Building and Environment 80 (2014) 204–212

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Methods to determine whole building hygrothermal performance of hemp–lime buildings

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ARTICLE INFO

Article history:
Received 25 April 2014
Received in revised form
5 June 2014
Accepted 7 June 2014
Available online 14 June 2014

Keywords:
Hemp–lime
Hygrothermal analysis
Effective moisture capacitance model
IES simulation

ABSTRACT

Hemp–lime is a potentially useful building material with relatively low embodied energy and moderate-to-good thermal performance, coupled with good moisture buffering capacity. However, some uncertainty remains with regards to its in-situ thermal performance and the capability of building energy simulation tools to accurately predict envelope performance and subsequent energy demand of buildings constructed of such vapour-active materials. In this paper we investigate the hygrothermal performance of buildings with walls constructed from hemp–lime. Component-level moisture buffering simulation employing the EnergyPlus simulation tool is found to be within 18% of Wufi Pro analysis and laboratory measurements. The coarseness of component discretization is shown to effect moisture buffering leading to the observation that finer discretization should be employed to improve EnergyPlus HAMT model accuracy. Whole building simulation of the BESTEST building with hemp–lime components indicates that moisture transport inclusion has a large influence on zone relative humidity but little influence on overall heating and cooling demand. A simple effective-capacitance model is able to represent humidity buffering but is less good at representing the response to sudden moisture loading. An additional resistance parameter is added to the model and an IES-ve simulation using this approach is shown to give a close match to the full hygric simulation.

1. Introduction

The use of natural fibre materials, such as hemp–lime, hemp-fibre, flax, straw etc., as building elements e.g. external walls, internal partitions etc. combines the benefits of renewable low carbon materials with hygric and thermal performance. Hemp–lime has many benefits compared to conventional building materials and a number of these were outlined by Shea et al. [1] as follows:

- Potentially useful hygrothermal performance,
- Sequestration of atmospheric CO_2,
- Hemp shiv is more resistant to biological decay than some other bio-based building materials (e.g. straw),
- Hemp cultivation requires lower levels of fertilisation and irrigation than other crops,
- The hemp plant grows very rapidly, to heights of up to 4 m within 4 months, which gives it the potential to act as a 'break crop', allowing optimisation of yields of the primary crop.

Indoor humidity is important to comfort and health and the durability of construction materials. Indoor humidity affects respiratory comfort, skin humidity and perceived indoor air quality (IAQ) [2,3]. Since perceived IAQ is closely linked to humidity, the moisture buffering of the building fabric has potential for reduced energy use through reduction of the required ventilation rate [4]. Humidity and mould growth also have significant implications for occupant health [5]. These issues are particularly important for natural fibre materials as they tend to have higher vapour permeability than conventional building materials. One barrier to the more widespread use of hygrothermal simulation is the shortage of complete sets of hygroscopic material property data particularly for natural fibre materials.

The high vapour permeability of such materials can be useful but hygroscopically complex behaviour also presents challenges in describing the thermal performance of the materials, which then affects any subsequent whole building performance analysis of any development containing such materials. Whilst a number of tools such as Wufi, EnergyPlus and ESP-r have successfully integrated heat and moisture transport models, there are still a number of barriers to their widespread use, not least where material property data are scarce. Kramer et al. [6], in their systematic review of

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http://dx.doi.org/10.1016/j.buildenv.2014.06.003
0360-1323/

simplified thermal and hygric models, highlight the need for simplified 'white box' hygric and thermal building model with physical meaning. Wufi, EnergyPlus and ESP-r use numerical approaches as outlined by Künzel [7] to simulate combined heat and moisture in construction components. Annex 41 studied a number of software tools for whole building hygric performance simulation [8], which included inter-model comparison [9]. An alternative, and simpler, option for the simulation of humidity buffering in whole building models employs the use an effective capacitance model. Such models attenuate moisture when it is introduced into the zone by multiplying the air volume into which the moisture is mixed. These simplified models have benefits over complex models such as ease of use, speed of calculation, and, in the case of effective capacitance models, the parameters have real physical meaning [10], which aids interpretation and understanding.

In the following section we present the hygric and thermal material properties of hemp–lime and in Section 3 the accuracy of different modelling approaches is investigated by inter-model comparison and comparison with laboratory measurements. The HAMT model in EnergyPlus is compared with laboratory results and Wufi Pro component level results in terms of component moisture buffering.

In Section 4 the HAMT model is then used to investigate the sensitivity of whole building performance to moisture transport in hemp–lime building components. Building simulation tools that incorporate moisture transport are not always widely used in practice. For example, in the UK the most widely used simulation tool is IES, which does not currently calculate moisture transport. For this reason, the performance of the zone effective capacitance model is investigated in this paper, as it is an approximate model that could readily be incorporated into this popular simulation tool. The capacitance concept is applied in IES with the addition of a connecting air network adding a resistance parameter.

2. Hemp–lime hygrothermal material parameters

Hemp–lime can be produced at different densities, depending on its use, and typically ranges from 200 to 500 kg/m^3. Density has a significant effect on the hygrothermal properties of hemp–lime, although other factors may have an influence, such as the types of lime and hemp used; the ratio of lime, hemp and water when mixed; the sample age, and, therefore, the extent of carbonation of the lime.

Most of the characterisation of hemp–lime has been conducted in France and Belgium, where there is a tendency to use a more dense mix for walls compared to the UK. Lower density has been favoured in the UK as it results in a lower thermal conductivity, therefore achieving compliance with building regulations without the need to make excessively thick walls. There is little published experimental data for lower density hemp–lime (less than approx. 300 kg/m^3) and consequently experiments are currently underway which will determine the key hygrothermal properties for lower density hemp–lime composites. To make prior estimates, the results of previous studies have been used to extrapolate some key values. The parameters used in the simulations presented in this paper are a mixture of experimental and estimated values.

The following parameters are required for combined heat and moisture simulation:

- Bulk density,
- Porosity,
- Specific heat capacity,
- Moisture-dependant thermal conductivity,
- Moisture storage function,
- Liquid transport coefficient for suction,
- Liquid transport coefficient for redistribution,
- Water vapour diffusion resistance factor.

2.1. Methods to gain model parameters

Porosity was estimated via linear extrapolation when plotted against density using data from Cerezo [11], Collet [12] and Collet et al. [13]. In these studies porosity varied between 72% for a 460 kg/m^3 sample to 80% for 256 kg/m^3. The specific heat capacity was similarly estimated using Evrard [14], Evrard & De Herde [15] and Tran Le et al. [16], which gave values between 1000 J/kg K and 1560 J/kg K. The material data is summarised in Table 1.

Experiments have been conducted in accordance with ISO 12572 [17] to determine the water vapour diffusion resistance factor (μ), whereby a relative humidity gradient is created across the sample so the resulting difference in partial vapour pressure creates a vapour flux. The rate of water vapour diffusion is measured gravimetrically and used to calculate μ. The rate varies depending on the humidity gradient chosen, particularly at high humidity when liquid water forms in the pores so that liquid transport takes over from diffusion. Collet et al. [12] produced equations for curves fitted to experimental data for samples of hemp–lime measured at different humidity gradients. These equations were used in combination with experimental data to estimate a full set of values presented in Table 2. This data is used as input for the simulation that produced the results presented later.

The thermal conductivity (λ) of a conditioned hemp–lime sample was measured using a Fox 600 heat flow meter (HFM) as described in Holcroft & Shea [18], whereby a temperature gradient is created across the sample and the heat flux measured once it has reached steady-state, which is then used to calculate λ. There are however potential inaccuracies in this technique as it takes much longer for the sample to reach hygric than thermal equilibrium, although subsequent tests at smaller temperature gradients, and for a range of sample moisture contents, provide confidence in the accuracy of the results presented here.

The thermal conductivity was assumed to increase linearly as the moisture content increased as shown in Evrard & De Herde [15]. The same gradient of increase was assumed but aligned with the value measured using the HFM and presented in Table 3. The values produced by Evrard & De Herde for the moisture storage function (sorption isotherm) were also used in the simulation and this is presented in Table 4. The same paper was the source of the liquid storage functions presented in Tables 5 and 6.

3. Component level moisture buffering

Laboratory measurements were compared with simulation results of moisture buffering for a sample of hemp–lime. Two simulation tools were used, Wufi Pro and the EnergyPlus HAMT model.

3.1. Laboratory moisture buffer test method

The moisture buffer measurements were conducted according to ISO 24353 [19]. For this method, a 200 × 200 mm sample is

Table 1
Material parameters for hemp–lime.

Material parameter	Parameter value
Bulk Density (kg/m^3)	304
Porosity (–)	0.8
Specific heat capacity (J/kg K)	1270