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Effect of moisture and temperature on thermal properties of three bio-based materials

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HIGHLIGHTS

- Two news bio-based materials "Straw-rape and Flax concretes".
- Experimental protocol validation with the reference material (hemp concrete).
- Measurement of physical–thermal properties of studied materials.
- Investigation of the affect temperature and moisture on the thermal conductivity.
- Modeling and validation of thermal conductivity by self-consistent scheme model.

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ABSTRACT

This article focuses on the investigation of the thermal properties of three bio-based materials called hemp concrete, flax concrete and rape straw concrete. The results showed that these materials have an interesting heat storage capacity and a low thermal conductivity, which provides a good thermal insulating capacity. For a range of temperature from 10 to 40 °C, the effects of temperature and water content on thermal conductivity are important. The self-consistent scheme (SCS) model is applied to model the thermal conductivity of the materials depending on their initial components. Compared with the experimental measurement, the SCS model gives satisfactory results for the studied materials.

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1. Introduction

In the context of sustainable development, the bio-based building materials can effectively contribute to the optimization of a raw natural resources and the reduction of energy consumption and of greenhouse gases emissions. For this purpose, several aggregates derived from plants such as straw rape [1,2], straw-wheat [3] or diss fiber [4] have already been studied in order to investigate their efficiency.

Up to now, the hemp concrete (HLC) can be considered as the reference material considering the amount of research works published in recent years [5–8]. This material is increasingly recommended because it has a low environmental impact and corresponds perfectly to High Environment Quality Buildings [9,10]. Concerning the hemp concrete case, the life-cycle analysis shows, that it has a very low carbon footprint and it can store 0.35 kg CO_2 eq./UF/year [11].

This material is manufactured by the mix of water, binder and hemp shives. It can be produced by spraying, molding or precasting methods. Depending on the specific mixing rations, it has various applications in building construction; wall infilling, floor and roof insulation or plasters [12].

The thermal and physical properties of hemp concrete have been the subject of several studies [8,13–15,2,12]. This one has a low density and high porosity (more than 70%), giving it a good thermal insulation power which allows reduce building energy consumption [9,10]. Its thermal conductivity depends on both density and water content [15,16]. The increase of shavings content in the formulation allows decreasing the density of concrete and thus its thermal conductivity [17]. Elfordy et al. [18] presented results for the relationship between density and RH. They found that thermal conductivity increased with increasing density. Referring to the study of Benfratello [19], the dry thermal conductivity of HLC

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Nomenclature

C	specific heat capacity (J/(kg K))
e	thickness (m)
m	mass (kg)
n	total porosity (%)
q	thermal heat flow density (W/m^2)
R	radius (m)
S	surface (m^2)
T	temperature °C
V	volume (m^3)
w	water content (kg/kg)
Ø	thermal heat flow (W)
ρ	density (kg/m^3)
λ	thermal conductivity (W/(m K))
λ^*	effective thermal conductivity (W/(m K))

Subscripts

a	air
av	average
bn	binder
c	cold
bot	bottom side
cr	concrete
h	hot
i	initial
m	matrix
pc	bulk particles
PC	particle
top	top side
w	water
0	dry

measured at 15 °C decreases from 0.14 to 0.09 W/(m K) when the density decreases from 600 to 370 kg/m^3. For the same proportion mix, the density of concrete depends on the compaction or the mode of process fabrication [16,20]. In addition, according to Nguyen et al. [16], the direction of compaction of HLC affects the thermal properties. It is shown that the thermal conductivity perpendicular to the long-axis of hemp particle is lower than thermal conductivity parallel to the long-axis of particle [16]. The proportion mix of binder or hemp shives can be adapted to enhance thermal performance. De Bruijn et al. [21] showed that a larger amount of hemp in the mix resulted in more advantageous thermal properties, with lower thermal conductivity and lower specific heat capacity. This indicates that, in a cold and wet climate, HLC with more hemp in the mix would be more suitable from a hygrothermal perspective [21]. Furthermore, the type of binder used in fabrication of hemp concrete also affects its thermal properties. As shown in [14], the binder hydraulicity has trend to reduce its thermal conductivity and increase its heat capacity. However, it is shown in [22], that used binder hydraulicity combined with complex mineralizer leads to enhance the compressive strength of hemp concrete (up to 8 MPa) without compromising the thermal conductivity (0.137 W/(m K)).

For a wide range of relative humidity, the thermal conductivity can increase by about 15–20% [12]. The same conclusions have been drawn in case of wood concrete composite [23]. To reduce the perturbation of thermal properties upon a change of relative humidity, the treatment of wood shavings can be a solution [24,25].

The hygric properties of hemp concrete and flax concrete have been presented in a previous study [2,13]. The two materials exhibit high hygroscopic capacity. Their water vapor permeability are nearly similar and approximately 2.5×10^{-11} kg/(Pa ms). In addition, these materials have excellent moisture buffering capacity (MBV values are 2.02, 2.27 and 2.59 g/(m^2.%RH) for HLC, FLC and SLC, respectively) [2,13], according to the Nordtest project classification [26]. At whole building level, using materials with a high moisture capacity can effectively reduce the amplitude of the daily variation of humidity [27,28] and reduce energy consumption [29–31]. For hemp concrete case, the study of Tran Le et al. [29] showed that the coupled use of sensitive relative humidity ventilation strategy and moisture buffering capacity of HLC can reduce energy consumption about 15%, compared to the cellular concrete.

The aim of this article is to investigate the thermal properties of three bio-based materials; the rape straw concrete and flax concrete are the both new materials, while the hemp concrete, considered as the reference material, is used to validate the experimental protocol by comparing the results to the ones published by others. The choice of these resources for aggregates is related to their wide availability. Concerning the rapeseed, the amount of cultivated area in France is approximately 1,555,000 ha with a yield of straw is nearly 3.45 tons per hectare.

The tests are conducted on the measure of the physical properties, the thermal conductivity and the specific heat capacity. Due to the high hygroscopic capacity of these materials, the thermal conductivity is investigated as a function of water content and temperature. In addition, the self-consistent scheme (SCS) model is used for modeling the thermal conductivity as a function of density resulting from compaction and the effect of water content on thermal conductivity is investigated.

2. Materials

2.1. Manufacturing

Three types of plant derived-aggregates were used for the fabrication of three concretes called HLC, FLC (Flax concrete) and SLC (Straw concrete). The samples have been manufacturing by a molding method. After mixing the aggregates, water and the binder in the concrete mixer, the mixture was manually filled in the mould and then damped, in order to avoid empty zones. The fabrication of concrete has been performed manually using a concrete mixer in order to reflect the similar fabrication in real site. Special attention has been taken to achieve the similar compaction force for three concretes. Three days later, the samples were removed from the mould and stored in the laboratory for about 9 months in order to ensure the compete carbonation of concrete [20].

The binder used in the formulation of concretes is the Tradical PF70 containing around 75% of hydrated lime (CL-90S), 15% of hydraulic lime and 10% of pozzolanic binders. The type of aggregates are presented as follow:

- Hemp shives are coming from the inner woody core of the plant.
- Flax shives are coming from the woody core of flax stalk.
- Rape straw is the woody heart of stems of plant.

Table 1 shows the proportions presented by mass percentage of lime binder, aggregates and water used in the fabrication of the three concretes.

2.2. Physical properties

The dry density, matrix density and porosity of concretes and aggregates were investigated. The total porosity is calculated from the matrix density and the bulk dry density of material. The matrix density is performed experimentally according to the pycnometer method which consists to fill the pores with toluene. Concerning

Table 1
Proportion of lime binder, shives/straw and water by mass for concretes.

Material	Aggregates	Lime	Water
HLC, FLC, SLC	16%	36%	48%

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