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Hygrothermal performance of bio-based insulation materials

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Bio-based insulation materials have the potential to make a significant contribution to the reduction in the global warming potential of the construction industry world-wide. They contribute in two ways. First they provide the opportunity to reduce the embodied energy in the fabric of buildings. They do this because they are renewable and recyclable. Plant-based insulation materials also sequester carbon dioxide through photosynthesis, sealing up atmospheric carbon dioxide for the life-time of the building. Second they are able to reduce the in-use energy consumption of buildings in more ways than by simply reducing energy transmission. They have the ability to buffer heat and moisture, which is most evident in dynamic situations. This paper discusses the hygrothermal performance of bio-based insulation materials, examining the hygrothermal effects associated with their vapour activity. The incremental performance offered by these materials is not allowed for in building regulations, nor is it readily accounted for in many commercially available building physics models. The paper discusses the reasons for this and identifies the need for the transient performance of bio-based insulation materials to be taken into account, because this will better reflect their actual contribution to the energy performance of a building.

Notation

dmp_{th}	thermal damping (%)
P	density (kg/m^3)
phs_{th}	thermal phase shift (h)
Q	heat flux (W/m^2)
Q_{24h}	ratio of energy effectively transferred during the first 24 h (%)
$t_{s\text{-}s}$	time needed to reach 95% of the heat flow at steady state (h)
U	thermal transmittance (W/m^2 per K)
λ	thermal conductivity (W/m per K)

1. Introduction

Bio-based insulation materials are a novel class of insulation materials manufactured from natural, renewable plant- or animal-based materials. Interest in these materials is growing because they are renewable, they are often readily recyclable, and the plant-based ones sequester atmospheric carbon dioxide through photosynthesis. Typically, the sequestered carbon dioxide is greater than the embodied carbon dioxide involved in their manufacture. This means that their use in construction reduces the net embodied carbon dioxide of the building, in some cases resulting in a 'negative' carbon footprint. These materials can be used on their own, with minimal processing, for example straw bales; they can be processed to form regular-shaped units such as Stramit, sheep's wool or wood wool batts; or they can be combined with other materials to form composites such as hemp–lime. A common feature of bio-based insulation materials is that they are 'vapour active'. This means that they are not only vapour permeable, but they are also capable of buffering moisture, and can act as thermal stores. It is this characteristic that distinguishes them from oil- and chemical-based insulation materials.

This paper discusses the hygrothermal performance of bio-based insulation materials, examining the hygrothermal effects associated with their vapour activity. The incremental performance offered by these materials is not allowed for in building regulations, nor is it readily accounted for in many commercially available building physics models. This paper discusses the reasons for this and identifies the need for the transient performance of bio-based insulation materials to be taken into account, because this will better reflect their actual contribution to the energy performance of a building.

2. Background

The construction industry is of major economic importance to the EU, accounting for 10% of EU27 gross domestic product (GDP) and 30% of industrial employment in the EU within 3·1 million enterprises, 95% of which are small to medium-sized enterprises (SMEs). Historically it has been a highly polluting and wasteful industry, using 2 billion t of raw materials. The industry is the highest energy consumer in the EU (about 40% of total energy consumption), and is the main contributor to greenhouse gas emissions (about 36% of the EU total carbon dioxide emissions). The construction and refurbishment of buildings accounted for 80% (€1200 billion) of the total construction sector output (€1519 billion) of EU27 in 2007. The construction industry therefore has a crucial role to play in helping to meet the target of a 20% reduction of greenhouse gas emissions from 1990 levels by 2020 under the EU's climate change package.

Bio-based insulation materials, such as natural fibre batts, offer a number of benefits in comparison with more established mineral- and oil-based alternatives, such as mineral wool and polyurethane rigid foam (PUR)-based products. Resourcing advantages include a renewable supply chain and significantly reduced carbon footprint through the photosynthetic carbon stored within plant-based materials. A traditional brick and block domestic house has 100 kg/m^2 carbon dioxide and equivalent emissions embodied in the wall construction (Hammond and Jones, 2008). A hemp–lime house has 35 kg/m^2 CO_2e sequestered in the wall construction (Boutin *et al.*, 2005). A typical house has around 80 m^2 of external wall, which, if constructed from hemp–lime, would save 10·8 t carbon dioxide and equivalent emissions in embodied energy. If 50% of the UK government's target for domestic housing (250 000 houses) were constructed using hemp–lime, for example, this would deliver 10% of the average total annual saving required to meet the UK government's carbon emission targets (DECC, 2012), and 100% of the targeted savings in the building sector (DECC, 2011a). The construction of buildings was responsible for 10% of the total UK carbon emissions in 2008, and their use (heating, lighting etc.) was responsible for 47% of carbon emissions (DECC, 2011b; Innovation and Growth Team, 2010). Of the 'in use' figure, space heating is responsible for 53% in domestic buildings, and air conditioning and space heating is responsible for 57% in non-domestic buildings (Innovation and Growth Team, 2010).

The thermal resistance of bio-based insulation materials is generally inferior to that provided by mineral and in particular rigid foam insulation products. Although simply increasing wall thickness will overcome this, as well as increase in captured carbon content, pressures on land use and value, combined with desire for minimal impact retrofitting solutions, places bio-based insulation materials at a distinct disadvantage. However, bio-based insulation materials exhibit other advantageous characteristics that, if able to be recognised in design, place them ahead of artificial materials. Bio-based insulation materials, such as hemp–lime, are hygroscopic: Evrard and de Herde (2010) showed that in a hemp–lime wall (U-value 0·44 W/m^2 per K) 17% energy is transferred compared with 75% for a mineral wool wall (U-value 0·14 W/m^2 per K) over 24 h when subjected to a sudden temperature drop.

Insulation materials are typically compared based on thermal conductivity *(λ)* and wall thickness. Thermal conductivity is measured in a 'steady state', with a stable heat flux across a known thickness of dry material. Such measurements take no account of the influence of moisture or of mass transfer. Building physics models make allowance for these influences by factoring in the increased thermal conductivity of water according to moisture content. Among the most commonly used modelling software packages, only WUFI (Wärme und Feuchte instationär software, which models transient coupled one- and two-dimensional heat and moisture transport) acknowledges any heat of sorption effects (Künzel, 1995). The significance of these effects needs to be measured and understood in order to correctly characterise their thermal performance and use them beneficially in design.

At present synthetic insulation materials dominate the building industry, although interest in the use of bio-based insulation products is steadily increasing (Hill *et al.*, 2009). In Europe inorganic fibrous materials, for example stone wool and glass wool, account for 60% of the market. Organic foamy materials such as expanded and extruded polystyrene account for 27% of the market, whereas all other materials combined make up less than 13% (Papadopoulus, 2005). In the case of the mineral fibre materials, adhesives and water-repellent oils are often added to increase mechanical strength. Expanded and extruded polystyrene are both oil-based polymerised polystyrol and the production process requires blowing agents which, since the phase-out of ozone-depleting chlorofluorocarbons (CFCs), are typically pentane and carbon dioxide. Pentane contributes to smog and ground-level ozone (Harvey, 2007) and carbon dioxide, owing to its low solubility and high diffusivity in polymers, makes it difficult to produce low-density foams, which results in poorer thermal performance compared with insulation materials made using hydrochlorofluorocarbon (HCFC) blowing agents (Yang *et al.*, 2009), as well as releasing surplus carbon dioxide into the atmosphere.

3. Properties of bio-based insulation materials

Table 1 shows the thermal conductivity of a range of the most commonly available bio-based insulation materials. These range from 0·035 W/m^2 per K to 0·102 W/m^2 per K; they are generally more thermally conductive than synthetic materials, which tend to range between 0·023 W/m^2 per K (polyurethane) and 0·044 W/m^2 per K (mineral fibre). Oil-derived insulation has an embodied energy of between 95 and 108 MJ/kg, and mineral insulation between 15·7 and 53 MJ/kg. (Sources of data include: manufacturers' data sheets; Cripps *et al.* (2004);

Material	Typical thermal conductivity: W/m per K	Typical density: kg/m^3	Typical embodied energy, cradle to gate: MJ/kg
Wood fibre	0·038–0·050	160–240	17
Wood wool	0·038–0·040	50	10·8
Paper (cellulose)	0·035–0·040	32	4·9–16·64
Hemp fibre	0·038–0·040	40	10·5–33
Sheep's wool	0·038–0·040	25	12–36·8
Flax	0·038–0·040	30–35	11–39·5
Cork	0·038–0·070	105–120	26
Hemp–lime	0·070–0·150	220–330	35
Stramit® straw board	<0·102	250–600	N/A
Straw bale	0·052–0·080	100–130	0·24

Table 1. Properties of materials

Sutton *et al.* (2011); greenspec.co.uk; Hammond and Jones (2008).)

Much of the existing characterisation data for natural building materials relates to structural performance – compressive and flexural strength, modulus of elasticity and so on. Apart from traditional materials such as timber, hemp–lime is perhaps the most researched bio-based building material, but the characterisation of the hygrothermal properties of this and other bio-based building materials is at an early stage. Studies are on-going into characterisation and characterisation techniques – led by a RILEM international committee on bio-aggregate (RILEM TC BBM236, see http://www.rilem.org/gene/main.php?base=8750&gp_id=257), set up in 2011. Presentation of more comprehensive data sets in tabular form is therefore not possible, because even characterisation techniques have not been standardised.

A major advantage of bio-based insulation materials is their ability to create a breathable wall construction by readily absorbing and releasing moisture in response to changes in relative humidity and vapour pressure gradients in the surrounding environment. By doing so they are acting as a hygric buffer, reducing the energy requirements of air conditioning (Tran Le *et al.*, 2010). These materials are vapour active and their response to changing humidity conditions is associated with their pore structure and pore connectivity. Their adsorption/desorption characteristics involve thermal effects from latent heat to the extent that moisture condenses (releasing heat) and evaporates (absorbing heat) on the surface of the material and within its pores (Hill *et al.*, 2009). This phenomenon increases their effective thermal mass, allowing them to act as a thermal buffer in conjunction with their hygric buffering properties.

Previous research on the physical properties of hemp–lime (Collet, 2004; Evrard, 2008; Tran Le *et al.*, 2010) has highlighted that the material presents a good balance between low mass and heat storage capacity compared with classical insulation materials.

Bio-based insulation can be part of a vapour permeable wall, which can offer considerable benefits in terms of robustness of fabric and indoor air quality. In circumstances where moisture is allowed to penetrate the fabric of the structure, vapour permeability allied with good hygroscopicity (typical qualities of bio-based insulation materials) reduces the risk of moisture build-up and resulting mould and bacterial growth. These qualities are of particular value when the structural elements of the building are moisture sensitive (e.g. timber, which is susceptible to decay, and light steel, which is susceptible to rust).

Unlike many synthetic insulation materials, bio-based insulation is non-toxic and there is generally no requirement for protective clothing to be worn, which is of particular interest when used as retro fit in roof spaces, where overheating is common and the wearing of full protective suits becomes very uncomfortable for installers. Bio-based insulation rolls and batts are comparatively more robust to handle than their synthetic counterparts, ensuring a more effective final result. Off-cuts do not require specialist waste streams and can often be sent for composting rather than to land fill.

Many bio-based insulation materials are susceptible to decay if exposed to unsuitable environmental conditions. Typically those conditions involve excess moisture, and where this is not present, bio-based insulation materials are durable and long lasting. For this reason, they should not be used below damp proof courses, or in areas that are expected to get wet.

The sensitivity of bio-based materials to moisture-induced decay requires particular care to be taken in the detailing and construction methodologies. Many of these susceptibilities can be successfully addressed through off-site manufacture. For example the ModCell® system of straw bale construction (www.modcell.com) ensures that the straw bales are enclosed in weather-proof panels before delivery to site. Similarly, the Hembuild® system (http://www.limetechnology.co.uk/hembuild.htm) consists of factory-made pre-fabricated composite hemp–lime and hemp fibre panels, which have been pre-dried to remove the manufacturing water. This not only ensures that the panels are built to a high standard, but also ensures that the mixing water required to cast the hemp–lime has been removed before the building is erected. In the case of hemp–lime this is significant because otherwise it can take several years in the UK climate for this water to completely dry out and to achieve optimum thermal performance. Where water damage does occur, in many cases bio-based materials are relatively easy to remove and replace because they are rarely structural.

There are currently no comprehensive data sets for the embodied energy and environmental impact of bio-based insulation materials, but studies on some materials (Norton, 2008) show a considerable reduction in global warming potential, especially if carbon dioxide sequestration in plant-based materials is taken into account. Both plant- and animal-based materials benefit from renewability and very low environmental impact in re-use and/or disposal.

4. Sources of bio-based insulation materials

Wood fibre board is made from largely pre-consumer waste wood from saw mills. Wood chips are soaked in water prior to being pressed into boards and dried. This technology uses no additional bonding agents, relying on the natural resins within the wood. In some applications latex is added to give waterproof qualities.

Wood wool insulation is made from forestry thinnings and the residue from saw mills. The fibres are bound together with polyolefin fibres and a fire retardant is added, which is usually ammonium phosphate.

Paper (cellulose) insulation is generally made from recycled newspaper and magazines. The paper is shredded and then treated for fire and insect resistance with borax. Finally the treated and shredded paper is ground into fibres before being packaged.

Hemp fibre is made from the fibre surrounding the hemp stalk. The fibre is processed and can have recycled cotton fibres or wood fibres added during manufacture. Binding is provided by the use of polyester, and fire-resistant chemicals can be added.

Sheep's wool is sent in bales to a factory for processing. It is scoured (washed) and then treated for fire and insect resistance. Once dried, the wool is carded (combed) to align the fibres and then layered to form the required thickness. The layers are then mechanically bonded with a polyester binder before being formed into rolls or slabs. Sheep's wool insulation has been shown to have the capability of absorbing volatile organic compounds (VOCs) from the atmosphere, acting as a passive air filter (Curling *et al.*, 2012).

Flax fibre is made from the fibres surrounding the flax stalk. Potato starch or polyester are used as binders and borax is added for fire and insect resistance before the material is formed into slabs.

Cork insulation is made from the bark of the cork tree. Each tree is harvested every 25 years, and the bark is then allowed to regenerate. Cork granules are expanded and formed into blocks bound with natural resin using high temperature and pressure.

Hemp–lime is a composite made from the woody core of the hemp plant (shiv) and lime-based binders. The shiv is a co-product from the decortication process for the production of hemp fibre, whereby the internal woody core of the plant is separated from the external fibrous material. The shiv is chopped into particles between 5 mm and 30 mm in length and then packaged. It is mixed with lime-based binders and then cast or sprayed around a structural frame.

Stramit® straw board is manufactured from straw such as wheat or rice in a continuous process of heat and pressure, using resins to bind the panels together with a paper external surface. Thicknesses range from 35 mm to 60 mm.

Straw bales are the by-product of food production – generally wheat. Traditional straw bale construction uses 'small bales' about 1 m × 0·45 m × 0·35 m, but modern baling technology generally produces large bales (2·4 m × 1·2 m × 1·2 m) or round bales. These need to be re-manufactured to be usable in straw bale construction.

5. Dynamic hygrothermal performance

In practice, the thermal performance of domestic buildings is often only evaluated in terms of its thermal transmittance coefficient, U-value (W/m^2 per K), and, in recent years, UK building designers and contractors striving to meet ever more stringent building regulation targets, which are themselves defined by the U-value, appear to have neglected to consider other very important properties such as heat capacity, diffusivity and hygrothermal responses. Fraser (2009) highlighted the significant increase in the number of lightweight houses constructed in recent years and the corresponding increased risk of occupant discomfort due to large temperature fluctuations associated with the low thermal mass of the building. The increased risk of overheating will, at best, result in discomfort and dissatisfaction for building occupiers, but, at worst, could lead to increased retrofitting of air-conditioning systems, with the associated energy cost and other environmental damage. It is essential that the transient thermal performance is considered in addition to steady-state thermal transmittance coefficients to ensure the robust design of low-energy new buildings and rational appraisal of retrofit solutions.

6. Experimental and modelled dynamic thermal performance in hemp–lime

Evrard and de Herde (2010) demonstrated that the thermal transfer co-efficient, U (W/m per K) alone is not sufficient to evaluate transient performance of a wall subject to a rapidly changing climate. A WUFI simulation of a sudden cooling shock of 20°C was conducted on a 300 mm thick hemp–lime wall with a density of 474·5 kg/m^3, a thermal conductivity of 0·145 W/m per K, and a resultant U-value of 0·44 W/m^2 per K. An identical simulation was conducted on a lightweight mineral wool wall with a U-value of 0·14 W/m^2 per K. Two parameters were used to describe transient thermal behaviour of the walls

(*a*) time needed to reach 95% of the heat flow at steady state, $t_{\text{s-s}}$ (h)
(*b*) ratio of energy effectively transferred during the first 24 h, $Q_{24\text{h}}$ (%)

The heat flow at steady state for the hemp–lime wall was 8·78 W/m^2, which was achieved at $t_{\text{s-s}}$ of 68 h, and for the mineral wool wall 2·70 W/m^2, achieved at $t_{\text{s-s}}$ of 15 h. It was found that $Q_{24\text{ h}}$ for the hemp–lime wall was 17% whereas $Q_{24\text{ h}}$ for the mineral wool wall was 75%. The different percentages need to be taken in the context of the different thermal conductivities of the walls being compared. Although the difference in heat flux only amounts to 0·6 W/m^2 after 24 h for a temperature difference of 20°C, the U-values of the two walls are 0·3 W/m^2 per K^2 apart, which would lead one to expect a much greater difference in heat flow if only the U-value were to be considered.

A second simulation was run using day and night temperature cycles following a sine curve with a 24 h period and an amplitude of 10°C (between 0°C and 20°C). Two additional parameters were used to describe thermal phase shift phs_{th} (h) and thermal damping dmp_{th} (%). It was found that the phase shift was 15 h in the hemp–lime wall compared with 5 h in the mineral wool wall, and the thermal damping was 92% in the hemp–lime wall compared with 38% in the mineral wool wall. These differences are the result of the increased effective thermal mass of the hemp–lime compared with the mineral wool.

An experimental hemp–lime panel was tested using an identical temperature regime at the University of Bath. The panel was 300 mm thick with a density of 330 kg/m^3 and a calculated thermal transmittance of 0·3 W/m^2 per K (Lawrence *et al.*, 2012). GE Sensors Hygrostick® relative humidity and temperature sensors were cast into the wall at intervals through its thickness. A sudden drop in temperature was imposed by reducing the temperature on the cold side by 20° to 0°C, whereas the other side was maintained at 20°C. Figure 1

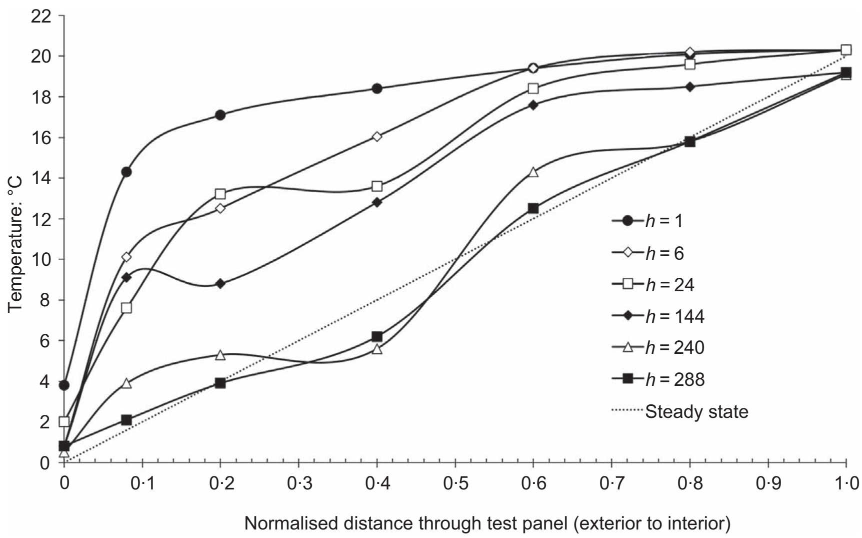

Figure 1. Temperature change in 300 mm hemp–lime wall after a sudden temperature drop

presents the temperature profile from the cold side to the hot side following the sudden temperature change. The panel was left for many hours in this condition before a steady state could be established. Taking a mean value from the closest to steady state experimental data, the time to steady state $t_{s\text{-}s}$ was established as being approximately 240 h. $Q_{24\ h}$ was 17% using the calculated thermal transmittance of 0·29 W/m^2 per K. A wall of the same thermal resistance was defined in the transient heat and moisture simulation software WUFI Pro 5, as used by Evrard and de Herde (2010) and the same thermal shock simulation was conducted. Considering temperature only, ignoring the effects of relative humidity, the simulated hemp–lime wall reaches a steady state within 72 h; this is considerably less than the experimental data from laboratory tests, which include the effects of phase change within the material. $Q_{24\ h}$ for the simulated wall was 19%, which is similar to the experimental data and to the simulations reported by Evrard and de Herde (2010).

The pore structure of hemp–lime is tri-modal with 50 μm pores connected to 10 μm pores by way of 1 μm pores (Figure 2). This has the effect of slowing down the rate of moisture sorption and desorption, such that a steady-state isotherm takes several weeks to be measured. This is because it requires a partial vapour pressure differential to be in existence across the 1 μm pore in order to force the moisture through.

Given that humidity is constantly changing, hemp–lime never achieves a steady-state moisture content, and as a result hysteresis plays an important part in the hygrothermal performance of hemp–lime. WUFI simulations do not take into account the differences in sorption and desorption as a function of time, and this is one reason why the simulations differ from the experimental data.

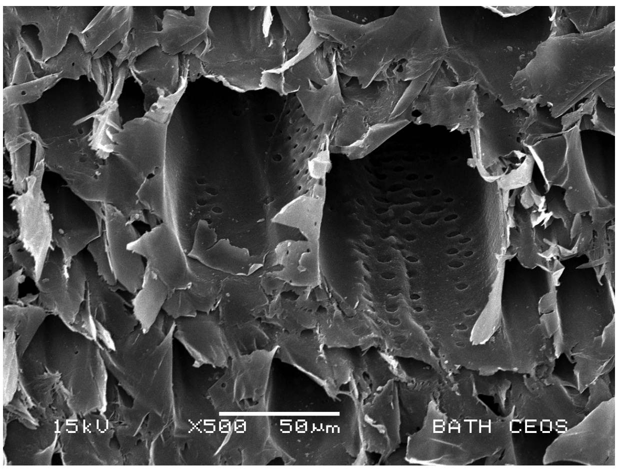

Figure 2. Pore structure of hemp shiv

7. Conclusion

Climate change, driven by global warming, is the single biggest environmental and humanitarian crisis of our time. The earth's atmosphere is overloaded with heat-trapping carbon dioxide, which threatens large-scale disruptions in climate with disastrous consequences. The UK government has developed a systematic approach to the reduction of emissions of carbon dioxide, and bio-based insulation can contribute to this approach in two ways.

First, in the context of embodied energy, plant-based insulation materials sequester carbon dioxide, reducing the environmental load. Their manufacture is typically less energy intensive than the manufacture of synthetic insulation materials, which on a like-for-like basis reduces the emissions related to the supply of insulation materials. Bio-based insulation materials are renewable and recyclable and, as a result, reduce the environmental load involved in their manufacture.

Second, in the context of in-use energy savings, the hygrothermal performance of bio-based insulation materials can contribute to the reduction of in-use energy consumption in more complex ways than simply by having a low thermal conductivity. Their superior performance in dynamic situations compared with most synthetic materials is not acknowledged in build regulations or in most building physics models. This performance advantage is not well publicised or appreciated by architects, specifiers, designers, building control officers and building owners and occupiers.

The undoubted benefits from carbon sequestration and enhanced hygrothermal performance can only be taken advantage of if a wider body of research is conducted and disseminated than is currently the case.

Although the thermal performance of hemp–lime is undoubtedly exaggerated by its unusual pore structure, the phase change effects found in this material are also seen to a greater or lesser degree in other vapour active bio-based insulation materials. The replacement of oil- and mineral-based insulation with bio-based renewable insulation is essential if carbon reduction targets are to be met. In order for these materials to be competitive with higher embodied energy equivalents, the full range of their hygrothermal performance needs to be taken into account. The key to this is to consider dynamic hygrothermal behaviour and thermal mass, rather than relying simply on steady-state thermal transmittance (U-value).

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