Impact of water retainers in lime hemp concrete with pozzolans.

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Abstract

Hemp-lime concrete is a sustainable building material. It often incorporates cement to speed up setting and strength development however, replacing cement with pozzolans improves the environmental credential of the concrete. This paper investigates hemp concrete made with a lime:pozzolan binder and examines the impact of water retainers on the concrete's performance. In hemp concrete, water is needed in the binder so that hardening (through hydration and carbonation) takes place. However, competition for water occurs between the hemp and the binder due to the high suction ability of the hemp, and this can undermine hydration and adversely affect strength and durability.

This paper investigates the effect of hydroxypropyl methyl cellulose water retainer on the water transfer properties, strength and durability of hemp concrete with pozzolans. The water retainer was found to reduce capillary action and permeability, increase strength development and increase resistance to freeze-thaw action for both GGBS and metakaolin pozzolan concretes. This is likely on account of improved hydration that results from the increased water retention of the binder.

1. Introduction

Lime hemp concretes have been used in France since the 1990s and are gaining popularity in Europe. They are sustainable, carbon negative materials, made with a lime based binder and hemp which can replace high embodied energy materials in certain applications, lowering the environmental impact of construction. Lime hemp concretes are non-load bearing and show good thermal and insulation properties. They are usually site-cast, projected or prefabricated as blocks or panels. This paper investigates hemp concrete made with a lime:pozzolan binder and examines the impact of water retainers on the concrete's water transfer properties, strength and durability.

Portland cement (PC) is usually incorporated in the lime binder to produce an early hydraulic set and improve early age properties such as setting and strength. This investigation replaces cement with pozzolans as a more sustainable alternative. Pozzolans are materials containing amorphous silica and/or alumina that react with portlandite ($Ca(OH)_2$) in the presence of water to form cementitious hydrates (calcium silicate hydrates –CSH- and calcium silicate aluminate hydrates –CSAH-) similar to those formed upon PC hydration thereby accelerating hardening of calcium limes by imparting a hydraulic set.

In hemp concrete, water is needed so that hydration takes place in the binder and cementing hydrates are formed. Water is chemically bound to these hydrates (CSH and CSAH), if water is not present, hydrates cannot form. The hemp aggregate (shiv) is a complex tissue from the xylem layer of the hemp stem whose main function is conducting water therefore, it absorbs large amounts of water, measured as 325% of its own weight at 24 hours (Walker and Pavía 2012). Nozahic et al.

(2012) and Colinart et al. (2012) state that, following mixing, there is a competition for water between the hemp and the binder due to the high absorption of the hemp.

Water retainers improve the binder's ability to hold water. They were developed for use when rapid dehydration occurs either by absorption of a substrate or evaporation due to drying (Paiva et al. 2009). In hemp concrete, the water retention capacity of the binder is very important due to the high suction of the hemp. Even lime binders which typically have a high water retention (values ranging from 94.2 to 99.5% have been consistently measured for hydrated and natural hydraulic limes, Pavía and Hanley 2010) may benefit from the use of water retainers to balance the high suction of the hemp. This paper investigates the effect of water retainers in lime-pozzolan concrete. Water retainers are used in an attempt to ensure that sufficient water remains in the binder to form hydrates through pozzolanic reaction. This is particularly important as pozzolanic reaction begins early but continues over long time periods therefore, water is required both initially and at later ages.

Insufficient water in the binder also delays carbonation (as $Ca(OH)_2$ and CO_2 must be in solution to react) however, carbonation typically occurs over months and years and does not significantly contribute to early age properties.

An earlier investigation of lime-pozzolan concrete showed that water retainers delay both setting and drying (Walker and Pavía 2012). The authors also found that water retainer hydroxypropyl methyl cellulose increased the compressive strength of lime-pozzolan concrete and pastes (probably due to enhancing hydration) while two commercial water retainers had no effect on compressive strength. This paper looks at the effect of hydroxypropyl methyl cellulose on the water transfer properties, strength and durability of hemp concrete with pozzolans.

2. Materials and Methods

2.1 Materials

A hydrated lime (CL90s—calcium lime) complying with EN 459-1 was used. Two pozzolans: metakaolin and GGBS; were identified as having potential for use in lime-hemp concrete on account of their fast setting and high reactivity (Walker and Pavía 2010). 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

40kV and 20mA. 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. Previous research identified the water retainer modified hydroxypropyl methyl cellulose as having potential for use in the concrete (Walker and Pavía 2012).

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	18.30

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

Industrial hemp shiv was supplied by La Chanvrière De L'aube in central 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 and was measured as 12.4% prior to mixing.

2.2 Composition of concrete

Four mixes were studied only differing in the binder composition as set out in Table 2.

The water content could not be kept constant as the metakaolin binder has a high water demand. Therefore, it was based on workability which was consistent in all concretes. As no workability test currently exists, the water content was determined by the expertise of a skilled building practitioner, Henry Thompson, who has built hemp-lime houses for over 10 years. According to Evrard (2003) experience is the best guarantee of a good mixture

Mix	Notation	Binder composition (% by weight)	Binder:hemp: water ratio (by weight)		
			B	H	W
GGBS	G	70% Calcium lime, 30% GGBS	2	1	3.1
GGBS+WR	G+WR	70% Calcium lime, 30% GGBS, 0.5% methyl cellulose	2	1	3.1
Metakaolin	M	80% Calcium lime, 20% Metakaolin	2	1	3.3
Metakaolin+WR	M+WR	80% Calcium lime, 20% GGBS, 0.5% methyl cellulose	2	1	3.1

Table 2. Composition of the hemp concretes

2.3 Mixing, moulding and curing

The mixing sequence in lime hemp concrete has not yet been established. Some authors wet the hemp prior to adding the binder (Cerezo, 2005; Nguyen, 2010) while others form a slurry with water and binder before adding the hemp (Hirst et al., 2010; Arnaud and Gourlay, 2012). A preliminary investigation revealed that, in hemp concretes with lime:pozzolan binder, prewetting the hemp increases water demand and does not impart significant benefits to the concrete (Walker and Pavía 2012) therefore, prewetting the hemp was therefore not considered.

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

An amount of concrete was weighted to ensure a dry density of c.360kg/m^3. The density was closely controlled due to its significant effect on concrete properties. 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. 100mm cubes were moulded for all tests.

2.4 Microstructure

The microstructure of the concretes was investigated using a Tescan MIRA Field Emission Scanning Electron Microscope. The samples were freshly fractured and covered with a gold coating in an 'Emscope SC500' plasma coating unit. The binder coating of the hemp particles was investigated for all concretes at 6 months in order to inform on adhesion at the interface, a vital area in relation to strength and durability.

2.5 Capillary action

The water absorption coefficient by capillarity was measured according to EN 1925:1999. The standard was altered in order to adapt it to the lime-hemp concrete. On account of the highly porous nature of the concrete, the duration of the test was 10,000 minutes. The samples were placed on a wire grill, in a container of water so that the water covered the lower 10mm 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.

2.6 Permeability

The water vapour permeability was measured in accordance with EN 12086:1997 (Figure 1). This test is based on the principle that, due to the difference in water vapour pressure between a humid and a dry environment, water vapour will travel through the sample from the humid to the 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 75g of calcium chloride, a desiccant that maintains the 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. 3 control samples were also weighed in order to control whether any weight variation was due to fluctuations in humidity or carbonation.

Figure 1. Hemp concrete undergoing permeability testing.

Figure 2. Failure of the concrete under axial load.

2.7 Compressive strength

As there is no standard procedure for the measurement of unconfined compressive strength of lime-hemp concrete, the test was guided by the testing procedure of EN 459-2 and EN 196-1 with a loading rate of 50N/s. Typically, the concrete does not break but continuously deforms (figure 2). therefore, the ultimate strength was set as the stress at which the stress/strain curve departs from linear.

2.8 Resistance to freeze-thaw action

Currently, there are no standards to measure the resistence of lime mortars or hemp concretes to frost action therefore, the test was guided by EN 15304:2010. Nine-month-old concretes were subject to 10 freeze-thaw cycles between –15 and 20°C.

Near saturation conditions provide the severest conditions for frost action as the effect of expanding ice is most detrimental. Therefore, the samples were soaked for 48hours prior to freezing, time by which they had absorpted 90% of their total water at saturation. Abundant water condensed in the freezer therefore, to ensure that water content remained near saturation, the samples were immersed for 12 hours after cycles 4 and 8.

Four specimens of each mix were tested. After cycling, the samples were allowed to dry for 2.5 months and the weight loss calculated. Finally, the compressive strength was determined and compared to those of reference samples and 1 year-old concretes. The reference samples were soaked for 48 hours and stored in polythene bags during testing to protect them against drying (EN 15304:2010). They are used to determine whether any deterioration is due to frost action or to water saturation during testing.

3. Results and Discussion

3.1 Microstructure

No significant difference was found in the microstructure of the paste in specimens made with and without methyl cellulose, both binders showed abundant hydrates (Walker and Pavía 2012). This agrees with Arizzi and

Cultrone (2012), who observed that a cellulose water retainer did not produce any mineralogical or morphological change in mortar pastes. However, differences were noted at the hemp interfaces: while hydration products did not appear at the interface in the concrete without methyl cellulose (Figures 3 and 5), some clusters of needle-shaped hydrates were evident when the concrete contained methyl cellulose (Figures 4 and 6). This can be attributed to the methyl cellulose retaining water in the binder facilitating pozzolanic reaction and thus the formation of hydrates. Therefore, hydration appears to be enhanced by the water retainer.

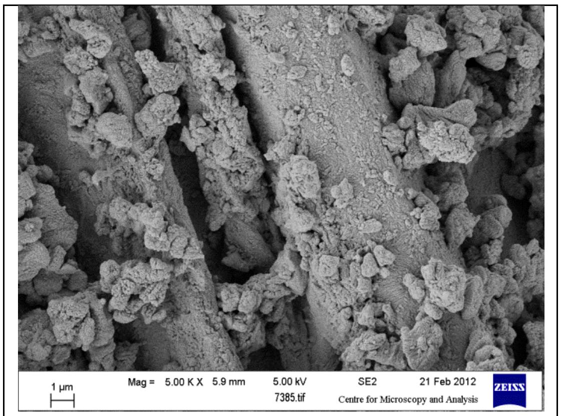

Figure 3. Hemp particle covered with calcium carbonate in a lime:pozzolan (GGBS) hemp concrete at 6 months

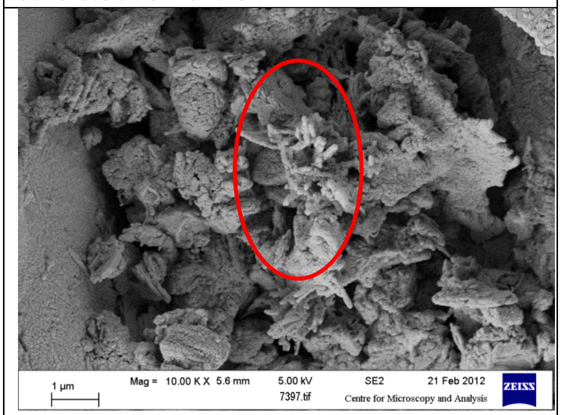

Figure 4. Hemp particle covered with calcium carbonate and clusters of hydrates, in a lime:pozzolan (GGBS) hemp concrete with methyl cellulose water retainer at 6 months

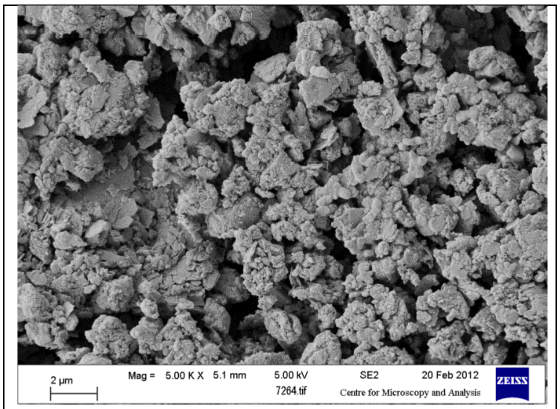

Figure 5. Hemp particle covered with calcium carbonate in a lime:pozzolan (metakaolin) hemp concrete at 6 months

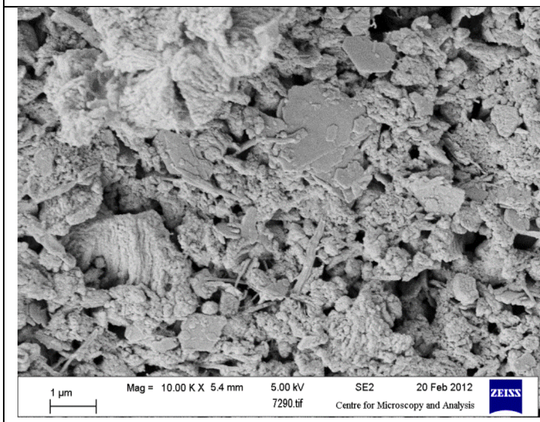

Figure 6. Hemp particle covered with calcium carbonate and several hydrate needles in a lime:pozzolan (metakaolin) hemp concrete with methyl cellulose water retainer at 6 months

3.2 Capillary action

The concretes behave similarly with respect to capillary suction: at early ages, they absorb water at a fast rate which decreases over time (Figure 7). The water sorption coefficient varied between 2.65 and 3.37kg/m^{2}h$^{1/2}$ over the first 24 hours (Table 3), reaching lower values than those reported by Evrard (2008) and deBruijn et al. (2009) (4.42 ± 0.27 kg/m^{2}h$^{1/2}$ and 9 kg/m^{2}h$^{1/2}$ (0.15kg/m^{2}s$^{1/2}$)

respectively for higher density hemp concretes).

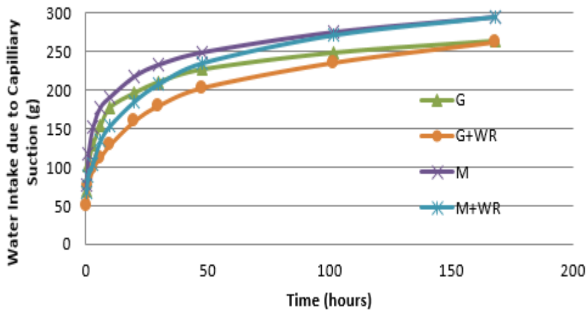

Figure 7. Water absorption by capillary action over time. G-lime and GGBS binder, G+WR – lime and GGBS binder with water retainer, M- lime and metakaolin binder, M+WR – lime and metakaolin binder with water retainer.

The results indicate that there is a significant difference in the capillary suction of the different concretes ($P<0.1$, ANOVA/Tukey's test): the concretes with water retainers have a lower capillary suction than those without them. This agrees with Paiva et al. (2009) who found that methyl cellulose decreases the capillary coefficient of cement mortars. The authors state that this is due to the water retainer introducing small pores which cut the capillary network. The reduction of capillary suction by the water retainer Is also probably due to the additional hydrates induced by the water retainer partially filling pores.

Concrete	Water absorption coefficient - kg/m^2 hour$^{1/2}$	R^2
G	3.16	0.945
G+WR	2.65	0.98
M	3.37	0.922
M+WR	2.97	0.991

Table 3. Water absorption coefficient. G-lime and GGBS binder, G+WR – lime and GGBS binder with water retainer, M- lime and metakaolin binder, M+WR – lime and metakaolin binder with water retainer.

3.3 Water vapour permeability

The average water vapour permeability and water vapour diffusion resistance factor of each concrete are set out in table 4. The average water vapour resistance factor (μ) is higher than the 4.8 value calculated by Evrard (2008) and lower than 8.7-11.7 and 7.8 reported by Collet (2004) and Chamoin et al. (2009) respectively. This is likely on account of density variations as permeability is strongly influenced by density (Evrard 2006). There is no significant difference in the permeability of the concrete made with or without water retainers which suggests that interparticular spaces and hemp porosity determine permeability to a greater extent than the binder's microstructure.

Although not statistically significant, the concretes with water retainers show the lowest permeability. The reduction of permeability by the water retainer can be due to similar reasons to those reported for the reduction of capillary action: the water retainer introducing small pores and the additional hydrates induced by the water retainer partially filling pores.

Sample	vapour diffusion resistance factor	vapour permeability (kg/m.s.Pa)	COV
G	5.56	4.1 x10-10	9.4%
G+WR	5.71	3.99 x10-10	7%
M	5.42	4.21 x10-10	7.7%
M+WR	5.71	3.99 x10-10	7%

Table 4. Average water vapour permeability and water vapour diffusion resistance factor of each concrete. G-lime and GGBS binder, G+WR – lime and GGBS binder with water retainer, M- lime and metakaolin binder, M+WR – lime and metakaolin binder with water retainer. The low coefficients of variation (COVs) indicate that the results are consistent and reliable.

3.4 Compressive strength

The compressive strength ranges between 0.29 and 0.41MPa at 1 year (table 5 and figure 8) which falls within the 0.05-1.2 MPa range observed by other authors (Evrard 2003; Cerezo 2005; De Bruijn 2008; Hirst et al. 2010; Arnaud and Gourlay 2012). As previously reported (Cerezo 2005; Arnaud and Gourlay 2012), strength increases with age and ductility reduces. The increase in strength is most readily observable between 5 and 28 days and is partially due to drying. The strength continues to increase up to 1 year except for the metakaolin samples.

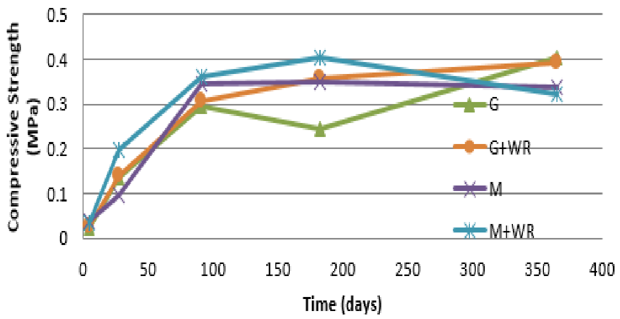

Figure 8. Development of compressive strength over time. G-lime and GGBS binder, G+WR – lime and GGBS binder with water retainer, M- lime and metakaolin binder, M+WR – lime and metakaolin binder with water retainer.

mix	5 days		28 days		3 months		6 months		1 year	
	CS	COV	CS	COV	CS	COV	CS	COV	CS	COV
G	0.02	13.7	0.13	12.9	0.29	19.5	0.24	13.2	0.41	15.9
G+WR	0.03	29.5	0.14	29.6	0.31	10.9	0.36	6.1	0.39	17.7
M	0.04	25.1	0.10	44.2	0.35	19.7	0.35	0.0	0.34	5.8
M+WR	0.04	20.9	0.20	22.9	0.36	17.8	0.40	3.1	0.32	2.5

Table 5. Compressive strength (MPa) of concrete over time. G-lime and GGBS binder, G+WR – lime and GGBS binder with water retainer, M- lime and metakaolin binder, M+WR – lime and metakaolin binder with water retainer.

The concretes with water retainers, show higher compressive strengths than those without them. However, at 1 year, the difference in compressive strength is no longer evident. This may partly be due to the fact that water retainers enhance hydration at early ages (as they increase the amount of cementing hydrates) while at later ages, carbonation also contributes to the strength of the lime:pozzolan concretes.

The GGBS pozzolan concrete achieves a relatively high compressive strength at 1 year despite showing a slower rate of strength gain than the metakaolin concrete at earlier ages. The drop of compressive strength of the GGBS concrete at 6 months is likely an error as there is an overall increasing trend between 3 months and 1 year.

The metakaolin concrete gains strength at a faster rate than the GGBS concrete. However, a reduction in strength is observed between 3 months and 1 year for metakaolin concrete, and between 6 months and 1 year for metakaolin with water retainer. Similarly, strength loss has been reported in lime: metakaolin pastes (Cizer et al. 2009; Donchev et al. 2010), lime:metakaolin hemp concretes (Eires et al. 2006). The strength drop has been attributed to changes in the morphology of the hydrates.

3.5 Resistance to freeze-thaw action

No cracks appeared in any of the concretes following freeze-thaw action however, they were soft prior to drying and the lime:pozzolan concretes were friable after drying (in particular the metakaolin ones). SEM analyses did not reveal any visual changes in the microstructure of the binder resulting from freezing. Strength, stiffness and mass were measured following freeze-thaw action, and the values compared to those of 1 year old and reference concretes (Table 3) to evaluate the damage. The weight loss and compressive strength loss are set out in Table 6 and figure 9. It is evident that freeze-thaw action has an impact on the lime:pozzolan concretes with a significant reduction in compressive strength and stiffness and weight loss. The presence of water retainer improves the performance of both pozzolan concretes, with lower weight loss and slightly lower compressive strength loss than the equivalent samples without water retainer. Water retainers increase the quantity of small pores which are believed to undermine frost resistance therefore, the improvement of frost resistance is probably partly due to the water retainer enhancing hydration. Therefore, the water retainer improves resistance to frost action. In addition, the wider pore size distribution induced by the water retainer reduces concrete water absorption which results in less water being available to cause damage by freeze-thaw action.

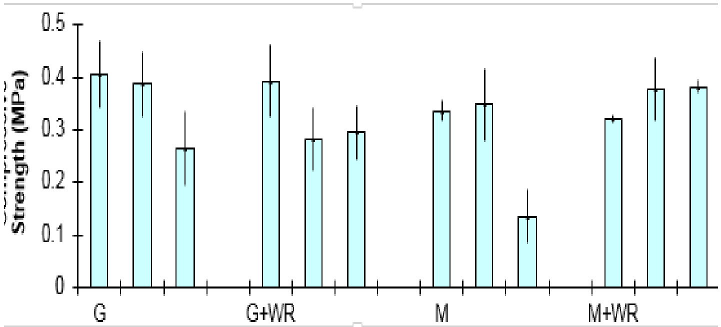

Figure 9. Compressive strength of the concrete at 1 year (bar 1), reference concrete (bar 2) and concrete subjected to freeze/thaw (bar 3). G-lime:GGBS binder, G+WR - lime:GGBS binder with water retainer, M- lime:metakaolin binder, M+WR - lime:metakaolin binder with water retainer.

Mix	Weight Loss	Concrete @ 1 year MPa		Soaked concrete MPa		Freeze/thaw concrete MPa		Strength loss @1y – F/T	Strength loss soaked F/T
			COV		COV		COV		
G	-2.6%	0.41	15.9	0.39	15.9	0.26	26.8	34.90%*	31.87%*
G+WR	-1.6%	0.39	17.7	0.28	20.9	0.30	17.6	24.84%*	-4.70%
M	-4%	0.34	6.3	0.35	21.4	0.14	29.5	59.7%*	60%*
M+WR	-2%	0.32	2.5	0.38	16.2	0.38	3.3	-19.02%	-1.10%

Table 6. Weight and compressive strength loss of concretes due to freeze/thaw cycling
**change in strength is significant (P<0.1). G-lime:GGBS binder, G+WR - lime:GGBS binder with water retainer, M- lime:metakaolin binder, M+WR - lime:metakaolin binder with water retainer.*

4. Conclusion

Water retainers were found to reduce capillary action and permeability, increase strength development and increase resistance to freeze-thaw action for both GGBS and metakaolin pozzolan concretes.

It is likely that the water retainers hold water in the lime:pozzolan binder for longer and that this water is used to form additional hydration products. This is supported by the microstructural analysis of the binder which shows an increase in the quantity of hydrates at the binder-hemp interface. The additional hydration products grow into pore spaces thereby introducing a larger quantity of small pores (under 0.1um) and increasing the pore size distribution. This explains the reduction in capillary action as water transfer is delayed/inhibited by smaller pores interrupting the capillary network (as also seen in cement mortars - Paiva et al. (2009)). Furthermore the increase in compressive strength (up to 6 months) and improved durability may also be largely attributed to the increased quantity of hydration products.

The water retainer methyl cellulose, was found to have a positive overall effect on the hemp concrete made with lime:pozzolan binder and therefore, it has the potential to increase the application of hemp concretes made with lime:pozzolan binders.

However, hemp-lime concrete with pozzolans has not yet been tested in full-scale construction, thus lime:pozzolan binders should be subject to further on-site verification of performance prior to use. Furthermore, a wider scope of additives could be considered to improve the performance of the hemp concrete with lime:pozzolan binder, in particular its durability.

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