Construction and Building Materials 65 (2014) 612–619

Contents lists available at ScienceDirect

Construction and Building Materials

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

Thermal conductivity of hemp concretes: Variation with formulation, density and water content

Florence Collet *, Sylvie Pretot

Université Européenne de Bretagne, Laboratoire de Génie Civil et Génie Mécanique, Equipe Matériaux Thermo Rhéologie, France

HIGHLIGHTS

- Thermal conductivity of hemp concrete is investigated.
- This study focuses on the effect of density and water content.
- Several formulations are studied, in link with end-use.
- This study is based on experimental investigations and numerical modelling.

ARTICLE INFO

Article history:
Received 31 January 2014
Received in revised form 16 April 2014
Accepted 15 May 2014
Available online 6 June 2014

Keywords:
Experimental
Hot wire
Self-consistent scheme
Hemp concrete

ABSTRACT

This study investigates the effect of formulation, density and water content on the thermal conductivity of hemp concretes. The investigations are based on experimental measurements and on self-consistent scheme modelling. The thermal conductivity of studied materials ranges from 90 to 160 mW/(m K) at (23 °C; 50%RH). The impact of density on thermal conductivity is much more important than the impact of moisture content. It is shown that the thermal conductivity increases by about 54% when the density increases by 2/3 while it increases by less than 15–20% from dry state to 90%RH.

1. Introduction

In a context of sustainable development, green buildings aim at reducing the environmental impacts of buildings while also ensuring high indoor environmental quality (comfortable and healthy). The main impacts of buildings on the environment are due to consumption of resources (energy, raw material, water, etc.) and to emissions (greenhouse gas, pollution, wastes, etc.). Thus, green buildings should be energy efficient while showing a light footprint on the environment over the entire life-cycle.

The energy efficiency of buildings depends on the hygrothermal behaviour of the building envelope and on the performance of systems. This behaviour is related to hygric and thermal properties of constitutive materials. Among these properties, the thermal conductivity is dependent on several parameters such as density, water content and temperature. The bibliography provides studies on the effect of density, of moisture content and of temperature on the thermal conductivity of building materials. For example, Uysal et al. studied the effect of cement dosage and of prumice aggregate ratio on density and thermal conductivity of concrete [42]. In all studied cases, the thermal conductivity increases with density. The prumice aggregate allows reducing the thermal conductivity by 46% while reducing the density by 40%. Del Coz Díaz et al. measured the thermal conductivity of lightweight concrete produced from expanded clay. The thermal conductivity increases from 176 to 256 mW/(m K) when the density increases from 973 to 1362 kg/m^3 at 23 °C, 50%RH. [5] have shown that the addition of wood shaving in dune sand concrete allows reducing the thermal conductivity from 1.20 to 0.55 W/(m K) while reducing the density from 2100 to 1400 kg/m^3 [5]. In addition, even if literature mainly provides dry state values, the thermal conductivity of hygroscopic materials increases with moisture content. For example, from dry state to saturated state, (i) the thermal conductivity of autoclaved aerated concrete increases up to six times [26] and (ii) the thermal conductivity of wood-concrete composite increases up to 2.76 times [40]. For lightweight concrete, the thermal conductivity increases by 2 from dry state to 100%RH [17]. These authors give

* Corresponding author. Address: IUT Génie Civil, 3, rue du Clos Courtel, BP 90422, 35704 Rennes, France. Tel.: +33 2 23 23 40 56; fax: +33 2 23 23 40 51.

E-mail addresses: florence.collet@univ-rennes1.fr (F. Collet), sylvie.pretot@univ-rennes1.fr (S. Pretot).

http://dx.doi.org/10.1016/j.conbuildmat.2014.05.039
0950-0618/

mathematical expression which defines the relationship between density, moisture content and thermal conductivity. Finally, Jerman et al. show that the dependence of thermal conductivity on temperature is less important than its dependence on moisture content for temperatures between 2 and 30 °C [26].

Bio-based building materials are derived from renewable biological resources. So, they are an answer to the problem of resource depletion. They are drawn from various raw materials such as wood [1], coconut [2], diss [36], sunflower [7], hemp, etc. Hemp straw provides two products used in building materials. Fibbers are used to produce insulating panels [4,13] and shiv are used as bio-aggregate in hemp composites (concrete, render, etc.). Hemp concrete is used for several applications: wall, floor or roof. The main difference between applications is the hemp to binder ratio in the mix. Furthermore, hemp concrete can be produced by spraying, moulding or precasting.

Hemp concrete is environmentally friendly as it is made of a renewable raw material (hemp) and as it allows carbon sequestration [10,25,31]. Hemp concrete is highly porous, with open and interconnected porosity. It is a lightweight material with densities between 200 and 600 kg/m^3, depending on application [3]. Therefore, it shows quite low thermal conductivity, about 100 mW/(m K) for a walling application [4] similar to other building materials with comparable density (cellular concrete for example). The thermal conductivity of hemp concrete depends on the amount of shiv which impacts density. For hemp percentage in weight between 20% and 40%, the density decreases from 611 to 369 kg/m^3 and the thermal conductivity decreases from 140.8 to 94.7 W/(m K) [6]. The open and interconnected porosity allows moisture transfer and storage. The hygric characteristics of the material are moisture permeability and sorption curves that are representative of steady state. Previous studies have shown that hemp concrete is strongly hygroscopic, with high moisture transfer and storage capacities (water vapour permeability about 3.2E−11 kg/(m s Pa) and sigmoid sorption curves with high hysteresis loop between adsorption and desorption curves) [12,14]. These properties allow hemp concrete to moderate ambient relative humidity variations. This ability is quantified through the Moisture Buffer Value of the material. Studies performed following the Nordtest Project classify hemp concrete from good to excellent hygric regulator (MBV around 2 g/(m^2 %RH)) [33,15,14]. For comparison, the MBV of cellular concrete is about 1 g/(m^2 %RH) [33]. Studies performed at wall, or building scale have highlighted sorption/desorption or condensation/evaporation phenomena in hemp concrete wall [30,37]. These phenomena involve binding or latent energy that impact energy balance of the wall. Thus, hemp concrete shows high hygrothermal performances which allow energy saving and high indoor comfort [41,20]. For example, Tran Le et al. performed a numerical study to compare hemp concrete behaviour to that of cellular concrete. They found that hemp concrete induces a reduction ranging from 15% to 45% in energy consumption, depending on ventilation strategy.

Actually, the energy needs (and indoor comfort) can be simulated thanks to dynamic thermal modelling which requires, among input data, the hydric and thermal properties of building materials. Such numerical models should take into account the variation of hydric and thermal properties with hygrothermal state like the variation of hydric properties with temperature or the variation of thermal properties with humidity.

This study deals with the thermal conductivity of five hemp concretes that differ from formulation. Firstly, the thermal conductivity of hemp concretes is studied versus formulation. The impact of raw materials and hemp to binder ratio is highlighted. Then, the increase of thermal conductivity with dry density and water content is considered. The investigations are based on experimental measurements and on self consistent scheme modelling.

2. Materials

2.1. Formulations and production methods

Hemp concrete is a bio-aggregate-based building material made of hemp shiv and binder. This study investigates five hemp concretes that differ from formulation and production method. This work was supported by two industrial partners. The studied materials are representative of the materials usually produced by the partners.

The spraying method consists in mixing hemp shiv and lime-based binder to constitute a dry mix that is blown along a pipe by means of a flow of compressed air. Water is added just before the hose outlet, the quantity of which may be controlled by the operator via one valve. This allows reducing the quantity of water compared to conventional mixing which requires more water due to the absorption capacity of hemp shiv. In this study, hemp concrete is sprayed into moulds (Fig. 1). Three hemp to binder ratios are considered regarding practices: wall, floor and roof (Table 1). Moreover, the spraying method induces small density variation due to the angle and the distance of spraying [18], so three densities of sprayed hemp concrete are considered (light, medium and heavy) for the wall mix.

The moulding method consists in mixing hemp shiv and lime-based binder in a mixer. Water content is adjusted to obtain a consistent workability of fresh hemp concrete. Moulds are filled with the mixture and the hemp concrete is slightly compacted.

The precasting method results from an industrial process. Firstly, slaked lime is produced from CaO and water. Hydraulic lime and hemp shiv are then added and the mixture is poured into moulds. Blocks are finally formed by compaction under vibrations (Fig. 2).

For this study, for all formulations and production methods, hemp concrete is manufactured in moulds of 30 cm × 30 cm × 16 cm (Figs. 1 and 2). This size is representative of a wall thickness or of industrial precast blocks. Once produced, blocks are stabilized at 23 °C, 50%RH. Then, the blocks are cut to obtain 15 × 10 × 5 cm^3 specimen. For SHC roof and for PHC, it was not possible to cut the blocks because they were exfoliating. For these materials the measurement are performed on blocks at (23 °C; 50%RH) only. Table 1 summarises the mix proportioning and manufacturing method of studied hemp concretes: Sprayed Hemp Concrete (SHC), Moulded Hemp Concrete (MHC) and Precast Hemp Concrete (PHC).

2.2. Density and porosity

Density is calculated from mass and dimensions of specimens. Porosity is measured by pycnometry. Table 2 gives the apparent density at (23 °C, 50%RH) and the total porosity of studied materials.

For sprayed hemp concretes, the apparent density ranges from 260 kg/m^3 for roof to 460 kg/m^3 for floor. For wall mix, it ranges from 390 kg/m^3 for light wall to 460 kg/m^3 for heavy wall. The moulded hemp concrete shows an apparent density of 381 kg/m^3 while the precast one shows an apparent density of 457 kg/m^3. These values are consistent with the values commonly found in literature [3].

The total porosity of studied hemp concretes ranges from 72% for precast hemp concrete to 85% for sprayed hemp concrete roof. This high porosity includes a wide range of pores from micrometric pores in binder matrix and hemp shiv to millimetric pores due to the arrangement between the hemp shiv and to the hemp–binder adhesion [12].

3. Methods

3.1. Experimental investigation of thermal conductivity

3.1.1. Hot wire method

The thermal conductivity λ (W m^{-1} K^{-1}) was measured using the commercial CT-meter device. In this study, this device was equipped with a five-centimeter-long hot wire (Fig. 3). The measurement is based on the analysis of the temperature rise versus heating time. For cylindrical geometry, Blackwell [8] and Carslaw and Jaeger [44] solve the equation of heat conduction for a two media system including (i) the probe, assumed as an ideal infinitely thin and long line heating source, and (ii) the studied material, that constitutes an infinite surrounding and is supposed to be homogeneous and isotropic. For a sufficiently long time, there is a proportional relationship between temperature rise ΔT and logarithmic heating time ($\ln(t)$) (Fig. 3) (1):

$$\Delta T = \frac{q}{4 \cdot \pi \cdot \lambda}(\ln(t) + K) \quad (1)$$

where q is the heat flow per metre (W m^{-1}) and K is a constant including the thermal diffusivity of the material.