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# Thermal properties of cob retrofitted with external hemp–lime

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**Insulating earth walls with an external layer of hemp–lime improves thermal performance in a sustainable way and could promote the wider use of earth in construction. Monolithic earth walls, known in Devon as cob, are widely used in many countries with temperate climates. Earth walls are a form of sustainable construction, but their thermal performance is poor when measured against current UK Building Regulations. Non-permeable, high-performance insulation materials may cause moisture-related problems in earth walling. Therefore, this paper describes the transient thermal properties of monolithic cob walls retrofitted with external hemp–lime insulation, which offers a permeable solution. The transient thermal properties of the walls are calculated using bespoke software developed for an earlier study of brick walls and the air-to-air thermal transmittance is determined for various thicknesses of hemp–lime insulation. Typical cob walls found in Devon have *U*-values >1 W/m$^2$ K, or about three times the 0·3 W/m$^2$ K UK Building Regulations target. For a 600 mm thick cob wall with 250 mm of external hemp–lime, a *U*-value of 0·3 W/m$^2$ K is achieved. Five areas of concern are discussed briefly: caution, sustainability, acceptability, uncertainty in data and the possible energy and carbon dioxide savings.**

## Notation

| | |
|---|---|
| $C$ | dwelling's annual fuel bill (£) |
| $D$ | fraction of total energy used in a dwelling for space heating |
| $1-D$ | fraction of total energy used in a dwelling for water heating, cooking, lighting and domestic electronics |
| $F$ | admittance surface factor |
| $f$ | admittance decrement factor |
| $S$ | fraction of total energy loss by way of wall fabric |
| $1-S$ | fraction of total energy loss by way of floor, roof, glazing, doors and ventilation |
| $U$ | wall's air-to-air thermal transmittance (W/m$^2$ K) |
| UR | $U$-value ratio, $(U_1-U_2)/U_1$ |
| $U_1$ | air-to-air thermal transmittance of the uninsulated wall (W/m$^2$ K) |
| $U_2$ | air-to air thermal transmittance of the insulated wall (W/m$^2$ K) |
| $Y$ | admittance (W/m$^2$ K) |
| $\phi$ | admittance decrement lag time (h) |
| $\psi$ | surface lag time (h) |
| $\omega$ | admittance lead time (h) |

## 1. Introduction

This paper describes the thermal properties of cob walls retrofitted with layers of hemp–lime insulation in order to promote the use of earth in construction and improve its thermal performance with due regard to the overarching sustainability of the finished construction. Building designers often compare the steady-state heat loss of envelope proposals using the thermal transmittance or *U*-value. However, to model the time-dependent performance of a building, the time-dependent, or transient, thermal properties of the building envelope are required.

Earth as a building material in the UK is reviewed by Hurd and Gourley (2000) and Walker *et al*. (2005), while Keefe (2005) discusses the construction methods, materials, repairs and conservation issues. Warren (2000) provides a map showing the main centres of earth building in the UK, with Devon and Cornwall as part of the West Country.

Cob, an earth wall construction technique used in the south-west of the UK, is an example of sustainable construction, but its thermal performance is poor by modern standards. Therefore, this paper proposes the external insulation of cob walls with a layer of hemp–lime, with the associated sustainability of the building element assessed by analysing energy and carbon dioxide ($CO_2$) savings.

Hemp–lime is a mixture of hemp stalks (shiv), a lime-based binder and water (Bevan and Woolley, 2008). This can be fabricated into blocks, trowelled or sprayed onto a surface. Hemp–lime offers sustainable advantages: a lower embodied energy than oil-based insulation materials and a principle component (hemp plant) that removes a significant amount of carbon dioxide from the atmosphere as it grows.

Pilkington *et al.* (2008) determined the thermal conductivity of cob using a time-dependent needle probe technique. The conductivity values reported will be used to determine the steady-state and transient thermal properties of cob walls. This follows earlier studies of Victorian brick and earth walls (Goodhew and Griffiths, 2005; Griffiths and Goodhew, 2012). The air-to-air thermal transmittance, or *U*-value, will be determined for both uninsulated cob and walls with hemp–lime insulation using bespoke software (Griffiths and Goodhew, 2012). The addition of an air cavity, between the cob and the hemp–lime, will also be studied.

The revised UK Building Regulations (BR, 2000, 2010) state a limiting external wall thermal transmittance of $0{\cdot}3$ W/m$^2$ K for new and existing dwellings, which sets the target value for this study. Any remedial strategy to reduce heat loss through cob walls (without the benefit of a cavity) must recognise the importance of controlling the moisture content in the construction. The advantage of hemp–lime is that it is breathable and will therefore allow water vapour to pass through it; the wall may get wet, but later it will dry.

## 2. Aims and methodology

The following four aims were identified.

- To highlight the need for additional insulation by reviewing the thermal properties of various examples of cob walls.
- To report the steady-state and transient thermal properties of the externally insulated walls.
- To demonstrate how cob's thermal properties might be upgraded to achieve a *U*-value equal to or less than $0{\cdot}3$ W/m$^2$ K.
- To indicate the possible energy and carbon dioxide savings of hemp–lime insulated cob.

The methodology comprised three stages.

- Establishment of the cob wall model. For this study, the cob wall was constructed on a plinth and the various dimensions of the wall were identified, such as the dimensions of the plinth, the height of clear plinth above the external ground level and the position of the internal floors and ceilings. The density, thermal conductivity and specific heat capacity of the various components are tabulated.
- Determination of the transient, or time-dependent, thermal properties of the cob-insulation model combinations using the admittance method proposed by Pipes (1957) and reproduced by CIBSE (2006). Excel spreadsheets, developed and tested for research on solid brick walls with hemp–lime (Griffiths and Goodhew, 2012), will be used.
- Discussion of related possible energy and carbon dioxide savings.

The practicalities of adding insulating hemp–lime to the exterior of earth walls are a further consideration. Potential problems of moisture in the structure need to be addressed carefully. However, external hemp–lime is a breathable material that, if used with care, could provide a sustainable solution to the relatively high heat loss from cob-walled dwellings.

## 3. Proposed model of a cob wall

Most cob buildings in the west of the UK (the UK counties of Cornwall, Devon, Somerset and Dorset) are of two storeys (Keefe, personal communication, 2011). A typical cob wall section is reproduced by Keefe and Childs (2000). The earth–straw mixture, or cob, is placed on a stone plinth 600 mm and 1·0 m high, with 450 mm of plinth above the ground level. For this study, the internal floor is assumed to be level with the external ground (in practice the internal floor level is usually some 250 mm above the external ground level). The earth is uniformly 600 mm thick from the plinth to the first floor level. The wall then tapers over the second floor height from 600 to 400 mm. Two plinth models will be considered in this work: heavy weight masonry (HM), constructed of stones and earth, and a mixture of earth or clay and granite with aggregate (EM). Here, 400 mm was chosen since the top of the cob wall, at the eaves, is of this thickness. Ideal dry-state cob will be compared with moist cob. The insulation will be added directly to the external surface of the cob and two cases will be studied: first, with an ideal layer of hemp–lime and, second, with a practical layer where the hemp–lime has an increased density caused by self-loading and an increased thermal conductivity due to dampness. A further study will introduce a 50 mm air cavity constructed using plywood sheathing and a stud frame. It is assumed that the cob, and/or hemp–lime, if protected by an air cavity, will be dry and both materials will have their lower thermal conductivity.

To assess the possible advantages of retrofitting external thermal insulation, the steady-state thermal transmittance, or *U*-value, will be determined. This can then be used to find the possible energy saving and reduction in carbon dioxide emissions associated with space heating.

## 4. Calculation of the thermal properties of the walls

The steady-state thermal transmittance and transient thermal properties of the walls were determined following the method reviewed briefly in CIBSE (2006: p. 3-26) and in Appendix 3.A6 (p. 3-32). Excel spreadsheets were constructed to determine the thermal properties of the various walls, assuming the wall was exposed to sinusoidal temperature variations over a 24 h cycle. The finite homogeneous solid layers of the walls were defined in terms of thickness, thermal conductivity, density and specific heat capacity. The conductivity and specific heat capacity of hemp–lime were given by Ian Pritchett, Lime Technology (personal communication, 2011). The mean specific heat capacity was used for the transient thermal properties (a number of alternative methods use mathematical solutions of the variable temperature heat conduction equation for heat flowing through the wall; these commercial pieces of software can be costly and are not as transparent as the chosen method).

Table 1 reproduces the thermal properties of the various materials, the thermal resistances of the internal and external surfaces and that of the air cavity, all taken from CIBSE (2006: p. 3-47). The internal and external surface resistances were taken as 0·13 and 0·040 $m^2$ K/W, respectively. The 50 mm air cavity thermal resistance was taken as 0·18 $m^2$ K/W (CIBSE, 2006: p. 3-47). Table 1 shows the cob data for two cases, namely protected, or dry, and exposed, or moist. These values were obtained from a study by Pilkington *et al.* (2008) that reported the thermal conductivity of the external surface of a cob wall: 180 mm above the plinth and 600 mm above ground level as 1·2 W/m K (standard deviation 0·1), and will be classified here as wet cob. On the same wall, at 2·67 m above the ground at the wall head, the thermal conductivity was 0·8 W/m K (standard deviation 0·1). It was assumed that the high conductivity value near the ground level was due to the higher moisture content, while at the wall head it was assumed that the cob was relatively dry. For the calculations in this study, dry thermal conductivity will be taken as 0·8 W/m K (Table 1) and moist cob will have a conductivity value of 1·0 W/m K (Table 1). This was taken as an average of the two values found by Pilkington *et al.* The cob, or earth, density and specific heat capacity are from CIBSE (2006). A sensitivity/uncertainty study is provided in Section 6.4. An inner layer of the cob separated by a continuous air space, or masonry protected by tile hanging or cladding, is classified as protected. Alternatively, rendered or unrendered masonry that is directly exposed to rain is classified as exposed. The insulation added externally to the cob is shown in Table 1: ideal hemp–lime which has 165 kg of lime binder to 110 kg of hemp shiv, to give a mixture density of 275 kg/$m^3$ of installed hemp–lime.

| Material | Thickness: m | Density: kg/$m^3$ | Conductivity: W/m K | Specific heat capacity: J/kg K |
|---|---|---|---|---|
| Internal plaster (lime and sand) | 0·02 | 1600 | 0·8 | 1000 |
| External render (lime and sand) | 0·025 | 1600 | 0·8 | 1000 |
| Plaster board | 0·013 | 950 | 0·16 | 840 |
| Plywood sheathing | 0·013 | 500 | 0·13 | 1600 |
| Dry cob, protected with cavity | | 1720 | 0·8[a] | 870 |
| Moist cob | | 1720 | 1[a] | 870 |
| Ideal wall hemp–lime[b] | | 275 | 0·06 | 1710 |
| Installed wall hemp–lime[b] | | 300 | 0·1 | 1700 |
| EPS | | 15 | 0·04 | 1450 |
| Heavy weight masonry (HM[c]) | | 1850 | 0·85 | 840 |
| Clay soil, granite and aggregate (EM)[c] | | 2360 | 2·2 | 840 |
| *Construction resistances* | | $m^2$ K/W | | |
| Internal surface | | 0·13 | | |
| External surface | | 0·04 | Normal exposure | |
| Air cavity (50 mm) and loft space | | 0·18 | Between high emissivity surfaces | |
| Tile hanging (air space, battens and tile) | | 0·12 | | |

[a] Pilkington *et al.* (2008)
[b] Pritchett (private communication, 2011)
[c] Estimated using CIBSE (2006) data

Table 1. Input data (from CIBSE, 2006) for transient thermal properties of cob walls and plinths with hemp–lime insulation

| Wall section, inside to out | *U*-value: $\mathrm{W/m^2\,K}$ | Admittance: $\mathrm{W/m^2\,K}$ | Time lead: h | Surface factor | Time lag: h | Decrement factor | Decrement time lag: h |
|---|---|---|---|---|---|---|---|
| 13 mm dense plaster, 220 mm solid brick | 2·09 [2·09] | 4·49 [4·51] | 1·3 [1·29] | 0·49 [0·49] | 1·6 [1·56] | 0·42 [0·41] | 7·4 [7·57] |
| 25 mm dense plaster on laths, 50 mm air space 600 mm stone | 1·38 [1·38] | 3 [3·0] | 1·4 [1·43] | 0·65 [0·65] | 0·8 [0·84] | 0·04 [0·038] | 17·3 [17·3] |
| 12·5 mm plaster board, 25 mm EPS insulation 50 mm air space, 600 mm stone | 0·72 [0·73] | 1·13 [1·13] | 1·8 [1·76] | 0·87 [0·87] | 0·3 [0·29] | 0·03 [0·028] | 17·0 [17·05] |
| 13 mm dense plaster, 200 mm dense concrete block, 19 mm render | 3·02 [3·14] | 5·19 [5·22] | 0·9 [0·87] | 0·38 [0·37] | 1·6 [1·62] | 0·42 [0·43] | 6·5 [6·4] |
| 12·5 mm plaster board, 140 mm studding with 140 mm mineral wool insulation between studs, 19 mm plywood sheathing, 50 mm air space, 105 mm brick | 0·29 [0·23] | 0·74 [0·75] | 4·3 [4·31] | 0·96 [0·96] | 0·3 [0·35] | 0·57 [0·56] | 6·5 [6·56] |
| 10 mm plaster board, 100 mm EPS slab, 25 mm air gap, breather paper, 10 mm tiles on battens[a] | 0·29 [0·29] | 0·71 [0·71] | 4·0 [3·98] | 0·96 [0·96] | 0 [0·29] | 0·99 [0·99] | 1·0 [0·95] |

Values in square brackets calculated using the Microsoft Excel admittance spreadsheets
[a] CIBS (1980: Table A3.16: p. A3-24)

**Table 2.** Transient thermal properties of some walls from the CIBSE guide, seventh edition (CIBSE, 2006)

Table 2 reproduces the thermal property data for a selection of walls taken from table 3·49 of the current *Environmental Design Guide* (CIBSE, 2006). In Table 2, it is shown that an internally plastered 220 mm solid brick wall has a *U*-value of 2·09 $\mathrm{W/m^2}$ K, with admittance about twice as large, and a decrement lag time of 7·4 h. This wall would lose about seven times too much heat in the steady state by modern standards, and would have shown a relatively rapid heat response to solar gain with a high decrement factor of 0·42 with a lag time of 7·4 h. Walls (Table 2) show various *U*-values and a mixed picture regarding the decrement factors and lag times. The timber-framed wall (Table 2) with 105 mm of brick has an acceptable *U*-value at 0·29 $\mathrm{W/m^2}$ K, but suffers from a high decrement factor and a relatively short lag time. The last example in Table 2 is a tile hung wall from CIBS (1980, table A3.16: p. A3-24). The construction consists of plaster board, with 100 mm expanded polystyrene (EPS) slab, 25 mm air gap, breather paper and finally 10 mm tiles on battens. This wall has a *U*-value of 0·29 $\mathrm{W/m^2}$ K, meeting the regulatory target, but has the potential for summertime overheating, with a high proportion of incident solar radiation (99%) appearing in the interior after a relatively short time lag of 1·0 h.

The thermal properties shown in Table 2 (square brackets) were calculated using the input thermal data from CIBSE (2006: p. 3-47) and the Excel spreadsheets constructed for earlier studies. The good agreement between the CIBSE wall thermal properties and the values obtained using the Excel spreadsheets allows confident application of the spreadsheets.

The following results will illustrate how the thermal performance of cob walls of various thicknesses can be improved by adding different thicknesses of insulating hemp–lime externally. It is not possible to illustrate all the combinations of earth, internal and external surface finishes together with various hemp–lime layers of differing thickness for walls with and without air cavities and tile hanging. A limited number of wall samples will be described to illustrate the thermal issues. The results will be presented following the CIBSE style; the time-dependent thermal properties will be given in a tabulated form.

## 5. Results

Results calculated for cob walls without added insulation will be presented first. Walls that meet the UK Building Regulations will be identified and some walls exposed to wind-driven rain will be discussed. This section will briefly discuss application of the insulation.

Table 3 shows a selection of cob walls, which are assumed to be moist (unprotected from the external environment by an

| Cob thickness: mm | Total thickness: mm | Mass per unit area: kg/m$^2$ | $U$-value W/m$^2$ K | Admittance $Y$: W/m$^2$ K | Admittance lead time $\omega$: h | Decrement factor $f$ | Decrement lag time $\phi$: h | Surface factor $F$ | Surface time lag $\psi$: h |
|---|---|---|---|---|---|---|---|---|---|
| 300 | 345 | 588 | 1·9 | 4·73 | 1·25 | 0·28 | 9·49 | 0·46 | 1·69 |
| 400 | 445 | 760 | 1·6 | 4·71 | 1·25 | 0·16 | 12·31 | 0·46 | 1·68 |
| 500 | 545 | 932 | 1·38 | 4·71 | 1·25 | 0·09 | 15·12 | 0·46 | 1·68 |
| 600 | 645 | 1104 | 1·21 | 4·71 | 1·25 | 0·05 | 17·94 | 0·46 | 1·68 |
| 700 | 745 | 1276 | 1·08 | 4·71 | 1·25 | 0·03 | 20·76 | 0·46 | 1·68 |
| 800 | 845 | 1448 | 0·97 | 4·71 | 1·25 | 0·01 | 23·58 | 0·46 | 1·68 |
| 900 | 945 | 1620 | 0·89 | 4·71 | 1·25 | 0·01 | 26·39 [2·39] | 0·46 | 1·68 |

Table 3. Transient thermal properties of various moist cob walls, all with 20 mm internal lime–sand plaster and 25 mm external lime–sand render

air gap). All have an internal 20 mm dense lime and sand plaster layer, and 25 mm external layer of lime and sand render. These lime and sand layers are assumed to be the typical finishes that might be found today, and the cob is assumed to range from 300 to 900 mm. The most thermally unacceptable wall shown in Table 3 is the 345 mm thick wall with a $U$-value of 1·90 W/m$^2$ K. The decrement factor and lag time show 28% of the incident solar radiation arriving at the interior after 9·5 h. This construction would not provide the adequate environmental filtering needed in a dwelling in temperate climates, with or without climate change. The thickest wall in this group (Table 3), at 945 mm, still only has a $U$-value of 0·89 W/m$^2$ K, but at least this wall has a very low decrement factor at 0·01 and a long lag time of 26·4 h. The selection of cob walls shown in Table 3, with the internal and external lime and sand layers demonstrates their poor thermal performance and they are all far from the modern requirement of 0·3 W/m$^2$ K. In the Excel spreadsheet admittance calculations, the lag time is determined and expressed as part of the daily 24 h cycle. The decrement lag time for this 900 mm wall (Table 3) is 2·39 h, as indicated in the square brackets. For comparison with the other times in Table 3, 24 h has been added to this time (2·39 h) and is shown as 26·39 h. This convention has been applied throughout this work. The surface factor and surface lag time remain constant with increasing cob thickness at 0·46 and 1·68 h, respectively. This is the expected behaviour (see CIBSE (2006: paragraph 3.7.1.3: p. 3-33)).

Table 4 shows a selection of 400 mm thick exposed cob walls, all with an internal 20 mm dense lime and sand plaster layer and 25 mm of lime–sand external render. This wall thickness might be found at the eaves of a two-storey cob dwelling. The walls have an increasing thickness of ideal wall hemp–lime (Table 1) sprayed directly onto the cob in thicknesses of 50 mm (Table 4) through to 300 mm before the addition of the external finish of 25 mm lime–sand render. Here, it is assumed that the original cob is sound, or if there was an external layer of cement render that this would be in need of maintenance and therefore removed before the addition of the hemp–lime insulation. For these 400 mm cob walls to meet current regulations and to have $U$-values of <0·3 W/m$^2$ K, 150 mm of ideal wall hemp–lime is inadequate, while 200 mm of ideal wall hemp–lime would provide a margin for error, see Table 4. The surface factor $F$ and surface lag time $\psi$ were omitted as they remain constant with increasing hemp–lime insulation thickness at 0·47 and 1·68 h, respectively.

Table 5 presents the thermal properties of 500 mm exposed cob walls with installed hemp–lime insulation. A value of 500 mm represents the mean wall thickness found in the West Country cob-walled buildings, and the installed hemp–lime properties are the more likely to be encountered in practice. The surface factor $F$ and surface lag time $\psi$ have again been omitted as they remain constant with increasing hemp–lime insulation thickness at 0·46 and 1·68 h, respectively. Table 5 shows that the wall with 300 mm of installed hemp–lime insulation meets the $U$-value target of 0·3 W/m$^2$ K (Table 5). However, this is an extremely large thickness of material to be added to the external surface of the cob wall, raising issues of aesthetics, construction and cost.

Table 6 presents the thermal properties of 600 mm exposed cob walls with installed hemp–lime insulation. A value of 600 mm represents the thickness of ground floor walls found in West Country cob-walled buildings, and the 600 mm is the model plinth thickness suggested in this work. The surface factor $F$ and surface lag time $\psi$ have again been omitted as they remain constant with increasing hemp–lime insulation thickness at 0·46 and 1·68 h, respectively. Table 6 shows an improvement in results over Table 5 in that the wall with 150 mm of installed hemp–lime insulation (Table 6) meets the

| Wall section, inside to out | Thickness: mm | Mass/m$^2$: kg/m$^2$ | *U*-value: W/m$^2$ K | Admittance: W/m$^2$ K | Time lead: h | Decrement factor | Decrement time lag: h |
|---|---|---|---|---|---|---|---|
| 20 mm lime–sand plaster, 400 mm cob, 25 mm lime–sand render | 445 | 760 | 1·6 | 4·72 | 1·25 | 0·16 | 12·31 |
| 20 mm lime–sand plaster, 400 mm cob, 50 mm ideal hemp–lime, 25 mm lime–sand render | 495 | 774 | 0·69 | 4·71 | 1·25 | 0·06 | 15·12 |
| 20 mm lime–sand plaster, 400 mm cob, 100 mm ideal hemp–lime, 25 mm lime–sand render | 545 | 788 | 0·44 | 4·71 | 1·25 | 0·04 | 17·88 |
| 20 mm lime–sand plaster, 400 mm cob, 150 mm ideal hemp–lime, 25 mm lime–sand render | 595 | 801 | 0·32 | 4·71 | 1·25 | 0·02 | 21·12 |
| 20 mm lime–sand plaster, 400 mm cob, 200 mm ideal hemp–lime, 25 mm lime–sand render | 645 | 815 | 0·25 | 4·71 | 1·25 | 0·013 | 24·36 |
| 20 mm lime–sand plaster, 400 mm cob, 250 mm ideal hemp–lime, 25 mm lime–sand render | 695 | 829 | 0·21 | 4·71 | 1·25 | 0·007 | 27·59 |
| 20 mm lime–sand plaster, 400 mm cob, 300 mm ideal hemp–lime, 25 mm lime–sand render | 745 | 843 | 0·18 | 4·71 | 1·25 | 0·003 | 30·81 |

The surface factor and surface lag time are constant with increasing hemp–lime at 0·47 and 1·68 h, respectively

**Table 4.** Transient thermal properties of 400 mm exposed or moist cob walls with ideal wall hemp–lime insulation

| Wall section, inside to out | Thickness: mm | Mass/m$^2$: kg/m$^2$ | *U*-value: W/m$^2$ K | Admittance: W/m$^2$ K | Time lead: h | Decrement factor | Decrement time lag: h |
|---|---|---|---|---|---|---|---|
| 20 mm lime–sand plaster, 500 mm cob, 25 mm lime–sand render | 545 | 932 | 1·38 | 4·71 | 1·25 | 0·09 | 15·12 |
| 20 mm lime–sand plaster, 500 mm cob, 50 mm installed hemp–lime, 25 mm lime–sand render | 595 | 947 | 0·82 | 4·72 | 1·25 | 0·035 | 17·5 |
| 20 mm lime–sand plaster, 500 mm cob, 100 mm installed hemp–lime, 25 mm lime–sand render | 645 | 962 | 0·58 | 4·72 | 1·25 | 0·024 | 19·59 |
| 20 mm lime–sand plaster, 500 mm cob, 150 mm installed hemp–lime, 25 mm lime–sand render | 695 | 977 | 0·45 | 4·72 | 1·25 | 0·016 | 22·12 |
| 20 mm lime–sand plaster, 500 mm cob, 200 mm installed hemp–lime, 25 mm lime–sand render | 745 | 992 | 0·37 | 4·72 | 1·25 | 0·01 | 24·75 |
| 20 mm lime–sand plaster, 500 mm cob, 250 mm installed hemp–lime, 25 mm lime–sand render | 795 | 1007 | 0·31 | 4·72 | 1·25 | 0·006 | 27·36 |
| 20 mm lime–sand plaster, 500 mm cob, 300 mm installed hemp–lime, 25 mm lime–sand render | 845 | 1022 | 0·27 | 4·72 | 1·25 | 0·004 | 29·96 |

The surface factor and surface lag time are constant at 0·46 and 1·68 h, respectively

**Table 5.** Transient thermal properties of 500 mm moist cob walls with installed hemp–lime insulation

**Table 6.** Transient thermal properties of 600 mm moist cob walls with ideal hemp–lime insulation

| Wall section, inside to out | Thickness: mm | Mass/m$^2$: kg/m$^2$ | *U*-value: W/m$^2$ K | Admittance: W/m$^2$ K | Time lead: h | Decrement factor | Decrement time lag: h |
|---|---|---|---|---|---|---|---|
| 20 mm lime–sand plaster, 600 mm cob, 25 mm lime–sand render | 645 | 1104 | 1·21 | 4·71 | 1·25 | 0·048 | 17·94 |
| 20 mm lime–sand plaster, 600 mm cob, 50 mm ideal hemp–lime, 25 mm lime–sand render | 695 | 1118 | 0·6 | 4·72 | 1·25 | 0·015 | 20·76 |
| 20 mm lime–sand plaster, 600 mm cob, 100 mm ideal hemp–lime, 25 mm lime–sand render | 745 | 1132 | 0·4 | 4·72 | 1·25 | 0·01 | 23·52 |
| 20 mm lime–sand plaster, 600 mm cob, 150 mm ideal hemp–lime, 25 mm lime–sand render | 795 | 1145 | 0·3 | 4·72 | 1·25 | 0·006 | 26·76 |
| 20 mm lime–sand plaster, 600 mm cob, 200 mm ideal hemp–lime, 25 mm lime–sand render | 845 | 1159 | 0·24 | 4·72 | 1·25 | 0·003 | 30·00 |
| 20 mm lime–sand plaster, 600 mm cob, 250 mm ideal hemp–lime, 25 mm lime–sand render | 895 | 1173 | 0·2 | 4·72 | 1·25 | 0·002 | 33·22 |
| 20 mm lime–sand plaster, 600 mm cob, 300 mm ideal hemp–lime, 25 mm lime–sand render | 945 | 1187 | 0·17 | 4·72 | 1·25 | 0·001 | 36·45 |

The surface factor and surface lag time are constant at 0·46 and 1·68 h, respectively

*U*-value target of 0·3 W/m$^2$ K, while a wall with 200 mm of hemp–lime insulation has a *U*-value of 0·24 W/m$^2$ K, well within the target figure.

Table 7 presents the thermal properties of 800 mm exposed cob walls with ideal hemp–lime insulation. The value 800 mm represents the typical thickness of cob walls found in West Country dwellings from medieval times to the sixteenth century. The surface factor *F* and the surface lag time $\psi$ remain constant with increasing hemp–lime insulation thickness at 0·46 and 1·68 h, respectively. Table 7 shows that the wall with 150 mm of ideal hemp–lime insulation (Table 7) easily meets the *U*-value target of 0·3 W/m$^2$ K.

Table 8 shows the thermal properties of a 500 mm cob wall with a 50 mm air cavity before the hemp–lime insulation layer. A stud frame is added to the wall exterior to support 13 mm plywood sheathing onto which the hemp–lime is sprayed. Since the cob is now protected by an air cavity, the calculations are completed with the cob's thermal conductivity taken as dry cob (Table 1). Table 8 shows that for this wall 250 mm of ideal hemp–lime is required to achieve the target *U*-value. The surface factor *F* and the surface lag time $\psi$ remain constant with increasing hemp–lime insulation thickness at 0·46 and 1·68 h, respectively. The studs to support the plywood sheathing thermally bridge the air gap, conducting heat from the cob to the plywood. This thermal bridging effect has been ignored in these preliminary studies.

Table 9 presents the thermal properties of plinths of 600 mm thickness that might be found at the base of cob walls. The thermal properties of these plinths were determined with ideal-wall hemp–lime properties (Table 1) and the installed hemp–lime (Table 1). Two types of plinth are used: HM, the thermal properties of which are given in Table 1, and a mixture of clay soil, granite stones with aggregate (EM), the properties are again shown in Table 1. Table 9 shows the uninsulated plinths, the EM plinth and the HM plinth. Table 9 shows that the insulated (EM) plinth achieves the target *U*-value with 250 mm of ideal hemp–lime, but fails with installed hemp–lime. With the HM plinth (Table 9), 150 mm of ideal hemp–lime meets the target *U*-value, but 250 mm of installed hemp–lime is required. For EM plinths, the surface factor *F* and surface lag time $\psi$ remain constant with increasing hemp–lime insulation thickness at 0·37 and 1·6 h, respectively. For HM plinths, the surface factor *F* and surface lag time $\psi$ remain constant with increasing hemp–lime insulation thickness at 0·48 and 1·68 h, respectively.

Table 10 presents the thermal properties of 500 mm exposed cob walls with 20 mm internal lime and sand plaster, installed hemp–lime insulation and tile hanging. As there is no air cavity in this construction, both the cob and the hemp–lime

| Wall section, inside to out | Thickness: mm | Mass/m$^2$: kg/m$^2$ | *U*-value: W/m$^2$ K | Admittance: W/m$^2$ K | Time lead: h | Decrement factor | Decrement time lag: h |
|---|---|---|---|---|---|---|---|
| 20 mm lime–sand plaster, 800 mm cob, 25 mm lime–sand render | 845 | 1448 | 0·97 | 4·71 | 1·25 | 0·014 | 23·58 |
| 20 mm lime–sand plaster, 800 mm cob, 50 mm ideal hemp–lime, 25 mm lime–sand render | 895 | 1462 | 0·54 | 4·71 | 1·25 | 0·004 | 26·39 |
| 20 mm lime–sand plaster, 800 mm cob, 100 mm ideal hemp–lime, 25 mm lime–sand render | 945 | 1476 | 0·37 | 4·71 | 1·25 | 0·002 | 29·16 |
| 20 mm lime–sand plaster, 800 mm cob, 150 mm ideal hemp–lime, 25 mm lime–sand render | 995 | 1489 | 0·28 | 4·71 | 1·25 | 0·001 | 32·4 |
| 20 mm lime–sand plaster, 800 mm cob, 200 mm ideal hemp–lime, 25 mm lime–sand render | 1045 | 1503 | 0·23 | 4·71 | 1·25 | 0·001 | 36·64 |
| 20 mm lime–sand plaster, 800 mm cob, 250 mm ideal hemp–lime, 25 mm lime–sand render | 1095 | 1517 | 0·19 | 4·71 | 1·25 | 0 | 38·86 |
| 20 mm lime–sand plaster, 800 mm cob, 300 mm ideal hemp–lime, 25 mm lime–sand render | 1145 | 1531 | 0·17 | 4·71 | 1·25 | 0 | 42·08 |

The surface factor and surface lag time are constant at 0·46 and 1·68 h, respectively

**Table 7.** Transient thermal properties of 800 mm moist cob walls with ideal hemp–lime insulation

| Wall section, inside to out | Thickness: mm | Mass/m$^2$: kg/m$^2$ | *U*-value: W/m$^2$ K | Admittance: W/m$^2$ K | Time lead: h | Decrement factor | Decrement time lag: h |
|---|---|---|---|---|---|---|---|
| 20 mm lime–sand plaster, 500 mm cob, 50 mm air cavity, 13 mm plywood, 50 mm installed hemp–lime, 25 mm lime–sand render | 658 | 954 | 0·61 | 4·59 | 1·35 | 0·02 | 20·29 |
| 20 mm lime–sand plaster, 500 mm cob, 50 mm air cavity, 13 mm plywood, 100 mm installed hemp–lime, 25 mm lime–sand render | 708 | 969 | 0·47 | 4·59 | 1·35 | 0·014 | 22·69 |
| 20 mm lime–sand plaster, 500 mm cob, 50 mm air cavity, 13 mm plywood, 150 mm installed hemp–lime, 25 mm lime–sand render | 758 | 984 | 0·38 | 4·59 | 1·35 | 0·009 | 25·3 |
| 20 mm lime–sand plaster, 500 mm cob, 50 mm air cavity, 13 mm plywood, 200 mm installed hemp–lime, 25 mm lime–sand render | 808 | 999 | 0·32 | 4·59 | 1·35 | 0·005 | 27·91 |
| 20 mm lime–sand plaster, 500 mm cob, 50 mm air cavity, 13 mm plywood, 250 mm installed hemp–lime, 25 mm lime–sand render | 858 | 1014 | 0·28 | 4·59 | 1·35 | 0·003 | 30·51 |
| 20 mm lime–sand plaster, 500 mm cob, 50 mm air cavity, 13 mm plywood, 300 mm installed hemp–lime, 25 mm lime–sand render | 908 | 1029 | 0·24 | 4·59 | 1·35 | 0·002 | 33·11 |

The surface factor and surface lag time are constant at 0·49 and 1·68 h, respectively

**Table 8.** Transient thermal properties of 500 mm dry cob walls with air cavity and installed hemp–lime insulation

| Plinth section, inside to out | Thickness: mm | Mass/m$^2$: kg/m$^2$ | *U*-value: W/m$^2$ K | Admittance: W/m$^2$ K | Time lead: h | Decrement factor | Decrement time lag: h |
|---|---|---|---|---|---|---|---|
| 20 mm lime–sand plaster, 600 mm mixed plinth (EM), 25 mm lime–sand render | 645 | 1488 | 2 | 5·26 | 0·84 | 0·071 | 14·72 |
| 20 mm lime–sand plaster, 600 mm mixed plinth (EM), 150 mm ideal hemp–lime, 25 mm lime–sand render | 795 | 1529 | 0·33 | 5·26 | 0·84 | 0·01 | 23·2 |
| 20 mm lime–sand plaster, 600 mm mixed plinth (EM), 250 mm ideal hemp–lime, 25 mm lime–sand render | 895 | 1557 | 0·21 | 5·26 | 0·84 | 0·003 | 29·66 |
| 20 mm lime–sand plaster, 600 mm mixed plinth (EM), 150 mm installed hemp–lime, 25 mm lime–sand render | 795 | 1533 | 0·5 | 5·26 | 0·84 | 0·01 | 21·37 |
| 20 mm lime–sand plaster, 600 mm mixed plinth (EM), 250 mm installed hemp–lime, 25 mm lime–sand render | 895 | 1563 | 0·33 | 5·26 | 0·84 | 0·005 | 26·61 |
| 20 mm lime–sand plaster, 600 mm heavy weight plinth (HM), 25 mm lime–sand render | 645 | 1182 | 1·07 | 4·65 | 1·31 | 0·034 | 19·65 |
| 20 mm lime–sand plaster, 600 mm heavy weight plinth (HM), 150 mm ideal hemp–lime, 25 mm lime–sand render | 795 | 1223 | 0·29 | 4·65 | 1·31 | 0·004 | 28·51 |
| 20 mm lime–sand plaster, 600 mm heavy weight plinth (HM), 250 mm ideal hemp–lime, 25 mm lime–sand render | 895 | 1251 | 0·2 | 4·65 | 1·31 | 0·001 | 34·98 |
| 20 mm lime–sand plaster, 600 mm heavy weight plinth (HM), 150 mm installed hemp–lime, 25 mm lime–sand render | 795 | 1227 | 0·41 | 4·65 | 1·31 | 0·005 | 26·69 |
| 20 mm lime–sand plaster, 600 mm heavy weight plinth (HM), 250 mm installed hemp–lime, 25 mm lime–sand render | 895 | 1257 | 0·29 | 4·65 | 1·31 | 0·002 | 31·93 |

For the first five plinths in Table 9, the surface factor $F$ is 0·37 and surface lag time $\psi$ is 1·6 h; for the last five plinths, $F$ is 0·48 and $\psi$ is 1·68 h

**Table 9.** Transient thermal properties of clay mixture (EM) and heavy weight mixture (HM) 600 mm plinths, 20 mm internal lime–sand plaster with ideal and installed hemp–lime insulation

| Hemp–lime thickness: mm | Total thickness: mm | Mass per unit area: kg/m$^2$ | *U*-value *U*: W/m$^2$ K | Admittance *Y*: W/m$^2$ K | Admittance lead time $\omega$: h | Decrement factor *f* | Decrement lag time $\phi$: h |
|---|---|---|---|---|---|---|---|
| 50 | 620 | 907 | 0·76 | 4·71 | 1·25 | 0·03 | 17·15 |
| 100 | 670 | 922 | 0·55 | 4·71 | 1·25 | 0·02 | 19·33 |
| 150 | 720 | 937 | 0·43 | 4·71 | 1·25 | 0·02 | 21·9 |
| 200 | 770 | 952 | 0·36 | 4·71 | 1·25 | 0·01 | 24·53 |
| 250 | 820 | 967 | 0·3 | 4·71 | 1·25 | 0·006 | 27·14 |

No air cavity. The surface factor *F* is 0·46 and surface lag time $\psi$ is 1·68 h

**Table 10.** Transient thermal properties of 500 mm exposed or moist cob walls with 20 mm internal lime–sand plaster, installed hemp–lime insulation and tile hanging

| Hemp–lime thickness: mm | Total thickness: mm | Mass per unit area: kg/m$^2$ | *U*-value *U*: W/m$^2$ K | Admittance *Y*: W/m$^2$ K | Admittance Lead time $\omega$: h | Decrement factor *f* | Decrement lag time $\phi$:h |
|---|---|---|---|---|---|---|---|
| 50 | 683 | 914 | 0·58 | 4·59 | 1·35 | 0·02 | 19·87 |
| 100 | 733 | 929 | 0·45 | 4·59 | 1·35 | 0·01 | 22·33 |
| 150 | 783 | 944 | 0·37 | 4·6 | 1·35 | 0·008 | 25 |
| 200 | 833 | 959 | 0·31 | 4·59 | 1·35 | 0·005 | 28·57 |
| 250 | 883 | 974 | 0·27 | 4·59 | 1·35 | 0·003 | 30·17 |

The surface factor 0·49 and surface lag time 1·68 h are constant

**Table 11.** Transient thermal properties of 500 mm dry cob walls, 20 mm internal lime–sand plaster, air cavity with installed hemp–lime insulation and tile hanging to shed driving rain

are exposed, but the tile hanging sheds wind-driven rain. The surface factor *F* and the surface lag time $\psi$ have again been omitted as they remain constant with increasing hemp–lime insulation thickness at 0·46 and 1·68 h, respectively. Table 10 shows that the wall with 250 mm of installed hemp–lime insulation meets the *U*-value target of 0·3 W/m$^2$ K.

Care must be taken when spraying hemp–lime onto the cob at the eaves, around doors and windows to avoid jeopardising these architectural features. A possible solution would be to construct a timber frame – some sections temporary, some permanent – around these features, allowing an air cavity between the cob and the insulation. Before the addition of the hemp–lime, the exposed top sections of these cavities could be sealed with timber to prevent water penetration when rain water flows vertically down the wall.

Table 11 presents the thermal properties of 500 mm dry cob walls with 20 mm internal lime and sand plaster, a stud frame with plywood sheathing giving a 50 mm air cavity before the installed hemp–lime insulation and then tile hanging. With the air cavity in this construction, the cob is protected and the hemp–lime is exposed. The surface factor *F* and the surface lag time $\psi$ have again been omitted as they remain constant with increasing hemp–lime insulation thickness at 0·49 and 1·68 h, respectively. Table 11 shows that the wall with 250 mm of installed hemp–lime insulation meets the target *U*-value of 0·3 W/m$^2$ K.

## 6. Discussion

Five concerns are now discussed: caution, sustainability, acceptability, uncertainty in data and possible savings in energy, money and carbon dioxide.

### 6.1 Caution

The wall of a building separates the internal and external climates, and the material of the wall experiences hydrothermal changes. By way of illustration, low-permeability sand–cement render has been implicated in 73% of cob failures (Keefe *et al.*, 2001). It follows that the retrofitting of insulation to traditional buildings requires a careful and sympathetic approach. Traditional buildings were continuously heated, predominantly with radiative heat sources, and continuously occupied by people wearing many layers of natural material clothing. After World War II, dwellings were increasingly centrally heated by convection, fewer layers of clothing made from artificial fibres were worn and dwellings were occupied and heated intermittently. Interior design comfort temperatures rose by some 6°C between 1880 and 1980 (Griffiths, 2007). The burning of coal, coke or wood in fireplaces for domestic heating produced unhealthy atmospheres and was discouraged. Retrofitting insulation to a heritage building structure should therefore be undertaken with care.

## 6.2 Sustainability

Sustainability has three interwoven strands (Otto, 2003)

- social aspects, about people
- environmental aspects, about the planet
- economic aspects, about the profit.

Clearly, the upgrading of cob walls will depend strongly on people and the social aspects of the proposed modifications. The method of upgrading the thermal performance of heritage buildings will have to be socially acceptable, as well as efficient and economic.

## 6.3 Acceptability

Probert (2010) reported a study of possible tenant participation in the sustainable issues involved in Victorian property refurbishment. The tenants were very proud of their properties and expressed the preference that savings in energy should be made by installing water-saving devices, draught proofing, loft insulation and double glazing, rather than making potentially damaging changes to the external appearance of their homes. The survey suggested that people were more interested in comfort and security, in a new boiler and controls, than in increased wall insulation.

Following Probert (2010), at a Devon Earth Building Association meeting in 2010, a simple attendee questionnaire showed a similar response. A concern about external appearance was again expressed.

## 6.4 Uncertainty in data

All the tables in this paper have uncertainty. To indicate the degree of uncertainty, a number of cob samples with different hemp–lime insulation layers were studied and the wall $U$-value plotted as a function of the thickness of hemp–lime insulation. Figure 1 illustrates these studies for a 600 mm cob wall with similar internal plaster and external render lime–sand layers. Four cases were explored. The worst case had wet cob with a thermal conductivity of 1·2 W/m K insulated with installed hemp–lime. Here, it is assumed that the hemp–lime has a conductivity of 0·1 W/m K and a density of 300 kg/m$^3$, due to self-loading. Figure 1 shows that this example requires 250 mm of insulation to achieve the target $U$-value of 0·3 W/m$^2$ K. Second, the likely case had moist cob, conductivity of 1·0 W/m K, with an installed hemp–lime. Again, 250 mm of hemp–lime insulation is required to meet the target. The best case had dry cob, a conductivity of 0·8 W/m K with installed hemp–lime. Again, 250 mm of insulation is required. Finally, the special case had dry cob with ideal hemp–lime insulation and a conductivity of 0·06 W/m K. This wall has the advantage of the air cavity formed using plywood sheathing on a stud frame before the insulation. In this example, the external surface is protected by tile hanging and the target $U$-value is achieved with only 125 mm of hemp–lime insulation. Alternatively, if EPS (Table 1), with a thermal conductivity of 0·04 W/m K, is used instead of hemp–lime insulation, then a moist cob wall requires only 100 mm of EPS to achieve a $U$-value of 0·3 W/m$^2$ K. However, EPS is not considered a sustainable material. Paper or wool, with a thermal conductivity of 0·042 and 0·038 W/m K, respectively, might provide a sustainable alternative, achieving similar insulation with layers of about 100 mm thickness.

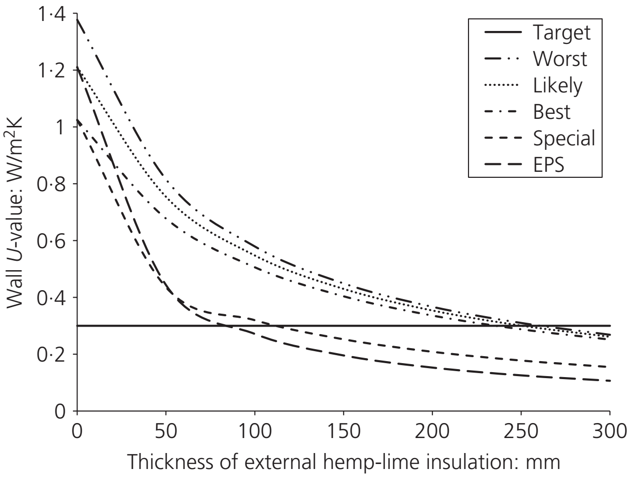

**Figure 1.** Variation of $U$-value (W/m$^2$ K) for a 600 mm cob wall for worst, likely, best and special case of cob with hemp–lime insulation, plotted against hemp–lime thickness (mm)

A measure of the advantage of adding hemp–lime insulation was explored using the $U$-value ratio (UR). If the uninsulated $U$-value is $U_1$ and the insulated $U$-value is $U_2$, then UR is $(U_1-U_2)/U_1$. The values of UR for both 500 and 600 mm cob walls, as worst, likely and best cases described above, with two thicknesses of hemp–lime insulations were studied; namely 150 mm, a practical layer and 250 mm, a layer to meet the Building Regulations target of 0·3 W/m$^2$ K. The UR values for all these combinations range from 0·64 to 0·85, or a mean value of 0·75. These values of UR are used below to discuss the possible energy and carbon dioxide savings.

### 6.5 Possible savings – energy, money and carbon dioxide

The retrofitting of external hemp–lime insulation to cob has three green/sustainable advantages

- it produces a saving in the energy required to space heat dwellings
- the sequestration of carbon dioxide by growing hemp reduces the carbon dioxide in the atmosphere
- the reduction in heating energy demand reduces the annual production of carbon dioxide.

The sequestration of carbon dioxide and its subsequent storage within the hemp–lime insulation is a single contribution to the reduction in carbon dioxide. However, the reduced energy demand provides an additional annual contribution to this reduction.

To illustrate this, three fractions are used. First, the fraction $D$ is the fuel used for space heating relative to the total fuel used, $1-D$ being the fraction used for water heating, cooking, lighting and domestic electronics. Using this fraction will overcome the problem of isolating the various energy components in the dwelling. When a dwelling uses both gas and electricity for space heating, water heating and cooking, it is difficult to distinguish the contributions made by separate fuels to the space heating. Second, assume that for the uninsulated cob walls the fraction of the total space heating lost by way of the wall fabric transmittance is $S$; $1-S$ being the fraction lost by way of the floor, ceiling, glazing, doors and ventilation. The third fraction UR was introduced in Section 6.4. As an example, consider the likely wall with 150 mm of installed hemp–lime insulation, the wall $U$-value decreases from 1·21 to 0·43 W/m$^2$ K. The value of UR is (1·21–0·43)/1·21 or 0·64. The money saving can now be found since it is equal to the total annual fuel bill $C$ multiplied by $D$ (taken as 0·7) times $S$ (taken as 0·35) times UR (0·64), or the annual fuel bill $C$ times 0·16. For a total annual bill of £1100, this amounts to a saving of £170 per year.

The spread in possible energy saving can be assessed using the values from Section 6.4. Here, it was reported that the UR had a range from 0·64 to 0·85. This would achieve a reduction in fuel bills in the range of 0·16 times $C$ to 0·21 times $C$. Again, using the total annual fuel bill of £1100, the annual saving would be from £170 to £230.

The sequestration of carbon dioxide can be summarised following Weight *et al.* (2010). They report that the production of lime binder produces 0·43 kg carbon dioxide per kg of lime binder, while growing hemp shiv removes 1·41 kg carbon dioxide per kg of shiv. The ideal hemp–lime mixture has 165 kg of binder to 110 kg of shiv (Section 4) and therefore an overall reduction in carbon dioxide of 0·31 kg carbon dioxide per kg of hemp–lime mixture. If a layer of hemp–lime insulation of thickness 150 mm is applied, then the mass of insulation per unit area is 40 kg/m$^2$. The sequestration of carbon dioxide per unit area of wall is 13 kg carbon dioxide per unit area. This is a significant contribution to carbon dioxide reduction, given that the total wall area of a dwelling is of the order of 80 m$^2$.

The reduction in annual energy demand produced by the hemp–lime insulation leads to an annual reduction in the carbon dioxide produced by space heating the dwelling. A simple estimate of this reduction can be obtained by assuming the mean price of fuel to be £0·06/kWh. Therefore, the mean saving in kWh is £170, from above, divided by £0·06/kWh or 2830 kWh of gas per year. This 2830 kWh of gas burning is equivalent to 520 kg carbon dioxide per year, since the CT (2010) suggests that 1 kWh of gas utilised produces 0·184 kg of carbon dioxide.

These calculations are intended to illustrate the possible savings and a number of assumptions have been made. The energy used in a dwelling is subjective, depending on the building design, the condition and maintenance, lifestyle and comfort conditions sought by occupants and the local climate.

## 7. Conclusions

There was excellent agreement between the reported wall thermal properties (CIBSE, 2006) and the values obtained using the bespoke Excel spreadsheets.

To conclude, the following four identified aims are addressed.

- The results highlight the need for insulation if cob dwellings are to meet the requirements of present regulations. Typical cob walls have $U$-values >1 W/m$^2$ K, or about three times the 0·3 W/m$^2$ K target.
- The transient thermal properties of a number of cob wall models with various thicknesses of hemp–lime insulation retrofitted to the exterior have been given in the tables.
- The work demonstrates how the thermal properties of cob walls might be upgraded to meet the current UK thermal Building Regulations (BR, 2010) to achieve a $U$-value equal to or less than 0·3 W/m$^2$ K. The overall conclusion is that 250 mm of hemp–lime is required to achieve the target $U$-value.

- The possible energy saving and carbon dioxide reduction have been explored when cob walls are insulated with 150 mm of external hemp–lime. A thickness of 150 mm is more practical (smaller building footprint) and it would have a lower capital cost than 250 mm of hemp–lime insulation. However, the heat loss reduction would be smaller since the 150 mm hemp–lime insulation only reduces the *U*-value to 0·45 $W/m^2$ K, whereas the 250 mm layer would achieve the target value of 0·3 $W/m^2$ K. The present cost of insulating with hemp–lime together with the present cost of energy suggests that the proposal is uneconomic at this time.

A further study will examine the thermal performance, capital costs and payback periods for a number of cob dwelling models of different designs retrofitted with external hemp–lime. Discussing the economic issues of adding hemp–lime to the exterior of cob buildings is a complex task. The area of cob wall is required and its relative heat loss assessed in relation to all the other heat loss routes from a given dwelling.

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