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Moisture transfer and thermal properties of hemp–lime concretes

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HIGHLIGHTS

- The effect of binder type on moisture transfer and thermal properties of hemp concrete is investigated.
- Increasing binder hydraulicity and adding water retainers to the binder reduces capillary absorption.
- Binder type did not significantly influence permeability suggesting interparticular space largely contribute to permeability.
- Binder type did not significantly influence thermal conductivity or heat capacity.
- However a trend suggests that binder hydraulicity reduces conductivity and increases heat capacity.

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ABSTRACT

Lime–hemp concrete is a low-embodied energy, carbon-negative, sustainable construction material made with a lime-based binder and hemp aggregate. This work investigates moisture and thermal properties of hemp concretes made with hydrated lime and pozzolans, and those including hydraulic lime and cement. The paper concludes that the type of binder influences capillary action of hemp concrete and that increasing the hydraulicity of the binder, as well as adding a water retainer, reduces capillary absorption. The impact of the binder type on permeability is less evident, and the results indicate that the large interparticular spaces between hemp particles (macropores) contribute to permeability to a greater extent than micropores (which are influenced by the hydraulicity of the binder).

Finally, the binder type did not have a statistically significant impact on either thermal conductivity or specific heat capacity. A trend however suggests that increasing the binder's hydraulic content reduces thermal conductivity and increases heat capacity; and that the presence of water retainers enhances both conductivity and heat capacity.

1. Introduction

Due to the high primary energy use and CO_2 emissions generated by the construction industry, it is important to develop sustainable building materials to replace conventional products. Hemp–lime concrete is a low-embodied-energy, carbon-negative building material made with a lime-based binder and hemp aggregate. It is typically non-structural and used with a load bearing frame. It was developed in France in the late 1980s/early 1990s and has since been used in the construction and thermal upgrading of hundreds of buildings in Europe.

One of the most outstanding qualities of hemp concrete is that it is a carbon negative material; 1 m^2 of hemp–lime wall (260 mm thick) requires 370–394 MJ of energy for production and sequesters 14–35 kg of CO_2 over its 100 year life span compared to an equivalent cellular Portland cement (PC) concrete wall that needs 560 MJ of energy for production and releases 52.3 kg of CO_2 [1].

The aim of this research is to investigate the effect of the type of binder on the moisture transfer and thermal properties of hemp–lime concrete. Currently, PC and hydraulic lime are added to hemp–lime concrete to speed up setting and hardening however, using pozzolans instead should lower environmental impact. This paper compares hemp–lime concretes made with hydrated lime and pozzolans to those including hydraulic lime and cement. Two pozzolans, metakaolin and GGBS, were identified as having potential for use in hemp–lime concrete on account of their fast setting and high reactivity [2,3]. GGBS is a by-product of the iron and steel manufacturing process. It is created by a polluting industry but is a waste product that would otherwise be disposed of in landfill. GGBS is a latent hydraulic material which hydrates in the presence of water and as such, it is sometimes not considered a true pozzolan. The self hydration of GGBS however is very slow but lime acts as an activator [4]. The hydration reaction of GGBS

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is accompanied by the slower lime–GGBS pozzolanic reaction; the amorphous silica and alumina in the slag react with lime forming additional hydration products. Metakaolin is calcined kaolin clay that reacts with lime forming calcium silica hydrate (CSH) and calcium aluminosilicate hydrates. Metakaolin is a less energy intensive processed material than cement [5].

Former research has discussed the mechanical properties and durability of hemp concretes made with the same binders as those in this study [6]. The authors concluded that increasing binder hydraulicity enhances early strength development but does not significantly affect ultimate strength – all concretes reached similar strength at 1 year irrespective of the binder type (0.29–0.39 MPa). The authors also concluded that the hemp concretes are sensitive to freeze–thaw (10 cycles) however, salt exposure (1 month) and biodeterioration (7 month exposure) did not have a detrimental impact on the concrete.

In addition to its sustainable credentials, hemp–lime concretes usually exhibit an excellent thermal performance; a high thermal capacity coupled with a medium density and a low thermal conductivity grant the concretes a good insulation capability. The thermal conductivity values of lime–hemp concretes range between 0.05 and 0.12 W/m K depending on composition and density [7]. Thermal conductivity depends primarily on the density of the material and increases in a quasi linear manner in relation to it [8–11]. Air has low thermal conductivity therefore a concrete incorporating a large quantity of air will be less thermally conductive. The hemp aggregate is a highly porous wooden tissue including substantial air therefore, increasing hemp in the concrete reduces thermal conductivity [12]. The binder is the most thermally conductive component [13] consequently, a rise in binder content increases thermal conductivity [8]. It appears that binder hydraulicity reduces thermal conductivity; Gourlay and Arnaud found that hemp concretes made with cement had a lower thermal conductivity than equivalent samples made with lime or hydraulic lime; and that the effect of the binder on thermal conductivity became smaller as the water content increased [14]. Shea et al. state that thermal conductivity alone is not suitable for determining the thermal performance of hemp–lime concrete walls subjected to real weather conditions [11]. BRE found that buildings performed better than predicted by their *U*-value calculations [15]. Despite these shortcomings, *U*-values are the most common method of evaluating thermal performance and were therefore measured in this research.

Lime–hemp concrete has a high thermal mass compared to other light-weight building materials. Previous research has identified a thermal heat capacity ranging between 1000 J/kg K for a concrete with a density of 413 kg/m^3 [16 referring to 17] and 1560 ± 30 J/kg K for a "wall mixture" with a density of 480 kg/m^3 [18]. The effect of the binder on the thermal capacity of hemp concrete has not yet been investigated in detail, although in mortars, Černý et al. observed that a lime plaster had a lower specific heat capacity than a lime–pozzolan plaster suggesting that hydration products increase specific heat capacity [19].

Hemp–lime concrete is commonly described as having good water vapour permeability: the common industry figure of water vapour diffusion resistance factor (μ) of lime–hemp concrete is 4.85 ± 0.24 measured in accordance with EN12572 for samples with a binder:hemp:water ratio of 2:1:3 and a density of c. 400 kg/m^3 [18,20]. Collet for a binder:hemp ratio of 2:1 and density of c. 420 kg/m^3 obtained a value 1.7×10^{-11} kg/ms Pa [21] and Collet et al. for moulded, sprayed and precast concrete with a density of 430–460 kg/m^3 recorded values between 1.7×10^{-11} and 1.7×10^{-10} kg/ms Pa [22]. It is not possible to suggest a trend based on the results of former authors due to varying densities and composition (binder type and content). However, although density varied between samples, Tran Le (2011 referring to Grelat 2005) states that binder type strongly influences concrete permeability, with less hydraulic binders having a lower water vapour diffusion resistance factor [16 referring to 23]. Similarly, the water vapour permeability of lime mortars drops with increasing cement content [24].

Lime–hemp concretes have a very high capacity to hold water in their capillaries on account of their open pore structure. Evrard (2008) obtained a water absorption coefficient of 4.42 ± 0.27 $kg/m^2 h^{1/2}$ (0.0736 ± 0.0045 $kg/m^2 s^{1/2}$) for a 487 kg/m^3 density concrete made with a proprietary binder (DIN52617) [13]. De Bruijn et al. measured average values of 0.15 $kg/m^2 s^{1/2}$ for samples with binders including lime, hydraulic lime and cement and densities ranging from 587 to 733 kg/m^3 [25]. It is not possible to suggest a trend based on the results of former authors due to varying densities and composition (binder type and content). However, the authors above did not observe a significant difference in water sorption when varying proportions of hydrated lime, hydraulic lime and cement [25] while Evrard states that hemp concretes with more hydraulic binders have lower capillary absorption [12]. This is similar to the behaviour of cement–lime pastes, where the capillary coefficient drops with increasing cement content due to the hydration products increasing the number of smaller pores [26].

2. Materials and methods

2.1. Materials

Hydrated lime (CL90s—calcium lime), natural hydraulic lime (NHL 3.5) complying with EN459-1 [27] and Portland cement (CEM I, EN197-1:2011 [28]) were used as binders. A lime based "commercial mix" with hydraulic additions specifically developed for use with hemp was also used.

Portland cement and hydraulic lime are often added to hemp–lime concrete to speed up setting and hardening. Pozzolans can speed up setting and hardening of lime [2,3] and therefore they could replace PC and HL in the concrete lowering environmental impact. Two pozzolans: metakaolin and Ground Granulated Blastfurnace Slag (GGBS); were identified as having potential for use in lime–hemp concrete on account of their fast setting and high reactivity [2,3]. The pozzolans' chemical composition, amorphousness and surface area are included in Table 1. The chemical composition was assessed by XRF using a Quant'X EDX Spectrometer and UniQuant analysis package. The degree of amorphousness was indicated by X-ray diffraction (XRD), using a Phillips PW1720 XRD with a PW1050/80 goniometer and a PW3313/20 Cu K-alpha anode tube at 40 kV and 20 mA. The specific surface area was measured using a Quantachrome Nova 4200e and the BET method, a model isotherm based on adsorption of gas on a surface.

The aggregate is industrial hemp shiv supplied by La Chanvrière De L'aube, France. Hemp properties vary with growing conditions and harvesting, and this influences the properties of the concrete. Therefore, hemp from the same consignment, stored in the same conditions was used in all concretes to ensure that variability of hemp did not influence the results. The water content of the hemp depends on the relative humidity and also impacts the properties of the concrete. This was measured as 12.4% prior to mixing.

The hemp aggregate absorbs large quantities of water (325% of its own weight at 24 h [29], as a result it can hold mixing water which is required for hydration and carbonation undermining the properties and durability of hemp concrete. Hence, in an effort to offset this detrimental effect, some of the concretes investigated include a water retainer (modified hydroxypropyl methyl cellulose).

2.2. Composition of the hemp concrete

Six mixes were studied, only differing in the binder composition as set out in Table 2. Each binder has a different water demand which depends on its composition, hence the water content could not be kept constant. Consequently, the water

Table 1
Chemical composition, amorphousness and surface area of pozzolans.

Composition, amorphousness and surface area	GGBS	Metakaolin
SiO_2	34.14	51.37
Al_2O_3	13.85	45.26
CaO	39.27	–
Fe_2O_3	0.41	0.52
SO_3	2.43	–
MgO	8.63	0.55
Rate of amorphousness	Totally	Mostly
Surface area (m^2/g)	2.65	18.3