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Goodhew, Steve

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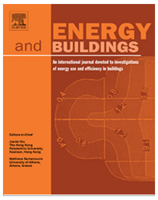

Improving the thermal performance of earthen walls to satisfy current building regulations

Steve Goodhew [a], Mohamed Boutouil [b], François Streiff [c], Malo Le Guern [b], Jim Carfrae [a], Matthew Fox [a,*]

[a] Plymouth University, United Kingdom
[b] Ecole Supérieure d'Ingénieurs des Travaux de la Construction de Caen (ESITC Caen), France
[c] Parc Naturel Régional des Marais du Cotentin et du Bessin (PnrMCB), France

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ABSTRACT

Earth building materials offer architects, engineers and clients a low carbon walling solution for low rise properties (under 3 storeys). Unfortunately, the mixture of sub-soil and fibre known as Cob does not currently comply with the thermal aspects of many building regulations across the world. This paper designs and optimises a low-density cob mix intended to maintain the material's low carbon credentials whilst conforming to the thermal aspects of building regulations. Samples of a range of unmodified subsoils, dug from the ground near to the sites of some prospective buildings are described. These subsoils are combined with a range of commonly grown fibres. Practical and laboratory measurements are undertaken on these mixes and the results are compared with pure subsoil and separate fibres to provide a model that can predict the thermal conductivity of a theoretical soil-fibre mix. It was found that fibre contents over 50% gave very little reduction in thermal conductivity. Furthermore, if the optimal low-density mix is combined into a single composite 2-layer cob wall this can offer a ready-made solution for compliant low-carbon energy-efficient low rise properties or the extension of existing historic buildings.

1. Introduction

Earthen architecture is one of the oldest forms of construction, with early man making use of earth as a simple material to form shelter [28]. Today it is still one of the most common forms of construction found throughout the world, with approximately one third of the world's population currently living in a building made from earth [5]. Such buildings make use of earth in a variety of forms, which include rammed earth, light earth, wattle and daub and adobe blocks [20,28,39], yet one of the simplest earthen techniques is cob.

A common vernacular material to parts of the UK and France, where it is known as *bauge*, cob comprises of clay based sub-soil, water and a fibrous material, traditionally straw, to help bind the material together [12,46]. These materials are mixed and formed in situ into monolithic structural wall constructions that sit above a 600 mm stone plinth [10] to give protection from ground moisture penetration and rain splashback. A traditional cob wall is formed out of several layers called 'lifts', which are allowed to dry before adding additional lifts to minimise structural deformation [24].

As a natural material, cob construction has several sustainable benefits over other commonly used conventional building materials. Such benefits include [37]:

- Hygroscopic nature, which can regulate internal humidity levels to be at around 50% RH, thereby minimising the negative effects to human health from for example, dust mites, mould spores and sick building syndrome.
- Low embodied energy. Earth for cob can be sourced on the site of construction [7] (depending on soil quality) thereby minimising the carbon footprint of importing material. Research shows [18] that earth has a lower embodied energy compared with other common construction materials such as masonry/concrete, which have far more processes in manufacture.
- Waste and recyclability of earth. Earthen construction can make use of waste soil, which currently totals 26.7% (54.2 million tonnes) of the UK's waste generation [13] and 175 Mt/year in France [47]. The waste from cob production is relatively inert and has been described as a 'zero-waste process' [37].

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* Corresponding author at: School of Art, Design and Architecture, Plymouth University, Room 302, Roland Levinsky Building, PL4 8AA, United Kingdom.
E-mail address: matthew.fox4@plymouth.ac.uk (M. Fox).

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Despite these benefits, cob construction has seen minimal use in new building constructions. Watson & McCabe [49] discuss this factor, citing lengthy construction timescales, labour intensity, skill shortage and the availability of more processed materials as reasons for this, which has led to a perceived inertia from the construction industry towards cob as a current viable building material.

Another barrier to the future application of cob construction is its thermal performance. The thermal performance of buildings is significant, since EU buildings are currently recognised as consuming 40% of the total EU generated energy [17]. As the EU seeks to reduce energy use by 20% by 2020 [16] the emphasis is therefore on lowering the energy use and carbon emissions from buildings. One means of addressing this target is to set stringent standards of thermal performance, which all new buildings must achieve. The most common form of assessing thermal performance in buildings is through the calculation of steady-state thermal transmittance (U-value). In England and Wales, Part L1A (2013 edition) of the building regulations stipulate that new buildings should be constructed with 'limiting' / minimum U-value standards of 0.30 W/m^{2}K for walls [11]. This limiting U-value is the same in France [43], however, since the 'Grenelle de l'environnement II' Act in 2010 [43] all new buildings in France from 2013 need to be designed to use less than 50 kwh/m^2/year energy for space heating in order to comply with thermal legislation. In 2020, France will move to new Environmental Regulations [40], that aim at reducing the overall carbon footprint of new buildings, in addition to lowering energy consumption targets. The main extra requirement that RE2020 takes into account is the incorporation of Life Cycle assessment in the form of upper limits of Carbon footprint by the building (in Kg equivalent CO_2). For individual housing, the new targets will be 630 kg equivalent CO2/m^2 (from 2021 to 2023), then 510 (in 2024) ; 450 in 2027 and 370 in 2030.

The performance levels for a new building will be characterised by an energy level based on the positive energy (E+) indicator (BEPOS) and a carbon (C-) level based on greenhouse gas emissions throughout the building's life cycle (Eges) and greenhouse gases produced via the construction process and equipment used [40]. Four energy performance levels have been defined for positive energy buildings, along with two environmental performance levels regarding greenhouse gas emissions. Hence, a cob material could help to achieve low carbon buildings.

Whilst the stated U-values in both the UK and French regulations can be achieved using high specification conventional materials, existing cob constructions offer higher U-values, which are not regulation compliant using traditional mixes of fibre and subsoil. For instance, Rye and Scott [44] undertook in situ heat flux measurements and found that existing cob wall U-values varied from 2.26 W/m^{2}K for a 510 mm thick wall to 0.76 W/m^{2}K for a 680 mm thick wall. Though the U-value is largely dependent on the density of the material being used, with Ley and Widgery [33] giving cob U-values of 0.94 W/m^{2}K for a low-density wall of 600 mm and 1.14 W/m^{2}K for higher density wall at the same thickness. This illustrates the gap between target U-values which current cob constructions are able to achieve.

Seeking to improve the thermal transmittance of cob walls using the addition of insulated renders, Griffiths & Goodhew [22] proposed wall thicknesses of between 645 mm and 995 mm before meeting current building regulations or 0.3 W/m^{2}K, and could be argued as excessively thick in comparison with other wall constructions. For instance, an insulated brick / lightweight block cavity wall with similar thermal transmittance values is calculated by CIBSE [8] to be only 318 mm thick. Whilst cob walls are likely to be thicker than more modern constructions for structural performance, Williams et al. [50] comment that with wall thicknesses of greater than 600 mm equate to increased construction costs and a reduction in habitable floor space, making such constructions less desirable for many developments.

Yet this focus on steady-state thermal transmittance belies another benefit to cob, which is that of the thermal mass. Rempel & Rempel [41] discuss this, suggesting that constructions with such high thermally massive properties can regulate the flow of heat through the material. This enables the stabilisation of internal air temperatures [21]. In addition, specific heat capacity is an important aspect of building performance, but in this instance this work is focused on steady state analysis due to the requirements of building regulations, who focus on steady state compliance. The thermal conductivity and therefore the proceeding thermal transmittance of earth (subsoil) is of particular interest in this paper.

Whilst several hygrothermal studies have been undertaken upon rammed earth and other forms of 'unbaked' earth construction techniques, [2,3,6,30,35,51], less work has been undertaken on the thermal properties of Cob. According to several authors [15,31,36,42], the thermal conductivity of cob is in a range between 0.47 and 1 W.m^{-1}.K^{-1} depending on density, fibre and water content. A range of thermal conductivities for traditional earth building materials measured by others are presented in Table 1. This shows that thermal conductivity of varies from 0.20 W.m^{-1}K^{-1} (for a light earth fibre mix) to 1.40 W.m^{-1}K^{-1} (for rammed earth).

The addition of fibre in an earth matrix will influence cob density and, consequently, its thermal conductivity. This influence was studied by [31] through a soil-fibre mix. This shows that a fibre content variation between 0.5 and 22 % leads to a density decrease from 1700 kg.m^{-3} to 600 kg.m^{-3} introducing an additional porosity almost proportional to its content and, consequently, decreases thermal conductivity. Laurent's results show that measured thermal conductivity varied with a factor of one to five (0,2–1 W.m^{-1}.K^{-1}) and confirmed the lead role of dry density on thermal conductivity variation for earth fibre materials. Table 2 presents the relationship between dry density and thermal conductivity according to Minke [36].

There is a strong tradition for low density light earth constructions, especially in Germany [48], however, this system of construction relies on a secondary structure. Cob on the other hand

Table 1
Thermal conductivity of earth building materials from literature.

References	Earth building technique	Density (kg.m^{-3})	λ (W.m^{-1}.K^{-1})
Röhlen et al., [42]	BTC	1600–2100	0.70–1.20
	Rammed earth	1600–2200	0.70–1.40
	Cob	1400–1700	0.60–0.80
	Earth coating	1000–1800	0.35–0.91
El Azhary et al [15]	Unfired clay bricks	1610–1890	0.35–0.46
Laurent [31]	Earth fibre mix	600–1700	0.20–1.00
Leguern et al. [32]	Cob	1419	0.45
Minke [36]	Cob	1200–2000	0.47–0.93

Table 2
Thermal conductivity of earth fibre material [36].

Soil	Dry density (kg.m^{-3})	Thermal conductivity (W.m^{-1}.K^{-1})
High density	2000	0,93
Middle density	1200–1700	0,70
Low density	1200	0,47

is utilised as a wall construction on the basis of it being a monolithic structure.

Yet in spite of past research into earth fibre at different densities, there remains a failure of traditional cob constructions to meet current building standards, and this limits the application of cob for new build constructions.

Therefore, the aim of this work is to develop an optimised cob construction, which will have thermal transmittance properties that meet with current building standards. To investigate this, the paper explores the following objectives:

1. To measure the thermal conductivity of small-scale cob samples using a variety of earth and fibre mixes at different densities.
2. To review the optimised theoretical wall construction of a Cob-Bauge wall that delivers a compliant U-value without the inclusion of conventional materials, while maintaining the key benefits to cob as a construction material and meeting current building standards.
3. To determine whether one material can be used to achieve building standards or whether multiple materials are required. And if multiple materials are requied, what the composition of these materials might be.

The earth material being investigated in this paper is hygroscopic and, as with all other open cell building materials will absorb moisture. It is known that hygrothermal performance can impact on thermal transmittance [19], which is especially true under in-situ situations, where materials are subject to dynamic moisture and temperature influences. However, the measurements undertaken in this paper have been conducted in a controlled laboratory environment and in accordance ISO8301:1991 [25], which sipulates that the moisture content of samples should vary by no more than 1% when measured over three consecutive 24 h periods. It is anticipated that future work will explore the hygrothermal performance of this material, as the material is used in a live building case study.

2. Methodology

2.1. Approach

This research uses a number of methods to investigate the thermal properties of subsoils, fibres and the subsequent subsoil/fibre mixtures with an aim to produce a cob wall that will be compliant to the French, UK and equivalent thermal building regulations across the world.

It is important to assess the characteristics of the ingredients of any final wall design, both separately but also as a mixture. Sections 2.2 and 2.3 describes the detailed soil and fibre characteristics allowing other researchers the opportunity to replicate or adapt this work to their local conditions. Section 2.4 describes the soil/fibre mixes chosen because of their even distribution of particle sizes and optimal fibres. Section 2.5 describes sample production to ensure representative measurements. Finally, sections 2.6 and 2.7 describe the method used to analyse the thermal characteristics of the samples and the uniformity of the sample preparation between the two laboratories.

2.2. Soil characterisation

Cob is reliant on the clay content of soil to bind other elements of the mixture together. In traditional cob construction it is known that the clay content of soils should be in the region of 10 – 25% [10].

Cob is also dependant on other soil fractions, such as silt, sand and gravel, which are defined more closely in Table 4 and provide successful cob samples.

For these investigations, 12 different soil samples were sourced from different sites within the South West of England and North West of France, two regions known for their tradition in cob construction. These samples of soils contained adequate levels of clay for cob construction.

Particle size distribution of each soil was determined by wet sieving for the fraction greater than 80 μm (XP P94-041) and by laser diffraction method for elements smaller than 80 μm (ISO 13320:2009). European Standard ISO 14688-1 [26] and 14688-2 [27] enable classification of soils according to their engineering properties.

Another soil classification used was the Unified Soil Classification System based on particle size distribution and the Atterberg limits [4]. To classify soils used in this study, Atterberg limits were determined according to XP CEN ISO/TS 17892-12 [1]. As all soils were to have more than 50% passing through sieve #200 (75 μm), to be considered as fine-grained soil.

Finally, a methylene blue value was determined according to NF P 94-068.

2.3. Fibre characterisation

In this study, reed and hemp shiv plant fibres were used to make cob mixes. These fibres were sourced from Normandy (France) but are grown in a wide range of countries. An important characteristic of vegetable fibres is the water absorption coefficient. Indeed, this characteristic will influence, on one hand, the mix in the fresh state (absorption of available water) and, on the other hand, the long-term behaviour (change in fibre volume, fibres/soil interface modification). The water absorption coefficient was determined by fibres immersion in water during several periods (5 min, 15 min, 1 h, 4 h and 24 h). Fibres were then spun with a centrifuge at a speed of 500 revolutions per minute for 15 s.

2.4. Subsoil/fibre mixes

In order to study the influence of fibre, soil and water content, eight mixes were used in this study (Table 3). The length of the fibres needed to be < 50 mm due to size of the samples. Therefore, fibres were cut to the required length, added randomly and mixed into a homogeneous sample.

Determination of the water content was achieved through using the viscosity or ‘puddle’ test. This methodology was used as it is commonly practiced by earth builders [48]. The test comprises of pouring 100 ml of soil slip from a height of 100 mm onto a glass

Table 3
The composition of the subsoil/fibre mixes.

Mix	Soil type code	Fibre	Fibre added mass content (%)	Water content (%)	Type of mix
1	*UK3*	Hemp shiv	50	65.6	Dry
2	*UK3*	Hemp shiv	50	107.3	Wet
3	*UK3*	Hemp shiv	25	107.3	Wet
4	*UK3*	Reed	25	107.3	Wet
5	*FR3*	Reed	25	131.3	Wet
6	*FR3*	Hemp shiv	25	131.3	Wet
7	*UK4*	Reed	25	62.1	Wet
8	*UK4*	Reed	50	62.1	Wet

Table 4
Soils particle size distribution.

Soil	Clay fraction(% < 2 μm)	Silt fraction(2 < % < 63 μm)	Sand fraction(63 μm < % < 2 mm)	Gravel Fraction(2 mm < % < 63 mm)	D_{max}(mm)
UK3	12.83	68.93	17.80	0.44	20
UK4	5.59	58.64	16.74	19.03	31.5
FR3	12.85	65.43	12.36	9.36	50

surface to form a puddle. This test uses soil fraction under 5 mm. Experiments explored results using two different viscosities. These corresponded to a puddle diameter of 7 cm (referred to as a dry mix) and 14 cm (referred to as a wet mix).

All samples were stored at 20 ± 2 °C and 50 ± 5% relative humidity.

2.5. Sample preparation

Sample preparation is an important step in the development of an optimised thermal cob material. Not only to measure repeatability of results, but also to assess sample cohesion with consideration of how this material might work as part of a practical construction material.

Before forming into measurable samples, the wet slip is left to 'sour' for at least 24 h. Souring wet clay rich soil improves the application within the mixture by changing the behaviour of the slip from alkalinity to acidity. Harrison [23] reports on souring as a bacterial process, which encourages clay flocculation.

To form the measurable samples, the specific quantity of fibre and slip is calculated and weighed (based on dry weights) to determine the correct ratio for the density of sample desired. The slip is then mechanically mixed with the fibre to form the cob material. This mixture is left for a further 24 h before being evenly hand tamped into uniform rectangular moulds (300 mm (W) × 300 mm (L) × 70 mm (D). The dimensions of the mould are dictated by the capacity to measure the samples in a heat flow meter. Fig. 1 shows each stage of the sample preparation process.

Once the samples were removed from the mould, they were oven dried at 40 °C until they reached an equilibrium weight, where 3 consecutive weighing's at 24 h intervals were within 1% of each other. The dry samples were finally re-measured to calculate their density.

For this study, 40 thermally optimised cob samples were prepared to investigate each of the 8 separate combinations of soil and fibre (mixes). For each mix, 5 matching samples were prepared. Split between the two laboratories, there were 3 sets of 8 samples prepared and measured in the UK, with 2 sets of the same 8 samples prepared and measured in FR.

2.6. Thermal conductivity measurements

To investigate the thermal conductivity of the mixtures a Netzsch HFM446 heat flow meter (HFM) [38] was used. Fig. 2 shows the heat flow meter apparatus.

The HFM was used in accordance with ISO 8301:1991 [25]. For measurement, the samples were placed between the two plates (hot and cold plates) of the HFM. A thin rubber mat was placed between the surface of the plate and the sample to minimise the effects of undulating surface features. The HFM is calibrated to take the mat into account when measuring samples.

To explore the effects of temperature on thermal conductivity, each sample was measured at three different temperature ranges: 0 °C–20 °C, 10 °C–30 °C and 20 °C–40 °C.

2.7. Uniformity of samples

The UK and French laboratories replicated each of the samples using equivalent mixes that used the same soils, which were extracted at the same time from the same source. Both laboratories also sourced fibres from the same origin, which were shared between the laboratories.

3. Results

3.1. Soil and fibre characterisation

Investigations into the twelve soil types identified three that presented the most suitable characteristics for use within a thermal cob mixture. Soil characterisation results of the three suitable soils are presented in Table 4. This table shows that the main soil fraction is of silt, which ranges from 58 to 69%. The clay content of soil UK3 and FR3 is in the region of 10–25%, which corresponds with adequate levels of clay for cob construction [10]. UK4 with a clay content of 5.59% was included to explore the effects of a lower clay content on the mixes.

Due to their silt fraction, soils UK3 an FR3 are categorised under ISO 14688-2:2018 [29] as being "clSa", Clayey Sand and soil UK4 as "siSa", Silty Sand.

Fig. 1. Sample preparation stages. (left to right. Cut fibre, weighed slip, mechanical mixing, hand tamping, completed sample).

Fig. 2. Heat Flow Meter.

Further analysis using the Atterberg limits [4] found that the liquid limit of UK3 and FR3 is under 50%. This leads to the classifications of "ML", low-plasticity silt. For soil UK4, the liquid limit was above 50%, giving a classification of "CH", high-plasticity clay.

Results show that despite having a similar clay content, soil FR3 has a higher methylene blue value than UK3. This indicates that clay from FR3 has a higher specific area than UK3. This will result in a higher water content for FR3 compared to UK3 to obtain the same viscosity.

Characterisation results from water absorption coefficient investigation on hemp and reed natural fibres, showed that the water absorption coefficient varied between 180 and 340% at 24 h.

3.2. Thermal conductivity of samples

For each of the 8 optimised mixtures of soil and fibre, at least three samples were prepared and measured using the HFM. Experiments were conducted in two laboratories before corroborating results for the mixes. Table 5 presents the average density and conductivity results from the samples analysed for the 8 mixes.

While initial experiments trialled both wet (14 cm puddle test) and dry mixes (7 cm puddle test), it became apparent that a wetter mix was easier to form into a sample and likely to be more practical than a dry mix.

Mixes with 25%, 35% and 50% fibre content were investigated. Densities lower than 25% fibre content were found to have too poor a thermal conductivity, while increasing the density above 50% fibre content resulted in samples with poor cohesion, which would be structurally impractical to use.

In most insulating materials there is a relationship between conductivity and density [14], especially within a group of similar earthen materials [48].

A similar relationship was therefore expected between the density of the samples and their conductivity. Fig. 3, presents the results from all 40 experiments and demonstrate this correlation. Results illustrate that it is the density of each mix that has as much, if not more, effect on the conductivity than the percentage and type of fibre added.

Using an exponential trend line, results show a general pattern of similarity according to the different mixes. The first two mixes comprised of 50% fibre content and yielded the lowest conductivity value. An outlier was found from the 4th sample measured for mix no.7. This gave a significantly higher conductivity value than other samples of the same mix.

Exploring this relationship further, experiments were conducted on the thermal conductivity of the fibres on their own and soil samples without fibre included (Fig. 4). This demonstrated that little improvement could be made to thermal conductivity from increasing the fibre content of samples beyond 50% in comparison with the conductivity gains by adding 25%–50% to the soil. Furthermore, increasing the fibre content of samples beyond 50% led to mixtures with very poor cohesion that would unlikely be structurally practical to work with.

Fig. 4 also includes lambda values from literature for raw fibres (shown as the lowest two literature sourced lambda values) and similar cob constructions [15,20,31,32,36,42,48]. These were found to fit closely within the curve established from the measured samples and helps to give context to the results in this paper.

4. Discussion

The aim of this research is to investigate the thermal properties of local subsoil and fibre mixes, leading to a new form of cob construction that complies with current standards of thermal transmission (typically 0.30 W/m^{2}K). This is significant, since traditional cob, measured at between 2.26 W/m^{2}K and 0.76 W/m^{2}K [44] does not currently comply without the addition of other insulating materials. As the wall thicknesses for these two measurements are 510 mm and 680 mm respectively, any additional hygroscopic insulation layer is likely to significantly increase wall thicknesses.

Results from this work have examined the core material constituents of cob and have led to the production of a curve that

Table 5
Comparison of the mean density with mean thermal conductivity of the eight selected mixes.

Matrix mix no.	Material (Soil with % fibre)	Mean density Kg/m3	Coefficient of Variation	Mean conductivity W/m.K	Coefficient of Variation
1	UK3 50% Shiv Dry (D)	398.73	12.3	0.12	14.0
2	UK3 50% Shiv Wet (W)	426.82	17.6	0.13	18.0
3	UK3 25% Shiv (W)	702.78	3.9	0.20	7.0
4	UK3 25% Reed (W)	684.10	3.0	0.18	4.7
5	FR3 25% Reed (W)	637.92	4.1	0.16	7.6
6	FR3 25% Shiv (W)	654.54	9.0	0.18	9.9
7	UK4 25% Reed (W)	664.60	17.2	0.18	24.7
8	UK4 35% Reed (W)	542.87	2.3	0.14	5.4

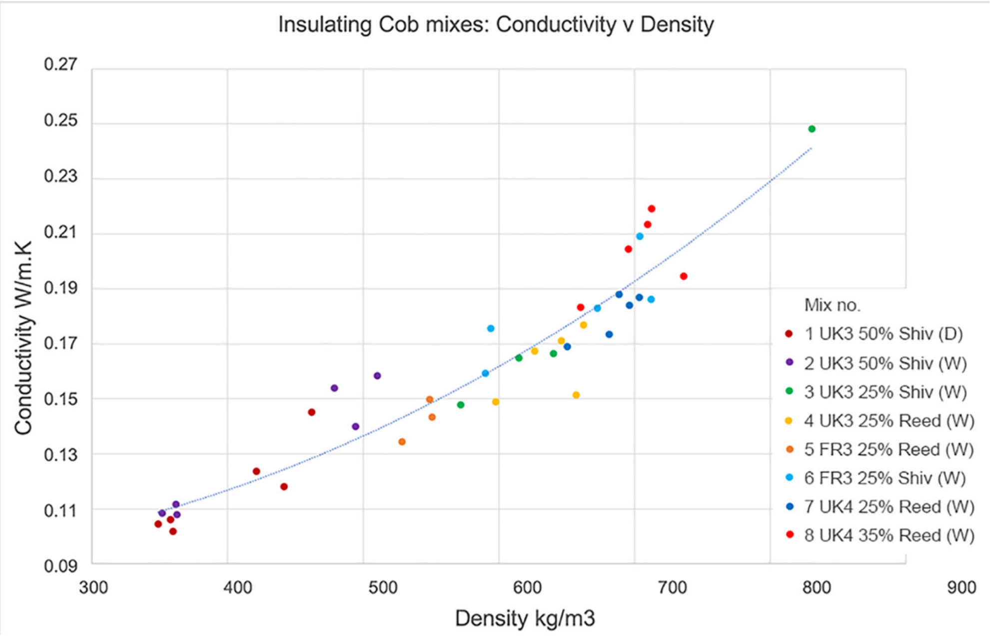

Fig. 3. The relationship between sample conductivity and density (coloured according to mix number).

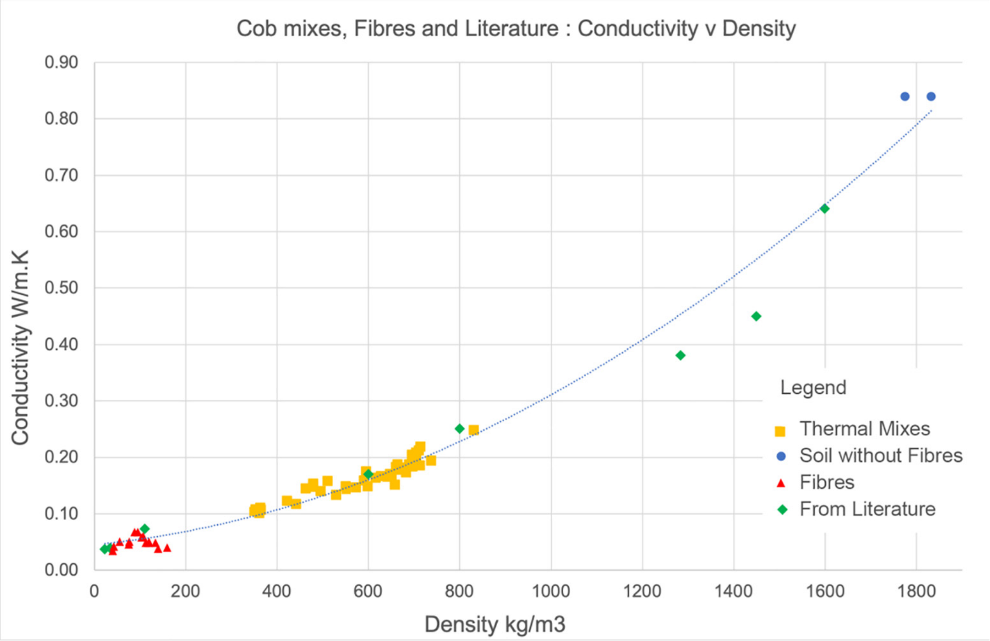

Fig. 4. Conductivity comparison between thermal mixes, 100% fibres and 100% soil samples.

defines the relationship between density and thermal conductivity. This research expands on Volhard's [48] thermal conductivity versus density relationship in Figs. 4 & 5. This allows the reader to estimate the thermal conductivity of a finished cob mix. This will rely on appropriate moisture contents and the quality of soil and fibre.

As presented in Fig. 3, it became clear that those samples, which contained 50% fibre by dry weight of soil resulted in lower conductivity values than those at 25 – 35% fibre. This is in part due to their lower density. Investigations found that hemp shiv retained its hollow core structure even when trimmed to <50 mm length and wetted. This property permitted air to be trapped within the fibre strand, which was retained when dried. Increasing the density of fibre as a ratio to soil consequently led to the increase in air pockets within the samples, which helped deliver increased thermal resistance as typically found in other conventional insulation materials. There was some degree of variance in results for matching mixes in Fig. 3. While the materials, quantities and mixing methodologies were identical, this was theorised as being due to the hand tamping process into the moulds, where some samples will have been compressed into the mould slightly more than that for another sample with identical sample mix. To account for this variation, a mean conductivity value has been presented in table 5. From this, mix number 1 is presented as offering the greatest thermal conductivity with a value of 0.12 W/m.K. This conductivity value is lower than those measured in traditional cob walls [33,44]

Fig. 5. Photo of one-to-one scale CobBauge wall sample.

and represents the potential for inclusion within a wall construction to meet the thermal building standards.

Despite complying with the thermal regulations, it was found that the cohesion of the samples using 50% fibre content was more friable than traditional cob mixtures. This correlates with work by Volhard [48] on light Earth construction, which cannot be used without the addition of a separate timber framed structural system for load-bearing purposes. It is therefore likely that if the low-density high-fibre mixture proposed by this paper was used without a structural cob layer, it will also require a separate structural system.

Whilst other materials, such as timber could be used to fulfil a structural role such as in light earth construction, the core aim of this project is to develop an optimised construction entirely out of cob. This is important since:

1. Utilising different materials increases the risk of material incompatability. Where materials with different properties dry, shrink and adhere differently.
2. Earth construction brings a number of aforementioned unique additional attributes discussed in the introduction, which this project is seeking to retain.

It is possible to propose a single layer of traditional cob, which meets the thermal building regulations. However, the thickness of such a wall (un-finished) would be approximately 1400 mm using a conductivity of 0.45 W/m.K [32], which would not only be regarded as inpractical, but would also increase the building footprint, quantity of materials, cost of building, time scale to construct and drying times. This therefore suggests that wall thickness is an important constraint in the theoretical proposal of a compliant cob wall construction.

Wall thicknesses are discussed in the introduction. While traditional cob can be found in a range of thicknesses, Goodhew & Griffiths [21] determine that the typical thickness for this form of construction is 600 mm. Therefore, it seems reasonable that a proposed optimised cob wall construction should match the traditional thickness expected from this material.

Working within the limitation of a 600 mm thick cob wall, a likely single optimised cob mixture that meets the thermal building regulations could be mix number 6. This mix comprised of 25% hemp shiv cob mix, with a conductivity of 0.18 W/m.K and resulted in a compliant U-value of 0.28 W/m^{2}K. Yet, this material, like that of mix number 1, was found to be too friable to be considered as a single monolithic wall construction.

It is therefore practical to consider a dual layer composite of two different forms of cob, whereby each of the cob layers is optimised for their separate purposes.

Layer 1. The first layer shall provide structural performance and comprises of a traditional cob mixture, which has a measured compressive strength of between 1.2 & 2.0 MPa for a cob density of 1700 kg/m^3 [45]. 300 mm is the narrowest thickness of traditional cob walling used in research by Collet et al. [9].

Layer 2. The second layer shall provide thermal conductivity performance and comprises of a cob mix, which is formed from one of the mixtures researched as part of this paper. To meet the 600 mm total wall thickness target, this layer also should be 300 mm.

Taking this further, Table 6 presents the calculations for a theoretical 600 mm thick composite wall, which is made from 300 mm of mixture 1 in Table 5, which was chosen as it had the lowest thermal conductivity (0.12 W/m.K). It also includes a 300 mm layer of a traditional cob, which is selected for known structural performance. This calculation demonstrates how a composite wall using the research from this paper can meet current thermal standards whilst retaining the structural criteria inherent in tradtional cob without the need for additional materials or structural members.

Whilst embodied energy has not been the focus of this paper, research found a comparatively low 0.065 MJ-eq/kg [34] value for traditional cob in comparison with other conventional materials, which suggests that CobBauge, comprising of the same materials and construction methods as traditional cob can be a low embodied energy construction system. While significant for present day low energy construction decisions, this will be particularly important in the future as new versions of ICE come out, and in light of the RE202 future reduced embodied energy requirements for new dwellings. It therefore can be expected that earth constructions, such as CobBauge will see a greater demand in order to comply with future regulations.

4.1. Conclusion and future work

This paper has presented a natural composite construction material, which builds upon established performance characteristics of traditional monolithic cob construction.

Although literature indicates that traditional cob offers acceptable load bearing capacity, other sources show that this material does not meet current standards of thermal transmission.

Research presented in this paper shows that a low density (398.73 kg/m^3) layer of cob delivers a lambda value of 0.12 W/m.K, which far exceeds the thermal conductivity performance of traditional cob.

The data from this paper makes it possible to consider the low-density cob material as part of theoretical U-value calculations. This paper proposes a dual layer composite cob material, which illustrates a new wall design that will comply with building regulations. The proposed composite construction comprises of a layer of the low-density cob mixture alongside a secondary layer of traditional high-density cob that has a known structural load bearing capacity.

Retaining a wall thickness of 600 mm, which is typical of traditional cob buildings, initial calculations have demonstrated that even with the 50% addition of a high-density layer of cob, the CobBauge composite construction material can meet current thermal building standards with calculated U-values of 0.30 W/m^{2}K.

Table 6
Calculated U-Value for a twin layer composite construction of lightweight (mix no.1) and dense cob.

Monolithic Wall	Density kg/m3	Thickness m	Conductivity W/m K	Resistance m^2 K/W
Internal surface		n/a	n/a	0.12
Traditional Cob:Leguern et al. [32] 2.5% Flax Straw	1419	0.300	0.45	0.67
Thermal Cob: Mix 1:UK3 50% Hemp Shiv	398.73	0.300	0.12	2.50
External Surface		n/a	n/a	0.06
Total Resistance				3.35
U-Value W/m^2K				**0.30**

Whilst there remains scope for future research into structural testing and in-situ thermal conductivity investigations to demonstrate in-use performance, the research in this paper specifically addresses compliance with building standards from a design perspective, which is the benchmark used by all current conventional materials.

This completed section of work presents a substantial part of the CobBauge project, which explores the optimisation of this composite construction material. There are three clear contributions to research from this work:

1. The first-time thermal conductivity has been plotted against density for such a wide range of natural fibres, soil and fibre / soil mixes in their dry form.
2. The proposal of a dual layer (thermal and traditional structural) free standing monolithic cob wall.
3. The introduction of a new low carbon building technique based on earth.

The next stage in the project will investigate the load bearing capacity of the composite wall. To achieve this, full scale wall samples will be constructed and subject to load stresses. Fig. 5 shows initial work to construct a full scale wall sample. Scaling the wall samples will allow investigations over the thickness ratio of low density to high density within a wall construction.

Declaration of Competing Interest

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

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