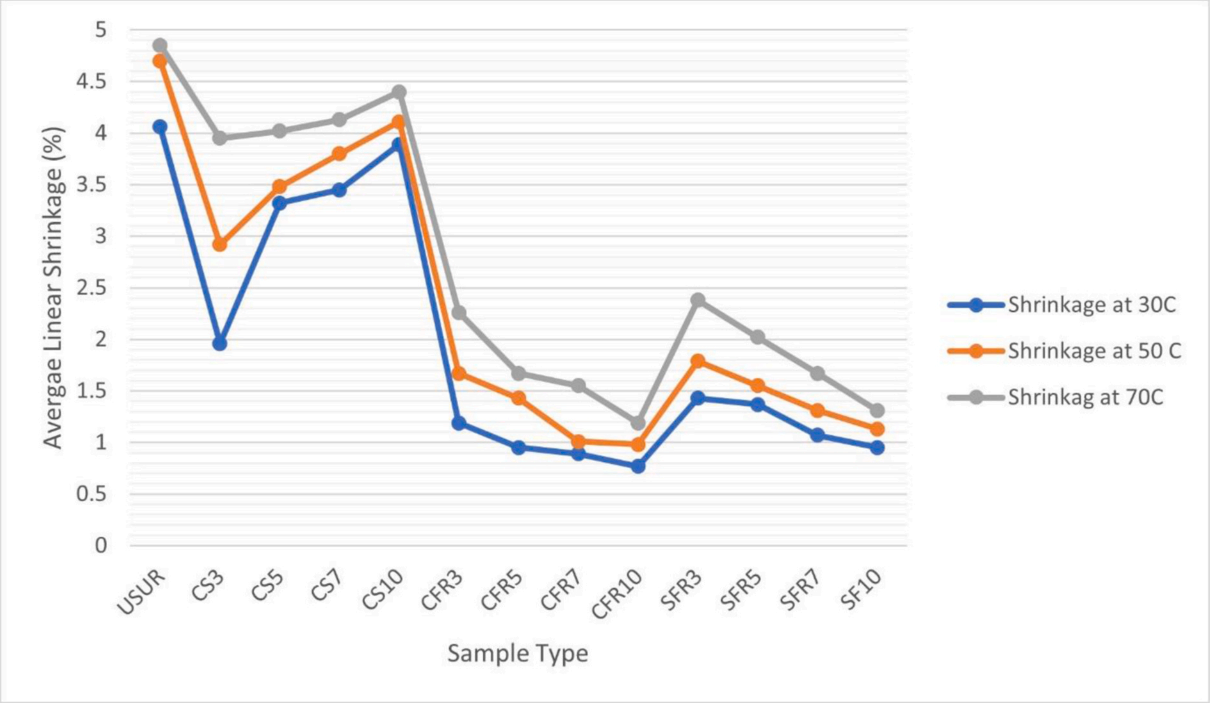

**Fig. 4.** The calculated average linear shrinkage for cob mixtures with different types and proportions of aggregates at different drying temperature at initial water content of 33.7% based on [9].

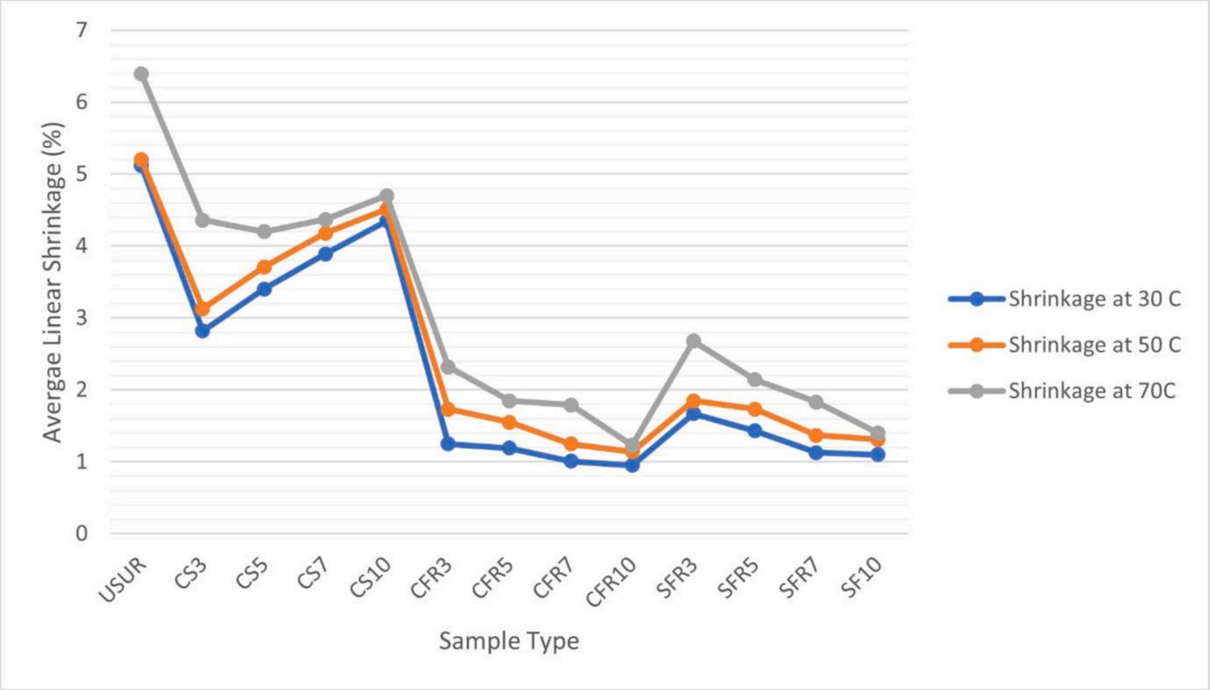

**Fig. 5.** The calculated average linear shrinkage for cob mixtures with different types and proportions of aggregates at different drying temperature at initial water content of 35.7% based on [9].

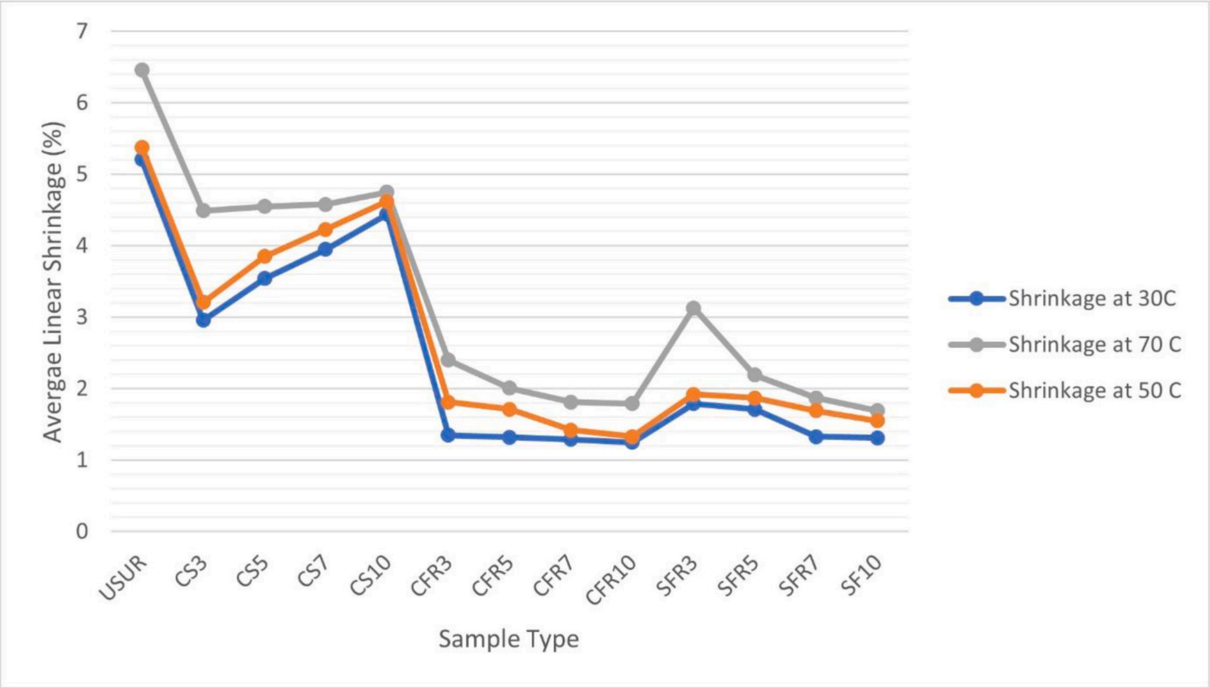

**Fig. 6.** The calculated average linear shrinkage for cob mixtures with different types and proportions of aggregates at different drying temperature at initial water content of 40% based on [9].

was ranging from 3.18% at 30 °C and 31.7% of moulding water content to 6.46% at 70 °C and 40% moulding water content. Meanwhile, adding 3% of coir reduced the linear shrinkage levels to 1.07% at 30 °C and 31.7% moulding water content and recorded

1.23% at 70 °C and 40% mould water content. For samples that had a straw content of 3% the value was 1.31% at 30 °C and 40% moulding water content and was reported to be 1.69% at 10% of fibre content and at 70 °C and 40% of moulding water content.

According to a study by Tchiotsop et al. the volumetric shrinkage was found to be 13.07 ± 0.12% for unfibred materials; 17.13 ± 0.96% and 16.44 ± 0.18% for 1% and 3% flax yarns composites respectively; 16.89 ± 2.41% and 11.57 ± 0.12% for 1% and 3% hemp shives composites; 13.69 ± 2.02% and 5.13 ± 0.45% for 1% and 3% hay stalks composites [12]. For 3D printed mixtures, Gomaa et al. have reported that the printed layers have impacted the shrinkage of the specimens where it was approximately 2% [21].

Vinceslas et al. have followed the protocols by Hamard et al. for cob construction worked on finding shrinkage ratio by dividing the vertical shrinkage over the horizontal shrinkage for the different samples where the highest ratio was for the cob wall while the lowest was for CDA [28].

## 6. Discussion of hygrothermal performance of cob

Primarily, the investigation of the hygrothermal properties of materials has become a critical aspect of understanding occupant's comfort [63,64]. Research has explored the hygroscopic and thermal efficiency of earthen materials [12,63,65,66]. It has been found that using a natural material that is able to moderate and regulate the temperature and humidity passively, can contribute to a reduction in heating and cooling energy footprints by up to 5% and 30% respectively [67,68].

Due to the significance of indoor humidity control, numerous researchers [67,69–72] have investigated the application of different hygroscopic materials to regulate indoor humidity levels. These investigations, encompassing laboratory experiments, field trials, and numerical analyses, have demonstrated the effectiveness of hygroscopic materials in moderating indoor humidity levels. Consequently, they enhance thermal comfort and perceived air quality within buildings, whilst maintaining low energy consumption [73].

This section of the review will describe the different tests conducted and the hygrothermal performance of cob, including porosity, bulk density, thermal conductivity, water vapor permeability, moisture buffering value, and moisture sorption isotherm. The various hygothermal tests discussed in this section are listed in Table 3.

### 6.1. Porosity tests

Earth, being an unsaturated and porous material, has an impact not only on the hygrothermal but also on the structural performance of cob. The young modulus of raw earth ranges between 1 GPa and 5.5 GPa, with higher porosity resulting in higher young's modulus values [74]. Goodhew et al. investigated the relationship between adding fibres to cob mixtures and the resulting porosity. The study found that adding fibres increased porosity because fibres are considered materials with high porosity [14].

Tchiotsop et al. have shown the distribution curves of materials for several fibre contents, including the differential distribution curve and the cumulative distribution curve. The modal porosity for the 1% fibre mixtures is consistent at 2 μm, indicating that the

**Table 3**
A matrix of the hygrothermal tests of analysed research.

| Test | | Density (kg/m$^3$) | λ (W/m.K) | Water Vapor Permeability (kg/m s Pa) | MBV (g m$^{-2}$ % RH$^{-1}$) | Moisture Sorption Isotherm (%) RH 12%–90% | | Ref |
|---|---|---|---|---|---|---|---|---|
| # | Mix ID | | | | | Adsorption | Desorption | |
| 1 | 0 | 1200–2000 | 0.47–0.93 | – | – | – | – | [37] |
| 2 | UK3 50% Shiv Dry (D) | 398.73 | 0.12 | – | – | – | – | [13, 14] |
| | UK3 50% Shiv Wet (W) | 426.82 | 0.13 | – | – | – | – | |
| | UK3 25% Shiv (W) | 702.78 | 0.2 | – | – | – | – | |
| | UK3 25% Reed (W) | 684.1 | 0.18 | – | – | – | – | |
| | FR3 25% Reed (W) | 637.92 | 0.16 | – | – | – | – | |
| | FR3 25% Shiv (W) | 654.54 | 0.18 | – | – | – | – | |
| | UK4 25% Reed (W) | 664.6 | 0.18 | – | – | – | – | |
| | UK4 35% Reed (W) | 542.87 | 0.14 | – | – | – | – | |
| 3 | Hemp straw 5% | 1520 | 0.57 | – | – | – | – | [16] |
| | Hemp straw 2.5% | 1530 | 0.74 | – | – | – | – | |
| | Flax straw 2.5% | 1460 | 0.42 | – | – | – | – | |
| | Reed 2.5% | 1540 | 0.36 | – | – | – | – | |
| | Wheat straw 2.5% | 1320 | 0.32 | – | – | – | – | |
| | Wheat straw 5% | 1120 | 0.24 | – | – | – | – | |
| | Reed 25% | 780 | 0.2 | – | – | – | – | |
| | Hemp Shiv 25% | 955 | 0.22 | – | – | – | – | |
| 4 | WF | 1846 | 1.08 | $9.13 \times 10^{-12}$ | 1.06 | 0.62–2.17 | 0.66–2.79 | [12] |
| | FL-1% | 1841 | 1.06 | $8.69 \times 10^{-12}$ | | 0.74–2.75 | | |
| | Ha-1% | 1749 | 0.92 | $1.32 \times 10^{-11}$ | 1.73 | 0.71–2.78 | 0.81–3.52 | |
| | He-1% | 1709 | 0.91 | $1.14 \times 10^{-11}$ | 1.73 | 0.85–3.42 | 0.77–3.49 | |
| | Fl-3% | 1733 | 0.95 | $6.48 \times 10^{-11}$ | 1.68 | – | – | |
| | Ha-3% | 1471 | 0.7 | $1.05 \times 10^{-11}$ | 1.54 | 0.95–2.67 | 0.68–3.11 | |
| | He-3% | 1537 | 0.7 | $1.05 \times 10^{-11}$ | 1.74 | – | – | |
| 5 | Straw | – | – | $2.33 \times 10^{-11}$ | – | – | – | [43] |

earth matrix is well-represented in the mixtures. However, the samples with 3% hay stalks have a diverse range of pores textures and a uniform distribution, which could lead to an increase in the number of characteristics associated with fibre content [12].

### 6.2. *Bulk density of specimens*

Zeghari et al.'s study resulted in a density range between 1107 kg/m$^3$ and 1583 kg/m$^3$ for structural walls, while the density of insulation walls was less than 700 kg/m$^3$ [16]. Tchiotsop et al. have studied the effect of plant add-ons on the hygric and thermal performance of cob buildings [12].

Miccoli et al. used DIN 18945 (DIN 2013a) [59] to obtain a bulk density of 1475 kg/m$^3$ after drying their specimens [31]. Sangma and Tripura found that unstabilised cob mixtures had a density of 1690 kg/m$^3$. For cement-stabilised samples, the density varied between 1710 kg/m$^3$ for 3% cement content and 1780 kg/m$^3$ for 10% cement content. When 3% coir was added, the density was 1650 kg/m$^3$ and it reached 1630 kg/m$^3$ when the added content was 10%. Straw samples had a density of 1640 kg/m$^3$ with 3% sand and 1610 kg/m$^3$ when 10% was added [32]. The bulk density reported by Miccoli et al. was 1475 kg/m$^3$, which aligns with other studies and literature that showed density variation between 1200 kg/m3 and 1700 kg/m$^3$ [31].

### 6.3. *Thermal conductivity*

Laurent et al. conducted a study and reported that the thermal conductivity of cob had an average value of 0.45 W/m.K, while Minke's study resulted in a range of 0.47 W/m.K to 0.93 W/m.K [37]. Goodhew et al. used a Netzsch HFM446 heat flow meter (HFM) to measure thermal conductivity (λ) and made eight different cob mixes using three different soils (UK3, UK4, and FR3) to investigate the structural and hygrothermal performance of a dual cob wall [14].According to Zeghari et al., a mixture with a thermal conductivity of 0.4 W/m.K could have improved insulation due to its low density [16]. The researchers of the study assessed the local thermal conductivity of the tested mixture by measuring the average thermal conductivity based on the distribution of fibres within the specimen. To ensure the accuracy of the measurements, a highly conductive thermal paste was applied between the upper cooling brass plate and the lower heating brass plate since the rough texture of the samples' surfaces could have affected the readings. In the dual wall system, the structural samples with 5% wheat straw had the lowest thermal conductivity of 0.244 W/m.K, while the highest value of 0.75 W/m.K was recorded for 2.5% small fibre content. The insulation section of the system had the highest recorded value of 0.19 W/m.K [16].

Tchiotsop et al. conducted a study on various cob specimens with different plant aggregates added to the mixture. To determine the thermal conductivity of the mixtures, the authors used a hot disk device. The results showed that the mixtures without any added fibre had a thermal conductivity of 0.062 W/m.K. Among the mixtures with added fibre, the highest thermal conductivity was recorded for 3% hemp shiv with 0.079 W/m.K, while the lowest value was observed for 3% flax yarn with a thermal conductivity of 0.031 W/m.K [12].

### 6.4. *Water vapor permeability*

Water vapor permeability ($k_m$) or vapor diffusion in a building is responsible for the ability to allow moisture exchange between the indoor and outdoor surfaces of the building [66]. A higher permeability value indicates a better exchange, which is characterized by the water vapor resistance factor (μ). This factor is calculated by dividing the permeabilities of air and the sample by water vapor, and the higher the value of this factor, the more difficult it is for moisture to be exchanged [66,75]. EN ISO 1015-19 [76] outlines various methods for measuring permeability.

Tchiotsop et al. utilized the NF EN ISO 12572:2016 Standard's dry cup test [77] to evaluate km both manually and automatically. Their Gravitest results of vapor transmission produced a global CV (coefficient of variation) of 11%, with specimens lacking fibre having a CV 12% higher than manual DCT. Manual DCT resulted in CVs of 50% and 56% for composites containing 1% hemp shiv and 1% flax yarn, while Gravitest yielded CVs of 7% and 14%. For 3% hemp shiv and 3% flax yarn, lower values (19% and 27%, respectively) were observed using manual DCT. A modest 11% increase in CV was noted for hay stalk composites using manual DCT [12].

Alassaad et al. also investigated water vapor permeability using the ISO 12572 standard [77], but they preconditioned all samples to a temperature of 23 °C and a relative humidity (RH) of 50%. This created a moisture gradient from around 0% RH on the inside to an approximate RH of 50% on the outside. In another study by Stazi et al., the effectiveness of coatings in protecting earthen walls against weathering was evaluated and the water vapor permeability was experimentally determined to be 2.33 E$^{-11}$ kg/m/s/Pa [43]. Other researchers, such as Collet-Foucault, reported that the average permeabilities obtained at 23 °C are between 1.5 E$^{-11}$ kg/m/s/Pa and 1.7 E$^{-11}$ kg/m/s/Pa [78].

### 6.5. *Moisture buffering value (MBV)*

The moisture buffering value is a principal factor that assess a material's capacity to uptake and release moisture [66]. Tchiotsop and colleagues created specimens using PVC moulds measuring 110 × 40 mm and conditioned them to 20 °C and 50% relative humidity following the NORDTEST protocol. The specimens were tested in a climate chamber at 23 °C and subjected to a daily humidity cycle of 75% RH for 8 h and 33% RH for 16 h. The specimens were weighed regularly during the adsorption and desorption cycles, and the MBV was calculated by dividing the mean mass variation of the last two cycles by the specimen's exchange surface (A) and the difference in RH between cycles. Non-fibrous mixes had an MBV of 1.06 gm$^{-2}$ %RH$^{-1}$, while mixtures with 1% hemp shiv and 1% hey stalk had the highest MBV of 1.73 gm$^{-2}$ %RH$^{-1}$, and mixtures with 3% hey stalk had the lowest MBV of 1.54 gm$^{-2}$ %RH$^{-1}$ [12].

### 6.6. Moisture sorption isotherm

Moisture sorption isotherm is a term used to describe the capacity of a material to absorb and release moisture at a range of relative humidity conditions between 0 and 100 and at a constant temperature of 23 °C [66]. The two primary parameters used to determine the sorption isotherms are the adsorption isotherms and the desorption isotherms. Adsorption and desorption differ in that desorption refers to the release of an adsorbed substance from a surface, while adsorption refers to the process by which certain substances hold the molecules of a gas, liquid, or solute in a thin layer [79]. Adsorption-desorption isotherms vary for each material and temperature.

Tchiotsop et al. conducted a study on sorption isotherms using two different devices: ProUmid and Saturated Salt Solutions (SSS) box (see Fig. 6). ProUmid was used to test 7 specimens of 10 × 10 × 10 $mm^3$ size, while SSS was used to test 10 specimens of 50 × 50 × 20 $mm^3$ size. The SSS box had RH values of 12%, 33%, 55%, 65%, 76%, 86%, and 97% for the inner environment. The specimens were considered to have reached equilibrium moisture content when their relative mass variation was less than 0.5%. For the ProUmid specimens, the relative error of mass variation was set at 0.01% and the specimens were dried at 50 °C before being tested at RH levels between 10% and 95%. The study found that for most of the imposed RH values, the water content values of the adsorption and desorption curves recorded using SSS were higher than those obtained with the ProUmid device [12]. Figs. 7 and 8 in the study show the normal values for the adsorption and desorption isotherms for the mixtures, respectively.

A study performed by Alassaad et al. used the dynamic vapor sorption (DVS) technique, which follows the ISO 12571 standard [80]. They utilized a ProUmid SPSx-1μ sorption/desorption analyser and a precision balance (±1 μg) to obtain accurate measurements of sample mass and sorption kinetics, with tight temperature and humidity control. This approach was used to evaluate the sorption and desorption values [23].

### 6.7. Thermal inertia and heat capacity

Inertia refers to the ability of a material to absorb and release heat gradually [75]. This characteristic allows for the transfer of temperature changes between the interior and exterior of a building. Greater thermal mass in a material typically leads to higher levels of inertia, which can help reduce energy consumption and maintain comfortable indoor temperatures by stabilising the ambient temperature within the building envelope [66,75].

The main method used to evaluate the heat capacity of earthen materials is by determining the volumetric heat capacity, which is calculated by multiplying the specific heat capacity (c) (measured in J/kg.K) and the mass density (measured in $kg/m^3$) of the material as presented in equation (1) below. The specific heat capacity (Cp) is a crucial factor that indicates a material's ability to store heat [75].

$$C = c\,\rho \tag{1}$$

Alassaad et al. employed Differential Scanning Calorimetry (DSC), following the ISO 11357-4 standard [81], to determine the heat

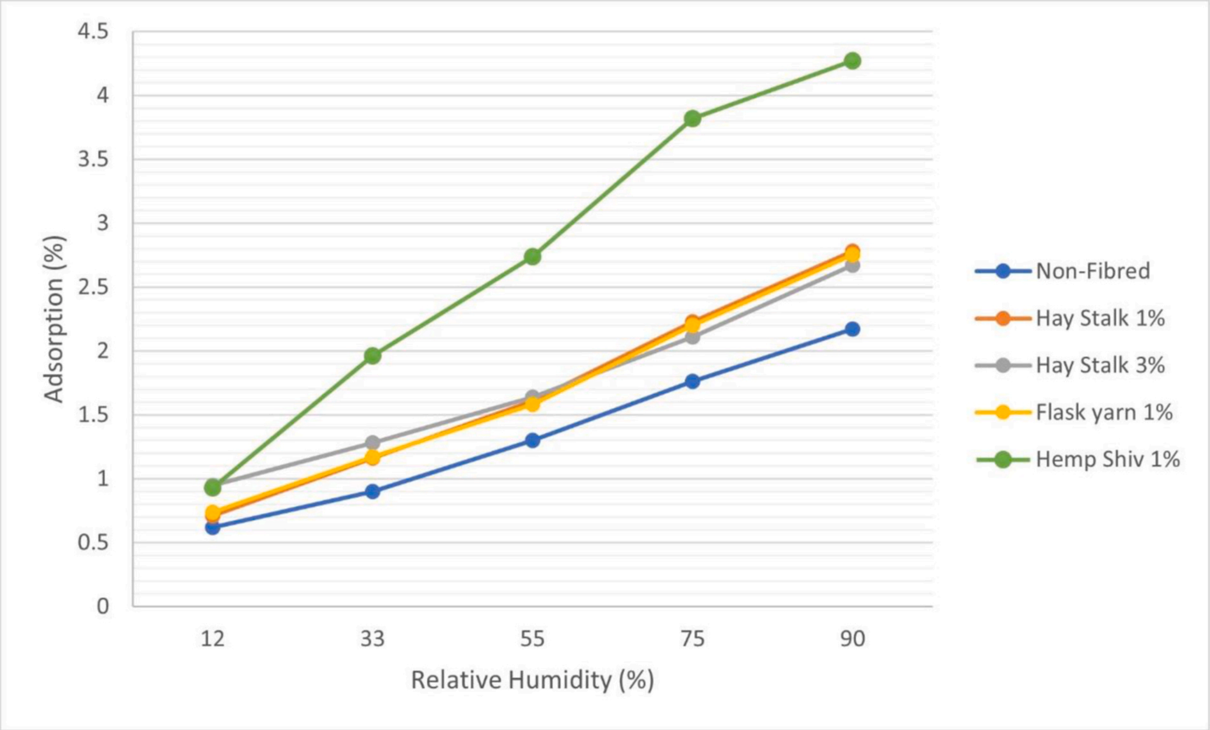

**Fig. 7.** Moisture adsorption isotherms of mixtures based on [12].

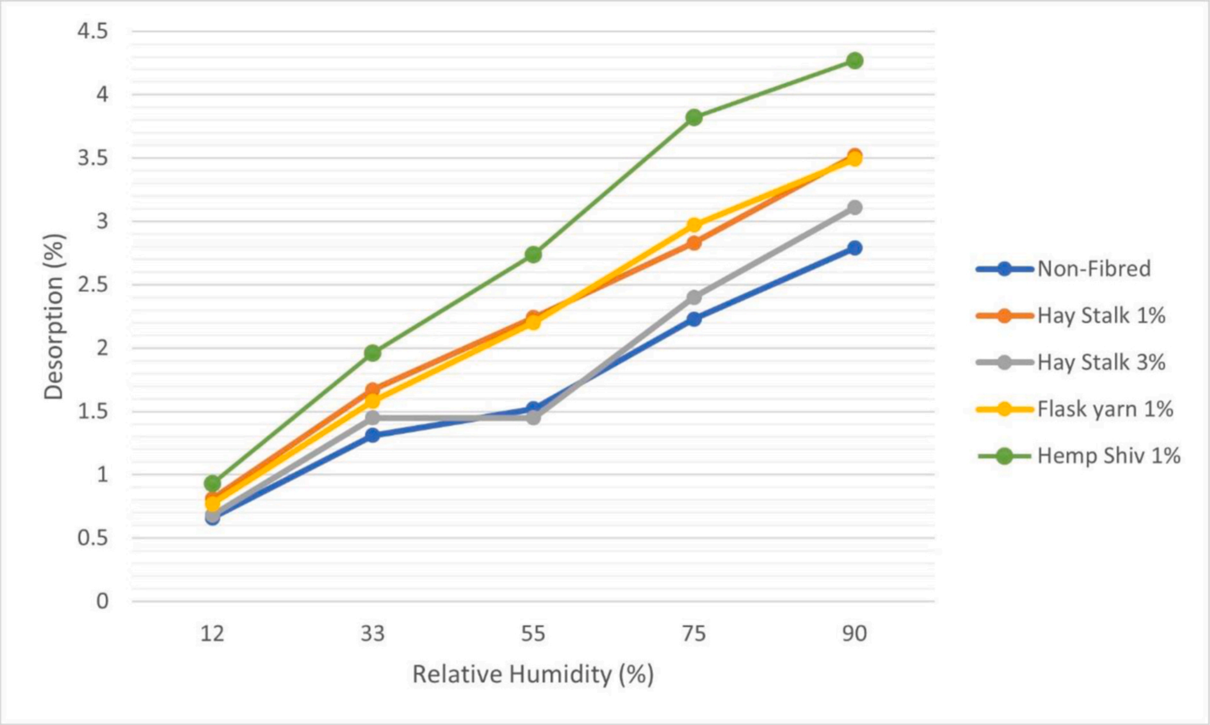

**Fig. 8.** Moisture desorption isotherms of mixtures based on [12].

capacity of the mixtures used in their experiment. The specimens were heated from 0 °C to 40 °C at a fixed rate of 1 °C per minute. The results showed that as the temperature increased, the heat capacity also increased [23].

Tchiotsop et al. have used a Hot Disk device to assess the specific heat capacity of the cob specimens. The experimental process was repeated on each specimen's four flat faces to acquire a representative value of the volumetric heat capacity as the Hot Disk device [12]. The table below shows the measured specific heating values for the specimens in addition to the total and intrinsic variabilities of the different mixtures (see Table 4).

Zeghari et al. have diffusivity, density, and heat capacity of cob [16]. According to the study, reducing density results in superior insulating values and a higher heat capacity when thermal conductivity is less than 0.4 W/m.K. The density and heat capacity of cob mixtures with thermal conductivities greater than 0.4 W/m.K are constant; the average density is 1519 kg/m$^3$, and the average heat capacity is 1205 J/kg.K. For density and heat capacity, the relative standard deviation calculated in this thermal conductivity range is approximately 3% and 8%, respectively [15,16].

### 6.8. *Thermal diffusivity and effusivity*

Zeghari et investigated the thermal diffusivity and effusivity to have a better thermal characterisation of both structural and insulation mixtures. The study discussed that mixtures with the lowest and highest diffusivity have the lowest and highest effusivity levels as well. The highest thermal diffusivity was found to be around 0.19 mm$^2$/s for T5, and the lowest insulation mix diffusivity recorded is 0.1 mm$^2$/s. Thermal diffusivity reaches a high value for the sample S2 of 0.342 mm$^2$/s and low value of 0.168 mm$^2$/s for structural mixtures. Structural mixtures, on the other hand, have the lowest effusivity at 428 J/m$^2$.K.s$^{1/2}$ due to their increased thermal conductivity and less capacity for heat storage. Meanwhile, insulating mixtures with a maximum value of 1290 J/m$^2$.K.s$^{1/2}$ are found to have the highest value. This can be explained by the significant capacity of insulating mixtures to store energy, resulting in improved thermal comfort indoors. Therefore, it was recommended that using two different materials in a cob wall is necessary to have better

**Table 4**
Specific heat capacity values, total variability, and intrinsic variability for cob mixtures with distinct fibre content.

| Fibre | Volumetric heat capacity (MJ/m$^3$ K) | Total variability (%) | Intrinsic variability (%) |
|---|---|---|---|
| WF | 0.195 | 12.64 | 11.79 |
| FL- 1% | 0.119 | 8.31 | 6.91 |
| FL- 3% | 0.111 | 12.58 | 10.52 |
| Ha-1% | 0.428 | 36.19 | 35.07 |
| Ha-3% | 0.14 | 11.35 | 6.58 |
| He-1% | 0.503 | 26.66 | 23.71 |
| He-3% | 0.218 | 14.97 | 14.01 |

thermal comfort; one material with low diffusivity and located on the other side of the cob wall (insulating material with diffusivity of 0.14 $mm^2/s$) while the second on the inner side of the wall with the highest effusivity value of 1290 $J/m^2.K.s^{1/2}$ [16].

Equation (2) below represents thermal diffusivity and equation (3) defines the effusivity of a material where D is the thermal diffusivity, E is the thermal effusivity, λ is the thermal conductivity, ρ is the density, and C is the heat capacity [66].

$$D = \lambda / \rho c \tag{2}$$

$$E = \sqrt{\lambda \rho c} \tag{3}$$

## 7. Summary of used standards and testing methods

As discussed, many tests are needed to assess the hygrothermal performance of materials. Table 5 summarises the various tests and the associated standards that can be followed to obtain a detailed view of the structural and hygrothermal performance of cob specimens.

## 8. Review Overview and discussion

The research performed a systematic analysis and review of the existing literature of cob construction. The review focused on identifying the variations of cob mixtures with an exploration of the concentration of cob constituents. Furthermore, a methodical exploration of the structural, hygroscopic, and thermal performances of the different cob mixtures was carried out. This section discusses the key findings and results of the reviewed research. Additionally, a discussion of the research limitations, opportunities, and recommendations of future work are included.

### 8.1. Overview on cob mixtures

The formulation of cob mixes significantly shapes their structural performance and hygrothermal characteristics. Recent studies have underscored the pivotal role of sub-soil attributes, water content, and fibrous additives in attaining desired properties. Optimal structural robustness typically hinges on cob blends containing 15–25% clay, with suggestions leaning towards well-graded soils [21,23] The initial water content, varying between 19% and 40% for structural formulations and reaching up to 131.3% for enhancing hygrothermal efficiency, profoundly influences bonding and homogeneity, with higher initial moisture levels often fostering superior cohesion among constituents [23]. Furthermore, the use of fibres such as straw or coconut coir, within proportions ranging from 0.6% to 3%, serves to bolster cohesion and mitigate cracking, thereby elevating the overall hygric performance of cob [32].

As cob gains prominence in contemporary construction practices, efforts are directed towards tailoring mixtures for specific applications like 3D printing, where precise control over water content is imperative for ensuring extrusion stability. Concurrently, standardisation of soil characterisation techniques, coupled with the exploration of diverse fibre types, perpetuates the expansion of knowledge and application within the domain [17,21,23,32]. This comprehensive investigation into cob mixtures underscores its potential as a sustainable alternative, seamlessly blending traditional art-based materials with the imperatives of eco-conscious building materials.

**Table 5**
A list of the hygrothermal testing methods based on researched studies.

| Test | Method |
|---|---|
| Compressive strength test | EN 1052-1 (CEN 1998)<br>DIN 18945<br>EN 1015-11<br>IS 4332 Part 5 |
| Tensile strength test | IS 5816<br>ASTM-C109/C109 M<br>ASTM-C496/C496 M |
| Elastic Modulus | EN 10002-1, ASTM E8/E8M − 08, ISO 6892-1, ASTM E111 |
| Shear strength test | ASTM E 519 (ASTM 2010) |
| Flexural strength test | ASTM-C293/C293 M |
| Bulk Density | DIN 18945 (DIN 2013a)<br>NF ISO 5017 |
| Water vapor permeability | Dry cup method following ISO 12572 |
| Thermal conductivity | Transit hot wire method<br>heat flow meter/Guarded hot plate<br>Flash method |
| Sorption isotherm | Saturated salt solution (SSS)<br>Dynamic vapor sorption (DVS) |
| Thermal Diffusivity | Flash method |
| Specific heat capacity | Adiabatic calorimeter<br>Flash method<br>Differential Scanning Calorimetry (DSC) following ISO 11357-4 |
| Moisture buffering value | NORDTEST protocol |

### 8.2. Overview on structural performance of cob

Cob, although characterized by lower compressive strength compared to other earthen materials, exhibits favourable shear properties [30]. Throughout the drying process, cob gains compressive strength, with tensile strength derived from organic fibres aiding structural integrity [30]. Additionally, cob demonstrates resilience beyond the elastic range, withstanding stress even after peak stress has subsided, albeit with a gradual reduction in capacity [17].

In adapting cob to comply with contemporary building regulations, extensive research has scrutinised its structural capabilities through various laboratory tests. These assessments encompass compressive strength, tensile strength, elastic modulus, Poisson's ratio, shear, and flexural strengths, as well as shrinkage and cracking levels. Notably, compressive strength tests across multiple studies have revealed a wide range of results, from 0.10 MPa to as high as 2.98 MPa for cement-stabilised samples [32]. Similarly, tensile strength tests have demonstrated variations, with values ranging between 0.13 MPa and 0.75 MPa for coir specimens and 0.29 MPa–0.35 MPa for those with straw fibres [32]. Furthermore, investigations into elastic modulus and Poisson's ratio have yielded diverse findings, underscoring the complexity of cob's mechanical properties [30]. Shear and flexural strength tests have provided valuable insights, with cob exhibiting mean shear strengths of 0.50 MPa and flexural strengths ranging from 0.124 MPa to 0.903 MPa for 3D printed specimens [30,29]. Moreover, shrinkage and cracking analyses have highlighted the impact of factors such as fibre content and drying temperature on cob's structural stability [9]. In general, the moderate structural performance of Cob can be improved by adding optimal number of fibres.

### 8.3. Overview on hygrothermal performance of cob

The exploration of cob's properties spans diverse tests, unveiling pivotal insights into its thermal behaviour and moisture behaviour and characteristics. Porosity examinations, for instance, highlight notable variations in cob's structural and hygrothermal traits, with findings indicating a range of porosity values shaped by factors like fibre incorporation. For example, Tchiotsop et al. revealed that cob blends containing 3% hay stalks exhibited a spectrum of pore textures and a uniform distribution, potentially influencing their hygrothermal efficacy [12].

Bulk density assessments yield tangible evidence of cob's density fluctuations, impacting both its structural robustness and insulating prowess. Studies unveil bulk density figures spanning from 1107 kg/m$^3$ to 1780 kg/m$^3$ for distinct cob formulations, with disparities attributed to variables such as cement stabilisation and the infusion of plant-based aggregates [16,32]. Thermal conductivity analyses further shed light on cob's insulation capabilities, with recorded values ranging between 0.12 W/m.K [13] and 1.06 W/m.K [12]. Remarkably, lower thermal conductivity readings have been linked to enhanced insulation, particularly evident in mixtures featuring reduced densities [12,14,16,37].

Evaluations of cob's hygroscopic properties, such as water vapor permeability and moisture buffering value (MBV), provide valuable insights into its moisture exchange potential and its capacity for indoor humidity regulation. Water vapor permeability (km) governs moisture exchange between indoor and outdoor surfaces in buildings, with higher values indicating higher exchange. Tchiotsop et al. utilized the NF EN ISO 12572:2016 Standard's dry cup test, revealing a global coefficient of variation (CV) of 11% [12]. Alassaad et al., examined water vapor permeability, preconditioning all samples to 23 °C and 50% RH, thus establishing a moisture gradient from 0% RH internally to approximately 50% RH externally [23]. Stazi et al. determined water vapor permeability experimentally at 2.33 E$^{-11}$ kg/m/s/Pa [43]. Other researchers, such as Collet-Foucault, reported average permeabilities ranging from 1.5 E$^{-11}$ kg/m/s/Pa to 1.7 E$^{-11}$ kg/m/s/Pa at 23 °C [78]. These findings suggest that cob demonstrates diverse moisture exchange capabilities, influenced by factors such as material composition and environmental conditions. Similarly, moisture sorption isotherm studies have depicted cob's moderate efficiency in absorbing and desorbing moisture across varied relative humidity levels, with equilibrium moisture content values varying accordingly [12].

## 9. Conclusion

This study provides a comprehensive literature review encompassing various aspects of cob building, such as its constituent elements, mixing ratios, and methods for evaluating its structural and hygrothermal properties. Importantly, the examined literature highlighted variations in the use of fibres and mixing ratios among different manufactured cob specimens. Straw emerged as the most frequently mentioned fibre, followed by flax, hemp, hay, and reed. However, in-depth investigations into mixing ratios were limited to a select few publications. Furthermore, the absence of standardized nomenclature in describing cob material and its components was evident, as the term "aggregates" was inconsistently used to refer to both additional fibre material and coarse sand/gravel in subsoil.

Additionally, the lack of a uniform approach in describing mix ratios, with some researchers relying on mass percentages, fibre-to-water or fibre-to-soil ratios, and weights of constituents, has led to the need for a unified measuring unit. These inconsistencies in material description could potentially pose challenges and serve as a significant obstacle to validating the material and regulating it within the domain of building and construction.

The primary focus of this research revolved around publications exploring both the structural and hygrothermal properties of cob. The findings confirmed the exceptional hygrothermal performance of cob, thus establishing its suitability for sustainable construction. However, only a limited number of studies comprehensively investigated both structural and hygrothermal aspects, and not all aspects were thoroughly examined. Most studies predominantly concentrated on assessing thermal conductivity, while evaluating structural integrity through compressive strength and modulus of elasticity tests.

The research identified key limitations of researching cobsuch as following concrete standard for testing cob in evaluating the structural performance. However, as discussed, cob has a lower result regarding compressive strength and the other discussed parameter. Therefore, the development of standards for testing such materials is needed.

To position cob as a viable component for energy-efficient structures, with reduced embodied and operational carbon, it is crucial to develop a blend that optimally balances both its structural and hygrothermal performance. Moreover, a comprehensive exploration of cob's structural and hygrothermal performance is imperative to bridge the current gaps in research. Cob exhibits significant potential for low-rise buildings in terms of structural performance, thereby necessitating further studies and material refinement.

The research explored research projected that investigated cob, however, the current review was limited to the use of the term "cob" since it has been the common name scientifically, however, other names and terminologies may have been used. Furthermore, the primary language of conducting the research was English. Therefore, future work can explore other languages such as French as earthen construction is gaining momentum. Future research endeavours will delve into investigating the impact of formulation on cob's hygrothermal and structural performance. Researchers will also strive to establish a comprehensive framework for evaluating the structural, hygroscopic, and thermal characteristics of optimised cob mixtures. Additionally, the collected data of this review can be used as a databank for developing and investigating the holistic performance of cob mixtures which would be vital to evaluate cob as a building material. As such, having such large dataset of cob mixtures that are evaluated for their structural and hygrothermal performances can be used to facilitate the optimisation of cob mixtures which would ease the path for net zero construction and low carbon built environment.

## CRediT authorship contribution statement

**Kamal Haddad:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Simon Lannon:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Eshrar Latif:** Writing – review & editing, Writing – original draft, Supervision, Resources, Methodology, Investigation, Formal analysis, Conceptualization.

## 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.

## Data availability

Data will be made available on request.

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