The state of the art of cob construction: A comprehensive review of the optimal mixtures and testing methods

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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. Therefore, to further optimise the material, this review explores peer-reviewed research articles that relate to different materials used in cob mixes and the different testing methods used to assess the produced specimen's hygrothermal performance. For data collection, a systematic keyword search was carried out on ScienceDirect, Scopus, Google scholar search engines and relevant books. 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 experimented with 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. However, there is no consensus and robust collated data available about the ratios of the mixes concerning the hygrothermal performance of the specimens. Therefore, a matrix for mixes and testing methods was developed with the available data to aid the progression of any future optimisation effort.

Keywords: Earthen Construction, Mixing Ratio, Hygrothermal Testing, Cob.

1 Introduction and Background

Conventional construction materials such as concrete and steel have gained momentum since the industrial revolution sparked due to their structural performance. Yet, global statistics have demonstrated that cement has a contribution of 8% to the worldwide total of CO2 emissions [1]. According to the International Energy Agency (IEA), such materials are responsible for 30% of total global final energy consumption and 27% of total energy sector emissions [2].

Earthen construction has been defined as construction that uses building materials in which clay is a binder [3]. Saxton, in one of his early publications on earthen buildings, has discussed that around one-third of the world's population lives in earth-constructed domestic buildings [4]. Saxton has also elaborated that many developed countries, such as England, France, Germany, and China, in addition to a wide number of developing countries, have adopted this type of construction due to its affordability [4].

Even though the earth is an old construction and building material that has been used since early civilizations, recent demand for using the material has been on the rise due to the increased interest in sustainable and green building practices [5]. Besides, it is considered a natural concrete alternative with lower embodied carbon as well as having a lower need for energy for production and operation compared to other materials [6].

According to Hamard et al., earthen construction can be classified into two groups based on the construction method used: wet methods and dry methods. Dry earthen construction methods consist of masonry units like compressed earth blocks and monolithic walls that are implemented moistly, which is rammed earth construction. On the other hand, wet construction methods include four other systems of earthen construction, namely adobe, wattle and daub, earthen-based plaster, and cob as a monolithic wall [7].

The presented paper will explore cob as a potentially promising building material. Furthermore, it will review the current literature that relates to the different mixes of cob and the different ratios used in the mixes, as well as the mixing conditions and processes used in the production of the material. In parallel, the paper will discuss the various methods that have been discussed in the literature that evaluate the hygrothermal performance of cob.

2 Methodology

This paper focuses on presenting a comprehensive review of cob and its associated hygrothermal testing methods. In this research, data collection was fulfilled through a systematic keyword-based search using ScienceDirect, Scopus, and Google Scholar search engines and relevant books. The keywords in the search process were cob, earthen construction, cob mixtures, and hygrothermal tests of cob. Then, the papers' abstracts and their content were thoroughly analysed and studied, which resulted in the selection of 25 studies that studied cob in particular or as a partial study on earthen construction. The selected studies have discussed mix ratios and hygrothermal testing methods.

3 Cob as a building material

Generally, the term "cob" has been defined as a lump of rounded shape [8]. In the field of earthen construction, cob is defined as a sustainable material that consists of soil, water, and fibrous materials [8]. A cob wall is an ancient, traditional building material used primarily for structural purposes [9]. Meanwhile, recent research has started to focus on enhancing its hygrothermal performance [10-14].

Cob as a building material has unique characteristics when compared to other earthen materials. For instance, cob exhibits higher material ductility when compared to rammed earth and adobe [15]. Besides, as a wet-based construction material, cob gives further freedom in design during all phases of construction when compared to dry methods like rammed earth [16]. Furthermore, such a characteristic enhances the durability of the material since its maintenance will be smoother and more flexible.

4 Content of cob mixtures

Cob as a material consists of three main constituents: subsoil, fibres, and water. To enhance its structural stability, many researchers have added other materials such as clay, lime, or cement. Generally, it has been recommended for conventional construction of cob that the composition of the mixture averages 78% subsoil, 20% water, and 2% fibre (typically straw) by weight [16].

The general composition of earth that is used in cob mixtures has been suggested to be 15–25% clay to 75–85% aggregate/sand [15]. It is crucial to mention that in order to increase cob density, well-graded soils were preferred since they had good space-filling properties that improved cob strength. Topsoil has been deemed unsuitable for cob construction because it decomposes quickly after application and causes a mechanical weakening in earth walls. Therefore, it has been found that the most suitable soil for cob mixtures is just under the topsoil [7]. Literature has discussed that water content and the initial moisture level of a cob mixture have a significant effect on the strength of the material [15]. Furthermore, it has been concluded that mixtures that are reinforced with fibres tend to require more water content in the mixture [17].

Even though the tensile strength and bonding of straw help in the reduction of cracking [4], some studies have argued that adding large amounts would increase the strain at failure due to loading. Many studies investigate 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 [8].

It has been discussed in the literature that fibre content has several advantages that contribute to 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 improve weathering resistance. The effect of fibres on thermal insulation was discussed in some studies, whereas other studies suggested that fibres' effect on thermal conductivity would be noticeable when the content of fibres in the fabric is about 25% by mass [18].

As introduced in an exhaustive review on plant aggregates and fibres in earthen construction materials [19], distinct types of plant fibres and aggregates were studied in the earthen construction literature and classified into eight main categories, which can be classified as cereal straw, which includes wheat straw, barely straw, and oat straw; wood aggregates such as wood shavings and wood fibres; Bast fibres which includes hemp fibre, hemp hurds, jute fibre, kenaf fibre, and diss fibre; Palm tree fibres including coir, oil palm fibre, and date palm fibre; Waste and residues like cassava peel, millet residue, cotton residue, tea residue, tobacco residue, and grass; Leaf fibres, including sisal, banana fibres, and pineapple fibre; aquatic plants like Phragmites, Typha, and seaweed fibre; Wool (sheep wool).

5 Cob mixes in literature

Several researchers have started to study and assess the implications of using cob as a building material [3, 4, 7, 14, 16, 20]. As discussed, cob consists of subsoil, water, fibres, and a binder like clay. Most studies presented have focused on the optimisation of the structural performance of the material, while a few have focused on enhancing its hygrothermal performance. In this section, these studies will be explored at the constituent level. This section will discuss the different ratios of cob's constituents that are presented in literature. Table 1 demonstrates a comprehensive review of the mixing ratios that have been adopted in previous research.

5.1 Sub-soil and binder ratios and granulometric characterisation

The selection and creation of the soil that will be used in the mix have a significant impact on the materials' structural and hygrothermal performance[12, 13, 21-23]. The used soil needed to be obtained from a local source, which would help in the reduction of the embodied carbon emissions caused by transportation, as will be discussed later in the review.

One of the early papers on studying cob has been published by Saxton, who has concluded that typical soil contains 30% gravel, 35% sand, and 35% silt and clay [4]. Alassaad et al. have used two types of soil; the first's Unified Soil Classification (UCS) as low plasticity silt (ML) with a plasticity of 24% and a plasticity index of 3.6%, and the second's USC as silty sand with gravel (SM), which had a plasticity of 21% and a plasticity index of 2.7%. In the same study, both soils have quartz, mica, feldspar, iron oxyhydroxides, and limonite [21].

Quagliarini et al. have focused on performing a detailed analysis of a historic cob. After analysing the building's fabric, it is shown that it consists of 34% clay, 17% sand, and 49% silt, with a plastic index of 19% and a liquid index of 38% [24]. Meanwhile, the researchers have tried to make a mixture that has a similar character with 36% clay, 13.5% sand, and 50.5% silt with a plastic index and a liquid index of 21% and 42%, respectively, and used 3 kg of the created soil in the cob mix. Alhumayani et al. have used 80 kg of subsoil in their separate study [25].

Miccoli et al. have utilised a mixture that contained 18% gravel and sand, 61% silt, and 21% clay [22, 23, 26]. Ben-Alon et al. have used 257 kg of clay-rich soil with a 50% clay content for one square metre of cob and a thickness of 457 mm [3]. Medero et al. have experimented with soil that is characterised to contain 24.4% gravel, 19.7% coarse sand, and 32.5% fine sand [27]. In addition, Sangma and Tripura have worked on multiple studies to improve the structural performance of cob. For their mixtures, the soil's characterisation is 60.5% sand, 22.25% silt, and 14.25% clay, with a plastic index of 11.43% [17, 28].

Alqenaee and Memari have primarily focused on optimising a mixture that will be efficient and stable for 3D printing. The authors have created 36 different mixtures, nine of which are described in the paper and shown in Table 1. The clay content ranges from 38.53% to 52.63%, the sand content varies between 11.11% and 17.73%, and the lime content is between 7.08% and 11.63%. In their study, mix M30 and M31 have had enough cement to work as binders with values of 2.40% and 2.48%, respectively. The final mixture, M36 consists of 49% clay, 15.31% sand, and 10.00% lime [29]. For the same purpose of developing a 3D printable mixture, Gomaa et al. have used 73% of the soil that was found to contain 19–20% clay and 80–81% aggregate/sand of the total mixture [30].

Various standards for determining the soil properties and characterisation were used in studies and can be used for further research, such as ISO 13320:2009 [31] and IS 2720 Parts 4, 5, and 7 [32]. Furthermore, a study by Vinceslas et al. thoroughly discusses the methods to characterise the tested soil; Particle size distribution has been assessed using NF P 94-056 [33], the absorption capacity value has been determined using NF P 94-068 [34], the plastic limit, liquid limit, and plastic index have been determined using NF P 94-051 [35], the normal proportional water content and density of the main materials have been configured using NF P 94-093 [36], the specific gravity of the produced specimens using NF P 94-050 [37] and Soil characterisation has been tested by following ASTM D2487-11 [38].

5.2 Water content in mixes

The concentration of water in cob mixtures is controlled by other constituents, such as fibre content and type. For instance, Akinkurolere O.O. et al. have argued that the addition of fibre to a mixture with a high initial water content has beneficial effects on the strength of the mix as it will enhance the bonding and homogeneity between the components within the cob mixture [20].

Generally, mixtures that are designed for structural purposes have a significantly lower amount of water than those designed to be hygrothermally effective or insulation materials. Accordingly, the water content in studies that focused on evaluating the structural performance ranges between 19% and 40%, while the ones designed to enhance the thermal insulation varied between 62.1% and 131.3% as the fibre content was greatly increased in the mix [20].

Alassaad et al. have established the added water content as a ratio, where the water-to-soil ratio was equivalent to 0.3 [39]. Alhumayani et al. in their paper have used an amount of 20 kg of water, which have resulted in a ratio of 1:4 concerning the soil content in the mix [25] which aligns with Weismann and Bryce, who proposed a water-to-subsoil ratio of one part water to every four parts soil [40]. To determine the water content in the produced cob specimens, researchers like Vinceslas et al. have referred to the French standard NF P 94-050 [37] after drying the specimens at 105 °C [41].

As many of the selected papers in the review have worked on the traditional construction of cob methods, some of the studies have explored creating mixtures that are designed for 3D printing. Water content may be the main constraint for 3D printing cob as the mixture needs to be consistent and stable while being viscous enough to be extruded through the nozzle. In 2021, Gomaa et al. have published a paper that focuses on developing an extrusion system that can be used for cob's 3D printing. In their study, the authors have assessed different concentrations of water content in the mix (22%, 24%, 26% and 28%) where it has been concluded that the optimum water content was 25% [15]. Alqenaee and Memari have experimented with water contents between 24.19% and 34.25% [29]. It has been observed by Gomaa et al. that the moisture content of the final printed cob is slightly reduced by the 3DP extrusion process. This is caused by the pressurisation of the mixture inside the extrusion system, which leads to moisture release in the form of leakage around the cartridge connections [15, 16].

5.3 Fibres and aggregates in cob mixtures

Fibre content ratios and fibre type are essential aspects that need to be considered while studying a material like cob. Fibres have a vital role that affects the structural, hygrothermal, and environmental performance under study. In current literature, many fibre types have been studied, like seaweed fibre [42], sheep wool [43], and tobacco residue grass [44]. In this review, different studies have used several types of straw, including hemp straw, flax straw, wheat straw, paddy straw, and rice straw, meanwhile, other studies have used other aggregates in their mixes, such as coconut coir [28, 45], hemp shives [10, 12-14], and reed [12, 14].

Generally, the use of fibres and added aggregates in cob mixtures has been extensively studied due to its effects on the mix's performance. The fibre content in the majority of studies ranged from 0.6% to 3%. Alassaad et al. have used 2.5% flax straw of the dry soil mass [39]. In parallel, Ben-Alon et al. in their research have used 10.1 kg of wheat straw that is added to 256 kg of clay-rich soil with a calculated soil/fibre ratio of 0.039 [3]. Goodhew et al., in a study that focuses on optimising cob for better insulation and thermal performance, have added a higher amount of fibre within different mixes [12].

Zeghari et al. have developed eight mixtures that are optimised for better structural performance using hemp straw, flax straw, wheat straw, and reed [14]. Simultaneously, the study has worked on developing two mixes using hemp shiv and reed for the insulation part of the dual-system wall.

Within the different studies, it was observed that the fibre lengths have ranged between 20 mm and 300 mm, as shorter fibres demonstrated better performance since they blended in the mix, which created a homogeneous cob mixture. In their study, Sangma and Tripura used a systematic comparative analysis to compare the structural performance of cob mixtures made with coconut coir and straw fibres, and they concluded that coconut coir performs better enhancing the structural performance [17, 28].

Table 1. A 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/m3	Lime (%)			
1	Soil 0	15–25		75–85		78				20	2%	[7]
2	Soil 0	35		35	30					17-29	0%-3%	[4]
	Soil 1	4	76	17	3							
	Soil 2	1	13	51	35							
3	Cob 0					1500 kg/m3		0		375 kg/m3	37.5 kg/m3	[39]
	Cob 2					1475 kg/m3		30.2		368 kg/m3	36.9 kg/m3	
	Cob 5					1450 kg/m3		74.3		362 kg/m3	36.3 kg/m3	
	Cob 10					1390 kg/m3		142.5		347 kg/m3	34.8 kg/m3	
4	Original soil	34	49	17								[21]
	Yellow soil	36	50.50	13.50		3kg				28	0.02 kg	
5	Conventional Cob					78.0				20.0	2.0% Straw	[25]
	3DP Cob					73.0				25.0	2.0% Straw	
6	Soil 0	21	61	18							20-30kg/m3	[23]
7	Soil 0					256 kg				185 kg	10.1 kg	[3]
8	Soil 0	20.60		52.2	24.40	79.20				1.55	1.25% Straw	[27]
9	All Mixes Average	14.25	22.25	60.50			3-10			31.7 - 40	3-10% Straw 3-10% Coir	[17]
	UK3 Soil	12.83	68.93	17.80	0.44							
	UK4 Soil	5.59	58.64	16.74	19.03							

	FR3 Soil	12.85	65.43	12.36	9.36			
10	Soil 0			UK3		65.60	Hemp shiv: 50%	[12]
	Soil 1			UK3		107.30	Hemp shiv: 50%	
	Soil 2			UK3		107.3	Hemp shiv: 25%	
	Soil 3			UK3		107.30	Reed: 25%	
	Soil 4			FR3		131.30	Reed: 25%	
	Soil 5			FR3		131.30	Hemp shiv: 25%	
	Soil 6			UK4		62.10	Reed: 25%	
	Soil 7			UK4		62.10	Reed: 50%	
11	S1			Three different French soils were used		25.00	Hemp straw: 5%	[14]
	S2					28.00	Hemp straw: 5%	
	S3					28.00	Hemp straw: 2.5%	
	S4					28.00	Flax straw: 2.5%	
	S5					31.00	Flax straw: 2.5%	
	S6					31.00	Wheat straw: 2.5%	
	S7					31.00	Reed: 2.5%	
	S8					31.00	Wheat straw: 5%	
	I1					131.00	Reed: 25%	
	I2					131.00	Hemp shiv:25%	

9									
12	Soil 0	3	18	42	37			0.9% Straw (by mass)	[46]
13	Soil 0						33 - 47	Rice straw that varies from 0.6%-3%	[20]
14	S3			FR2 soil			28.50	2.5% hemp straw	[13]
	T1			UK 3 soil			107.30	25% hemp shiv	
15	WF	8	47	45		100 kg	19	0%	[10]
	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%					100 kg	23	3% Hay stalk	
	HE-3%					100 kg	23	3% Hemp shiv	
16	Soil 0						22, 24, 26, and 28		[15]
17	Soil 0	19 - 20			80-81	73	25	2% Straw	[16]

	M23	50.51		11.11		10.10	28.28		
	M25	52.63		11.58		7.37	28.42		
	M26	46.51		12.79		11.63	29.07		
	M27	49.78		14.60		7.08	28.54	-	
	M28	48.39		14.19		9.68	27.74		
	M30	38.53		17.12	2.40%	7.71	34.25		
18	M31	39.89		17.73	2.48%	7.98	31.91		[29]
	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		10.00	24.19	1.50%	
19	Soil 0	21	61	18			24	1.7% Wheat straw	[26]

Table 2. A matrix of the hygrothermal tests of analysed research.

Test		Density (kg/m^3)	λ (W. m^{-1}.K^{-1})	Water Vapour 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					[47]
2	UK3 50% Shiv Dry (D)	398.73	0.12					[12]
	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					
	Hemp straw 5%	1520	0.57					
	Hemp straw 2.5%	1530	0.74					
	Flax straw 2.5%	1460	0.42					
3	Reed 2.5%	1540	0.36					[14]
	Wheat straw 2.5%	1320	0.32					
	Wheat straw 5%	1120	0.24					
	Reed 25%	780	0.2					
	HEMP SHIV 25%	955	0.22					
	WF	1846	1.08	9.13×10^{-12}	1.06	0.62-2.17	0.66-2.79	
	FL-1%	1841	1.06	8.69×10^{-12}		0.74-2.75		
	Ha-1%	1749	0.92	1.32×10^{-11}	1.73	0.71-2.78	0.81-3.52	
4	He-1%	1709	0.91	1.14×10^{-11}	1.73	0.85-3.42	0.77-3.49	[10]
	Fl-3%	1733	0.95	6.48×10^{-11}	1.68			
	Ha-3%	1471	0.7	1.05×10^{-11}	1.54	0.95-2.67	0.68-3.11	
	He-3%	1537	0.7	1.05×10^{-11}	1.74			
5	Straw			2.33×10^{-11}				[48]

6 Assessing the hygrothermal performance of cob

In general, earthen materials offer various economic advantages due to their thermal inertia. For example, cob walls with lower conductivity and lower density have a higher insulation value and are lighter in weight [30]. As for 3D-printed cob, a significant increase in thermal performance can be noticed in 3D-printed cob structures compared to their manually structured counterparts [30]. This section will go over the various tests that were carried out, such as porosity, bulk density, thermal conductivity, water vapour permeability, moisture buffering value, and moisture sorption isotherm.

6.1 Porosity tests

Earth is a porous, unsaturated material. In addition to its effect on the hygrothermal performance of the material, it also has a significant effect on the structural performance of cob mixtures. For instance, the young modulus for raw earth material ranges between 1 GPa and 5.5 GPa, where the higher the porosity, the higher the young modulus value will be [49]. A study by Goodhew et al. discussed the correlation between adding fibres to the mixture and its measured porosity, where the addition of fibre would increase the porosity since fibres are considered materials with high porosity [12].

Tchiotsop et al. have presented the differential distribution curve and the cumulative distribution curve of material for a number of fibres with different fibre contents. The modal porosity is the same at 2 µm for 1% fibered mixes, indicating that the earth matrix is consistently well-represented in mixtures. While Ha-3% samples have a uniform distribution and a variety of pore textures. This might result in a rise in the variety of attributes associated with fibre content [10].

6.2 Bulk density of specimens

Bulk density is one of the most important factors that need to be deeply studied and investigated, as it has an impact on the structural and hygrothermal performance of building materials. Alassaad et al. followed the French standard, NF ISO 5017 [50]. In his experiments, it was observed that the addition of PCMs will reduce the density of the samples as well as the mechanical strength of cob where the Unconfined Compressive Strength of cob decreased and became more ductile. The density of cob samples that had the Micronal DS 5038 X added was approximately 1500 kg/m3 [39].

Zeghari et al.'s study resulted in a density range between 1107 kg/m3 and 1583 kg/m3 for structural walls, while the density of insulation walls was less than 700 kg/m3 [14]. Tchiotsop et al have studied the effect of plant add-ons on the hygric and thermal performance of cob buildings [10].

According to DIN 18945 (DIN 2013a) [51], Miccoli et al have retrieved a bulk density of 1475 kg/m3 after the testing specimens were dried [22]. Sangma and Tripura, in their study of the effect of stabilisers on the structural performance of cob, recorded a density of 1690 kg/m3 for unstabilised mixtures. For cement stabilised samples, the densities varied between 1710 kg/m3 for 3% cement content and 1780 kg/m3 for 10% cement content. Samples with 3% added coir had a density of 1650 kg/m3 and reached 1630 kg/m3 when the added content was 10%. Straw samples recorded a density of 1640 kg/m3 for 3% sand and reached 1610 kg/m3 when 10% was added [28]. The chart below illustrates the densities variation with different fibre types and content in addition to the measured average moisture content. Miccoli et al. reported a bulk density of 1475 kg/m3, which aligns with other studies and existing literature that showed density variation between 1200 kg/m3 and 1700 kg/m3 [22].

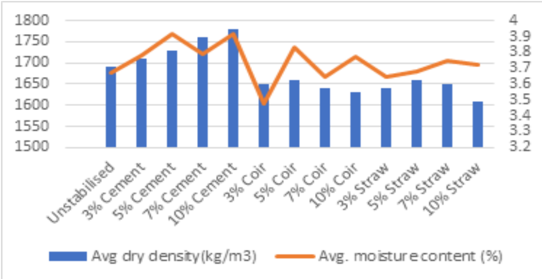

Fig. 1. The average dry density (left axis) and average moisture (right axis) content in cob mixtures with cement, coir, and straw as stabilisers [28].

6.3 Thermal conductivity

Thermal conductivity can be considered the most explored parameter that affects the hygrothermal performance of a material. This can be explained by the fact that the conductivity of cob has a significant effect on the thermal comfort of users, in addition to the heating and cooling loads that will be used to assure the users' comfort rather than minimising operational energy consumption [52].

Thermal conductivity λ can be defined as the amount of heat (in W) that goes through an area of one sq. meter/one-meter thickness when its interior and exterior faces differ in temperature by one Kelvin [52]. Besides, it is a physical parameter that characterises the ability of a substance to conduct heat and is measured by W/m.K. It is critical to mention that the lower the value of thermal conductivity, the better the insulation [52, 53].

A study by Laurent et al have found that the thermal conductivity of cob was a mean of 0.45 W. $m^{-1}.K^{-1}$ while a study by Minke have resulted in a range from 0.47 W. $m^{-1}.K^{-1}$ and 0.93 W. $m^{-1}.K^{-1}$ [47] For the measuring of λ, a Netzsch HFM446 heat flow meter (HFM) was used by Goodhew et al. The researchers have used three different soils (UK3, UK4, and FR3) to make eight different mixes aiming to find a dual cob wall that performs structurally and hygrothermally, and the results are demonstrated in figure 2 [12].

Zeghari et al. have discussed that a mixture with a thermal conductivity of 0.4 $Wm^{-1}K^{-1}$ would have a low density, leading to better insulation [14]. In this study, the researchers have found the local thermal conductivity by evaluating the average thermal conductivity regarding the fibre distributions within the tested mixture. The test was carried out in a laboratory setting, with each specimen placed between the upper cooling brass plate and the lower heating brass plate. A highly conductive thermal paste was then used to ensure the success of the tests because the texture of the samples' surfaces was rough, which could have impacted the measurement's accuracy. For the structural samples in the dual wall system, the lowest thermal conductivity was recorded for samples with 5% wheat straw of 0.244 W. $m^{-1}.K^{-1}$ and the highest recorded result of 0.75 W. m−1.K−1 was for 2.5% of small fibre content, meanwhile, the highest value for the insulation section of the system was reported to be 0.19 W. $m^{-1}.K^{-1}$ [14].

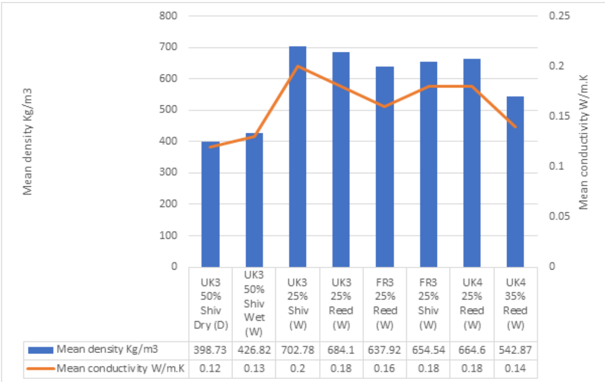

Fig. 2. The relationship between mean thermal conductivity and mean density for cob mixtures with several soil compositions and fibre content for the CobBauge project [12].

Tchiotsop et al. have studied several specimens with different plant aggregates in the mixtures. The authors have used a hot disk device to measure and assess the thermal conductivity of the different mixtures. Mixtures without any added fibre have recorded a thermal conductivity of 0.062 W. $m^{-1}.K^{-1}$. The highest reported value of mixtures with added fibre was for 3% hemp shiv with 0.079%, while the lowest was for 3% flax yarn with a recorded result of 0.031 W. $m^{-1}.K^{-1}$ [10].

6.4 Water Vapour permeability

The importance of vapour diffusion or water vapour permeability (k_m) in a building complies with allowing the moisture exchange between the indoor and outdoor envelopes of buildings, which significantly impacts the comfort of the users within that building [52]. The higher the value of permeability, the better the exchange will be, which can be characterised using the factor of resistance to water vapour (μ). This factor is equal to the ratio between the permeabilities of air and the sample to water vapour, and the higher that factor value is, the harder it is for the moisture to be exchanged [52, 53]. According to EN ISO 1015-19 [54], permeability can be measured either using dry or wet cup methods, the saturated salt solution method (SSS), or by using a climate chamber.

Tchiotsop et al. have followed the dry cup test as stated in NF EN ISO 12572:2016 Standard [55] to evaluate k_m manually and automatically. Gravitest results have resulted in a global CV (coefficient of variation) of 11%, and the CV for specimens with no fibre was 12% higher than manual DCT. For composites having 1% hemp shiv and 1% flax yarn, manual DCT revealed CVs of 50% and 56%, while Gravitest has revealed CVs of 7% and 14%. Lower values (19% and 27% using manual DCT, respectively) have been investigated for He-3% and FL-3%. A modest 11% increase in CV with manual DCT is observed for hay stalk composites[10].

Alassaad et al have also studied water vapour permeability, but by following the ISO 12572 standard [55] have preconditioned all samples to 23°C and 50% relative humidity (RH). Therefore, a moisture gradient of around 0% RH to the outside with an approximate RH of 50% was achieved. Stazi et al, in their study that aimed to evaluate the effectiveness of the coatings in protecting the earthen walls against weathering, have experimentally determined the water vapour permeability to be 2.33E^{-11} kg/m/s/Pa [48]. Other researchers, such as Collet-Foucault discussed 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 [56].

6.5 Moisture Buffering Value (MBV)

Moisture buffering value is another key parameter that has a critical effect on the hygroscopic behaviour of a material as it describes the moisture uptake/release capacity of the material [52].

Tchiotsop et al. have used 110 × 40 mm PVC moulds to make specimens, which were kept at 20 °C and relative humidity of 50% before the tests according to the NORDTEST protocol, where specimens have been tested within a climate chamber at 23 °C and have been submitted to a daily relative humidity loading cycle of 75% RH during 8 h and 33% RH during 16 h. Specimens were then weighed regularly every 2 hours during the adsorption cycle and twice during the desorption cycle. Afterwards, MBV has been calculated as the ratio of the mean mass variation of the last two cycles by the exchange surface of the specimen (A) and the gap in RH between cycles. MBV for non-fibred mixes was recorded at 1.06 g m^{-2} %RH^{-1}. The highest MBV was for mixes with 1% hemp shiv and 1% hey stalk of 1.73 g m^{-2} %RH^{-1}, while the lowest was for mixtures with 3% hay stalk with a value of 1.54 g m^{-2} %RH^{-1}[10].

6.6 Moisture sorption isotherm

The term "moisture sorption isotherm" refers to a material's capacity to absorb and expel moisture from its surroundings [52]. The moisture sorption isotherm has different values for each material and temperature. The adsorption isotherms and desorption isotherms values are the two main parameters used to determine sorption isotherms. Generally, adsorption and desorption differ primarily in that desorption refers to the release of an adsorbed substance from a surface, whereas adsorption refers to the process by which some substances keep the molecules of a gas, liquid, or solute in a thin layer [57].

In a study by Tchiotsop et al., 7 specimens of 10 × 10 × 10 mm^3 and 10 specimens of 50 × 50 × 20 mm^3 size have been tested for sorption isotherms with ProUmid and Saturated Salt Solutions box devices, respectively. For SSS, RH for the inner environment is at 12%, 33%, 55%, 65%, 76%, 86%, and 97%. The equilibrium moisture content was determined using a relative mass variation of less than 0.5% of the specimens. For specimens that were tested with ProUmid, the relative error of mass variation was set at 0.01% Instead, the specimens were dried at 50°C and the specimen's water content was tested at different RH levels between 10% and 95%. For the majority of the imposed RH values, it was found that the water content values of the adsorption and desorption curves recorded using SSS were higher than those obtained with the ProUmid device [10]. Table 3 shows the normal values for the adsorption isotherms for the mixtures, and Table 4 demonstrates the desorption isotherms for the same mixtures.

Table 3. Distribution model parameters of adsorption isotherms of mixtures [10].

RH level (%)	Non-Fibred	Hay stalk 1%	Flask yarn 1%	Hemp shiv 1%	Hay stalk 3%
12	0.62	0.71	0.74	0.93	0.95
33	0.95	1.16	1.17	1.96	1.28
55	1.3	1.61	1.58	2.74	1.64
75	1.76	2.23	2.20	3.82	2.11
90	2.17	2.78	2.75	4.27	2.67

Table 4. Distribution model parameters of desorption isotherms of mixtures [10].

RH level (%)	Non-Fibred	Hay stalk 1%	Flask yarn 1%	Hemp shiv 1%	Hay stalk 3%
12	0.66	0.81	0.77	0.93	0.68
33	1.31	1.67	1.58	1.96	1.45
55	1.52	2.24	2.20	2.74	1.45
75	2.23	2.83	2.97	3.82	2.40
90	2.79	3.52	3.49	4.27	3.11

Alassaad et al. have conducted a different study using the dynamic vapour sorption (DVS) technique according to the ISO 12571 standard [58]. To assess the sorption/desorption values, a ProUmid SPSx-1μ sorption/desorption analyser was used with a precision balance (±1 μg) and tight temperature and humidity control, allowing accurate measurements of sample mass and sorption kinetics [39].

As discussed, a large number of tests are needed to assess the hygrothermal performance of materials. Table 5 below 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.

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

Test	Method	Ref
Bulk Density	DIN 18945 (DIN 2013a) [51]	[23, 26]
	NF ISO 5017 [50]	[39]

Water vapour permeability	Dry cup method following ISO 12572 [59]	[39]
Thermal conductivity	Transit hot wire method heat flow meter/Guarded hot plate Flash method	[52]
Sorption isotherms	Saturated salt solution (SSS) Dynamic vapour sorption (DVS)	[41]
Thermal Diffusivity	Flash method	[52]
Specific heat capacity	Adiabatic calorimeter Flash method The guarded hot plate method	[52]
	Differential Scanning Calorimetry (DSC) following ISO 11357-4 [60]	[39]
Moisture buffering value	NORDTEST protocol	[10]

7 Conclusion

The paper presents a literature review on cob construction, its constituents, mixing ratios, and hygrothermal testing methods. It is observed that the different produced specimens vary in their mixing ratios and the use of fibres. Primarily, straw fibre has been the most used and explored throughout literature, followed by other fibres like coconut coir, flax, hemp, hay, and reed. Generally, only a few research articles have thoroughly studied and discussed the mix ratios. Furthermore, when discussing earthen materials such as cob, a fixed terminology may be required. For instance, some studies have referred to the added fibrous content as "aggregates," while other studies have used the term "aggregates" in reference to coarse sand and gravel within the subsoil.

The research has investigated studies that explored the hygrothermal performance of cob. The study presents results that support the significant hygrothermal performance advantage of cob when compared to other materials. On the other hand, it is noticed that no study has fully explored the structural and hygrothermal performances of a cob specimen.

According to the reviewed literature, the researchers believe that studying and developing a mixture that ensures adequate structural and hygrothermal performance is required for it to be part of an energy-efficient construction with lower embodied and operational carbon. Besides, the researchers encourage performing a comprehensive study that investigates the structural and hygrothermal performance of cob to fill the current gap within relevant research.

As this research has provided the available data on hygrothermal tastings and its assessment standards and methods, future work will undertake a detailed analysis of the effect of formulation on the hygrothermal performance of cob. Furthermore, the researchers will work on developing a comprehensive farmwork that provides a robust method to evaluate the hygroscopic and thermal properties of cob.

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