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Sustainability of solid brick walls with retrofitted external hemp-lime insulation.

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Abstract

Purpose

Dwellings constructed before 1920 often had solid brick walls with poor thermal performance. Today there is a drive to reduce both energy demand and carbon dioxide production. This paper will demonstrate that mixtures of chopped hemp straw with lime based binders added to the external surface of brick walls can substantially reduce the air to air thermal transmittance, or U-value W/m^2K , and that these mixtures provide a sustainable remedial treatment for solid brick walls. The aim is to achieve wall U-values as good as, or better than, the current UK Building Regulations design value of $0.30 W/m^2K$.

Methodology

Several Microsoft Excel spread sheets have been constructed to determine the steady state and transient thermal properties of various brick walls. These spread sheets are validated by comparing their output with the published thermal data to be found in the CIBSE Design Guide. The sustainable aspects of a number of different externally hemp-lime insulated Victorian brick walls are described and discussed.

Findings

The U-values and the transient thermal properties of solid brick walls with thickness 110 mm, 220 mm and 340 mm are presented. The transient properties include the admittance, decrement factor and lag time. These walls are then considered with various added external layers of hemp-lime ranging in thickness from 50 mm to 300 mm. Some solid brick walls have an added air cavity, created with studding and plywood sheathing, before the layer of hemp-lime. Walls with external tile hanging for sites with high exposure to driving rain are also discussed.

Originality

This work demonstrate the advantages of the energy saving and carbon dioxide sequestration achieved by adding 200 mm of a hemp-lime binder insulation to the exterior of Victorian brick walls of terraced dwellings.

Words: 285

Key words: brick walls, hemp-lime, thermal properties, energy, carbon dioxide.

Paper type: Research paper

1. Introduction

In temperate climates earth fired bricks have been used to construct terraced dwellings for many centuries. These terraces can be found in Europe and North America, for example in Belfast, Loughborough, Philadelphia and Toronto. Many of these solid brick walled dwellings are difficult to heat, HSB (2011) and HSB (2008), and the thermal performance could be improved by the addition of thermal insulation, thereby reducing both the demand for energy and production of carbon dioxide. The search for possible remedial strategies was discussed by Pett (2004).

The original builders were unconcerned about fuel efficiency, the production of carbon dioxide to the atmosphere or the embodied energy of materials. Today there is a need to minimise the use of energy and to decrease the production of carbon dioxide (CO₂). To this end sustainable building materials are sought, materials that will provide a thermally efficient wall, floor, or roof; materials that will not require large amounts of energy in the building construction, modification in use, or in the deconstruction processes. This paper will demonstrate that mixtures of chopped hemp straw with lime based binders added to the external surface of brick walls can substantially reduce the air to air thermal transmittance, or U-value W/m²K, and that these mixtures provide a sustainable remedial treatment for solid brick walls.

Hemp-lime, Bevan and Woolley (2008), is a mixture of hemp stalks, sometimes called shiv, with a lime-based binder and water. This mixture can be fabricated into blocks, and trowelled or sprayed onto a surface. Two important advantages of hemp-lime can be identified. (1) Using hemp-lime, rather than an oil-based insulation material, utilises a material with a lower embodied energy. (2) The

utilisation of hemp shiv with lime based binders produces a unique building material with the advantage that while growing the hemp plant removes CO₂ from the atmosphere. The lower embodied energy is debatable, but it is agreed that the sequestration of CO₂ by growing hemp is significant. Hemp-lime can be fashioned into blocks to replicate thermal concrete blocks, Lime Technology (2009a), and structural blocks, Lime Technology (2009b). The production of these two hemp-lime blocks, however, tends not to be economically viable. The manufacture, curing and transport of the blocks from factory to site require considerable resources of space, time and energy. Mixing the hemp and lime binder with water on site and then trowelling or spraying the mixture into a shuttered timber frame construction or directly onto a brick surface has practical advantages.

Making building materials with straw and a binder is not new. For example, in the West Country, Devon UK, earth is mixed with straw and water to form a material called cob. The cob is then raised in layers to form walls with high thermal mass and low embodied energy. Again, using hemp, rice or wheat straw locks CO₂ into the building material. A natural waste product is conveniently removed and a green building material is achieved when these straws are combined with a lime binder. Moreover, in November health issues arise in Egypt by the burning of rice straw, IRIN (2009). Incorporating rice straw in Egyptian building materials would therefore have two benefits, (a) reduction of the 'black cloud' health hazard, and (b) the sequestration of CO₂.

The UK Building Regulations (2000) were revised in 2010. The 2010 edition of the thermal regulations were divided into (a), "Approved Document L1A: Conservation of Fuel and Power (New dwellings)", and (b), "Approved Document L1B: Conservation of Fuel and Power (Existing dwellings)", Building Regulations (2010). Similarly, two further documents concern buildings other than dwellings. The UK Building Regulations state that the limiting external wall thermal transmittance is 0.30 W/m²K for both new and existing dwellings. This value (0.30 W/m²K) will be taken as the target thermal transmittance for this study. To illustrate the benefits of retrofitting insulation to the external surface of solid brick walls, Victorian dwellings in England will be used as the vehicle, since quantitative building details of Victorian terraced dwellings are available in the literature, Allen and Pinney (1990).

The term Victorian dwelling is used to describe UK houses built between 1840 and 1918, or sometimes called 'pre 1919'. Rivington (2004) discusses the various construction and materials found

in the external walls of these houses. Any remedial strategy to reduce the heat loss through Victorian solid brick walls, walls without the benefit of a cavity, will need to recognise the importance of controlling the moisture content in the construction. The application of hemp-lime to the exterior has the advantage that the material is breathable, and it will therefore allow water vapour to pass through the material. The modified wall may get wet, but later it will dry.

2. Aims

This paper will present thermal data on solid brick walls modified by the addition of hemp-lime externally to improve the thermal performance of the walls. The discussion will compare the steady-state and transient thermal properties of some proposed brick wall constructions with added layers of insulating hemp-lime of various thicknesses.

Four aims can be identified.

- 1 To review the thermal properties of various examples of solid brick walls, and to highlight the need for additional insulation. The results of this section will also be used to validate the spread sheets constructed for this work to determine the thermal properties.
- 2 To report the steady-state and transient thermal properties of these walls when insulation has been added to the external surface.
- 3 To demonstrate how the thermal properties of these brick walls might be upgraded to meet the current UK thermal Building Regulations (2010); that is to achieve a U-value equal to or less than $0.30 \text{ W/m}^2\text{K}$.
- 4 To indicate potential energy saving and carbon dioxide reduction if solid single brick walls were insulated with external hemp-lime.

3. Materials; walls and insulation

A number of solid brick walls of various thicknesses with a variety of hemp-lime insulation added to the external surface of the walls will be considered. The addition of insulation to the exterior is considered to be the most effective and least intrusive method for decreasing the heat loss from these walls. However, the detailing will need careful control especially at the eaves, around windows, doors, ventilating bricks and at the party wall in semi-detached and terraced dwellings. At the eaves, a large roof overhang and suitable capping of the added insulation will be needed. The problem of

thermal bridging at the external surface of the party walls may need to be resolved. In the present paper only the thermal properties will be discussed.

The solid walls measured in brick thicknesses will be from 0.5 brick to 3.0 brick, or from 110mm to 690mm before the remedial hemp-lime layer is added. Hemp-lime can then be trowelled or sprayed into a suitable cavity, or directly onto the external surface. This material can also be placed in shuttering, adding layers carefully to avoid over compaction of the material, thereby reducing the thermal advantage gained by the inclusion of large quantities of still air. The mixture will then set and has the advantages of low embodied energy, high fire resistance, and resistant to fungal decay.

Following the timber frame technique, it is proposed that for some walls an external frame is constructed to allow temporary or permanent shuttering to be used. Simple plywood can be used, and where permanent external weather protection is necessary, tile hanging or tongued and grooved timber facing might be used to protect the insulation from wind driven rain in exposed areas. Problems of moisture penetration, structural stability and buildability would need to be considered carefully. Moreover, the problem of the hemp-lime possibly biodegrading if maintain in a wet condition would need to be addressed, especially at and just above ground level.

4. Calculation of the time-dependent properties of walls

The steady state thermal transmittance and transient thermal properties of the walls were determined following the method reviewed briefly in CIBSE (2006), pages 3-24 to 3-26 and in the Appendix 3.A6, pages 3-31 and 3-32. Microsoft Excel spread sheets were constructed to determine the thermal properties of the various walls, assuming the wall was exposed to sinusoidal temperature variations over a 24 hour 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 values at the three densities of hemp-lime were given by Ian Pritchett, Lime Technology Ltd., (private communication, 19 September 2011). For the transient thermal properties described in this work the mean specific heat capacity has been used and a sensitivity study will be given later.

Insert Table 1

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, taken from CIBSE (2006) page 3-47. The internal and external surface resistances were taken as 0.13 and 0.040 m²K/W respectively. The 50 mm air cavity thermal resistance was taken as 0.18 m²K/W, again see CIBSE (2006) page 3-47. Table 1 shows brickwork data given for two cases, namely (1.5) protected and (1.6) exposed. An inner layer of brickwork separated by a continuous air space, or masonry protected by tile hanging or cladding is classified as protected. Alternatively, rendered or un-rendered masonry which is directly exposed to rain is classified as exposed. The insulation added externally to the brick walls is chosen from one of the three hemp-lime materials shown in Table 1, (1.7), (1.8) or (1.9). The ratios of the mass of hemp shiv to mass of lime based binder and the resulting material densities are given in Table 9. The new wall (1.7) and the roof hemp-lime (1.9) are recent improvements over the original old wall hemp-lime (1.8).

Insert Table 2

Table 2 reproduces thermal property data for a selection of walls taken from the current Design Guide, CIBSE (2006), Table 3.49. At Table 2, (2.1) an internally plastered 220mm brick wall has a U-value of 2.09 W/m²K, an admittance about twice as large and a decrement lag time of 7.4 hours. 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 0.42 with the lag time 7.4 hours. Walls (2.3), (2.4) and (2.5) show improving U-values with increasing insulation and a mixed picture regarding the decrement factors and lag times. The timber framed wall with 105mm of brick has an acceptable U-value at 0.29 W/m²K, but suffers with a high decrement factor and relatively short lag time. Here there is the potential for summertime overheating, when a high proportion, decrement factor 0.57, of the incident solar radiation appears in the interior after a relatively short time lag time 6.5 hours.

The thermal properties shown in Table 2 in square brackets have been determined using the input thermal data given by CIBSE (2006) page 3-47, and the Microsoft Excel spread sheets constructed

for this study. The good agreement between the CIBSE thermal properties and the values obtained using the spread sheets validates the software, and allows confident application of the spread sheets. The following results will illustrate how the thermal performance of brick walls of various thicknesses can be improved by adding different thicknesses of insulating hemp-lime externally.

5. Results

Following the aims stated earlier, the calculated results for the thermal properties of the existing brick walls, without added insulation, will be presented first. This will be followed by the presentation of the calculated thermal properties of the insulated walls. Finally, some walls for exposed weather areas will be discussed and walls able to meet the UK Building Regulations identified.

This section will include some discussion on how the insulation might be added to the exterior surface.

Insert Table 3

Table 3 shows a selection of brick walls all with the exposed classification and an internal 13 mm dense cement plaster layer, Table 3, (3.1) to (3.5), but some with an additional 25 mm external layer of cement render, Table 3, (3.6) to (3.11). These are assumed to be the two most likely states that the early brick walls might be found today, and the brickwork is assumed to range from 110 mm (0.5 brick) to 680 mm (3 bricks). The most thermally unacceptable wall is the half brick with U-value 2.98 W/m²K, Table 3, (3.1), 78% of the incident solar radiation arriving at the interior after only 3.6 hours. This construction would not provide adequate environmental filtering needed in a dwelling in temperate climates, with or without climate change. The thickest wall in this group, wall (3.5) at 693 mm still only has an U-value of 0.93 W/m²K, but at least this wall has a very low decrement factor at 0.01 and a long lag time of 23.5 hours. The group of walls with the additional external cement render show some thermal improvement, but again the wall U-values are far from the modern requirement of 0.30 W/m²K. At wall (3.11) with total thickness 718 mm, U-value 0.91 W/m²K, the lag time is calculated at 0.31 hours. In the admittance calculations this lag time is determined and expressed as part of the daily twenty four hour cycle. For comparison with the other times in Table 3, this 0.31

hours has been added to 24 and shown in brackets as 24.31 hours. This convention will be adopted for the remaining tables and is used again in Table 5.

Insert Table 4

Table 4 shows a selection of solid walls all with the exposed classification for the 220 mm brickwork either with an internal 13 mm dense cement plaster layer, walls (4.1) to (4.4), or with 13 mm of lightweight plaster, walls (4.5) to (4.8), but all walls with 25 mm of lime and sand external render. The two groups of walls have an increasing thickness of new wall hemp-lime, Table 1, (1.7), sprayed directly onto the brickwork in thicknesses of 50 mm, 100 mm, 150 mm and 200 mm before the addition of the external finish of 25 mm lime and sand render. Here it is assumed that the original brickwork is sound, or if there was an external layer of cement render, or pebble-dash, that this would be in need of maintenance and therefore removed before the addition of the hemp-lime insulation. Comparing the two groups of results for the thermal performance of these walls given in Table 4 it is clear that the difference between dense and lightweight plasters is negligible. The dense plastered 50 mm insulated wall (4.1) has a U-value some 4% higher than the lightweight plastered wall (4.5), while the decrement factors differ by 7% and lag times are similar. The important conclusion to be drawn from the results shown in Table 4 is that for these 220 mm brick walls to meet the current Building Regulations and to have U-values less than $0.30 \text{ W/m}^2\text{K}$, then 150 mm of new wall hemp-lime is inadequate, while 200 mm of new wall hemp-lime would provide a margin for error. This is illustrated by comparing the U-values at (4.3) with (4.4) and at (4.7) with (4.8).

As mentioned above, when insulating these walls by spraying hemp-lime onto the brickwork, care would be needed to ensure the detailing at the eaves, around doors, windows and ventilating air bricks allowed effective treatment, and did not jeopardize these architectural features.

A possible solution to this problem would be to construct a timber frame, some sections temporary some permanent, around these architectural features allowing an air cavity between the brick 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. The next section presents some walls with air cavities formed using 50 mm studs and 12 mm plywood sheathing.

Insert Table 5

Table 5 shows the thermal properties of twelve brick walls. There are three thicknesses of brickwork each with four different thicknesses of additional hemp-lime insulation. The brickwork thicknesses are 110 mm, (5.1) to (5.4), 220 mm (5.5) to (5.8) and 340 mm (5.9) to (5.12). Each wall has an air cavity of 50 mm, 12 mm of plywood sheathing then the layer of hemp-lime insulation followed by 25 mm of lime and sand render. The insulation is added in 50 mm, 100 mm, 150 mm or 200 mm thick layers. The thermal performance analysis is undertaken ignoring the parallel heat conduction through the timber studding. Temporary external plywood sheathing may be used as shuttering with studding of the appropriate thickness, and the internal timber may remain in place as it will be unaffected by the hemp-lime insulation. Table 5 shows that for the 110mm brickwork only 200 mm of insulation would provide the necessary U-value to meet the Building Regulations, Table 5, (5.4), while for the 220 and 340 mm walls both 150 mm and 200 mm of insulation would achieve sufficiently low U-values, in the range 0.30 to 0.23 W/m²K. Note that the lag time for the most massive wall, 340 mm brickwork with 200 mm of hemp-lime, Table 5, (5.12), is greater than twenty four hours at 27.8 hours, suggesting an extremely small contribution to the internal heat gain as the decrement factor is 0.01. With the current interest in climate change, here is another advantage achieved by the addition of hemp-lime insulation; the insulation is helping to reduce the heat energy required in winter and helping to reduce the fabric solar gain in summer.

Insert Table 6

Table 6 shows the thermal properties of some 220 mm brick walls with an air cavity, plywood sheathing and the addition of various thicknesses of hemp-lime insulation. This table gives the properties of these walls when tile hanging is added to provide a rain screen for locations where the driving rain index is high. In the South West of England for example dwellings located on high moorland and coastal regions can be exposed to very heavy rain driven by high winds. While the hemp-lime insulation and the external lime and sand render are both breathable, they can take up water and then dry out. Nevertheless the conditions presented by a high driving rain index might cause wall

damage over time. It would be sensible under these circumstances to protect the wall and shed the driving rain water using a tile hanging or similar screen. Table 6 shows the time-dependent thermal properties of air cavity hemp-lime insulated tile hung walls, again indicating that 200 mm of insulation would be required to satisfactorily meet the Building Regulations. The wall shown at Table 6, (6.4), has a U-value of $0.25 \text{ W/m}^2\text{K}$, while the small decrement factor 0.03 and long lag time of 20.17 hours show the thermal advantage possible in high summer.

5.1 Sensitivity study

There are two aspects of uncertainty in the results presented above that should be considered.

Firstly, there is a possible increase in thermal conductivity of the hemp-lime insulation due to moisture content and increase in density, due to the self-loading of the hemp-lime at installation. Secondly, the uncertainty in the thermal capacity creates uncertainty in the transient thermal properties.

5.1.1 Uncertainty in thermal conductivity

The hemp-lime thermal conductivity values given in Table 1 are for dry hemp-lime samples. Two factors cause the conductivity to increase, (a) increases in moisture content and (b) increases in density. Evrard (2008) has studied the influence of moisture content on hemp-lime samples and found a hemp-lime wall sample, with density 400 kg/m^3 , had a conductivity of 0.11 W/mK at relative humidity 0%, but a value of 0.15 W/mK when the RH% reached 80%. The hemp-lime thermal conductivities, shown in Table 1, demonstrate an increase with increasing density. In real walls the hemp-lime thermal conductivity might be greater than expected due to increases in moisture content and density. It will be assumed that a practical layer of new wall hemp-lime, called an installed layer, might have an increased thermal conductivity of 0.10 W/mK . Figure 1 shows that the U-value of a 220 mm solid brick wall varies with increasing thickness of added hemp-lime, and increases with increasing hemp-lime thermal conductivity. For this 220 mm solid brick wall with 200 mm of new wall hemp-lime to meet the target U-value the hemp-lime effective thermal conductivity should not be greater than about 0.07 W/mK , or below an increase of about 17%. Figure 1 shows that if 300 mm of installed hemp-lime with effective conductivity 0.10 W/mK , (increased from 0.06 W/mK due to density and moisture effects), was added to this 220 mm brick wall, the resulting insulated wall would still meet the target U-value of less than $0.30 \text{ W/m}^2\text{K}$. On the other hand, with 200 mm of installed hemp-

lime insulation, with conductivity 0.10 W/mK, again as the result of increased density and moisture content, was added to this wall then the installed wall U-value would be 0.4 W/m²K.

Insert Figure 1

Insert Table 7

5.1.2 Uncertainty in specific heat capacity of hemp-lime

Table 7 gives the thermal properties of the same 220 mm brick wall, but with different values of the hemp-lime thermal properties arising from the uncertainty in the thermal conductivity and specific heat capacity. Returning to Table 1 a range of specific heats were recorded for the three hemp-lime samples, and it is possible that the application of the hemp-lime by spraying or loading into shuttering may cause the density to be different from the values given for new wall hemp-lime, Table 1, (1.7). The insulation might be intended as low density 'roof' hemp-lime, Table 1, (1.9), but old wall hemp-lime, Table 1, (1.8) might result. Table 7 shows the results for walls of 220 mm brickwork with 150 mm of hemp-lime but with different insulation conductivities and specific heat capacities. The changes in conductivity will result in different U-values, while the ranges of specific heat capacity will be seen in the variation of the decrement factors and lag times. Comparing walls (7.1) and (7.2) the 7% increase in specific heat capacity has given a 2% increase in the lag time, while comparing walls (7.2) with (7.3), the new wall hemp-lime being replaced by new roof hemp-lime the reduction in conductivity of 16% has given a 12% reduction in the U-value. The two conclusions drawn from the results presented in Table 7 can be summarised as follows. Firstly, the lower density roof hemp-lime with its lower conductivity would be the insulation of choice as it leads to lower U-values. However, if this low density material was used then permanent shuttering would be an advantage to maintain the lower density, and care would be needed to stop the weight of subsequent layers compacting the earlier deposited hemp-lime, thereby increasing the density and increasing the conductivity. Secondly, the uncertainty in the specific heat capacities of the various hemp-lime materials does not lead to any significant changes in the overall picture of the transient thermal performance of these hemp-lime insulated brickwork walls.

6. Discussion

Sustainability has three interwoven strands, Otto (2003). The three are: (a) the social aspects, about people, (b) the environmental aspects, about the planet, and (c), the economic aspects, about the profit. Clearly, the upgrading of solid brick walls found in Victorian dwellings will depend strongly on the 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.

Probert (2010) reports a small sample study of possible tenant participation in the sustainable issues focussed on the refurbishment of Victorian properties. The tenants of Victorian houses were very proud of their properties and expressed the view that water saving devices, draught proofing, loft insulation and double glazing were more important than possibly spoiling the external appearance of their homes in order to save energy. The survey suggested that people were more interested in comfort and security, in a new boiler and controls, while external insulation was only a little more attractive than internal insulation. The retrofitting of hemp-lime insulation to the exterior of solid brick walls has three important green or sustainable advantages, and two further social advantages. (1) The additional insulation produces a saving in the energy required to space heat the dwelling. (2) The sequestration of CO₂ by growing hemp reduces the CO₂ in the atmosphere. (3) The reduction in heating energy demand reduces the annual production of CO₂. The sequestration of CO₂ and its subsequent storage within the hemp-lime insulation is a single contribution to the reduction in CO₂. However, the reduced energy demand provides an additional annual contribution to this reduction. The two further advantages of the addition of hemp-lime insulation are (4), the increase in comfort temperatures, and (5), the possible reduction in risk of occupant fuel poverty. These last two issues will not be discussed in this work. The first three sustainable advantages will now be discussed in detail.

6.1 Energy saving

Data produced by the National Building Agency and incorporated by Allen and Pinney (1990) shows the distribution of housing stock in the UK by house type, age and ownership. Table 1, Allen and Pinney (1990), shows that this stock has components; 3.4% pre-1919 semi-detached and 13.6% pre-

1919 terraced houses. A second table, Allen and Pinney (1990), shows the distribution of house type with external wall construction. Here it is shown that 1.76 million terraced houses have solid brick walls with no cavity, or 68% of the pre-1919 terrace houses. To this total the number of semi detached and end terraced properties 1.66 million must be added, giving a total of 3.4 million dwellings. The number of solid brick walled dwellings must decrease with time, as old condemned dwellings are demolished and modern dwellings are built, but there is a potential or possible energy saving if the remaining solid brick walls had an improved thermal performance. As existing housing accounts for over 25% of the UK CO₂ emissions, Department of Communities and Local Government (DCLG) (2006), and with around 4 million Victorian properties, then if 20% of these dwellings were insulated a considerable reduction in energy demand would result and the 25% of UK CO₂ emissions from dwellings reduced to 17%.

Insert Table 8

Table 8 shows the possible energy saving and CO₂ sequestration by the remedial measure of adding 200 mm of hemp-lime insulation externally to the brick walls of period terrace dwellings. Models for the three possible Victorian terrace dwelling constructions are taken from Allen and Pinney (1990). The terraced houses have external solid brick walls 220 mm thick, are single glazed with loft insulation. By adding 200 mm of hemp-lime to the external walls the air to air thermal transmittance, or U-value, is reduced from 2 to 0.26 W/m²K. The reduction in heat loss is summarised in Table 8, where the percentage reduction in design heating demand for hall to hall party wall, mid terrace and living room to living room party wall dwellings are 41%, 28% and 39% respectively. Assuming that space heating accounted for two-thirds of the total energy used in each dwelling then 27, 19 and 26%, represents the potential financial savings on original fuel bills for the three types of dwelling.

6.2 Sequestration of CO₂ by hemp

Table 8 also shows the potential for reducing carbon dioxide in the atmosphere by applying hemp-lime to these dwellings. Weight et al (2010) give the CO₂ produced in manufacturing the lime binder as 0.427 kgCO₂ per kg of binder and the sequestration of CO₂ by hemp as -1.41 kgCO₂ per kg of hemp shiv. The net sequestration of carbon dioxide by the hemp-lime material will vary with density.

Using the mixture proportions suggested by Lime Technology (2011), and reproduced in Table 9, the three types of hemp-lime studied in this paper, namely old wall with density 330 kg/m^3 , new wall with density 275 kg/m^3 and roof with density 220 kg/m^3 have net sequestration rates of 61, 85 and 108 kgCO_2 per kg of added hemp-lime respectively.

Insert Table 9

Applying externally 200 mm of the new wall mixture to the three dwelling types, hall to hall party wall, mid terrace and living room to living room party wall, the carbon dioxide sequestrations are 385, 212 and 352 tonne of carbon dioxide respectively. To place these sequestration rates in the context of the overall CO_2 reduction proposed for the UK during the next forty years, up to the year 2050, the present dwelling CO_2 production and the level proposed for 2050 are required. The CO_2 emission associated with UK dwellings was 42 MtCO_2 per year in 2004, and it is proposed to reduce this to 17 MtCO_2 by 2050, DCLG (2006). Given that there are 3.4 million Victorian properties, Allen and Pinney (1990), and taking the average sequestration rate of 316 tonne per dwelling, and if 20% of these properties were insulated with hemp-lime then the reduction in CO_2 would be 215 MtCO_2 . This would represent a significant contribution to the required reduction in CO_2 . If over the next 40 years the CO_2 dwelling production is to be reduced from 40 to 17 MtCO_2 per year, then the figure of 215 MtCO_2 corresponds to seven years of mean annual production of 30 MtCO_2 per year. This represents the one-off reduction in CO_2 by sequestration in the hemp-lime. There is a second reduction in CO_2 since as the energy demand for each hemp-lime insulated dwelling is reduced, so the CO_2 production associated with the energy conversion for space heating is also reduced.

6.3 Reduction in CO_2 due to reduced space heating energy demand

It is difficult to extrapolate the individual house savings in both energy and CO_2 production from space heating to give UK national figures. Firstly, there is the uncertainty in the total number of pre 1919 dwellings. Allen and Pinney (1990) gave the total number of pre 1919 terraced houses as 3.4 million. However, the Department of Communities and Local Government (2006) gives the number of pre 1919 dwellings as 4.4 million. Secondly, the energy used for space heating in dwellings is subjective and a function of remedial measures already undertaken, like the addition of double glazing,

increased levels of loft insulation and draught proofing. However, an order of magnitude of this reduction in CO₂ production can be obtained as follows.

Table 8 shows that for solid brick walls the mean reduction in heat loss as a result of the remedial addition of hemp-lime is 2470 W per dwelling. If the design temperature difference between the interior and exterior is 21C then this heat loss may be expressed as a heat loss rate per degree of 118 W/K. Taking the dwellings to be in the London area where heating is required for 2663 degree-days (K.days) (Heathrow (1982-2002), reference temperature 18C, CIBSE (2006), Table 2.23, page 2-14), then this saving is equivalent to 7517 kWh per year per dwelling. Assuming gas fired central heating, where 1 kWh gas heating produces 0.184 kg CO₂, Carbon Trust (2010), then the insulated dwelling provides a CO₂ saving of 1380 kgCO₂ per year per dwelling. Following the sequestration example, section 6.2 above, then assuming that 20% of the 3.4 million dwellings achieved this CO₂ reduction the saving for the UK is 0.94 MtCO₂ per year. This represents a 5% contribution to the proposed saving of 17 MtCO₂ per year sought by 2050. Moreover, if electricity is used for space heating in these dwellings, instead of gas, then the potential saving is about 15%, since 1 kWh of electricity produces 0.544 kgCO₂, Carbon Trust (2010).

7. Conclusions

Addressing the four aims identified earlier, in Section 2, the following conclusions can be drawn.

1 The thermal properties of some examples of Victorian solid brick walls have been determined. For example, a 110 mm (0.5 brick) thick wall with 13 mm of dense plaster has U-value (U) 3.0 W/m²K, lag time (L) 3.6 hr and decrement factor (D) 0.78, while a 680 mm (3.0 brick) thick wall has U, L, D; 0.9 W/m²K, 23.5 hr and 0.01 respectively. Clearly, these walls require additional insulation to meet current regulations with U-value of 0.30 W/m²K.

2 The thermal properties of these walls when hemp-lime insulation has been added to the exterior surface are given. For example, the thermal properties of a 220 mm (1.0 brick) thick wall with 13 mm of dense plaster with additional layers of hemp-lime 50, 100 and 200 mm are reported. This un-insulated wall has U, L, D of 2.1 W/m²K, 7.6 hr, and 0.41 respectively. With the addition of 50, 100 and 200 mm of hemp-lime the U, L D values are (0.75 W/m²K, 11.2 hr, 0.14); (0.46, W/m²K, 14 hr, 0.1) and (0.26 W/m²K, 20.5 hr, 0.03) respectively. Here the addition of 200 mm of hemp-lime would meet the UK thermal regulations. When a 50 mm air cavity is introduced between the brick and the

insulation for walls 220 and 340 mm thick, then 150 mm of hemp-lime is sufficient to meet the UK thermal regulations. A similar wall with 110mm brick would require 200mm to ensure that the U-value was less than 0.30 W/m²K.

3 This work demonstrates that the thermal properties of these brick walls might be upgraded to meet the current United Kingdom Building Regulations by the addition of suitable external layers of hemp-lime to achieve wall U-values less than 0.30 W/m²K.

4 The possible energy saving and CO₂ reduction if single brick walls were insulated with external hemp-lime is described and discussed. For Victorian terraced dwellings with 220 mm solid brick walls the addition of 200 mm of hemp-lime reduces the U-value from 2.0 to 0.26 W/m²K. For hall to hall party wall, mid terrace and living room to living room party wall dwellings the percentage reductions in design heating demand are 41%, 28% and 39% respectively. The potential sequestered CO₂ in these three types of dwellings with hemp-lime insulation to meet the UK thermal regulations are 385, 212 and 352 tCO₂ respectively.

This work demonstrates that there are possible energy and carbon dioxide savings when externally insulating these Victorian dwellings with hemp-lime. This conclusion would apply to all similar brick walled dwellings. However, the issues of acceptance in terms of appearance, buildability and cost have still to be resolved.

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