Lawrence, M., Fodde, E., Paine, K. and Walker, P. (2012) Hygrothermal Performance of an Experimental Hemp-Lime Building. Key Engineering Materials, 517. pp. 413-421.

Link to official URL (if available): http://www.ttp.net/978-3-03785-435-8.html

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Hygrothermal performance of an experimental hemp-lime building

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Keywords: Hemp-lime, hygrothermal performance, phase shift, phase change, hygrothermal damping.

Abstract. The use of hemp-lime as a construction technique is a novel approach which combines renewable low carbon materials with exceptional hygrothermal performance. The hemp plant can grow up to 4m over a four month period, with a low fertilizer and irrigation demand, making it very efficient in the use of time and material resources. All parts of the plant can be used – the seed for food stuffs, the fibre surrounding the stem for paper, clothing and resin reinforcement, and the woody core of the stem as animal bedding and aggregate in hemp-lime construction. The unique pore structure of the woody core (shiv) confers low thermal conductivity and thermal and hygric buffering to hemp-lime. The construction technique promotes good air tightness and minimal thermal bridging within the building envelope. All these factors combine to produce low carbon, hygrothermally efficient buildings which are low energy both in construction and in use, and offer opportunities for recycling at end of life.

This paper reports on the hygrothermal performance of an experimental hemp-lime building, and on the development of a computerized environmental model which takes account of the phase change effects seen in hemp-lime.

Introduction

Carbon dioxide (CO_2) is a greenhouse gas which is considered to be the major contributory factor in global warming. As a result international efforts are being made to reduce greenhouse gas emissions - including CO_2 - as part of the Kyoto protocol, back to below 1990 levels. Emissions of CO_2 in the UK in 2008 amounted to some 525 million tonnes (Mt) (1990 – 590Mt) [1]. Of this figure, construction was responsible for 298.4Mt [2]. Table 1 shows a full breakdown of the contribution of the construction industry towards the UK carbon emissions.

Construction

The construction sector has a greater influence on carbon emissions (56.7%) than all other sectors put together. Within this area, the use of buildings (heating, lighting, air conditioning) is responsible for nearly 47% of the total CO_2 emissions in the UK, with manufacture (building materials etc..) responsible for nearly 9%. It is within these two areas that the focus on the reduction in CO_2 emissions (carbon reduction) has concentrated. Carbon reduction in use is associated with improvements in thermal insulation, increased efficiency of lighting, heating and cooling and reduction in thermal losses through thermal bridges and poor air tightness. Carbon reduction in manufacturing is associated with a reduction in energy input in the manufacturing process (low carbon cements, substitution of high carbon materials with lower carbon ones). Another area of

interest is the use of building materials that sequester CO_2. This is most often achieved through the use of natural building materials which absorb atmospheric CO_2 through photosynthesis thereby locking it up within their fabric for the lifetime of the building. At end of life, some of these natural materials offer opportunities for recycling/re-use, extending their useful life. Some materials can be composted and recycled through agriculture. Interest in materials such as timber, straw and hemp have grown in recent years in response to this need.

Sub-sector	**CO_2 [Mt]**	**% of total**
Construction		
Design	1.3	0.25
Manufacture	45.2	8.61
Distribution	2.8	0.53
Operations on-site	2.6	0.50
In Use	246.4	46.93
Refurb./Demolition	1.3	0.25
Total Construction	**298.4**	**56.84**
Other Sectors	**226.6**	**43.16**
Total UK	**525.0**	**100**

Table 1: CO_2 emissions in 2008 for the Construction Industry [2]

Hemp-Lime

Hemp-lime is a building material often referred to in English as 'Hemcrete®' or Lime-Hemp. This material was originally developed as a replacement for wattle and daub infill in timber frame buildings in France, where the term used is 'Chaux-Chanvre'. It is made by mixing the chopped up woody core of the stalks of the hemp plant (*cannabis sativa*), known as the 'shiv', with a binder made from air lime with pozzolanic, cementitious or hydraulic lime additions, and in some cases minor amounts of other additives such as surfactants. This material is used to form building envelopes by casting between, or spraying against, temporary or permanent shuttering in-situ, or by pre-fabrication of building blocks or panels. Typically walls are constructed to be ~300mm in thickness. Hemp shiv can also be used as an insulating element in lime renders.

Interest in the use of hemp-lime is driven by the following factors:

- It is a low density material with associated low thermal conductivity.
- Its pore structure allows it to dampen variations in environmental heat and humidity.
- The high proportion of embodied bio-based material results in the sequestration of relatively large amounts of atmospheric CO_2 (through photosynthesis) compared with more traditional building materials.
- Hemp shiv is more resistant to biological decay than some other bio-based building materials (for example straw)
- Hemp shiv, in common with other bio-based materials, is a renewable resource, and offers the opportunity of being recycled at end of life.
- Hemp cultivation requires lower levels of fertilisation and irrigation than wheat and some other bio-based building materials, resulting in lower levels of eutrophication.
- The hemp plant grows very rapidly to heights of up to 4m within 4 months. This gives it the potential to act as a 'break crop' allowing optimisation of yields of the primary crop.

The density, thermal conductivity and compressive strength of hemp-lime are predominantly controlled by the relative proportions of shiv and binder. These characteristics are listed in Table 2.

Hemp shiv sequesters 2.1 kg CO_2 equivalent per kg [3], and $1m^2$ timber framed lime rendered 300mm thick wall made with a 1:2 mix sequesters 75.7 kg CO_2 equivalent [3] with the net CO_2

emissions including transport, construction and manufacturing processes (carbon footprint) being -35.5 kg CO_2 equivalent [3] - which equates to a 'negative' carbon footprint contributed by the wall element to the total carbon footprint of the construction.

Application	**Shiv: Binder proportions (by mass)**	**Target density [kg.m^{-3}]**	**Typical ultimate compressive strength [N.mm^{-2}]**	**Typical thermal conductivity λ [Wm^{-1}K^{-1}]**
Roof Insulation	1:1	220	0.05	0.06
Wall Construction	1:1.5	275	0.11	0.06-0.09
Wall Construction	1:2	330	0.22	0.09-0.115
Wall Construction	1:2 (compressed)	440	0.35	0.115
Floor	1:3	500	0.8	0.13
Floor	1:4	600	1.15	0.14
Pre-cast Structural	1:4 (compressed)	600-1000	2-6	0.14-0.27

Table 2: Mechanical and thermal characteristics of hemp-lime [4]

People who live in hemp-lime houses report high levels of comfort – uniform room temperatures, pleasant humidity levels – and energy use which is lower than might be expected from a purely scientific evaluation of the U value of the building envelope. Indeed based on SAP ratings and U value calculations hemp-lime houses at the Haverhill Project [5] should be using significantly more energy than the comparative brick houses on the same project. However this is demonstrably not the case[5]. The reasons for this are not clear, and several possible explanations have been proposed:

- Occupants may habitually set thermostats to lower levels than in conventional buildings because wall surfaces feel less cold.
- Hemp-lime walls might possess higher effective thermal mass (virtual thermal mass) than expected due to phase change effects occurring within the walls associated with the unique pore structure of hemp shiv. This would slow down the rate at which heat is transferred through the wall, thereby reducing the need for internal heating/cooling.

Experimental design

In order to investigate these characteristics, a series of sample panels were constructed and subjected to controlled environmental conditions. The panels were manufactured with humidity and temperature (RH/T) sensors embedded at varying depths through their thickness, which allowed temperature and humidity profiles through the wall to be measured over time whilst thermal and humidity fluxes of differing amplitude and frequency were produced across the thickness of the panel. These experiments allowed characterisation of the hygrothermal performance of the panels to be made. The results of this work will be published elsewhere.

The other avenue of research was to investigate the hygrothermal performance of an actual hemp-lime building (both internal conditions and across the thickness of the walls). To this end, an experimental building was constructed (the HemPod) (Fig.1) on the campus at the University of Bath, in the West of England. This building is a single story building, built off a suspended chipboard floor which is insulated with 200mm of closed cell insulation (λ=0.023W.m^{-1}.K^{-1}). The ceiling also consists of the same insulation behind 9mm gypsum plasterboard. Both floor and ceiling are calculated to have a U-value of 0.15W.m^{-2}.K^{-1}.

The building footprint is 5.86m x 4.64 m. Walls were formed from 75x50mm timber studwork at 600mm centres to act as structural support. These were positioned on the interior of the walls and clad with a permanent shuttering made from 9mm thick magnesium silicate board. A 200mm thick hemp-lime wall was cast using temporary shuttering, rising to above the level of the insulated

ceiling. Windows and doors are timber framed with low emissivity triple glazed argon filled glazing. The door has a U-value of 0.79 $W.m^{-2}.K^{-1}$ (south facing), the windows 0.97 $W.m^{-2}.K^{-1}$ (north facing) and 1.05 $W.m^{-2}.K^{-1}$ x2 (south facing). Junctions between wall and floor, wall and ceiling, wall and door/windows were sealed with vapour permeable tape. The ceiling was lined underneath the plasterboard with Intello® vapour check membrane, sealed to the walls. Air tightness of the interior of the building is exceptionally good at $0.55m^3.hr^{-1}.m^{-3}$ exceeding the PassivHaus standard of 0.6 $m^3.hr^{-1}.m^{-3}$. A thermographic survey with the interior heated to 20ºC when the external conditions were at -3ºC (Fig. 2) revealed no thermal bridges.

Figure 1: HemPod experimental hemp-lime building at the University of Bath

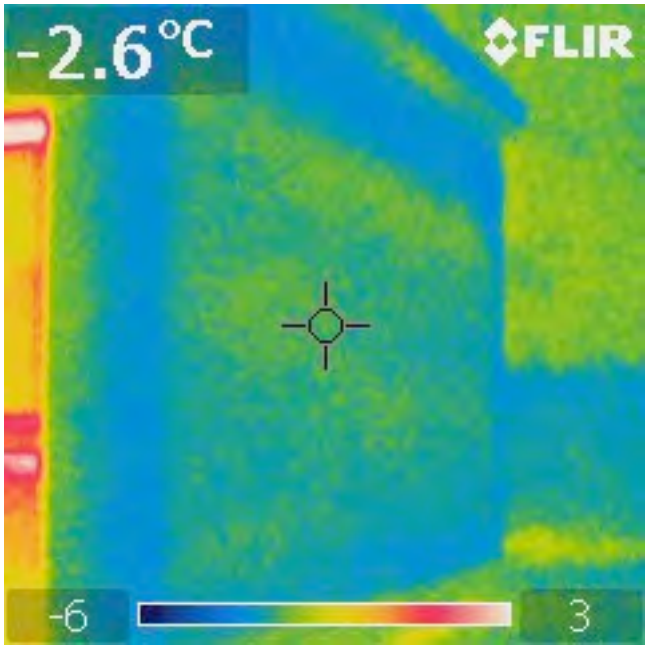

Figure 2: Thermographic image of East elevation

The interior of the walls in each elevation have Hygrotrac® RH/T sensors embedded at 40 mm intervals (Fig. 3), a timber moisture probe embedded into a timber strut in the centre of the wall and thermocouples attached to the internal and external faces (Fig.3). The sensors are located in the geometric centre of each wall. The mix used was 1 part Tradical®HF hemp shiv to 1.5 parts Tradical®HB binder, with minimal compression applied in order to achieve a target density of 275kg.m^{-3} (Table 2).

Figure 3: Sensors embedded in the hemp-lime wall during construction

Construction of the HemPod began in June 2010, taking 10 days from greenfield site to the removal of the external shuttering. The walls were left to dry for 8 weeks before the external render was applied. Over the autumn period the building was allowed to dry out, and experiments were conducted on the effect of artificial dehumidification. During this period the moisture content of the walls was monitored using a range of different techniques, and by January 2011 moisture levels inside the building had equilibrated with the external environment.

Performance data

Data presented in this paper relate to the period between 13th May 2011 and 24th May 2011. Where wall temperatures are given, these relate to the east wall of the HemPod. For comparison purposes data are also presented from an unheated building in Liskeard, Cornwall in the far south-west of England (the office). This building is timber framed with the walls insulated with 150mm of mineral wool insulation, lined with 12mm oriented strand board (OSB) with an external

timber rainscreen. It is used as an office and contains office equipment, books, furniture which will increase the thermal mass of the interior compared with the empty interior of the HemPod. The office is 10m x 5.6m x 2.4m internal dimensions. Internal and external conditions were acquired through a Davis Vantage Pro2® weather station. The office was unoccupied over this period. The volume of the office is about twice that of the HemPod, which will tend to give the internal conditions greater inertia, and due account should be taken of this when making comparisons. The two sites are some 200km apart and subject to different weather conditions. Temperature conditions were more variable at the office site, whilst humidity conditions were more variable at the HemPod site.

Temperature

Figs.4 and 5 show the internal and external temperature for the HemPod and the office.

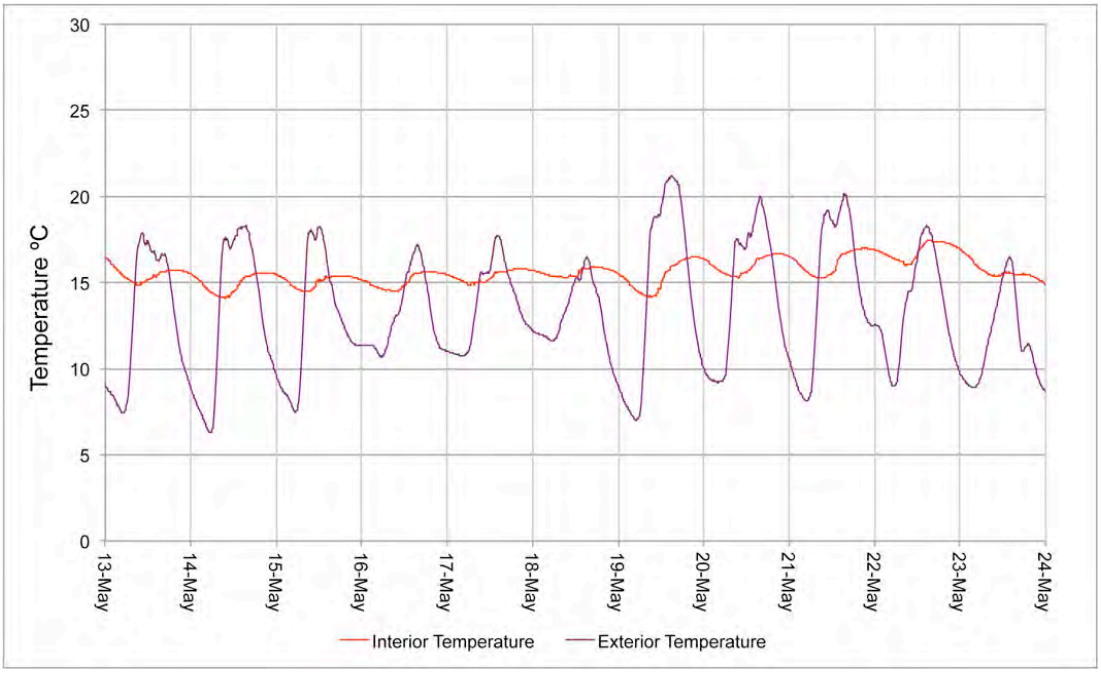

Figure 4: Internal and external temperature in the HemPod

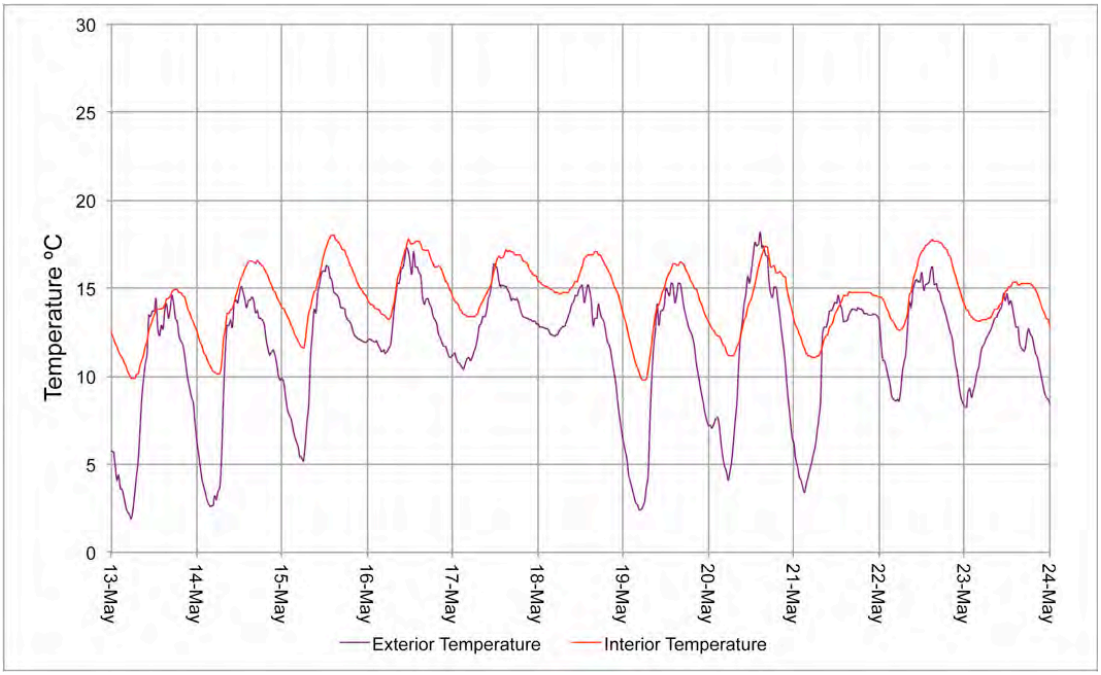

Figure 5: Internal and external temperature in the office

The external temperature variations at the HemPod were significantly moderated internally when compared with the performance in the office. The mean daily variation of the internal temperature in the HemPod was 2.3ºC against a mean daily variation of 11.6ºC for the exterior (equivalent to an 80% temperature damping effect). The mean daily variation of the internal temperature in the office was 6.8ºC against a mean daily variation of 13.5ºC for the exterior (equivalent to a 49% temperature damping effect).

Fig.6 shows the difference between the temperature of the surface of the exterior of the HemPod and the temperature on the surface of the interior.

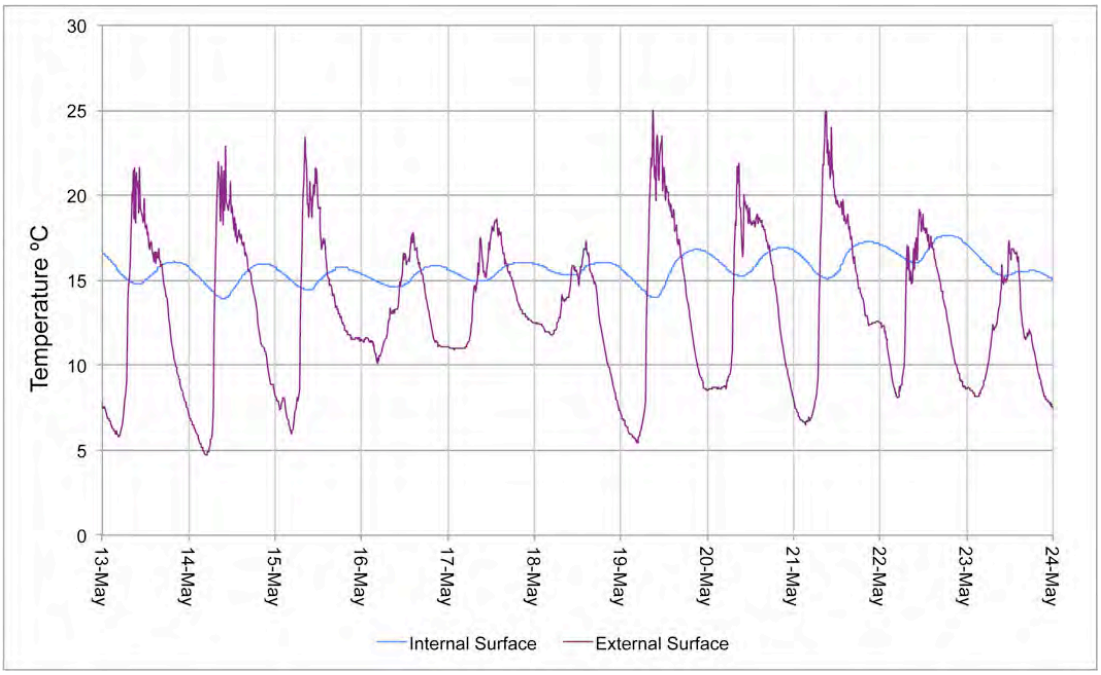

Figure 6: Comparison of the internal and external surface temperatures (HemPod)

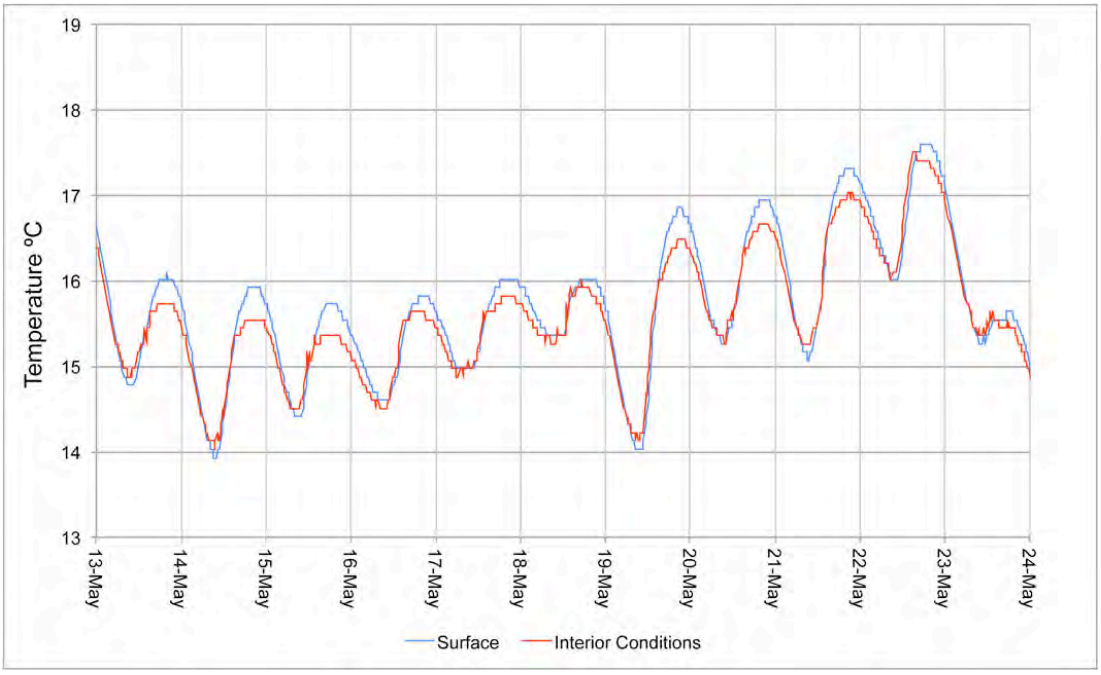

Figure 7: Comparison between internal environmental temperature and wall surface temperature (HemPod)

As with the environmental temperature, so the external temperatures has been considerably moderated by the time that it reached the interior. Fig. 7 shows the relationship between internal surface temperature and internal environmental temperature.

It can be seen that the surface temperature is generally marginally higher than the interior conditions, and as can be seen in Fig.8 on average the surface temperature is 0.09ºC higher than the air temperature of the interior, although it should be noted that differences this small are beyond the resolution of the thermistors. This means that the surface of the wall follows the temperature of the interior very closely rather than feeling cold to the occupants, which would reduce the incentive to increase the thermostat setting, as would be the case with cold wall surfaces.

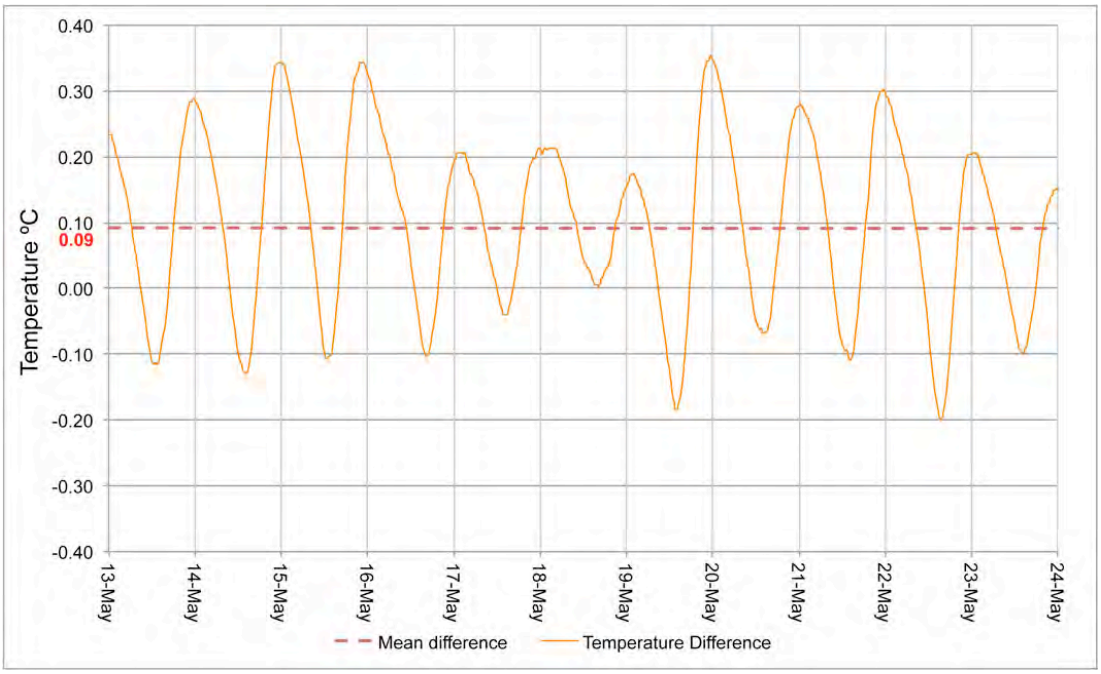

Figure 8: Temperature difference between surface and air temperature (Hempod)

Humidity

Figs. 9 and 10 show the internal and external humidity for the HemPod and the office. as with temperature, the humidity inside the HemPod is moderated to a far greater extent than that in the office. Indeed the periodic variation is ±2% compared with ±25% externally, resulting in a remarkably stable internal relative humidity.

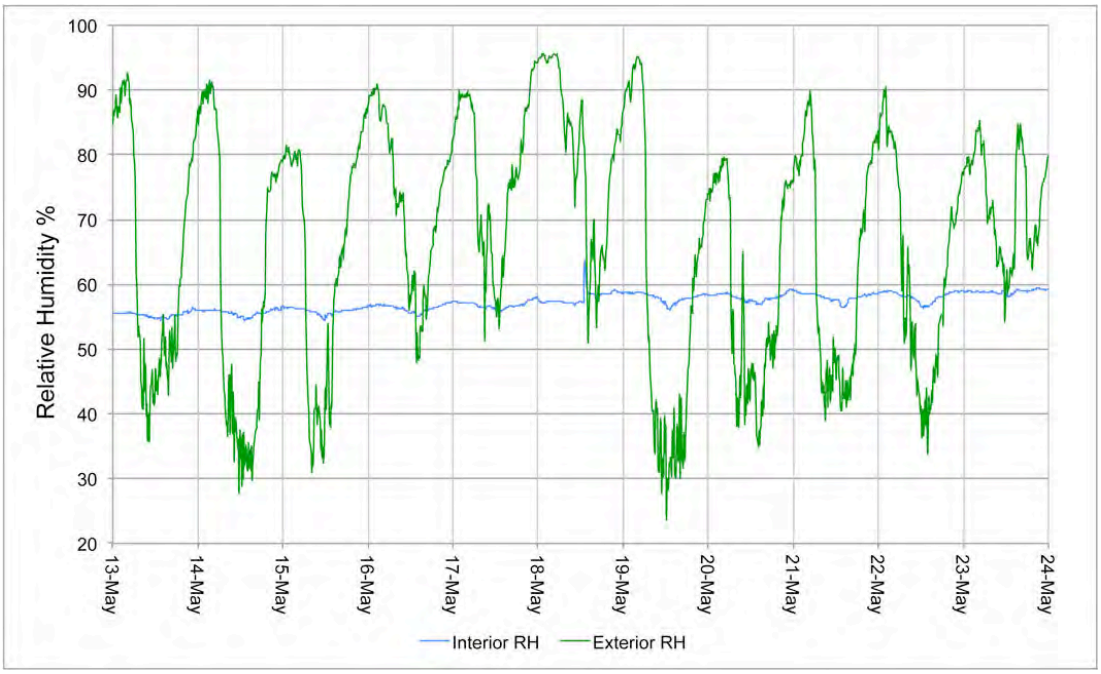

Figure 9: Internal and external relative humidity for the HemPod

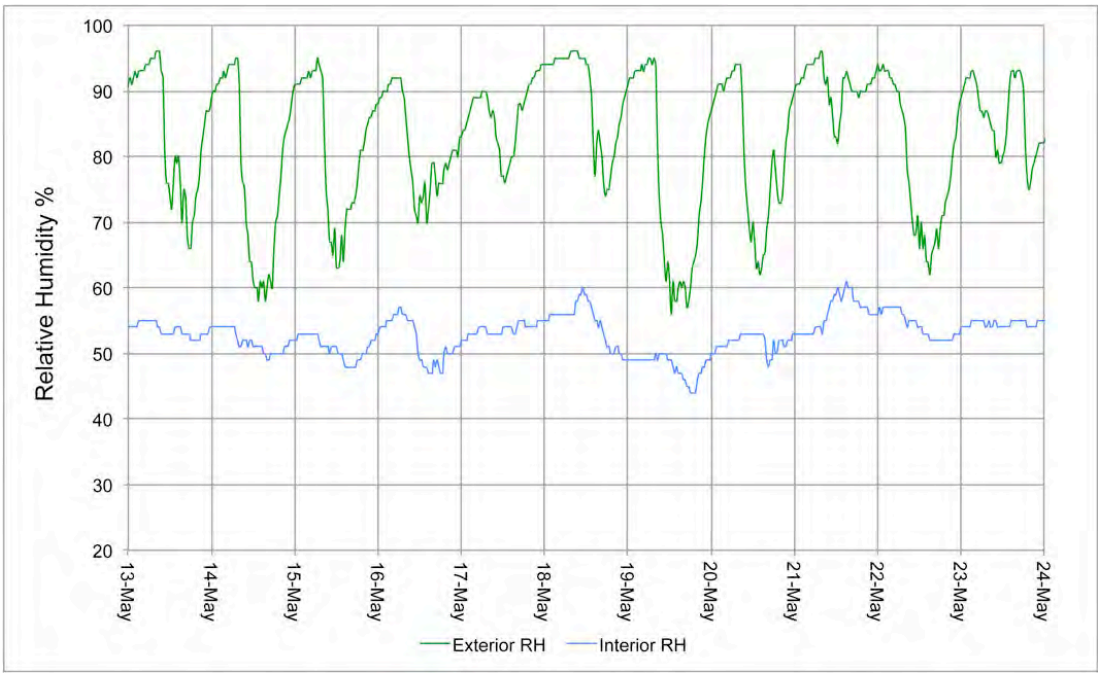

Figure 10: Internal and external relative humidity for the office

In the office the humidity varies by ±7% against the external humidity variation of ±20%. This variation is considerably greater than seen in the HemPod, and it should be borne in mind that the air volume is twice that of the HemPod, and the room contains considerable quantities of absorbent materials (Paper, wood, carpet), both of which would give the interior higher humidity inertia than the empty HemPod. Fig.11 shows the environmental conditions inside the HemPod.

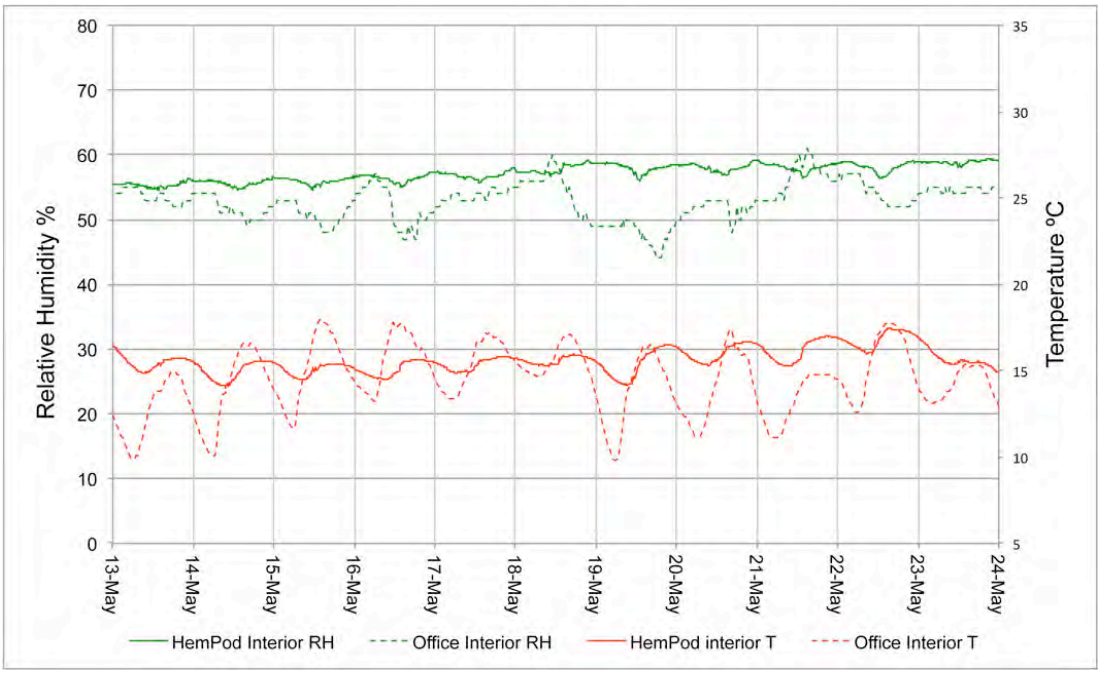

Figure 11: Temperature and Relative Humidity inside the office (dotted lines) and the HemPod (solid lines)

This demonstrates the considerable stability of conditions that are maintained within the HemPod making use of the hygrothermal sorption/desorption characteristics of hemp-lime, compared with a mineral wool insulated timber framed building.

Data analysis

Thermal damping

As can be seen from Fig.4, the temperature variations inside the HemPod are significantly dampened compared with the exterior temperature variations. In addition, there is a phase shift in the interior variations compared with the exterior variations, which is associated with the time that it takes for the thermal impulse to travel through the wall. (Fig 12)

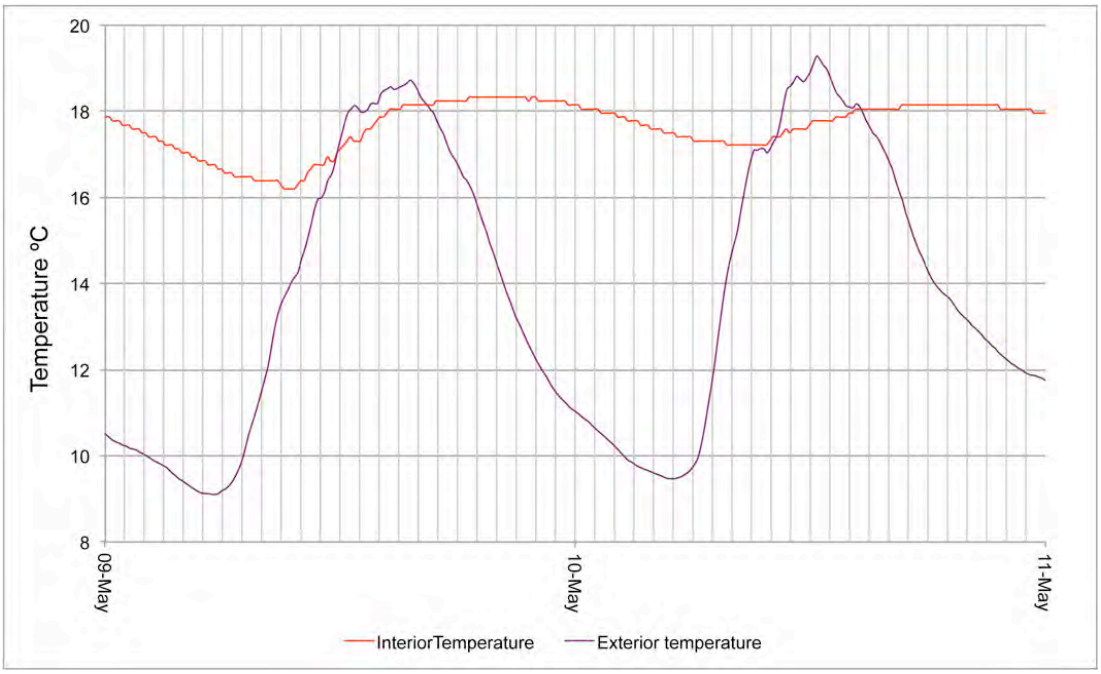

Figure 12: Thermal phase shift through the HemPod walls

For the 200mm thick wall in the HemPod, the thermal phase shift is ~5 hours and the thermal damping is ~80%. Evrard and De Herde [6] using WUFI® software report a simulated phase shift of 15 hours and a thermal damping of 92% for a 300mm thick hemp-lime wall, based on a thermal conductivity λ of 0.115W.m^{-1}.K^{-1}, a density ρ of 440 kg.m^{-3} and a dry thermal capacity c_0 of 1560J.kg^{-1}.K^{-1}. Their model using a 20º thermal shock gives a steady state heat flow $Q_{s\text{-}s}$ of 371.2kJ.m^{-2} for their rendered wall which has a U-value of 0.44W.m^{-2}.K^{-1}. However, the steady state flow does not actually occur until 68 hours have passed. After 12 hours the model predicts that the amount of heat transferred through the inside surface wall is 6.1kJ.m^{-2} which is only 1.6% of the steady state heat flow. The same model shows a 12-hour heat transfer through a 284.5mm thick mineral wool wall (with a U-value of 0.14W.m^{-2}-K^{-1}) of 31.1kJ.m^{-2} compared with a steady state heat transfer of 116.9kJ/m^{-2} - equivalent to 26.6% of the steady state heat transfer.

The performance of the HemPod appears to follow the trends predicted by the Evrard & De Herde model but this model requires amendment to reflect differences in density and binder content, since these will change the assumptions for thermal conductivity, vapour permeability, vapour vapour sorption/desorption and moisture buffer values. All of these will change the way in which the model works. Work is ongoing to confirm the hygrothermal data required to characterise the ID and 2D hygrothermal performance of low density hemp-lime using WUFI® software, and 3D performance using TAS® and IES VE® models.

Thermal comfort

The characteristics of the surface of a wall contribute to thermal comfort. Thermal comfort is affected by conduction, convection and radiation.

The contact temperature between the wall material and human skin partly depends on their relative temperatures, and partly depends on their contact coefficients capacitive materials with a high contact coefficient such as concrete feel cold or hot, whilst materials with a low contact coefficient feel comfortably warm because the contact surface adapts to the skin temperature. Hemp-lime, in common with all plant materials, has a low contact coefficient and thus feels warm to the touch.

Convective heat flow rate q_c is written as:

$$q_c = h_c\left(\theta_{fl} - \theta s\right) \qquad (1)$$

where h_c is the convective surface film coefficient (W.m^{-2}.K^{-1}), θ_{fl} is the temperature of the undisturbed air and θ_s is the surface temperature. The standard value for the inside surface film coefficient for convective heat transfer for vertical surfaces is ~3.5 W.m^{-2}.K^{-1} [7]. Over the surface of the long walls this means that the convective heat flow rate is 4.43W. This is a relatively low level of heat flow rate, which would barely be sensed by occupants.

Radiant heat flow rate q_r is written as:

$$q_r = h_r\left(\theta_{s1} - \theta_r\right) \tag{2}$$

where θ_{s1} is the temperature of the surface θ_r is the radiant temperature of the environment as seen by the surface and h_r is the surface film coefficient for radiation. The value for the inside surface film coefficient for radiation h_r(in W.m^{-2}.K^{-1}) for vertical surfaces is ~7.7 (EN Standard) [7]
Thus:

$$q_r = 7.7\left(\theta_{s1} - \theta_r\right) \tag{3}$$

$\theta_{s1} - \theta_r$ in the HemPod is +0.09º, thus over the surface of the long walls the radiant heat flow rate is 9.75W. This will have the effect of a mild radiant heat to occupants, which would improve the sense of comfort.

All three of these characteristics - contact temperature, convective heat and radiant heat - within the HemPod are relatively neutral, neither drawing heat from the system nor emitting significant heat. This will tend to create a comfortable atmosphere for the occupants.

Hygric damping

As with heat transfer, so the transfer of humidity through the walls is considerably moderated by the hemp-lime. The Evrard and De Herde WUFI model [6] uses a high moisture buffer value, but is unable to produce a model which matches actual short term performance. Hemp-lime is capable of rapid liquid transfer, high moisture retention and high water vapour permeability, all of which act to avoid condensation, and manage the internal environment to retain comfortable conditions. The hygrothermal performance is complicated by the unusual pore structure of hemp-lime which is tri-modal with 50µm pores connected to 10µm pores via 1µm connecting pores as shown in Fig 13. The movement of humid air from large pores to intermediate pores via small pores involves partial pressure differences between the two larger pores, which can result in evaporation and/or condensation with corresponding latent heat effects. The latent heat of condensation of water *L* can be expressed as (kJ.kg^{-1}) [8]:

$$L_{water} = -0.2222614342\theta^3 + 0.00158927\theta^2 - 2.36418\theta + 2500.79 \tag{4}$$

and the potential energy *Q* released by a change in water vapour density $\Delta\rho_{wvd}$ (J) is:

$$Q = L_{water} * \Delta\rho_{wvd} \tag{5}$$

This energy released has the potential to change the temperature of the hemp-lime $\Delta T_{hemp-lime}$ according to the expression:

$$\Delta T_{hemp-lime} = Q / c * \rho_{hemp-lime} \tag{6}$$

where c is the specific heat of hemp-lime and $\rho_{hemp-\mathrm{lime}}$ is the density of hemp-lime.

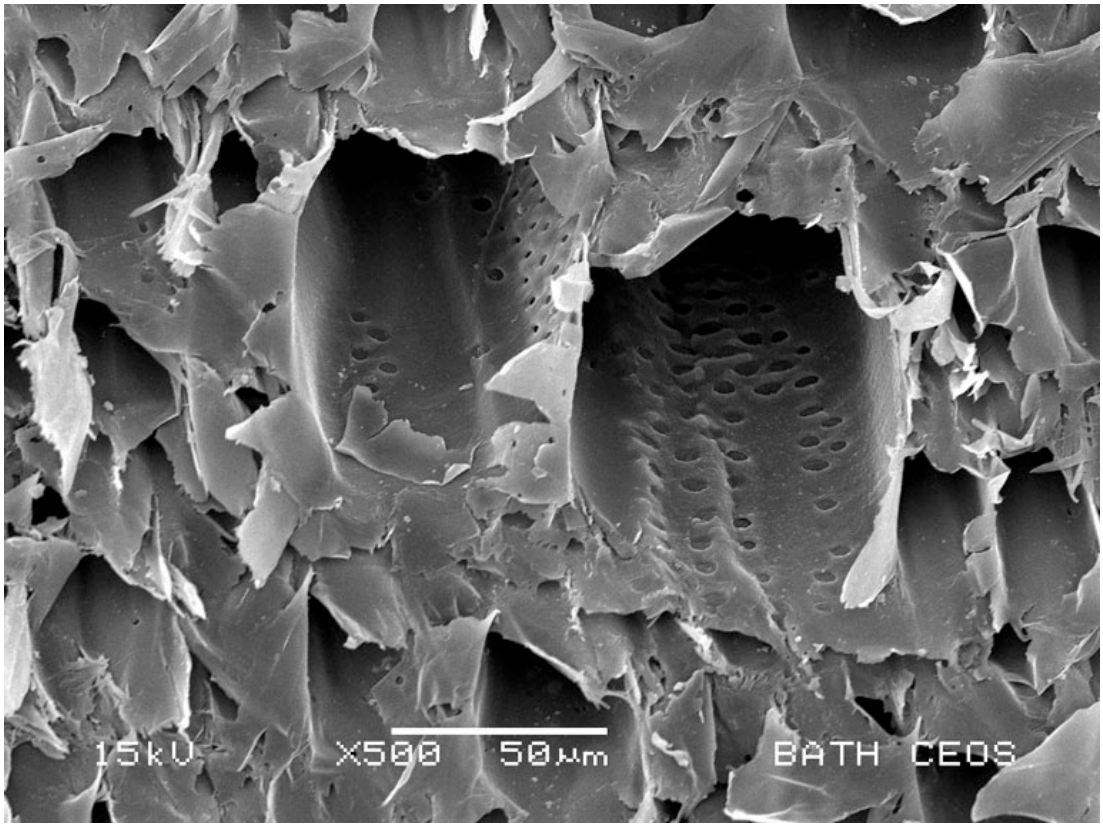

Figure 13: Interlinked pore structure of hemp shiv (Photomicrograph x 500)

Thus the movement of humid air through the wall can result in temperature effects, which will feed back into the thermal transfer model. Work is ongoing to incorporate this phase change effect into the hygrothermal model, and to calibrate it against measured effects. These phase change effects can be significant, producing temperature fluctuations within the hemp-lime of up to 8ºC.

Le Tran et al [9] have produced a model simulating whole building heat-air-moisture (HAM) behaviour using hemp-lime walls which demonstrate the moisture buffering performance of hemp-lime, along the lines of the measured performance in the HemPod, but showing greater amplitude of variations. They also demonstrate that the energy requirement for ventilating a hemp-lime building is 12-17% lower than that required for a cellular concrete building.

Conclusions

Interim results from the HemPod show that internal relative humidity is maintained at a remarkably stable level, well within the range of good comfort levels for occupiers. Temperature levels are also maintained at reasonably stable levels, and on average some 4ºC higher than the external conditions. These data are being combined with data from experimental panels to develop a hygrothermal computer model for hemp-lime buildings. It is evident that there is no single 'unique selling point' for the use of hemp-lime but rather an accumulation of different benefits. The use of low carbon materials contributes to the reduction of CO_2 emissions associated with the construction of buildings (8.61% of the total UK emissions). The reasonably low thermal conductivity of hemp lime, combined with phase shift, phase change effects, high internal thermal comfort, low initial energy transfer rates, passive humidity control and lower energy requirement for ventilation, all contribute to the reduction of 'in use' CO_2 emissions (46.93% of the total UK emissions).

Acknowledgements

The research programme is funded by DEFRA under their LINK programme, and supported by the following industrial partners: Lhoist (UK) Ltd, BRE, Hanson Ltd, Lime Technology Limited, Hemp Technology Limited, Wates Construction Ltd, Feilden Clegg Bradley studios, NNFCC. We also acknowledge the help and support of staff and students at BRECICM, Department of Architecture and Civil Engineering at the University of Bath and the donation of high performance door and windows by Janex Ltd.

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