

Mechanical properties and durability of hemp-lime concretes



R. Walker^{a,*}, S. Pavia^a, R. Mitchell^b

^a Dept. of Civil Engineering, Trinity College, Dublin, Ireland

^b School of Engineering and Applied Biology, Harvard University, Cambridge, MA 02138, USA

HIGHLIGHTS

- The effect of binder type on mechanical strength and durability is investigated.
- At the hemp interface, the commercial binder has abundant hydrates while lime:pozzolan binders are mainly carbonated.
- Binder hydraulicity contributes to strength development but has a lesser effect at 1 year when other factors also contribute.
- Hemp concretes made with lime:pozzolan binders are more sensitive to freeze:thaw action than more hydraulic binders.
- Short-term salt exposure resulted in the precipitation of salt layers but did not impact compressive strength at 1 year.

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ABSTRACT

Hemp-lime concrete is a sustainable and carbon negative construction material. This paper investigates the effect of binder type on mechanical strength and durability (resistance to freeze–thaw, salt exposure and biodeterioration). It compares hemp-lime concretes made with a hydrated lime and pozzolan binder to those including hydraulic lime and cement.

SEM analysis revealed abundant hydrates at the hemp interface of the strongly hydraulic commercial binder while the lime:pozzolan binders were mostly carbonated. Increasing binder hydraulicity enhances early strength development however, all concretes achieved similar compressive strengths at 1 year irrespective of the binder type. The concretes with lime:pozzolan binders are more sensitive to freeze:thaw action than those with more hydraulic binders. Salt exposure resulted in the precipitation of salt layers in the concrete however, this did not have a detrimental impact on the compressive strength of the concrete at 1 year. The results evidenced that hemp concrete is resistant to biodeterioration (7 month exposure). Finally, the addition of water retainer improved the early strength development and freeze:thaw resistance of the concrete with lime–pozzolan binder.

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1. Introduction

The built environment is responsible for 40% of primary energy use and 36% of energy related CO₂ emissions [1]. Therefore, it is important to develop low-embodied energy, carbon-negative, sustainable construction materials to replace cement-based products. Hemp-lime concrete is a mix of a lime-based binder and hemp. It was developed in the late 1980s/early 1990s in France as an alternative to wattle and daub for the restoration of historic buildings and to lighten portland cement (PC) concrete. Its potential as an environmentally sustainable construction material was quickly realised and it has since been used in the construction and thermal upgrading of hundreds of buildings in Europe.

One of its most outstanding environmental qualities of the concrete is that it is carbon negative. CO₂ is emitted during the production of lime however this is offset by the carbon sequestering of the hemp. As hemp grows it absorbs CO₂ and the carbon is integrated into the structure of the plant. The carbon therefore remains trapped in the hemp-lime walls. Boutin et al. (2006) determined that 1 m² of hemp-lime wall (260 mm thick) requires 370–394 MJ of energy for production and sequesters 14–35 kg of CO₂ over its 100 year life span [2]. In addition to its sustainable credentials, hemp-lime concretes exhibit an excellent thermal performance; a high thermal capacity coupled with a medium density and a low thermal conductivity that provides the concretes with good insulation capability.

The aim of this research is to investigate the effect of the type of binder on the mechanical strength and durability (resistance to freeze–thaw, salt exposure and biodeterioration) of hemp-lime concrete. Currently, PC and hydraulic lime are added to hemp-lime

* Corresponding author.

E-mail addresses: walkerro@tcd.ie (R. Walker), pavias@tcd.ie (S. Pavia), mitchell@seas.harvard.edu (R. Mitchell).

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 [3,4]. GGBS is a by-product of the iron and steel manufacturing process. GGBS is typically a latent hydraulic material and 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 and lime acts as an activator [5]. The hydration reaction of GGBS is accompanied by the slower lime:GGBS pozzolanic reaction: the amorphous silica and alumina in the slag react with lime forming additional hydrates. The replacement of PC by GGBS requires lower energy consumption and reduced CO₂ emissions [6]. GGBS is created by a polluting industry however, it is a waste product that would otherwise be disposed of in landfill. Metakaolin is a calcined kaolin clay that reacts with lime and forms hydrates: calcium silica hydrate (CSH) and calcium aluminosilicates. Metakaolin is a less energy intensive processed material than cement [7].

The hemp aggregate absorbs large quantities of water (325% of its own weight at 24 h [8]) and this can undermine hydration therefore, some of the concretes investigated include a water retainer.

Hemp concrete is largely a non-load bearing material that is typically used with a load bearing frame. However, its compressive strength is important as it is the most commonly measured property and allows comparison between the different binders. Furthermore, the early compressive strength development of the concrete is important as the hemp concrete must support its own self weight when wet (which can be over double its dry weight). The early strength of the hemp concrete may influence when shuttering is removed during construction and the spacing of the supporting structural timber frame. Typical compressive strengths for 2:1 (binder:hemp by weight) mixes range from 0.2 to 0.12 MPa [9–14] mainly depending on density, binder type and age. Flexural strength is also low and previous research has determined strengths between 0.06 and 1.2 MPa [12,15–17]. The low strength of the concrete is attributed by Boulloc et al. (2006) to the ductile nature of the hemp particles and their disordered arrangement [18]. Nguyen (2010) believes that the high porosity of the shiv gives the concrete a lower mechanical strength compared to other lightweight concretes [16].

The contribution of the binder's hydraulicity to the strength of the concrete has yielded varying opinions. Hirst et al. (2010) found that strength does not increase with the binder's strength [13]. However, Nguyen (2010) claims that stronger binders increase strength provided that their hydraulicity is not compromised by the absorption of water by the hemp [16]. Murphy et al. 2010 also observed that concretes made with a hydraulic commercial binder showed higher ultimate compressive and flexural strengths than those fabricated with hydrated lime, and that the rate of strength development depends on the hydraulicity of the binder, with hydraulic binders gaining strength faster [12]. De Bruijn et al. (2009) also showed that higher compressive strengths are obtained for cement-rich binders [19].

Little research has been undertaken on the durability of the hemp concrete. However, lime has been used since antiquity often including organic material such as timber (lath and beams), straw or hair, in structures that have shown great long-term durability. In addition, hemp-lime houses have been built in France for over 20 years without any serious reported weathering or durability failures [20]. Empirically, the material is widely regarded as being resistant to mould and insects on account of the alkalinity of the lime [21].

The principal concerns of PC concrete durability include freeze–thaw action, sulphate attack, alkali-aggregate reaction, chloride penetration and carbonation. Considering the lack of tri-calcium aluminate, silica based aggregate or steel reinforcement in the hemp concrete, it was considered that freeze–thaw action, salt crystallization and biodeterioration were amongst the most likely aggressors for the hemp concrete that have not been widely researched.

In relation to freeze:thaw, the ability of a mortar to resist freeze:thaw action partly depends on its pore structure being able to withstand strain caused by volume changes brought about by water freezing. Botas et al. (2010) reviewed the freeze:thaw resistance of lime and lime:cement mortars and noted that, as lime hydraulicity increased, resistance to freeze:thaw decreased likely due to the presence of smaller pores [22]. They also observed that, despite increasing open porosity, air entraining agents did not improve mortar resistance to freeze:thaw. The lime:cement mortars however displayed a greater resistance, as the effect of their superior mechanical strength supercedes the pore structure characteristics. A “wall mixture” hemp-lime concrete resisted 20 cycles of severe freeze–thaw (less than 1% loss in apparent volume) but it was noted that overly-hydraulic or unsuitable limes altered after two cycles [9 referring to 23]. Further research indicates that 25 freeze–thaw cycles does not have a negative influence on the compressive strength of the concrete [23].

Soluble salts greatly limit the durability of porous building materials. The performance of hemp-lime concrete following salt exposure has not yet been reported. This paper investigates the performance of hemp-lime concrete following exposure to sodium chloride (NaCl), one of the most common salts found in buildings and one of the main causes of material decay. Several theories exist on the mechanism of salt damage in inorganic porous materials [24]. Lubelli et al. (2006, 2010) studied NaCl in mortar and showed crystallization of salt layers on pore walls [25,26]. However, under the salt layer, most of the distinguishable pores appear empty. Benavente et al. (2004) observed that NaCl crystallizes heterogeneously on pore walls (of porous stone), and that there is a strong interaction between the salt and the pore wall [27].

2. Materials and methods

2.1. Materials

A hydrated lime (CL90s—calcium lime) and a hydraulic lime NHL 3.5 complying with EN 459-1 [28] and Portland cement (CEM I) complying with EN197-1:2011 [29] were used (only the builder's mix includes PC). The “commercial mix” includes a proprietary, lime-based binder with hydraulic additions developed for use with hemp. Its composition is not disclosed by the manufacturers for commercial reasons. 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 [3,4]. 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 α 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 water retainer investigated is modified hydroxypropyl methyl cellulose.

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

Six mixes were studied only differing in the binder composition as set out in Table 2. As each binder has a different water demand which depends on its composition, the water content could not be kept constant. Therefore, it was based on

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

Composition, amorphousness and surface area	GGBS	Metakaolin
SiO ₂	34.14%	51.37%
Al ₂ O ₃	13.85%	45.26%
CaO	39.27%	–
Fe ₂ O 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

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 for a good mixture [9].

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 [10,16] while others form a slurry with water and binder before adding the hemp [13,14]. A preliminary investigation revealed that, in the lime:pozzolan concretes, wetting the hemp before the addition of binder increases water demand and does not impart significant benefits to the properties measured [8] 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 $\frac{3}{4}$ 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.

An amount of concrete was weighted to ensure a dry density of c. 360 kg/m³. 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 $\pm$ 3 °C temperature and 55% $\pm$ 10% relative humidity. The effect of the curing conditions on the concrete is discussed in other research [30]. 100 mm cubes were moulded for compressive strength, freeze/thaw cycling and salt exposure and 100 * 100 * 400 prisms for flexural strength.

2.4. Microstructure

The microstructure of the concretes was investigated using a Tescan MIRA Field Emission Scanning Electron Microscope. 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. In addition, as the rate of hydration and pozzolanic reaction affect setting and strength development, the formation of hydrates in lime:pozzolan pastes was studied at 1, 3, 7, 14 and 28 days.

2.5. Compressive strength

As there is no standard procedure for the measurement of unconfined compressive strength of hemp-lime concrete, the test was guided by EN 459-2 [31] and EN 196-1 [32] with a loading rate of 50 N/s. Typically, the concrete does not break but continuously deforms therefore, the ultimate strength was set as the stress at which the stress/strain curve departs from linear (Fig. 6). Testing time was typically between 1 and 2 min. Glouannec et al. (2011) observed that geometry of the samples clearly influences the specimen's behaviour however cylinders and cubes exhibit similar ultimate compressive strength [33].

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% calcium Lime, 20% NHL3, 10% PC	2	1	3.1
Commercial mix	CM	100% commercial binder	2	1	2.9
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% metakaolin, 0.5% methyl cellulose	2	1	3.1

2.6. Flexural strength

The flexural strength was guided by EN 196-1 [32]. Adjustments were required to accommodate the behaviour of the concrete. The load was applied normal to the direction of compaction at a rate of 10 N/s. Large specimens were tested to ensure that the behaviour was representative of the concrete and not unduly affected by the larger particle size of the hemp compared to mineral aggregate.

2.7. Resistance to freeze–thaw

Currently, there are no standards to measure the resistance of lime mortars or hemp concretes to freeze:thaw action therefore, the test was guided by EN 15304:2010 [34]. Nine month concretes were subject to 10 freeze–thaw cycles between –15 and 20 °C.

Near saturation conditions provide the severest conditions for freeze:thaw action as the effect of expanding ice will be most detrimental. Therefore, the samples were soaked for 48 h prior to freezing, time by which they had absorbed 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 h 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. The 2.5 month limit was selected so that samples were fully dry and testing was undertaken at 1 year. Finally, the compressive strength was determined and compared to those of reference samples and 1 year concretes. The reference samples were soaked for 48 h and stored in polythene bags during testing to protect them against drying (EN 15304:2010); they are used to determine whether deterioration is due to freeze:thaw action or to water saturation during testing.

2.8. Resistance to salt exposure

No standards currently exist to test hemp-lime concrete on salt exposure. 9-month old concretes were subject to salt weathering in a SC1000 Open Lid Salt Fog Chamber. A 5% (or 0.86 M) NaCl solution was evenly dispersed as small droplets through nozzles into the chamber for 12 h. This was followed by 12 h of drying. The concretes underwent 4 weeks of cycles (the first two weeks at 20 °C and the remaining time at 40 °C). They were then allowed to dry for 2 months and their compressive strength determined. Four specimens of each concrete were tested. In order to evaluate the resistance of the concrete to salt exposure, the compressive strength after salt exposure was compared to that of the reference samples and the concrete values at 1 year. Comparison with the reference sample was used to determine whether deterioration is due to salt action or to water saturation during testing.

2.9. Biodeterioration

All the lime hemp concretes investigated were inoculated repeatedly with a high concentration of a mixed culture of microorganisms at 2 years. The microorganisms in the inoculum were typical organisms found in soil and in the air including the fungi *Aspergillus* and *Penicillium* and the bacterium *Bacillus*. The concretes were stored in a humidity chamber at 30 degrees centigrade and 80% relative humidity for 7 months. Intermittently the concretes dried out and were remoistened.

3. Results: strength and durability of hemp-lime concretes

3.1. Microstructure

In all concretes, SEM analysis evidenced good adhesion at the interface showing hemp particles well coated with scalehohedral calcium carbonate (carbonated lime) and/or hydrates.

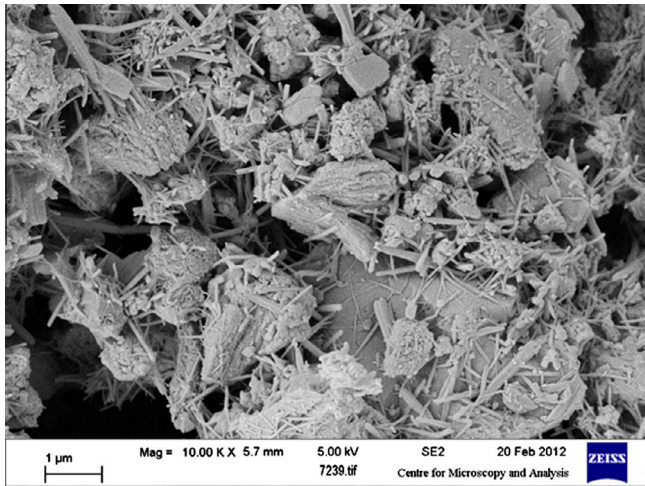


Fig. 1. Hemp interface in a commercial binder concrete at 6 months including abundant hydrates.

There are significant microstructural differences at the hemp interface in the different concretes at 6 months: the commercial binder includes abundant needle-shaped hydrates (Fig. 1) while the builder's mix shows a smaller amount of hydrates (Fig. 2) and the lime:pozzolan binders are largely carbonated with a very small amount of pozzolanic hydrates (Figs. 3 and 4). This indicates that the commercial binder has a significant hydraulic content. The methyl cellulose water retainer slightly increased the amount of hydrates in lime:pozzolan concretes; is discussed in other research [8] and suggests that retaining water by the water retainer has enhanced pozzolanic hydration.

It was noted that, in lime:pozzolan pastes, hydrates appear early (at 24 h of curing) and their morphology changed over time, from predominantly needle-shape at early ages (24 h) to sponge and gel types at later ages [35]. As aforementioned, the hemp interface in lime:pozzolan concretes is largely carbonated with little or no hydrates, while hydrates are found in the bulk paste. This was attributed to both the high water suction of the hemp and the water soluble hemp constituents inhibiting hydration of the lime:pozzolan binder at the interface [35].

A wide distribution of pore sizes was evident in all binders. At a 30,000 $\times$ magnification, most pores ranged from c. 200 to 2 µm. In

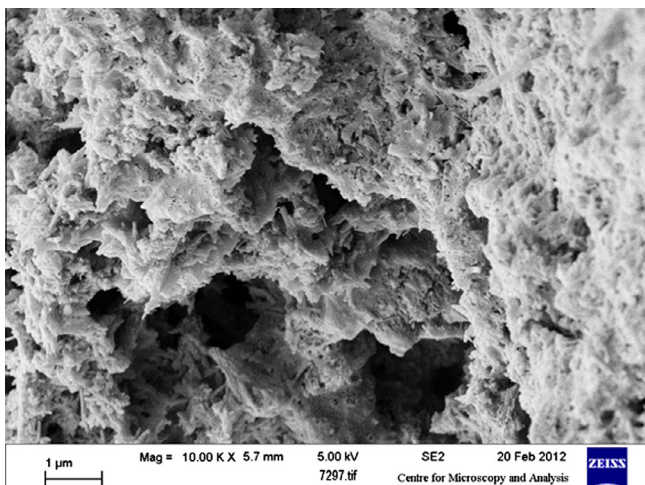


Fig. 2. Partially carbonated, hemp interface in a builder's binder concrete at 6 months including some hydrates.

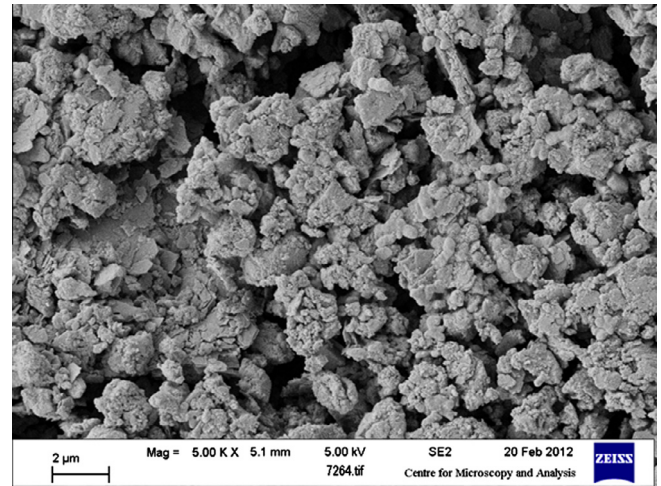


Fig. 3. Hemp interface in a metakaolin binder concrete at 6 months which appears mainly carbonated.

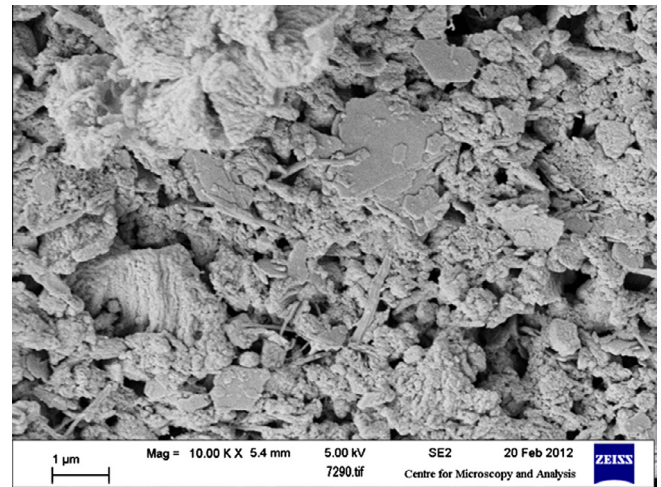


Fig. 4. Hemp interface in a metakaolin binder with methyl cellulose concrete at 6 months featuring strong carbonation and some needle-shaped hydrates.

the commercial binder, needle-like hydrates were evidenced growing into pores thus reducing pore size.

3.2. Mechanical behaviour of hemp-lime concrete under compression

The mechanical behaviour of the hemp concrete is similar to that of timber [36,37] and other cellular solids [38]. The concrete continuously compresses on load application (Fig. 5), and the deformation is similar to that shown by [17] whereby the stress-strain curve can be divided into three regions: linear, plateau and densification (Fig. 6). Initially, the curve is linear and the concrete behaviour is quasi-elastic [14]. Later, a cracking noise and binder powder appear indicating that the binder is failing. The behaviour then departs from linear and deformation significantly increases for a small stress increase (plateau region). During this phase, the hemp cells begin to collapse and the intensity of the cracking noise grows indicating that binder failure is becoming greater. Following the plateau region, there is a strain densification where the stress increases rapidly in relation to the strain. This is attributed to the collapse of the hemp particles [17] which increases the stiffness of the concrete as the contact between cell walls provides additional mechanical strength. The cube specimens deform in a differ-



Fig. 5. Typical failure of hemp-lime concrete under an axial compressive load.

ent manner to cylinders which typically show a decrease in stress rather than strain densification in the final stage. In this research, the point at which the mechanical behaviour departs from a linear stress/strain curve is considered as the ultimate strength, similarly to [17].

3.3. Compressive strength

Compressive strength varied between 0.02 and 0.04 MPa at 5 days and 0.29 and 0.39 MPa at 1 year (Fig. 7) falling within the range observed by the aforementioned authors. Most strength develops between 5 and 28 days mainly due to drying and hydration.

The metakaolin concrete shows the highest strengths at 3 and 6 months. A slight strength reduction is observed between 3 months and 1 year (metakaolin concrete) and 6 months and 1 year (metakaolin with water retainer). Similarly, strength loss has been reported in lime:metakaolin pastes [39,40], lime:metakaolin hemp concretes [41] and natural hydraulic lime mortars [42] being attributed to changes in the morphology of the hydrates. The GGBS concrete achieves the greatest compressive strength (not significant, $p < 0.1$) at 1 year despite showing a slower rate of strength gain at earlier ages. The strength drop at 6 months is likely an error as the overall trend is increasing strength between 3 months and 1 year. During the first 6 months, the water retainers increase the compressive strength of the pozzolan concretes. This is likely due to extra hydration resulting from the water retainer holding a greater amount of water in the binder [8]. However, at 1 year, the strength enhancement by the water retainer is no longer evident.

Despite its cement content, the builder's mix is the slowest to develop strength and, at 1 year, its compressive strength is slightly

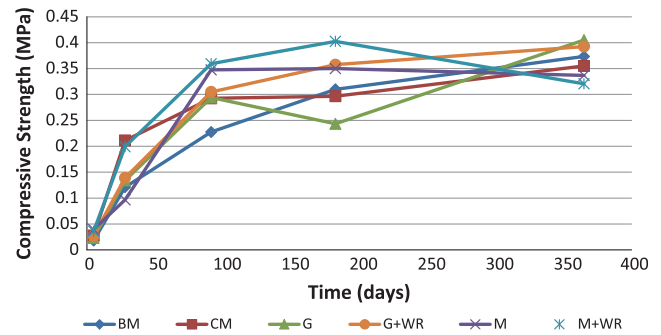


Fig. 7. Compressive strength of hemp-lime concretes over time. 80% of COVs < 20%. BM – builder's mix; CM – commercial mix; G – GGBS mix; G + WR – GGBS binder with water retainer; M – metakaolin mix; M + WR – metakaolin with water retainer.

lower than that of the other concretes. As expected, the commercial mix gains strength quickly due to the early formation of hydrates. However, its strength development after 28 days is slow. Similarly, Nguyen (2010) and Hirst et al. (2010) found that strength in commercial (hydraulic) binders did not increase significantly after 28 days [13,16]. In this research, commercial concretes which were immersed in water after curing nearly doubled their strength (reaching 0.63 MPa at 1 year), indicating that a low mixing water content/dry curing conditions inhibited binder hydration halting strength development [30].

The results suggest that the strength of hemp-lime concrete is not the sole function of binder hydration. Factors such as carbonation contribute towards strength at later ages [10]. The results agree with Ngoyen (2010) whereby natural hydraulic lime binders (NHL2/3.5) were found to reach higher compressive strengths than commercial binders of greater hydraulicity at 90 days [16].

3.4. Mechanical behaviour and flexural strength of hemp-lime concrete in bending

As the flexural load is applied, the concrete bar bends as shown in Fig. 8. Following the maximum flexural strength, a crack between the underside of the sample and prism's main axis develops.

The flexural strength of the concretes at 3 months and 1 year can be found in Table 3. The results are within the range previously reported by the aforementioned authors. At 3 months, the flexural strength of the builder's, commercial and lime:pozzolan with water retainer concretes were broadly similar ranging between 0.11 and 0.13 MPa. The lime:pozzolan concrete yielded lower values ranging between 0.06 and 0.09 MPa.

Between 3 months and 1 year, the flexural strength increase is larger in the commercial binder concrete. Similarly to compressive strength, water retainers increase the flexural strength of hemp concretes with lime:pozzolan binders. The flexural strength in-

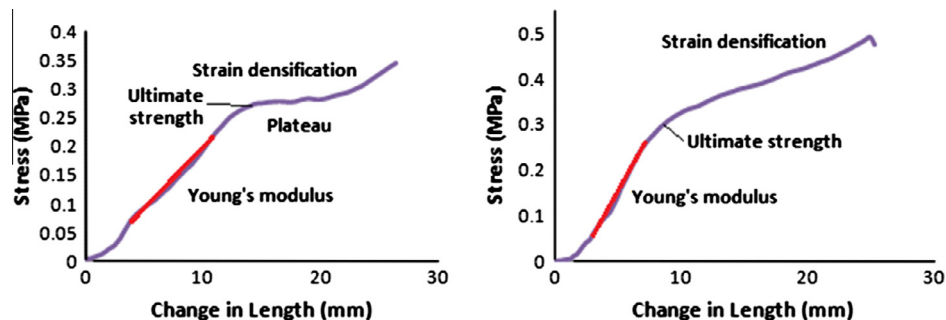


Fig. 6. Two representative diagrams of the typical behaviour of hemp-lime concrete under a compressive axial load. The left graph has a more distinct plateau region (large deformation for small increase in stress) than the right graph.



Fig. 8. Typical deflection of hemp-lime concrete in bending.

Table 3
Flexural Strength of concrete at 3 months and 1 year.

Name	Flexural strength @ 3 months	COV	Flexural strength @ 1 year	COV
Builder's mix	0.12	12.46	0.13	40.70
Commercial mix	0.11	10.69	0.19	17.56
GGBS	0.09	35.36	0.14	12.86
GGBS + WR	0.13	8.06	0.20	14.24
Metakaolin	0.06	18.25	0.10	33.06
Metakaolin + WR	0.11	3.44	0.14	24.05

crease between 3 months (0.06–0.12 MPa) and 1 year (0.1–0.2 MPa) is proportionally greater than the compressive strength increase. Similar trends have been found in lime mortars [43] and lime:cement mortars [44].

3.5. Durability: resistance to freeze–thaw

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 and mass were measured following freeze:thaw damage, and the values compared to those of 1 year old and reference concretes (Table 4). Carbonation of lime should confer similar properties to the concrete as in lime mortar; Waldum (1999), noted that a lime mortar achieved equivalent weather resistance

Table 4
Weight and compressive strength after freeze:thaw action.

Sample	% weight loss	% compressive strength loss	
		Relative to 1 year concrete	Relative to reference samples
BM	–0.23	10.94 ^b	14.30 ^b
CM	+7.2	–60.56 ^a	9.31
G	–2.6	34.90 ^b	31.87% ^b
G + WR	–1.6	24.84 ^b	–4.70
M	–4	59 ^b	60 ^b
M + WR	–2	–19.02	–1.10

^a $P < 0.1$.

^b $P < 0.3$.

(including exposure to freeze:thaw conditions) as a hydraulic lime mortar [45]. It is therefore evident that carbonation should contribute towards durability of the concrete. Furthermore, a reduction in the porosity of the binder due to the increase in size of CaCO_3 compared to $\text{Ca}(\text{OH})_2$ [46] should reduce the quantity of water absorbed and thereby minimise vulnerability to freeze–thaw action.

As it can be seen from the results, freezing conditions have a stronger impact on lime:pozzolan concretes, with a greater reduction in compressive strength and a higher weight loss for both pozzolans, in particular metakaolin (Tables 4 and 5). In relation to mass loss, the metakaolin and GGBS concretes show the highest weight loss while the builder concrete shows a negligible value and the commercial concrete increases weight due to additional hydration (Table 4). The water retainer reduced weight loss.

The commercial concrete substantially increases strength (60.56%) during freeze–thaw cycling relative to the 1 year old concrete (Table 4). This is due to additional hydration, taking place during the immersion episodes of cycling, increasing the amount of hydrates [30]. Slight compressive strength reductions are observed in the freeze:thaw samples when compared to the reference samples, suggesting that freeze:thaw action has a small effect on the commercial binder.

The GGBS and metakaolin concretes show significant strength losses after freeze:thaw action. The addition of water retainer improves resistance to freeze:thaw action and the reduced strength loss is likely due to enhanced hydration (Table 4). Water retainers increase the quantity of small pores which are believed to undermine freeze:thaw resistance therefore, the improvement observed is probably due to the water retainer lowering water absorption and enhancing hydration.

According to the results, the commercial binder concrete and, to a lesser extent, the builder's mix are more freeze:thaw resistant than the lime:pozzolan concretes. This is likely due to the higher mechanical strength of their hydraulic binders and their lower water absorption (they contain smaller, hydrate-filled pores) resulting in less water available to induce freeze:thaw damage.

3.6. Durability: resistance to salt exposure

Sodium chloride exposure during one month does not appear to damage the compressive strength of any concrete (Table 5). The metakaolin with water retainer concrete (showing a strength decrease) is an exception however, this is likely an inconsistency as all the other pozzolan concretes are consistently undamaged. Cracks were not visible following salt exposure, although the concretes became soft when wet due to water immersion and hardened again when dry. Similarly to freeze–thaw, the commercial concrete shows a significant increase in compressive strength following salt exposure and this is attributed to additional hydration due to the presence of water.

All concretes show an increase in weight due to the crystallization of salt within their pores. The salt content of the lime:pozzolan concrete is the lowest (c. 6% weight increase for the GGBS and metakaolin concretes). In contrast, the concretes with smaller pores (commercial, builder's and lime:pozzolan with water retainer) show higher salt contents (c. 8–9% weight increase for the builder and pozzolan with water retainer concretes). The commercial binder exhibits the highest weight gain of 16% which is due to both the presence of salt and additional hydration. The weight gain results suggest that small pores facilitate salt crystallization. This agrees with [47] who found that chlorides preferentially crystallized in small pores ranging between 0.1 and 1 μm .

SEM/EDX analyses revealed that the salt mainly crystallises in layers, and that the salt does not penetrate into pores under the

Table 5

Compressive strength loss of sample due to freeze/thaw and salt exposure cycling.

Sample	Concrete @ 1 year (Mpa)		Soaked concrete (Mpa)		Freeze/thaw concrete (Mpa)		Salt exposure concrete (Mpa)	
	COV		COV		COV		COV	
BM	0.37	10.1	0.39	6	0.33	16.9	0.43	6.8
CM	0.36	9.3	0.63	20.4	0.57	13	0.81	13.8
G	0.41	15.9	0.39	15.9	0.26	26.8	0.37	32.0
G + WR	0.39	17.7	0.28	20.9	0.30	17.6	0.37	6.0
M	0.34	6.3	0.35	21.4	0.29	29.5	0.40	8.2
M + WR	0.32	2.5	0.38	16.2	0.38	3.3	0.28	45.5

layers (Fig. 9). This agrees with mortar and porous stone results by Lubelli and coworkers [25,27].

The salt layers of NaCl, varying in extent and approximately 2 μm thick were identified with EDS (Fig. 10). Their morphology ranges from smooth to an agglomeration of regularly shaped cubic crystals (Fig. 11). Less frequently, single cubic or needle shaped crystals are also observed (Fig. 12). No difference in salt crystallization morphology was noted for the different binders.

The lack of salt crystallization damage in the concrete can be due to the short-term salt exposure. However, the high ductility of the concrete, accommodating the stresses imposed by the salt, is probably responsible for the lack of damage by salt crystallization. In addition, the hemp concrete pores may have a weaker affinity to salt than stone and mortar pores due to the organic nature of the aggregate, and this may lower the impact of salt action.

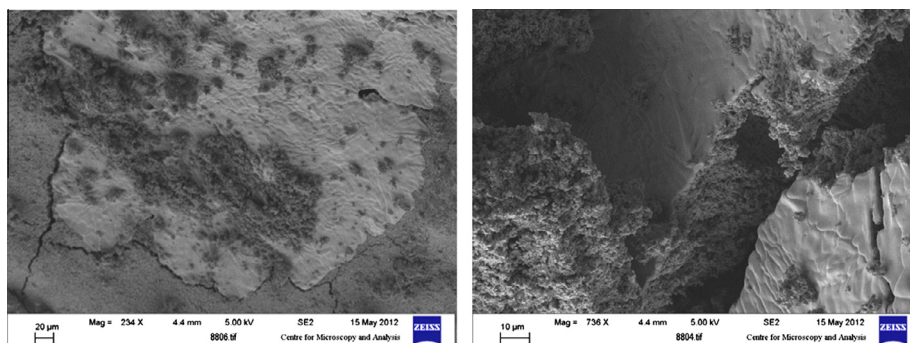


Fig. 9. Left image: typical salt layer on the binder surface. Right image: side view of salt layer crack showing that the salt does not penetrate into the binder.

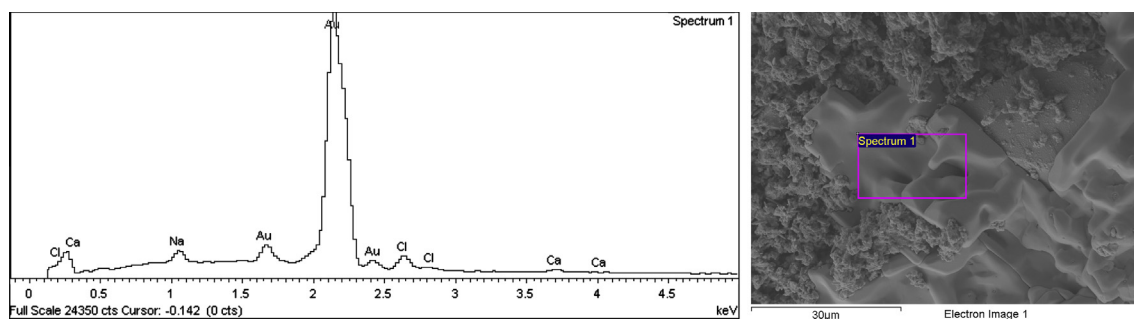


Fig. 10. Salt layer and its composition (EDS) (large peak resulting from gold coating).

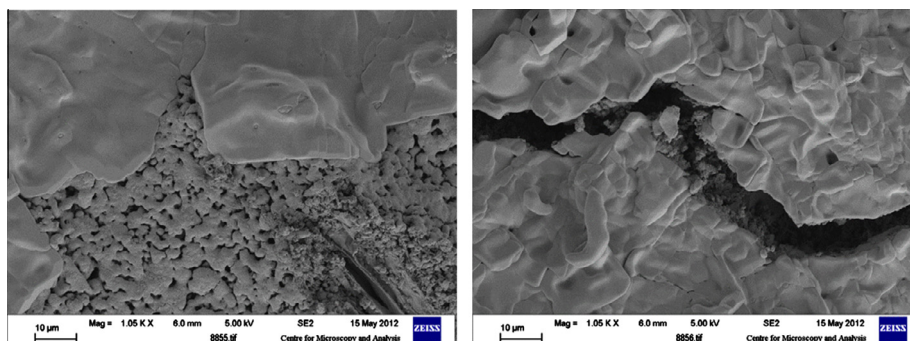


Fig. 11. SEM micrographs of salt layers with varying morphology. Left image: smooth salt layer. Right image: agglomeration of cubic NaCl crystals forming a layer.

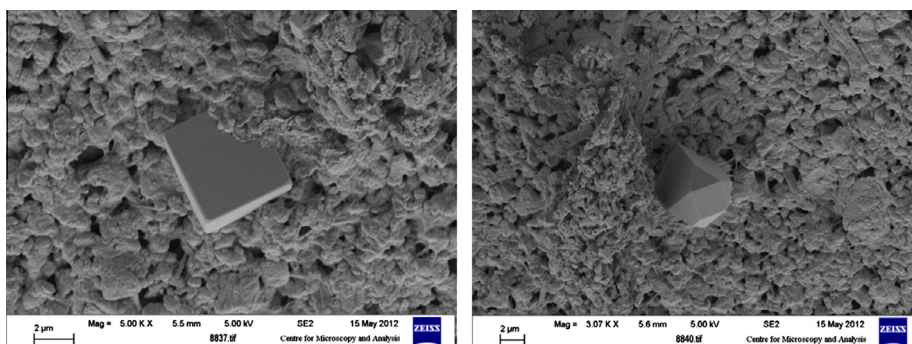


Fig. 12. Isolated NaCl crystals on the binder surface.

3.7. Durability: resistance to biological deterioration

As aforementioned, hemp concrete is widely regarded as being resistant to mould and insects on account of the alkalinity of the lime [21]. However, there are many microorganisms that grow well in alkaline conditions. Following inoculation and despite repeated efforts to keep them moist, the microorganisms frequently dried out and died during the seven months of testing. Within two months of the first inoculation, the microorganisms had died. None of the concretes showed any sign of deterioration despite a heavy inoculation of microorganisms and repeated inoculations after populations died off. This is due to insufficient available nutrients to support growth and/or unsuitable environmental conditions. These initial results suggest that hemp concrete is resistant to bio-deterioration when initial high humidity alternates with periods of drying, conditions which relate well to those on site in Europe. Research is ongoing into microbial attack in extreme conditions.

4. Conclusion

This paper investigates the effect of binder type on mechanical strength and durability (resistance to freeze–thaw, salt exposure and biodeterioration). It compares hemp–lime concretes made with hydrated lime and pozzolans (GGBS and metakaolin) to those including hydraulic lime and cement (commercial or site binders containing PC).

There are significant microstructural differences at the hemp interface in the different concretes at 6 months; the commercial binder displays abundant needle-shaped hydrates while the builder's mix shows a smaller amount of hydrates and the lime:pozzolan binders are largely carbonated with a small amount of pozzolanic hydrates. There is a small increase in hydration products evident in the lime:pozzolan binders with water retainer compared to those without.

The compressive strength results indicate that at early ages, the commercial binder with greatest binder hydraulicity displays the highest strength. However, as the concrete ages, other factors such as carbonation contribute towards strength and the lime:pozzolan concretes achieve similar strength to those including hydraulic lime and cement at 1 year. Water retainers improved early strength of lime:pozzolan hemp concrete. This is attributed to an increased amount of mixing water retained in the binder resulting in enhanced hydration.

In relation to flexural strength, the concrete with lime:pozzolan binders achieved lower strengths than the more hydraulic commercial binder at 3 months and 1 year; and water retainers improved the flexural strength of the lime:pozzolan concrete.

The freeze:thaw resistance of hemp concretes is a function of the hydraulicity of the binder: the binders of greatest hydraulicity (commercial and builder) show superior freeze:thaw resistance despite containing smaller pores. This suggests that the superior mechanical strength of the hydrates supersedes the pore structure characteristics of the binder with regard to freeze:thaw resistance. The concretes with the most hydraulic binders may also benefit from reduced water absorption resulting in less water available to induce freeze:thaw damage. Water retainers were found to improve freeze:thaw resistance of the lime:pozzolan binder.

Despite the high concrete porosity (which ensured near saturation conditions during testing) and the salt growth determined by SEM, the concretes did not suffer significant deterioration in a salt environment following 1 month exposure. The lack of salt damage of hemp–lime concrete is partially attributed to the high ductility of the pore walls accommodating expansive salt crystallization pressures. Salt crystallization was greater in the binders with smaller pore sizes.

The resistance to repeated heavy microbial inoculations indicates that hemp concrete is resistant to biodeterioration in environmental conditions close to those on site.

The improvements in strength development and resistance to freeze:thaw action of the binders with water retainers highlight the potential of additives to improve strength and durability of hemp concrete with lime:pozzolan binder.

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