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

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Text in red indicates areas for development / topics to elaborate on.

Abstract

Earth building materials offer architects, engineers and architects a very 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, including France and the UK. This paper reports the results of some joint research that, through a mixture of laboratory and practical measurements optimises two cob mixes, one low density (minimised thermal conductivity) and one high density (maximised compressive strength). Results are reported from a range of unmodified subsoils, dug from the ground near to the site of some propective buildings. These subsoils are combined with a range of commonly grown fibres at high and low densities and the results are compared. The optimal low and high density mixes are combined into a single composite 2-layer cob wall offering a ready made solution to complient low-carbon energy-efficient low rise properties or the extension of existing historic buildings.

Contents

Acknowledge

1.0 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 (Jaquin and Augarde, 2012). Today it is still one of the most common forms of construction found throughout the world, with approximately one third of the worlds population currently living in a building made from earth (Bee, 1997). Such buildings make use of earth in a variety of forms, which include rammed earth, light earth, wattle and daub and adobe blocks (Jaquin and Augarde, 2012, Niroumand et al., 2013, Goodhew, 2000), 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 (Stokes, 2008, DEBA, 1992). These materials are mixed together and formed in situ into monolithic structural wall constructions that sit above a 600mm stone plinth (Coventry, 2004) to give protection from rising damp. A cob wall is formed out of several layers called 'lifts', which are allowed to dry before adding additional lifts to minimise structural deformation (Hunter and Kiffmeyer, 2004).

As a natural material, cob construction has a number of sustainable benefits over other commonly used manmade building materials. Such benefits include (Morton, 2008):

- 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 (Chabriac et al., 2014) (depending on soil quality) thereby minimising the carbon footprint of importing material, when compared with other common construction materials such as masonry, which has 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 (DEFRA, 2018). The waste from cob production is relatively inert and has been described as a 'zero-waste process' (Morton, 2008).

Despite these benefits, cob construction has seen relatively minimal use in new building constructions. Watson & McCabe (2011) 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 (EU, 2010). As the EU seeks to reduce energy use by 20% by 2020 (EU, 2008) the emphasis is therefore on lowering 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 0.30W/m^{2}K for walls (DCLG, 2010). In France, the focus is slightly different to the UK and Thermal Regulation (RT, 2012) indicates a target of Uvalue of 0.3 W/m^2.k. for walls in order to insure an efficient thermal envelope. Since the 'Grenelle de l'environnement II' act (2010), efficient energy building (< 50 kwh/m^2/year) is the rule for new building from 2013. In 2020, the French regulation will shift to the new Environmental Regulation 'RE 2020, E+C-)' that aims at reducing the overall carbon footprint of new buildings, in addition to low energy consumption targets. The Performance levels for a new building are characterised by an energy level based on the positive energey (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 (EgesPCE).

Four energy performance levels have been defined for positive energy buildings, along with two environmental performance levels regarding greenhouse gas emissions. Hence, cob material could help to achieve low carbon buildings.

Whilst the stated U values in bothe the UK and French regulations can both be easily achievable through the use of high specification man-made materials, existing cob constructions offer much higher U-values, which are not compliant using traditional imensions or mixes of fibre and subsoil. For instance, Rye and Scott (2012) undertook in situ heat flux measurements and found that existing cob wall U-values varied from 2.26W/m^{2}K for a 510mm thick wall to 0.76W/m^{2}K for a 680mm thick wall. Though the U-value is largely dependant on the density of the material being used, with Ley and Widgery (1997) giving cob U-values of 0.94W/m^{2}K for a low density (0.7W/m^{2}K) 600mm thick wall and 1.14W/m^{2}K for higher density (0.95W/m^{2}K) cob 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 (2017) proposed wall thicknesses of between 645mm and 995mm before meeting current building regulations or 0.3W/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 (2017) to be only 318mm thick. Whilst cob walls are likely to be thicker than more modern constructions for structural performance, Williams *et al*. (2010) comment that with wall thicknesses of 600mm or higher 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 (2016) discuss this, suggesting that constructions with such high thermally massive properties are able to regulate the flow of heat through the material. This enables the stabilisation of internal air temperatures (Goodhew and Griffiths, 2005). However, as the regulations focus on steady state compliance, the thermal conductivity and therefore the proceeding thermal transmisstence of earth (subsoil) is of particular interest.

According to several authors (Laurent, 1986; Minke, 2000; Röhlen et al., 2013) in (Phung, TA, 2018), the thermal conductivity of cob is between 0.47 and 1 W.m^{-1}.K^{-1} depending on density and fibre and water content. The range of thermal conductivity of other earth building materials are presented in Figure 1. This shows that thermal conductivity of varies from 0.17 W.m^{-1}.K^{-1} (for light earth) to 1.40 W.m^{-1}.K^{-1} (for rammed earth).

References	Earth building technique	Density (kg.m^{-3})	λ (W.m^{-1}.K^{-1})
Röhlen et al., 2013	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
Laurent, (1986)	Earth fibre mix	600-1700	0,20-1,00
Minke, (2000)	Cob	1200-2000	0,47-0,93

Table 1. Thermal conductivity of earth building materials (PHUNG, TA, 2018)

The addition of fibre in an earth matrix influence cob density and, consequently, its thermal conductivity. This influence was studied by (Laurent, 1986) througth a soil-fiber mix. This shows that a fibre content variation between 0.5 to 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 thermal conductivity measured varies with a factor of one to five (0,2–1 W.m^{-1}.K^{-1}) and confirm the lead role of dry density on thermal conductivity variation for earth fibre materials. Figure 2 presents the relationship between dry density and thermal conductivity according to Minke (200).

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

Table 2. Thermal conductivity of earth fibre material (Minke, 2000)

In spite of this past research, the failure to meet current building standards is limiting the application of cob for new build constructions.

Therefore the aim of this work is to develop an optimised cob mix, which will have thermal transmittance properties that meet with current building standards whilst remaining structurally secure as a single monolithic wall construction.

3.0 Methodology

3.1 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 many other thermal building regulations across the world.

It is important to assess the charateristics of the ingredients of any final wall design, both separately but also as a mixture. Sections 3.2 and 3.3 describes the detailed soil and fibre characteristics allowing other researchers the chance to replicate or adapt this work to their local conditions. Section 3.4 describes the soil/fibre mixes choosen because of their even distribution of partical sizes and optimal fibres. Section 3.5 describes sample production to ensure representative measurements. Finally section 3.6 describes the method used to analyse the thermal charcteristics of the samples.

3.2 Soil characterisation

Cob is reliant on clay to bind or 'stick' 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% (Coventry, 2004). For these investigations, samples of soils were chosen based on their likelihood to contain adequate levels of clay for cob construction. 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.

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 and 14688-2 (SOURCE) 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 (ASTM D2487). To classify soils used in this study, Atterberg limits were determined according to XP CEN ISO/TS 17892-12 (SOURCE). As all soils were to have more than 50 % passing through sieve #200 (75μm), to be considered as fine grained soil.
Finally a Methylene blue value was determined according to NF P 94-068.

3.3 Fibre characterisation

In this study, reed and hemp shiv plants were used to make cob mixes . These fibres were sourced from Normandy (France) but are grown in a wide range of different countries. Both plant fibres have been known to offer good compatability with use in subsoil fibre mixes for constrcutiuon purposes (REF NEEDED). 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, in the other hand, the long term behaviour (change in fibre volume, fibres/soil interface modification). The water absorption coefficient was determined by fibres immersion of in water during several periods (5 minutes, 15 minutes, 1 hour, 4 hours and 24 hours). Fibres were then spun with a centrifuge at a speed of 500 rounds per minute for 15 seconds.

3.4 Subsoil/fibre Mixes

In order to study the influence of fibre, soil and water content, eight mixes were used in this study (Figure 3). The length of the fibres needed to be <50mm 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 achived through using the 'slip' test. This methodology was used as it is commonly practiced by earth builders (Gaia Architects, 2003). The slip test comprises of pouring 100ml of soil slip from a height of 100mm onto a glass 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.

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 3. The composition of the subsoil/fibre mixes.

3.5 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 on how this material might work as part of a practical construction material.

Before forming into a measurable samples, the wet slip is left to 'sour' for at least 24 hours. Souring wet clayey soil improves the application within the mixture by changing the behaviour of the slip from alkalinity to acidity. Harrison (1991) reports on souring as a bactierial process, which encourages clay flocculation.

To form the measureable 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 hours before being gently hand tamped into uniform rectangular moulds (300mm (W) x 300mm (L) x 70mm (D). The dimensions of the mould are dictated by the capacity to measure the samples in a heat flow meter. Figure 1 shows photos from each stage of the sample preparation process.

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

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

For this study, 39 thermally optimised cob samples were prepared to investigate 8 separate combinations of of soil and fibre.

3.5 Thermal conductivity measurements

To investigate the thermal conductivity of the mixtures a Netzsch HFM446 heat flow meter (HFM) (NETZSCH) was used. Figure 2 shows the heat flow meter apparatus.

The HFM was used in accordance with ISO 8301:1991 (ISO, 1991). 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.

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

Figure 2. Heat Flow Meter

4.0 Results

4.1 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 (Coventry, 2004).

Due to their silt fraction, soils UK3 an FR3 are categorised under ISO 14688-2:2018 (Kovačević et al., 2018) as being “clSa”, Clayey Sand and soil UK4 as “siSa”, Silty Sand.

Further analysis using the Atterberg limits (ASTM D2487) 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.

Soil	Clay fraction (% < 2μm)	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

Table 4. Soils particle size distribution.

Charaterisation 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 hours.

4.2 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 trialed both wet (14cm puddle test) and dry mixes (7cm 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. Furthermore, results were similar between wet and dry mix results. Therefore dry mix experimentation was not continued beyong mix number 1.

Mixes with 25%, 35% and 50% fibre content were investigated. Densities lower than 25% 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 inpractical to use.

Matrix mix no.	Material (Soil with % fibre)	Density Kg/m3	Conductivity W/m.K
1	UK3 50% Shiv Dry (D)	398.73	0.12
2	UK3 50% Shiv Wet (W)	426.82	0.13
3	UK3 25% Shiv (W)	702.78	0.20
4	UK3 25% Reed (W)	684.10	0.18
5	FR3 25% Reed (W)	637.92	0.16
6	FR3 25% Shiv (W)	654.54	0.18
7	UK4 25% Reed (W)	664.60	0.18
8	UK4 35% Reed (W)	542.87	0.14

Table 5. Average thermal mix results

Results from all 39 experiments are presented in Figure 3. Here, the conductivity results are grouped according to mix number.

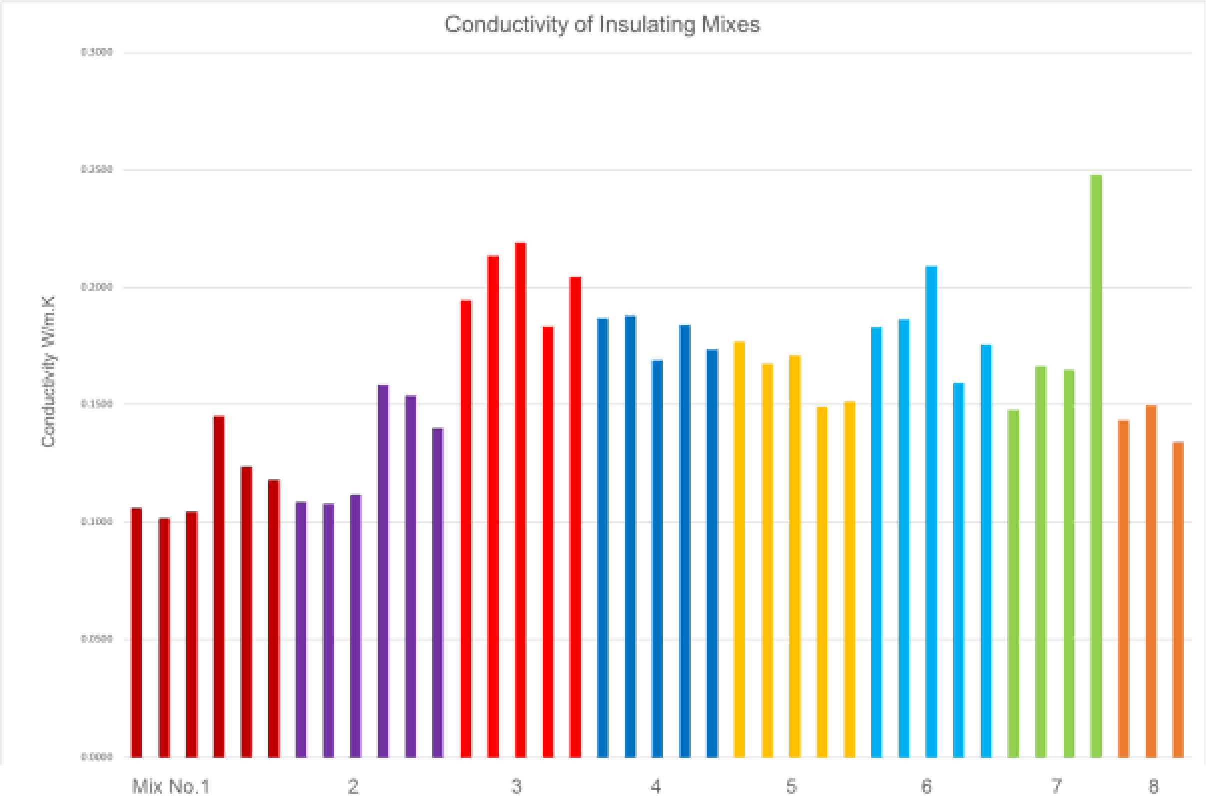


Figure 3. Complete conductivity results for the 39 samples.

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.

In most insulating materials there is a relationship between conductivity and density (Domínguez-Muñoz et al., 2010), especially within a group of similar earthen materials (Volhard, 2016).

Because we expect a similar relationship between the density of the samples and their conductivity, the results for each samples thermal conductivity can be presented against their density to demonstrate the correlation between density and conductivity. This relationship is presented in Figure 4, which demonstrates 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.

In this graph the previously observed outlier appears in the top left of the graph, but this time with density taken into account, it is entirely consistant with the other results.

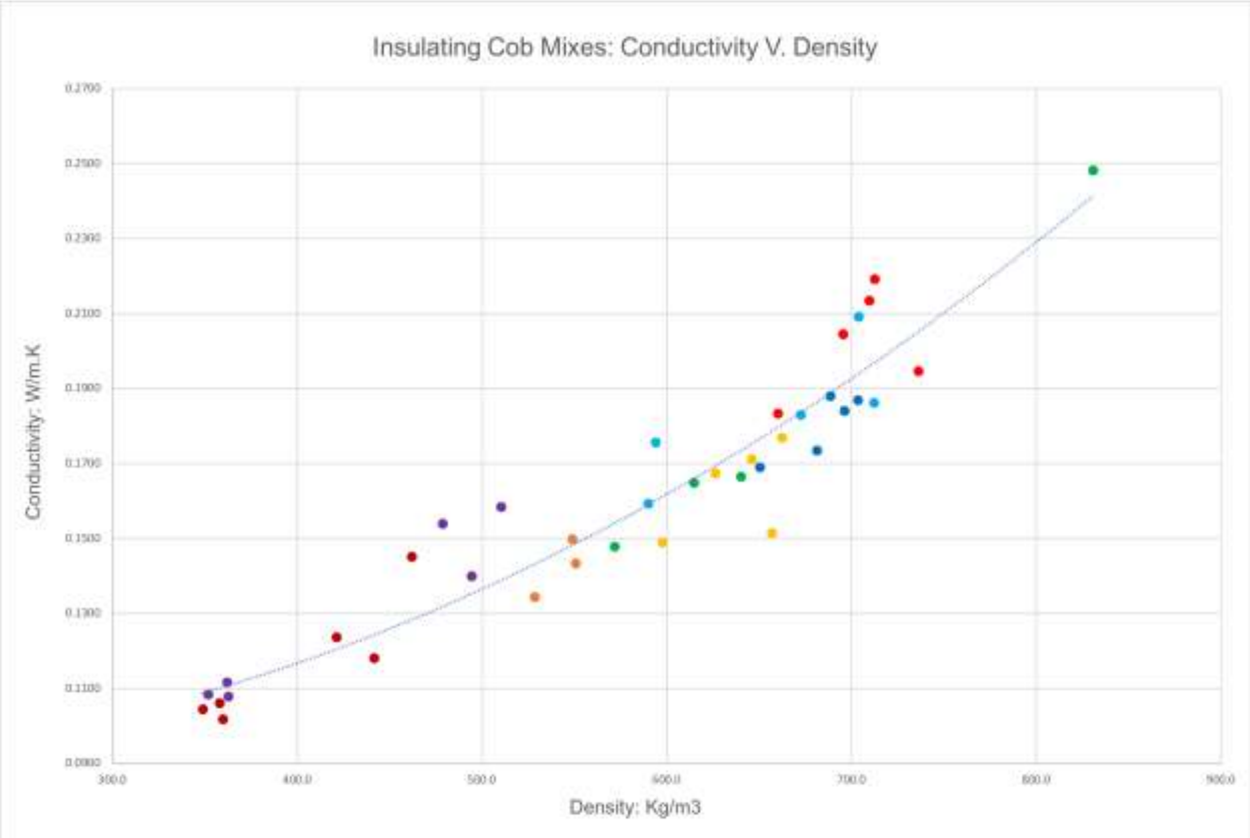


Figure 4. The relationship between sample conductivity and density (coloured according to mix number used in Figure 3).

Exploring this relationship further, experiments were conducted on the thermal conductivity of the fibres on their own and soil samples without fibre included. 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. Coupled with the poor cohesion of low density samples, these results demonstrated the optimal ratio of soil to fibre as being 50%, with a average conductivity value of 0.13W/m.K.

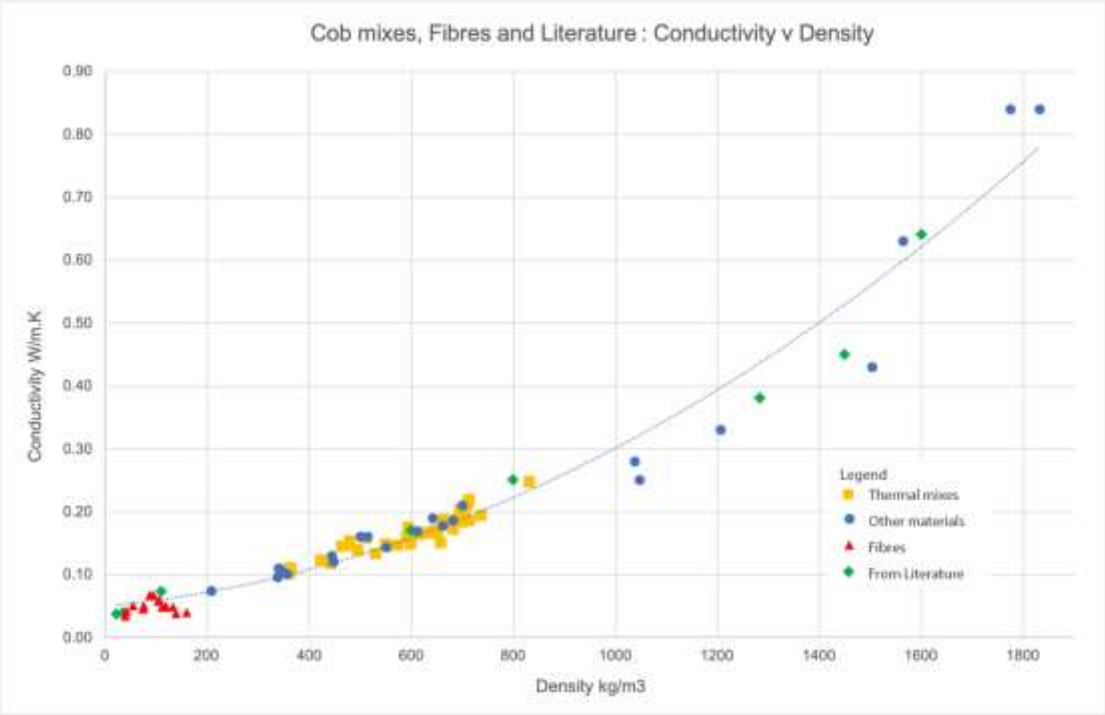


Table 6. Conductivity comparison between thermal mixes, 100% fibres and 100% soil samples.

5.0 Discussion

- How has the work met the regs.
- Density of cob mixes. High density = high thermal conductivity etc…
- You cannot have a uniform construction alone that meets the thermal regulations whilst meeting the structural performance. It was decided that a composite material would be needed, which would meet structural and thermal performance.
- CobBauge will be a composite construction Around 500 – 600mm thick.
    - Lightweight cobbauge material with heavier cobbauge mixed in at the same time. About 50% mix of each. Lightweight cobbauge will likely be on the outside with heavier / denser cobbauge on the inside. Lime render on both surfaces.
- Dense cob on inside due to thermal storage & moisture control. OR discussion on whether it could be the opposite way around. Benefits of either scenario.
- Linking results back to the literature

5.1 Parameters influence

With all these mixes, results can be used to determine each parameter role. Results will be studied according to soil characteristics (particle size distribution, methylene blue value), fibre content, fibre characteristics (water absorption, tensile strength) and viscosity.

To study the influence of soil characteristics, results from mixes 4, 5 and 7 will be analysed (tab. and). These results show that FR3 soil lead to a better thermal behaviour than UK3 soil. It has to be noted that UK3 and FR3 have the same content of clay but a different clay activity. Moreover, sandy fraction of UK3 is higher than FR3. This can explain the higher density of UK3 compared to FR3 and, consequently, the higher thermal conductivity. It was observed also that mixes with FR3 have a better cohesion, it seems that it is due to the clay activity.

Table. Thermal conductivity results of mixes

Mix	Soil	Fibre	Fibre added mass content (%)	Water content (%)	**λ (W.m^{-1}.K^{-1})** *(PU)*	**ρ (kg.m^{-3})** *(PU)*	**λ (W.m^{-1}.K^{-1})** *(ESITC)*	**ρ (kg.m^{-3})** *(ESITC)*
4	UK3	Reed	25	107.3	0.181	680.9	0.179	688.9
5	FR3	Reed	25	131.3	0.172	645.0	0.150	627.3
7	UK4	Reed	25	62.1	0.160	609.2	0.248	830.9

Table. Soils characteristics (FR3, UK3, UK4)

Sample	Clayed fraction (% < 2µm)	Silty fraction (2 < % < 63 µm)	Sandy fraction (63 µm < % < 2 mm)	MBV (g/100g)
FR3	12.85	63.32	14.47	5.34
UK3	12.83	66.66	20.07	3.64
UK4	5.59	55.94	19.44	0.83

To study the influence of fibre content, results from mixes 2 and 3 will be analysed (table). These results show that a higher fibre content lead to a better thermal behaviour. Nevertheless, it seems that a content of 50 % by weight is near to the maximum fibre content that can be use.

Table. Thermal conductivity results of structural mixes (2 and 3)

Mix	Soil	Fibre	Fibre added mass content (%)	Water content (%)	**λ (W.m^{-1}.K^{-1})** *(PU)*	**ρ (kg.m^{-3})** *(PU)*	**λ (W.m^{-1}.K^{-1})** *(ESITC)*	**ρ (kg.m^{-3})** *(ESITC)*
2	UK3	Hemp shiv	50	107.3	0.109	359.0	0.156	494.6
3	UK3	Hemp shiv	25	107.3	0.209	719.4	0.194	677.8

To study the influence of fibre type, results from mixes 3, 4, 5 and 6 will be analysed (table and). These results show that reed lead to a better thermal behaviour. This can be due to lower water absorption of reed which leads to a greater soil water content and more pore when the mix is dry.

Table. Thermal conductivity results of structural mixes (3, 4, 5 and 6)

Mix	Soil	Fibre	Fibre added mass content (%)	Water content (%)	**λ (W.m^{-1}.K^{-1})** *(PU)*	**ρ (kg.m^{-3})** *(PU)*	**λ (W.m^{-1}.K^{-1})** *(ESITC)*	**ρ (kg.m^{-3})** *(ESITC)*
3	UK3	Hemp shiv	25	107.3	0.209	719.4	0.194	677.8
4	UK3	Reed	25	107.3	0.181	680.9	0.179	688.9
5	FR3	Reed	25	131.3	0.172	645.0	0.150	627.3
6	FR3	Hemp shiv	25	131.3	0.193	696.2	0.167	592.0

Table. Fibre characteristics

Sample	Water absorption at 24h (%)
Hemp shiv	266
Reed	200

- Consistency :

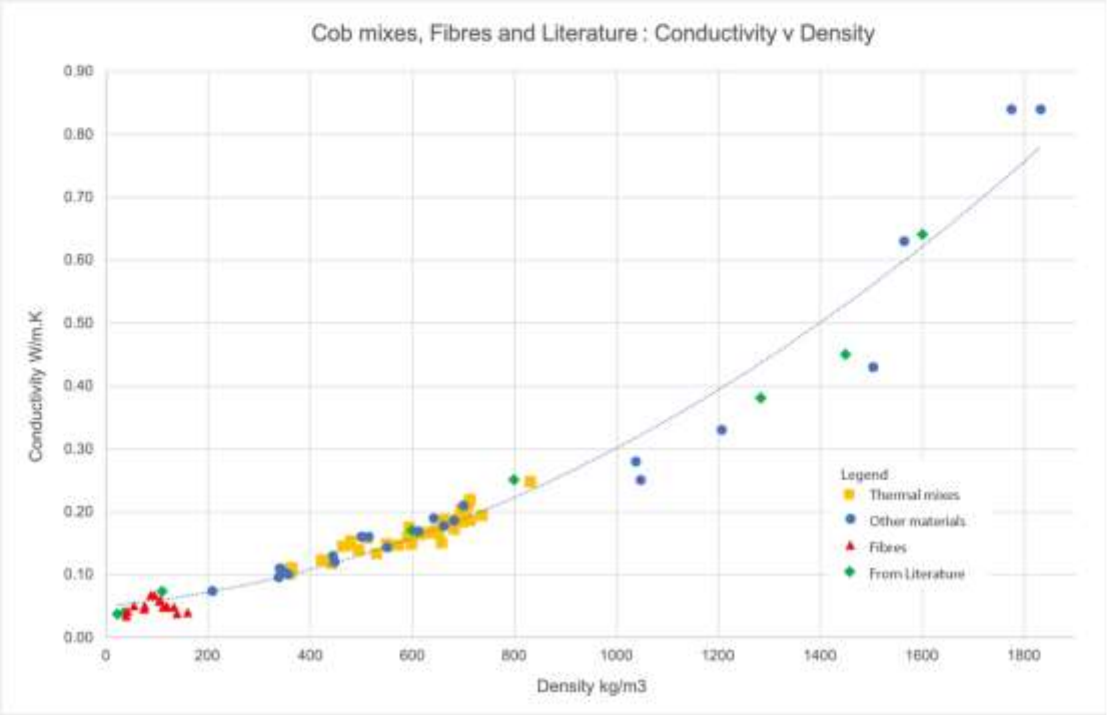
To study the influence of consistency on thermal conductivity, results from mixes 1 and 2 will be analysed (table). These results show that there is an issue. Indeed, difference between PU and ESITC results is significant and is due to density. These results do not give a clue on the water content role.

Table. Thermal conductivity results of structural mixes (3, 4, 5 and 6)

Mix	Soil	Fibre	Fibre added mass content (%)	Water content (%)	**λ (W.m^{-1}.K^{-1})** *(PU)*	**ρ (kg.m^{-3})** *(PU)*	**λ (W.m^{-1}.K^{-1})** *(ESITC)*	**ρ (kg.m^{-3})** *(ESITC)*
1	UK3	Hemp shiv	50	65.6	0.104	356.0	0.131	441.7
2	UK3	Hemp shiv	50	107.3	0.109	359.0	0.156	494.6

5.1 Comparison between measured results and literature results

To be discussed:
Results taken from literature (Minke, Volhard, Goodhew, El Azhary)



5.2 Calculated U values

Using the measured conductivities of the samples tested, we can calculate a U-value for a theoretical wall build up using the new mixes. The aim of this wall is to achieve a U-Value of at least 0.3W/m^{2}K, as this is the minimum requirement in the UK (as discussed in intro). If we want to use a single monolithic layer of insulating cob, it would need to have a conductivity similar to mix no.6 with 25% fibre.

Monolithic Wall	**Density kg/m3**	**Thickness m**	**Conductivity W/m K**	**Resistance m^2 K/W**
Internal surface		n/a	n/a	0.12
FR3 25% Shiv	673	0.600	0.183	3.28
External Surface		n/a	n/a	0.06
Total Resistance				3.46
U-Value W/m^{2}K				**0.29**

Table. Calculated U-Value for a single monolithic layer of lightweight cob using mix no.6

This monolithic wall would comply with the thermal regulations but with the 25% fibre content it would struggle to work as a structural element in the building as it has a compressive strength at 2% deformation of 0.20Mpa.

It was assumed at the start of this project that a wall made from optimised soil and fibre (CobBauge) would have to be a composite of an insulating mix and a structural mix.

Table. Calculated U value for a composit wall

The composit wall is the same thickness as the monolithic wall, and has a similar U-value, but is made up of two elements both optimised for their separate purposes. The Structural Cob is the mix from the matrix of structural mixes that had the greatest bearing capacity (compressive strength at 2 % shrinkage greater than 1.3 MPa). The Insulating Cob is the the mix that performed best in the conductivity testing shown in table?

6.0 Conclusion

- Thoughts on further work.
    - Structural paper
    - Characterisation paper
    - Aim and objective of the follow on project, CobBauge 2?
    - Kevin’s re-constituting cobbauge
    - Jim’s embodied energy
    - Use of waste in cob material.

7.0 References

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Composit Cob	**Density kg/m3**	**Thickness m**	**Conductivity W/m.K**	**Resistance m2 K/W**
Internal surface		n/a	n/a	0.12
Structural Cob UK6 2.5% Hemp straw	1423	0.300	0.42	0.72
Insulating Cob UK3 50% Hemp shiv	340	0.300	0.11	2.73
External Surface		n/a	n/a	0.06
Total Resistance				3.62
U-Value W/m2K				**0.28**

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