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Hygrothermal performance of an experimental hemp–lime building

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HIGHLIGHTS

- ▶ We review the environmental benefits of building with Hemp–Lime.
- ▶ We report the construction of a full-scale Hemp–Lime test building.
- ▶ We present the thermal performance testing of the completed building.
- ▶ A total heat loss coefficient for the test building was determined as 36.7 W/K.
- ▶ Laboratory tests show the time taken to reach a steady-state condition is in the order of 10 days.

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ABSTRACT

The use of hemp–lime as a construction material combines renewable low carbon materials with exceptional hygrothermal performance. The hemp plant can grow up to 4 m in 4 months, with 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 relatively low thermal conductivity and hygric buffering. The construction technique promotes good air tightness and minimal thermal bridging of the building envelope. All these factors combine to produce low carbon, hygrothermally efficient buildings that are low energy both in construction and in use, and offer opportunities for recycling at end of life. This paper presents the hygrothermal performance of an experimental hemp–lime building and compares the results of steady-state co-heating tests with laboratory tests and computer simulations of transient performance.

1. 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, to below 1990 levels. In 2008 emissions of CO_2 in the UK in were 525 million tonnes (Mt) compared with 590 Mt in 1990 [1]. Of this figure, the construction sector was responsible for 298.4 Mt [2]. Table 1 presents a breakdown of the CO_2 emissions contribution of the construction industry as part of total UK carbon emissions.

The construction sector has a greater influence on carbon emissions (56.7%) than all other sectors combined. Within buildings the use of services such as heating, lighting and air conditioning is responsible for nearly 47% of CO_2 emissions in the UK, whilst manufacture of building materials is 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 plant-fibre building materials which absorb atmospheric CO_2 through photosynthesis thereby locking it up within the material for the lifetime of the building. Many of these natural plant-fibre materials offer opportunities for recycling and re-use, which further extends their useful life. Some materials can be composted and recycled through agriculture. Accordingly, interest in materials such as timber, straw and hemp has grown in recent years in

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Table 1
Construction industry CO_2 emissions in 2008.

Sub-sector: Construction	CO_2 (Mt)	% of total
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

response to the need to source materials with a lower environmental impact.

1.1. 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 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 small amounts of other additives such as surfactants. The 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 ~300 mm 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 [3,4]:

- 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 also 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 4 m 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, and a 1 m^2 timber-framed lime-rendered 300 mm thick wall made with a 1:2 mix sequesters 75.7 kg CO_2 equivalent 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 contribution by the wall element to the total carbon footprint of the construction.

A major advantage of natural fibre 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. Heat flows are associated with these reactions, during absorption heat is released and on release of moisture heat is absorbed [5]. Previous research has presented the physical properties of hemp–lime [6–8] and highlighted that the material presents a good balance between low mass and heat storage capacity compared with classical insulation materials.

At present inorganic insulation materials dominate the building industry, although interest in the use of natural fibre insulation products is steadily increasing [5]. In Europe inorganic fibrous materials, e.g. 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, whilst all other materials combined make up less than 13% [9].

Laboratory experiments and field tests conducted at the University of Bath aimed to investigate the hygrothermal performance of hemp–lime and to establish robust data on its use as a construction material for use in low-carbon buildings. Research and development has focused on the construction of a full-scale test building. The construction and performance of this building is reported here. The results of laboratory tests performed on a 300 mm hemp–lime panel, heat flow meter tests, and WUFI simulations are also presented.

2. Method

2.1. Hempod test building

An experimental full-scale test-building, referred to as the Hempod, was constructed at The University of Bath, UK (Fig. 1). Construction of the Hempod began in June 2010; taking 10 days to complete. 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. During this period the moisture content of the walls was monitored and by January 2011 moisture levels inside the building had equilibrated with the external environment. Accordingly, all experiments characterising the performance of the finished building were conducted after January 2011.

The single-zone building was constructed on a suspended chipboard floor insulated with 200 mm closed-cell insulation (λ = 0.023 W/m K) and has a floor area of approximately 27 m^2. The ceiling was also constructed of 200 mm closed-cell insulation behind a 9 mm layer of gypsum plasterboard. Conventional surface heat transfer coefficients for floors and ceilings were used and overall thermal transmittance was calculated as 0.14 W/m^2 K for both the floor and the roof. 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 (south facing), the windows 0.97 W/m^2 K (north facing) and 1.05 W/m^2 K (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. Walls were formed from 75 × 50 mm timber studwork at 600 mm centres to act as structural support. These were positioned on the interior of the walls and clad with a permanent shuttering made from 9 mm thick magnesium silicate board. A 200 mm thick hemp–lime wall was cast using temporary shuttering, rising to above the level of the insulated ceiling. 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 275 kg/m^3.

Table 2
Mechanical and thermal characteristics of hemp–lime [4].

Application	Shiv – binder proportions (by mass)	Density (kg/m^3)	Compressive strength (N/mm^2)	Thermal conductivity (W/m K)
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