Building and Environment 82 (2014) 459–466

Contents lists available at ScienceDirect

Building and Environment

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

Experimental highlight of hygrothermal phenomena in hemp concrete wall

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A R T I C L E I N F O

Article history:
Received 17 July 2014
Received in revised form
12 September 2014
Accepted 19 September 2014
Available online 28 September 2014

Keywords:
Bio-based material
Hygrothermal behaviour
Sorption-desorption
Evaporation–condensation

A B S T R A C T

This study investigates the hygrothermal behaviour of a timber-framed hemp concrete wall made of precast blocks. Measurements are performed on an uncoated wall as well as on a coated wall. The experimental device consists in two air-conditioned rooms where ambient conditions are selected to induce temperature and/or vapour pressure gradient between the two sides of the wall. The monitoring deals with temperature and relative humidity within the wall. Kinetics of temperature and of vapour pressure are given. Profiles are drawn at several times of the transient phase. In the regular part of the wall, several kinds of hygric behaviours are highlighted such as homogeneous vapour diffusion and huge vapour pressure variations due to evaporation–condensation and/or sorption-desorption phenomena. The results in the line of frame show that the frame doesn't induce disturbances in the hygrothermal behaviour of the wall. It is also shown that the coating reduces and delays vapour diffusion.

1. Introduction

Nowadays, responsible construction should be energy efficient and made of environmentally friendly materials. Bio-based materials avoid depletion of raw material and exhibit low impact on environment (carbon storage, low embedded energy…) [1]. Hemp concrete is a bio-based building material made of lime and hemp shiv. This material can be used for several applications (wall, floor and roof) adjusting the composition. It is implemented by casting, spraying or pre-casting. Due to its low mechanical performances, hemp concrete is used with a framework that can be made of steel, concrete or wood. Usually, hemp concrete walls are coated on both sides but hemp concrete can occasionally be naked on the indoor side.

The experimental characterisation of hygrothermal behaviour of hemp concrete is widely investigated at material scale. Measurements provide thermal and hydric properties that are available in the literature.

Hemp concrete is a light weight building material. Its thermal conductivity depends both on its formulation, its density and its water content. It ranges from 0.07 to 0.3 $W.m^{-1}.K^{-1}$. Hemp concrete is therefore a good, not exceptional, thermal insulator [2–8]. Like all bio-aggregate based building materials, hemp concrete is strongly hygroscopic. Its water uptake is much higher than in usual building materials, as shown in Ref. [9] by comparing hemp concrete with Aerated Autoclaved Concrete and with Vertical Perforated Bricks. The water content at equilibrium at very high relative humidity (95 %RH) is much lower than the water content at saturation [10]. This is linked to the macroporosity due to the bio-based aggregate. Moreover, its sorption curves show hysteresis which extends all over the range of relative humidity [11–14]. The mainly open high porosity of bio-aggregate based building materials gives them high moisture vapour permeability (ie low water vapour diffusion resistance). The water vapour diffusion resistance, at dry point, ranges from 5 to 12 for hemp concrete [7,11,15] while it is equal to 130 for solid concrete, 50 for light weight aggregate (natural pumice stone) concrete, and 10 for aerated autoclaved concrete [16]. Finally, the moisture buffering quality of hemp concrete was studied by several authors [14,17–22]. The experimental investigations are generally performed following the Nordtest protocol [23]. It is shown that hemp concrete is an excellent hygric regulator with moisture buffer values globally higher than 2 g/(m^2.%RH).

The hygic and thermal properties of bio-aggregate based building materials give them a particular hygrothermal behaviour which allows reducing the energy demand of buildings while maintaining indoor relative humidity [24,25]. The investigations of the hygrothermal behaviour of building materials at large scale,

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http://dx.doi.org/10.1016/j.buildenv.2014.09.018
0360-1323/

found in literature, are generally performed numerically. Experimental studies are also performed at large scale (1 m^2, wall or building).

It was shown in Ref. [25] and in Ref. [26] that hemp concrete wall performs better than traditional wall assembling on a phase shift point of view. For example, in the simulation of [25] the phase shift was 15 h in the hemp concrete wall while it was 5 h in the mineral wool wall. These performances are correlated with hygric behaviour of hemp concrete. Actually, Shea et al. [26] underline that, after a sudden drop in temperature on one side of the experimental wall, the steady state is reached at approximately 240 h while it is reached within 72 h in simulations ignoring the effects of relative humidity. Thus, relative humidity has a strong effect on the hygrothermal behaviour of the wall. The experimental study reported by Arnaud, Samri and Gourlay in Ref. [9] shows that an internal source (or well) of heat and/or the presence of another flow of heat (notably by convection) exists in hemp concrete and directly impact the heat balance equation.

Mlakar and Strancar compared hygrothermal behaviour of small-scale test houses with several kinds of materials [27]. Among their results, the lack of moisture buffering materials leads to higher level and larger oscillation of indoor relative humidity. The authors underline that high moisture loads could have an impact on the durability of buildings and also on its energy performance. At building scale, Woloszyn et al. [28] studied the effect of combining relative-humidity-sensitive ventilation with moisture buffering materials on relative humidity and energy consumption. They show that the use of moisture buffering materials allows reducing the amplitude of daily moisture variation and that energy savings are realised, thanks to SRH ventilation. Tran Le et al. compare hemp concrete behaviour to that of cellular concrete [24]. They found that hemp concrete induces a reduction ranging from 15% to 45% in energy consumption, depending on ventilation strategy. More, Maalouf et al. compare hemp concrete with other building materials (cellular concrete, earth block, solid brick, concrete) [29]. They show that hemp concrete has the lowest thermal diffusivity and the highest time lag which means that it can better reduce the propagation of outdoor weather conditions through building envelope. However, these authors also show that, in South France, there is a risk of indoor superheating due to low effusivity of hemp concrete. Besides, they underline that hygric properties are high affecting parameters.

The aim of this study is to learn more about the practical behaviour of hemp concrete wall. This study is performed at wall scale in order to respect the usual implementation. The studied hemp concrete wood-framed wall is made of precast blocks. The experimental device is made of two air-conditioned rooms. The monitoring deals with temperature and relative humidity within the wall in the regular part of blocks and in the front of wood framework. The experimental device and the implementation of the wall are first presented. Then the results obtained under several ambient conditions in the rooms are given. These conditions are selected to have vapour transfer, heat transfer or simultaneous heat and vapour transfer. Kinetics of temperature and vapour pressure are given and profiles are drawn at several times of the transient phase.

2. Experimental method

2.1. Experimental device

This study focuses on the hygrothermal behaviour of a hemp concrete wall under hygrothermal stresses. The aim is to study the wall response under temperature gradient only, vapour pressure gradient only and finally under both temperature and vapour pressure gradients. So, in order to well control ambient temperature and relative humidity on both sides of the wall, the experimental device involves two adjacent air-conditioned rooms separated by the studied test-wall (Fig. 1).

Fig. 1. Experimental device: bi-climatic rooms.

Each room is 2.35 m deep, 2.78 m wide and 2.4 m high. The floor is made of concrete and all the other walls of the rooms are well insulated by polyurethane panels ($U = 0.40$ W.m^{-2}.K^{-1}) and are air and moisture tight. One of the air-conditioned rooms reproduces the indoor climate of common buildings ("indoor room") while the other one simulates outdoor climatic conditions ("outdoor room"). Table 1 gives the ranges of temperature and relative humidity for each room. The regulation of each parameter (T and RH) is ensured by universal controllers DR4020 used to define the setpoint and a bandwidth that governs the switch-on and the switch-off of the devices of the chambers. Each controller has two outputs: heating/cooling for the temperature regulation and humidification/dehumidification for the humidity regulation. Heating is provided by convectors, cooling and dehumidification by a refrigeration group and humidification by steam humidifiers. When systems are operating, fans with low rotational speed are employed. This induces low level of air movement, with mean vertical velocity lower than 0.1 m.s^{-1} in the studied part of the wall. This is not higher than the value commonly met in buildings. Hence, the rate of evaporation and moisture movement are not enhanced by the fan use.

2.2. Test wall and metrology

The test wall is built with precast hemp concrete blocks (see the dimensions of blocks in Fig. 6) and a wooden frame. The precasting consists in mixing binder and hemp shiv and then forming blocks. The binder is made of 72% in mass of CaO and 28% of hydraulic binder (lime and pozzolan). The hemp to binder mass ratio is 65% and the water to binder ratio is 120%. Firstly, CaO is mixed with water to obtain slaked lime. Then hydraulic lime and hemp shiv are added. The mixture is then poured into moulds and blocks are

Table 1
Ranges of temperature and relative humidity.

	Room 1 (indoor)		Room 2 (outdoor)	
	Range	Bandwidth	Range	Bandwidth
Temperature (°C)	18 – 27	±0.2	−5 to 35	±0.5
Relative humidity (%RH)	30 – 60	±0.3	30 – 90	±0.8