Moisture transfer and thermal properties of hemp–lime concretes

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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

content of each concrete was determined by attaining a suitable workability which was consistent in all concretes. No test currently exists to measure the workability of hemp concrete. Slump tests were attempted in this research but they did not yield consistent results. Therefore, the water content was determined by the expertise of an experienced building practitioner, Henry Thompson, who ensured that all the hemp concretes attained a suitable workability which was consistent in all concretes. According to Evrard, experience is the best guarantee for a good mixture [12].

2.3. Mixing, moulding and curing

The mixing sequence in hemp–lime concrete has not yet been established. Some authors wet the hemp prior to adding the binder [8,10] while others form a slurry with water and binder before adding the hemp [14,30]. A preliminary investigation revealed that, in lime–pozzolan concretes, wetting the hemp before adding the binder increases the water demand of the concrete and does not impart significant benefits to the properties measured therefore, prewetting the hemp was not considered.

Mixing was done in a large pan mixer with 2 batches per mix (total mixing time 7 min). The dry binder was premixed by hand and ¾ of the total mixing water was then added and mixed for 2.5 min to form a slurry. The hemp and remaining water were then gradually included.

The density was closely controlled due to its significant effect on concrete properties. An amount of concrete was weighted to ensure a dry density of c. 360 kg/m^3. The concrete was placed into cling-film lined timber moulds in a single layer and gently pressed generating a density similar to that of a typical wall construction. The mould was removed and the samples transferred to a curing room at 16 °C ± 3 °C temperature and 55 ± 10% relative humidity. The performance of the commercial binder is influenced by the low mixing water content and dry curing conditions which inhibited binder hydration [31]. Four 100 mm cubes were moulded for tesing permeability, capillary action and specific heat capacity.

One wall (1 m wide × 900 mm high × 300 mm thick) of each mix was constructed with shuttering and tamped into place every 300 mm in a similar manner to typical, on-site wall construction. The walls were tamped by hand and density varied depending on compaction of the concrete as set out in Table 3. The walls were cured outside for 1 year with protective covering. This was followed by 6 weeks curing in laboratory conditions prior to measuring thermal conductivity (*U*-value).

2.4. Permeability

The water vapour permeability was measured in accordance with EN 12086:1997 [32]. This test is based on the principle that water vapour will travel through a sample from a humid to a dry environment. The water vapour permeability is measured as a ratio of the resistance to moisture movement of the material to the resistance to moisture movement of the air and is known as the water vapour diffusion resistance factor (μ).

The specimens were placed on a dish with one side exposed to the humid environment of the curing room (20 ± 1 °C and 50 ± 5% RH) and the underside exposed to the dish containing 75 g of calcium chloride, a desiccant that maintains RH at 0%. The transfer of water vapour was measured by weighing the test assembly (specimen and dish) over time. The test was continued for 9 weeks and samples weighted at weekly intervals. The weight of the samples stabilised during the first week and the subsequent 8 weeks of readings allowed determining water vapour permeability. Three control samples were also weighed to establish whether any weight variation was due to fluctuations in ambient humidity or carbonation/hydration.

2.5. Capillary action

The water absorption coefficient by capillarity was measured according to EN 1925:199 [33], altered in order to adapt it to the hemp–lime concrete. On account of the highly porous nature of the concrete, the duration of the test was 10,000 min. The samples were placed on a wire grill, in a container of water so that the water covered the lower 10 mm of the samples and weighted at intervals over time. The coefficient is a measure of the water sorption as a function of the surface area of the specimen and time.

Table 3
Density of walls.

Concrete type	Approximate density[a] (kg/m^3)
Builder's mix (BM)	627
Commercial mix (CM)	627
GGBS (G)	565
GGBS + WR (G + WR)	569
Metakaolin (M)	508
Metakaolin + WR (M + WR)	531

[a] Density measured at 13.5 months (incomplete drying at this time may have provided values slightly higher than the final dry density).

2.6. Thermal conductivity

The thermal conductivity was assessed by measuring the thermal transmittance (*U*-value) of the walls using a Hukseflux TRSYS01 measurement system and a Loggernet software for in situ measurement complying with ISO 9869 and ASTM C1155. An insulated chamber was built of, 300 mm (6 × 50 mm) thick, PIR insulation boards and the two opposite ends fitted with hemp concrete walls. The interior of the chamber was heated by a radiator and the temperature controlled by a thermocouple temperature sensor to activate a relay. The average interior and exterior temperatures were 27 °C and 16 °C respectively. The builder's mix hemp concrete wall was kept in place as a constant for the duration of testing and the remaining walls tested for 2 weeks each. Although allowed to cure for 13.5 months prior to testing, it was likely that the walls had not fully dried at the time of testing (they lost a further 10% water in the following 3 months). The *U*-value of each wall was calculated as the average of the average daily *U*-value recorded in the range between 0.3 and 0.7 W/m^2 K.

2.7. Specific heat capacity

The heat capacity of the concrete was measured in an adiabatic surrounding with a similar method to [18,20]. The samples were heated in an oven at 100 °C for 24 h. A thermocouple measured the interior temperature of the sample. The samples were directly transferred from the oven into insulated containers filled with water at c. 15 °C and the temperature rise of the water monitored at 15 min intervals. The water temperature achieved equilibrium after 2 h. The temperature increase of the water was used to calculate the heat capacity of the concrete.

2.8. Microstructure

As aforementioned, in mortars and concretes, the presence of hydrates (formed on cement clinker and hydraulic lime hydration and pozzolanic reaction) influences permeability, capillary absorption and thermal properties. Both water vapour permeability and capillary absorption drop with increasing hydrates while rising hydrates decrease thermal conductivity and increase specific heat capacity. Therefore, it is important to analyse the microstructure of the binder in the hemp concretes, focusing on the presence and quantity of hydrates. The concrete microstructure was investigated using a Tescan MIRA Field Emission Scanning Electron Microscope.

3. Results

3.1. Microstructure

SEM analyses showed microstructural differences relating to the amount of hydrates in the binder of the concretes. At 6 months, the commercial binder included abundant needle-shaped hydrates

Table 2
Composition of the hemp concretes.

Name	Notation	Binder composition (% by weight)	Binder:hemp:water ratio (by weight)		
			B	H	W
Builder's mix	BM	70% CL90, 20% NHL3, 10% PC	2	1	3.1
Commercial mix	CM	100% commercial binder	2	1	2.9
GGBS	G	70% CL90, 30% GGBS	2	1	3.1
GGBS + WR	G + WR	70% CL90, 30% GGBS, 0.5% methyl cellulose	2	1	3.1
Metakaolin	M	80% CL90, 20% metakaolin	2	1	3.3
Metakaolin + WR	M + WR	80% CL90, 20% metakaolin, 0.5% methyl cellulose	2	1	3.1

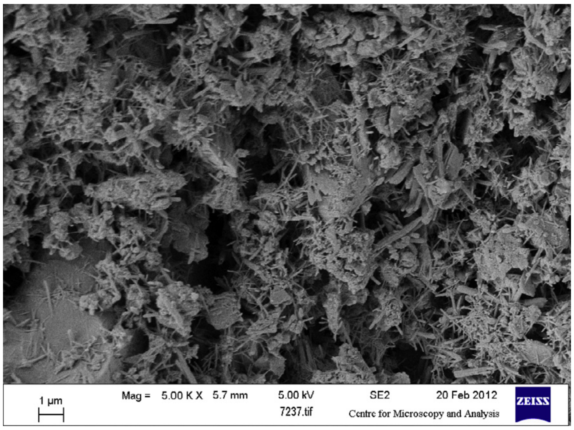

Fig. 1. Commercial binder concrete at 6 months showing abundant hydrates on the hemp interface and filling pores.

filling pores (Fig. 1) while the builder's mix showed a smaller amount of hydrates (Fig. 2) and the lime:pozzolan binders were largely carbonated with infrequent pozzolanic hydrates (Figs. 3 and 4). This indicates that the commercial binder has significant hydraulic additions. The methyl cellulose water retainer slightly increased the amount of hydrates in lime–pozzolan concretes suggesting that retaining water in the binder enhanced pozzolanic hydration [29,34].

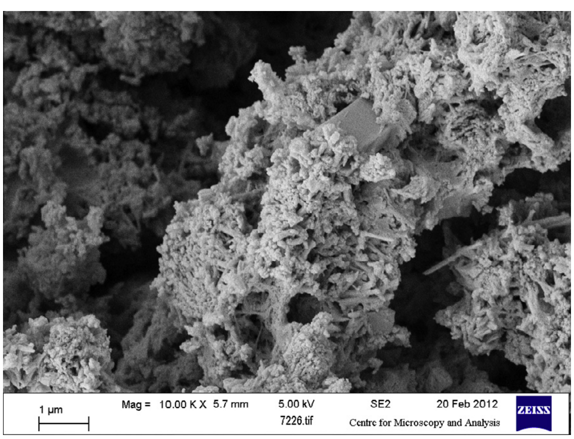

Fig. 2. Builder's binder concrete at 6 months showing some hydrates and abundant carbonated lime.

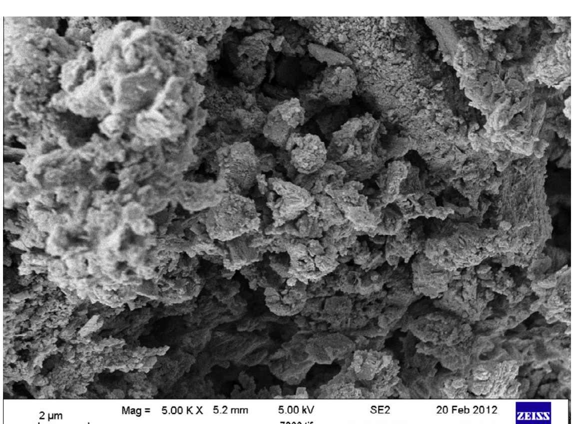

Fig. 3. Metakaolin binder concrete at 6 months which appears mainly carbonated.

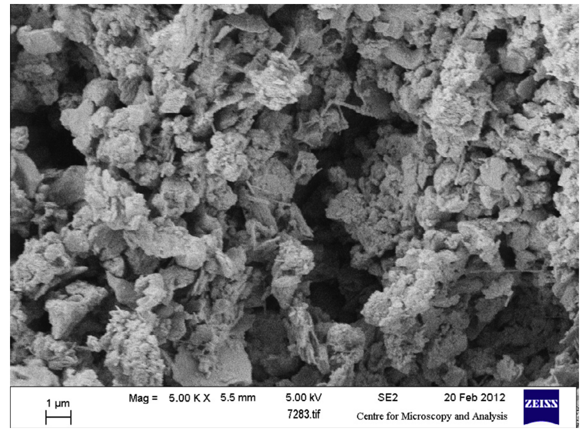

Fig. 4. Metakaolin with methyl cellulose concrete at 6 months displaying carbonation and needle-shaped hydrates.

Metakaolin is more reactive as a pozzolan [3]. However, it is present in a lower proportion in the hemp concrete (20% vs 30% of GGBS). In addition, metakaolin contains more mixing water that should result in more pores (see mixes). Despite these, no microstructural differences between the GGBS and metakaolin concretes were recorded with the SEM.

The results also indicate that, in spite of the abundant hydrates, the commercial binder had only partly hydrated during curing. This was evidenced by the microstructural analysis of commercial binder concretes that were saturated after curing which showed a substantial increase in hydration [31].

3.2. Permeability

The average water vapour permeability and water vapour diffusion resistance factor of each concrete are set out in Table 4. The permeability is lower than that observed by Evrard [13] but higher than that recorded by Collet [17,21,22]. This difference is likely on account of variations in density, composition, etc. of the hemp concretes.

Weight gain due to permeability ranged between 3.5% and 4% (as a percentage of the original weight of sample). The weight of the control samples at 9 weeks differed from the original weight by no more than 0.14%. Small positive and negative weight fluctuations took place over the curing weeks which were attributed to slight variations in the curing room environment rather than continuous weight gain due to carbonation.

In hemp concrete, macropores are present between hemp particles while micropores are found within the binder. Macropores are highly determined by compaction whereas micropores depend on the hydraulic content of the binder (hydrates fill pores).

Tran Le [16] referring to Grelat [23] observed that the type of binder strongly influences permeability of hemp concrete, with less hydraulic binders having a lower water vapour diffusion resistance factor. In contrast, the results in this research revealed that there is no statistically significant difference in the permeability of the concretes made with different binders. Therefore, the hydraulic content of the binder does not influence permeability to a great extent, and macropores between hemp particles have a greater influence on permeability than micropores. The results also evidenced that water retainers reduce water vapour permeability.

As aforementioned, this research evidences that the hydraulic content of the binder does not influence permeability to a great extent however, it is possible that binders with larger differences in hydraulic content than those in this research may provide a stronger relationship between permeability and hydraulicity.

Table 4
Average water vapour permeability and water vapour diffusion resistance factor of each concrete. BM – builder's mix, CM – commercial mix, G – lime:GGBS binder, G + WR – lime:GGBS binder with water retainer, M – lime:metakaolin binder, M + WR – lime:metakaolin binder with water retainer.

Concrete type (composition set out in Table 2)	Water vapour diffusion resistance factor (lower value – higher permeability)	Water vapour permeability (kg m^{-1} s^{-1} Pa^{-1})	Coefficient of variance (%)
BM	5.51	4.14×10^{-10}	9.4
CM	5.47	4.17×10^{-10}	8.5
G	5.56	4.1×10^{-10}	9.4
G + WR	5.71	3.99×10^{-10}	7
M	5.42	4.21×10^{-10}	7.7
M + WR	5.71	3.99×10^{-10}	7

The commercial binder exhibits a higher permeability than expected based on its hydraulic content however, this may be on account of the affinity of water molecules towards hydration products, or the water consumed to form additional hydrates due to incomplete hydration.

3.3. Capillary action

The water absorption by capillary suction over time and the water absorption coefficient are represented in Fig. 5 and Table 5 respectively. The water sorption coefficient varied between 2.65 and 3.37 kg/m^2 h$^{1/2}$ over the first 24 h (Table 5). These are lower values than those observed by Evrard [18] and de Bruijn et al. [25], at 4.42 ± 0.27 kg/m^2 h$^{1/2}$ and 9 kg/m^2 h$^{1/2}$ (0.15 kg/m^2 s$^{1/2}$) respectively, for higher density concrete samples.

As it can be seen from the results, the capillary behaviour of all the concretes is similar; water absorption is initially high, decreasing as time progresses. However, there is a statistically significant difference in the rate at which capillary water is absorbed. Therefore capillary action in the concrete is determined by the binder type, increasing as the hydraulic content of the binder lowers. It is likely that hydrates filling pores reduce capillary action. The metakaolin concrete has a high water absorption coefficient probably due to lesser hydraulic additions (lower pozzolan content) and a slightly higher mixing water content.

Both mixes with water retainers (GGBS and metakaolin binders) have a lower capillary absorption than those without them as set out in Table 5. This agrees with Paiva et al. who found that methyl cellulose decreases the capillary coefficient of cement mortars due to the introduction of small pores which can cut the capillary network [35]. The water retainers are highly effective at reducing capillary action as the samples with water retainers display the lowest capillary action, lower than the strongly hydraulic commercial binder.

Table 5
Water absorption coefficient in the first 24 h. BM – builder's mix, CM – commercial mix, G – lime:GGBS binder, G + WR – lime:GGBS binder with water retainer, M – lime:metakaolin binder, M + WR – lime:metakaolin binder with water retainer. R^2 – coefficient of determination.

Concrete type	Water absorption coefficient – C kg/m^2 h$^{1/2}$ (slope of line)	R^2
BM	3.09	0.964
CM	3.01	0.946
G	3.16	0.945
G + WR	2.65	0.98
M	3.37	0.922
M + WR	2.97	0.991

3.4. Thermal conductivity

The average *U*-values of the 300 mm hemp concrete walls range between 0.39 and 0.46 W/m^2 K (as set out in Table 6) and increase with the density. The values are within the range of 0.22–0.89 W/m^2 K observed (for 300 mm thick walls) by other authors [7].

Thermal properties are dependent on density. Cerezo established a relationship between increasing thermal conductivity and increasing density of hemp concrete, and derived an empirical relationship (Eq. (1)) for roof, walls and render mixes of hemp:binder:water ratios 1:1:2, 1:2:3 and 1:2.5:3.6 respectively [8].

$$\text{Conductivity} = 0.0002 \times (\text{density}) + 0.0194 \quad (1)$$

The relationship between thermal conductivity and density of the hemp concretes investigated is included in Fig. 6. Also plotted are the values obtained by applying the relationship established by Cerezo [8]. The concretes appear to have a slightly lower thermal conductivity than that predicted from the relationship above. The results show that thermal conductivity increases with density

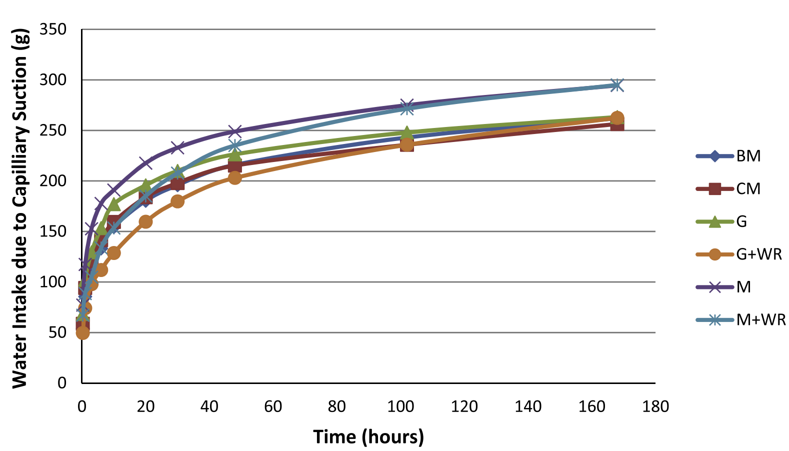

Fig. 5. Water absorption by capillary suction over time. BM – builder's mix, CM – commercial mix, G – lime:GGBS binder, G + WR – lime:GGBS binder with water retainer, M – lime:metakaolin binder, M + WR – lime:metakaolin binder with water retainer.

Table 6
U-value of hemp concrete walls. BM – builder's mix, CM – commercial mix, G – lime:GGBS binder, G + WR – lime:GGBS binder with water retainer, M – lime:metakaolin binder, M + WR – lime:metakaolin binder with water retainer.

Concrete type	Density	*U*-value (W/m^2 K)	Thermal conductivity (W/(m K))	Coefficient of variance	Measurement error (probes, sensor and standard deviation of results) (%)	Difference from value predicted by Cerezo [8] (W/m^2 K)
BM	627	0.46	0.138	6.8	14.6	0.0068
CM	627	0.46	0.138	3.0	16.2	0.0068
G	564	0.42	0.126	5.5	13.6	0.0062
G + WR	569	0.43	0.129	7.2	11.8	−0.008
M	508	0.39	0.117	7.8	13.6	0.008
M + WR	531	0.41	0.123	4.0	11.8	0.01

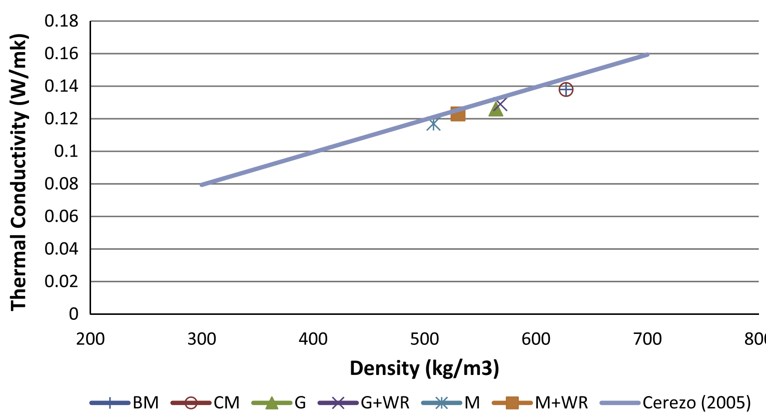

Fig. 6. Relationship between density and thermal conductivity of hemp concrete walls and the relationship established by Cerezo [8]. BM – builder's mix, CM – commercial mix, G – lime:GGBS binder, G + WR – lime:GGBS binder with water retainer, M – lime:metakaolin binder, M + WR – lime:metakaolin binder with water retainer.

and the type of binder does not appear to have a statistically significant effect on thermal conductivity. These results differ from Gourlay and Arnaud, who found that thermal conductivity significantly varies with the type of binder [14]. It is possible that the difference in the hydraulic content of the lime–pozzolan and partly hydrated commercial binder [31] in this research, is not as large as in the binders studied by Arnaud. It can also be possible that moisture content in the walls and some lack of accuracy of the measurement system may conceal differences in performance.

Interestingly, the metakaolin concretes diverge the least from the predicted values, and the concretes with water retainers differ less than the equivalent concretes without water retainers (Fig. 6). Therefore, at a particular density, the results suggest that metakaolin has a slightly higher thermal conductivity and that water retainers increase conductivity.

It was expected that, as air has very low thermal conductivity, increasing hydraulic content (increasing hydrates filling air spaces) would increase thermal conductivity. However, although not statistically significant, the results suggest the opposite trend whereby increasing hydration lowers thermal conductivity. This trend would agree with Gourlay and Arnaud (2010) and also with Černý et al. (2006), Xu and Chung (2000) who evidenced increasing hydration lowering thermal conductivity in mortars [14,19,36].

3.5. Specific heat capacity

The average specific heat capacity of the concretes ranged from 1240 to 1350 J/kg K (Table 7). The results are slightly higher than the 1000 J/kg K by [37] and lower than the 1560 J/kg K values reported for higher density concretes of 480 kg/m^3 [18].

The binder did not have a statistically significant effect on the heat capacity of the concrete. A trend however suggests that the lime–pozzolan samples have a slightly lower heat capacity than the more hydraulic concretes (builder's and commercial concretes); and that water retainers increase heat capacity. It is possible that larger differences in the hydraulic content of the binders may provide a stronger relationship between heat capacity and hydraulicity of the binder.

Table 7
Specific heat capacity of hemp concretes. BM – builder's mix, CM – commercial mix, G – lime:GGBS binder, G + WR – lime:GGBS binder with water retainer, M – lime:metakaolin binder, M + WR – lime:metakaolin binder with water retainer.

Concrete type	Specific heat capacity (J/ kg K)	COV (%)
BM	1340 ± 163	5.4
CM	1300 ± 176	7.5
G	1250 ± 162	5.5
G + WR	1350 ± 279	10.4
M	1240 ± 172	6.8
M + WR	1280 ± 165	5.9

Water contributes to heat capacity in hemp concrete: Evrard and de Herde note that the specific heat capacity increases with increasing relative humidity [20]. Chemically bound water in PC hydrates has a high heat capacity (2200 J/kg K [38 referring to 39]). The presence of hydrates in the hemp concrete should therefore increase its specific heat capacity and this is a possible explanation for the lime–pozzolan binders, with the least hydrates, displaying the lowest heat capacity.

The concrete has higher specific heat capacity than air (c. 1003 J/kg K). Therefore the slightly higher porosity of the lime–pozzolan concretes when compared to the builder's, commercial and equivalent concretes with water retainers may also contribute to their lower specific heat capacity.

4. Conclusion

This paper concludes that the type of binder influences the capillary absorption of hemp concrete, and that both increasing the hydraulicity of the binder and adding a water retainer reduce capillary absorption. This is probably due to hydrates filling micropores in the binder. The impact of the type of binder on hemp concrete permeability is less evident, and the results indicate that the large interparticular spaces between hemp particles (macropores) strongly contribute to permeability, while the concrete micropores (influenced by binder hydraulicity) contribute to permeability to a lesser extent.

The binder type did not have a statistically significant effect on either thermal conductivity or specific heat capacity. A trend however suggests that binder hydraulicity reduces thermal conductivity and increases heat capacity while the presence of water retainers increases both conductivity and heat capacity. The average *U*-values of the 300 mm hemp walls range between 0.39 and 0.46 $W/m^2 K$ evidencing a significant insulation capacity for the concrete.

As in Portland cement concrete, water promotes heat capacity, thus the hydrates in the hemp concrete increase its specific heat capacity; the pozzolan concretes, with the least hydrates, display the lowest heat capacity.

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