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EFFECT OF TESTING VARIABLES ON THE HYDRATION AND COMPRESSIVE STRENGTH OF LIME HEMP CONCRETE

S. Pavía[1]*, R. Walker[1], J. McGinn[1]
[1]Dept of Civil Engineering, Trinity College, Dublin 2, Ireland
*Corresponding author; e-mail: pavias@tcd.ie

Abstract

This paper investigates the effect of testing variables including curing conditions (65% *vs*>95% RH), time of demoulding and specimen geometry (cylinder *vs* cube) on the compressive strength of hemp concrete. It studies hydration in the concrete's microstructure and measures compressive strength development at intervals between 1 day and 1 month. Moulding time and curing conditions influence drying and therefore may impact binder hydration and consequently strength evolution. Specimen geometry may affect drying and can also determine how strain builds up in the concrete and thus when failure occurs.

The paper concludes that curing hemp-lime concrete with hydraulic content (50%CL90: 50%CEMII) at high RH (>95%) lowers compressive strength (65.4% drop at 10 weeks). It is unclear why this happens, as the presence of water vapour during curing at high RH should enhance hydration and consequently increase strength. It was also found that delaying specimen demoulding increases compressive strength of the CL90:CEMII concrete (22.9% increase at 10 weeks), probably due to the presence of moisture for longer enhancing hydration. The NHL3.5 concrete shows the same trends although the results are not statistically significant probably due to lack of sensitivity of the measuring instrument at low strength values.

The specimen geometry does not significantly impact the ultimate compressive strength of hemp-lime concrete however, it affects behaviour in compression. Initially, cylinders and cubes deform on load application up to a similar yield point. However, following this yield point, the cylinders fracture showing a more brittle behaviour while the cubes keep crushing to finally experience an additional stiffness produced by mechanical bridges being formed between opposing cell walls.

Keywords:
Lime hemp concrete; compressive strength, hydration, curing conditions, demoulding, geometry.

1 INTRODUCTION

Lime hemp concrete is a sustainable and carbon negative building material. It is made with a lime based binder and hemp which can replace high embodied energy materials in certain applications, lowering the environmental impact of construction.

It is a light-weight material with average wall density ranging between 275 and 800kg/m^3. It typically exhibits low strength (between 0.2 and 1.2MPa)[Evrard 2003; Cerezo 2005; De Brujin 2008; Murphy 2010; Hirst 2010; Arnaud 2012]and is normally used in combination with a load-bearing frame. The concrete has an open pore structure that contributes to its high water vapour permeability (water vapour diffusion resistance factor 4.85 ± 0.24 [Evrard 2005]) and high water absorption coefficient by capillary action (0.0736 ±0.0045 kg/m^{2}s$^{1/2}$ [Evrard 2008] and 0.15kg/ m^{2}s$^{1/2}$ [De Brujin 2009].Properties which make it compatible with breathable construction materials. Its thermal performance is its most outstanding physical characteristic combining a high thermal capacity (between 1000 J/kgK[Le Tran 2010] and 1560±30 J/kgK [Evrard 2008] and low thermal conductivity (0.05-0.12 W/mK [Daly 2012].

The lime-hemp concrete properties depend on several factors including: binder and hemp type, binder:hemp ratio, mixing water content, density, shiv properties, manufacturing method, curing conditions and age. On account of the novelty of the material and the wide range of factors affecting its properties, investigation is required to competently ascertain its properties.

This paper investigates some testing parameters that impact the material properties. It investigates the effect of curing conditions (65% *vs*>95% RH), time of demoulding and specimen geometry (cylinder *vs* cube) on the compressive strength of different types of hemp concrete.

Compressive strength is determined by drying and hydration/carbonation. Moulding time and curing conditions influence drying and therefore may impact binder hydration/carbonation and consequently strength evolution over time. Specimen geometry may also affect drying and can also determine how strain builds up in the concrete and thus when failure occurs.

Also, competition for mixing water between the binder and hemp particles (resulting in the binder not fully hydrating)can undermine strength.

High-humidity curing, long periods before demoulding and small surface area of specimens can result in longer drying of mixing water affecting hydration and compressive strength.

The effect of the binder on compressive strength has yielded varying opinions. Hirst [2010] found that the concrete strength does not increase with the strength of the binder. Nevertheless higher compressive strengths are usually obtained for cement-rich binders [Murphy 2010; de Bruijn 2009]. Nguyen [2010] found that, at 90 days, lime binders reached higher compressive strengths than commercial binders that are typically more hydraulic. The authors [Walker 2014] observed that strength development of hemp concrete was a function of the binder's hydraulic strength up to 6 months but, at 1 year, all concretes displayed a similar compressive strength (0.32-0.41MPa). The authors however noticed that the most hydraulic binders did not fully hydrate, and later reintroduction of water increased hydration significantly enhancing strength.

The curing environment (temperature and humidity) impact drying and speed of carbonation/hydration which lead to hardening, consequently affecting strength development and ultimate strength.

Following manufacture, lime-hemp concrete is placed in a constant environment of temperature and relative humidity (RH) until the time of testing.

Increasing temperature usually enhances carbonation and hydration rates (speeding strength development) while low temperatures can impede hardening and the development of strength.High temperatures may speed up drying. However, hemp concrete is typically cured at ambient temperature (approximately 20℃).

Hemp concrete is typically cured at relative humidity ranging from 50 to 65% although a wide variation has been reported including 20±1℃ and 60±5%RH [Hirst 2010];20℃ and 60%RH [Evrard 2006]; 22-26℃ and 30-60%RH [Colinart 2012] and 20℃ and 75%RH [Nguyen 2009]; 20℃ and humidity saturation [Nozahic 2012].

Arnaud [2012] determined 20℃ and 50% RH as the optimum curing conditions for the evolution of strength of four hydraulic binders at 28 days. Higher and lower RHs (30%, 75% and 90%) were found to reduce mechanical strength.

Retention of samples in their moulds during curing affects early moisture content and drying rate of the concrete, variables which determine hydration/carbonation of the binder which impacts early strength development. Early strength is important as it relates to building speed and the ability of the concrete to initially stand its own weight when it is heaviest (at highest moisture content).

Demoulding refers to the removal of samples from their moulds. The effect of time of demoulding has not been widely investigated. Demoulding has widely ranged, with some authors demoulding immediately after manufacture [Walker 2014] and others keeping the concrete in the moulds for the full duration of curing with only 1 or 2 faces exposed [Arnaud 2012]. Demoulding after 1 to 6 days is a popular option used by several authors: 1 day [Nguyen 2009]; 1 day followed by sealing until 5 days [Colinart 2012]; 2 days [Nozahic 2012] and 6 days [Hirst 2010].

As a result of the high moisture permeability of the concrete, fast drying can occur when the specimens are quickly removed from their moulds and left to cure unwrapped at 60% RH. As aforementioned, fast drying reduces available water and halts and retards hydration of binders with quick set.

Specimen geometrymay affect ultimate strength. Previous authors have found that using hydraulic limes, half prisms are on average 37% stronger than cubes, and that this may be due to the ratio of length to height which determines how strains build up in the specimen [Patterson 2012]. In PC mortar and concrete, cubes are reported to be stronger than cylinders. A factor of 1.2 is used to convert cylinder to cube strength for normal strength concrete. However, this factor becomes smaller as strength increases so that, for high-strength concrete, the influence of shape is much less significant [Yi 2006 citing Gonnerman 1925, Gyengo 1938, Murdock and Kesler 1957]

In PC composites, it has also been found that strength is an inverse function of the specimen size for cubic and prismatic samples whereas for larger cylinders the effect of size on strength is almost negligible [Yi 2006; del Viso 2008].

In hemp-lime concrete, specimen geometry widely varies in research –cylinders, blocks and small scale walls of varying scales have been investigated. Some examples include 50mm cubes [Elfordy 2008; Collet 2013]; 40*40*160mm prisms [Nozahic 2012]; 300*300*160mm blocks [Colinart 2012];100mm(d) *50mm(h) cylinders [Collet 2013], 190mm (d)*35mm (h) cylinders [Evrard 2006]; 100mm cubes [Walker 2014]; 160mm (d)*320mm (h) cylinders [Arnaud 2012]; 150mm (d)*300mm (h) cylinders [Hirst 2010]. Collet [2004] notes that 50mm cubes are representative of the material however, cylinders are typically more common for compression testing although 100mm cubes [Elfordy 2008; Walker 2014] have also been used.

Glouannec [2011] compared different geometry specimens and observed similar compressive strengths although their behaviour on load application differed. Tall specimens (height>width) showed a clear fracture plain, and their maximum compressive strength was followed by a decrease in stress. In contrast, stout specimens (height<width) crushed continuously.

2 MATERIALS AND METHODS

2.1 Materials

Two binders were investigated: 50%CL90s / 50% CEMII binder and a 100% NHL3.5. Hemp shiv was supplied by La Chanvrière De L'aube in central France.

2.2 Manufacture (mixing, curing and compaction)

The proportions for the mixes in both cases were 1:2:3.1 hemp:binder:water. The binder was dry mixed by hand to ensure it was homogenous. The binder and ¾ of the water were placed in a drum cement mixer and mixed for 2.5 minutes to form a slurry. The hemp was then gradually added along with the remaining water. The mixer was stopped half way through mixing to break up any clumps formed in the material. The total mixing time was 7 minutes.

Following the production of control mixes (as explained below), further specimens were prepared with varying testing variables including curing conditions, geometry and time of demoulding as presented in table 1. The specimens retained in moulds were coated with three layers of oil to facilitate removal.

For the preparation of control mixes, the concrete was weighed and put into 100mm cubic moulds in a single layer. The concrete was lightly compressed by hand as it was put into the mould and then immediately removed from the mould. Four specimens were made for each test. The samples had an initial wet density of 680kg/m^3. Following drying, the control concrete achieved an approximate density of 400kg/m^3 and 379kg/m^3 for the CL90:CEMII and NHL3.5 binders respectively. The control samples were removed from their moulds and transferred to a curing room at 20℃±2℃ and 60±5% RH until testing. Four specimens of each binder were fabricated with each of the 4 testing variables in table 1 and tested at 1 day and 1,2,4 and 10 weeks.

2.3 Compressive strength

Compressive strength was measured using a Zwick testing apparatus. The cubes were removed from the curing room at 1 day and 1, 2, 4 and 10 weeks and oven dried at 50℃for 24 hours prior to testing. Oven drying was necessary to measure early changes in strength development as samples up to 2 weeks are so wet (the CL90:CEMII and NHL3.5 concretes retain approximately 51% and 64% of the original mixing water respectively at 2 weeks), that they only compress under load application and consequently small changes in strength development are not discernible. Oven drying enhanced the sample's strength and allowed early changes in strength to be measured.

Tab. 1: Summary of variables in concrete specimens tested. Four specimens of each binder (CL90:CEMII and NHL3.5)were fabricated with each of the 4 testing variables in the table.Hemp:binder:water = 1:2:3.1. All dried for 24 hours prior to testing.

Testingvariables	Wetweight (g)	Geometry	Curingconditions	Time in mould (days)
1. Control	680	100 mmcube	20℃±2℃ 60±5% RH	0
2. 95% RH	680	100 mmcube	20℃±2℃ >95% RH	0
3. Mould	680	100 mmcube	20℃±2℃ 60±5% RH	70
4. Cylinders	1070 (tomaintain a wetdensityof 680 kg/m^3)	Cylinder d=100 h=200mm	20℃±2℃ 60±5% RH	70

Concrete strength arises from a combination of drying and binder carbonation/hydration. The contribution of drying is considered to remain the same for all dried samples and therefore the impact of binder hydration/carbonation can be seen in the increasing compressive strength.

No standards currently apply to hemp concrete thus the testing procedures of EN459-2 and EN196-1 were used to guide the test. The cubes did not break but continuously deformed in a plastic manner. Failure was considered as the point at which the stress/strain curve departs from linear behaviour.

Student's t-Tests were carried out to determine if the results were statistically significant ($P < 0.05$).

2.4 Microstructure

Investigating the microstructure of the concrete should reveal the presence of carbonates and hydrates that contribute to strength. The microstructure of the binder and the surface of the hemp aggregate were investigated using a Tescan MIRA Field Emission Scanning Electron Microscope (SEM). The samples were freshly fractured and covered with a gold coating in an 'Emscope SC500' plasma coating unit. Individual hemp particles were extracted from fractured surfaces and mounted on pin stubs prior to coating. Samples were sealed in air tight conditions until the analysis was undertaken.

3 RESULTS

3.1 Compressive strength and microstructure

Compressive strength increase (Fig. 1) is evident up to 28 days however, later, the increase was not statistically significant ($P>0.05$). This suggests that both binders achieved most of their entire compressive strength in the first month.

SEM analysis evidenced hydrates responsible for strength development at 1 day, increasing significantly by 1 month (figs 2-5). Needle-shaped hydrates were present in both concretes however, they were substantially more prolific in the CL90:CEMII binder than in the NHL3.5 binder (figs 2-5).

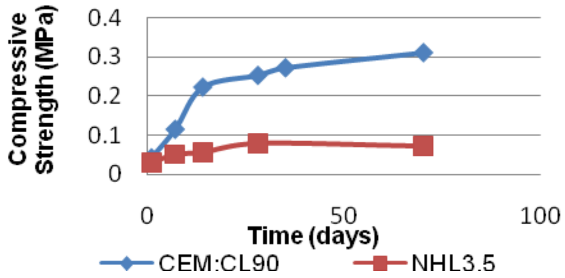

Fig. 1: Strength development of the concretes over time.

The CL90:CEMII concrete achieved a considerably greater strength than the NHL3.5 concrete(fig 1). The SEM results suggest that this is probably due to its greater hydraulic content (hydrates were much more prolific in the CL90:CEMII binder).

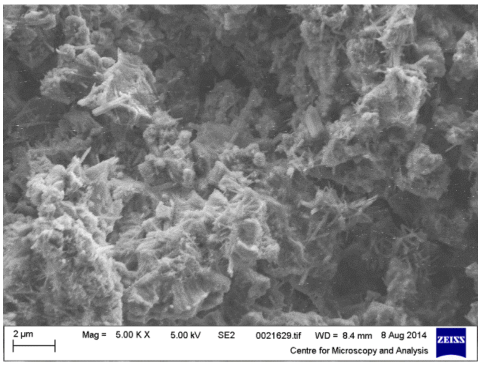

Fig. 2: SEM image of CL90:CEMII binder at 1 week showing significant, incipient, needle-shaped hydrates.

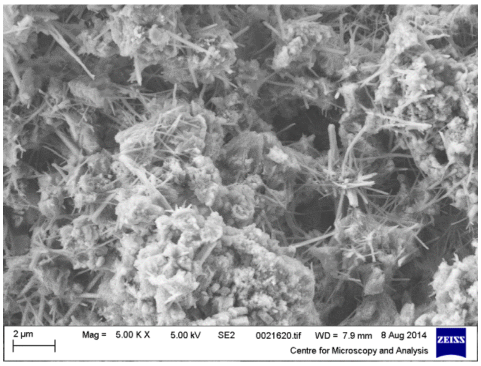

Fig. 3: SEM image of CL90:CEMII binder at 1 month including abundant large hydrates.

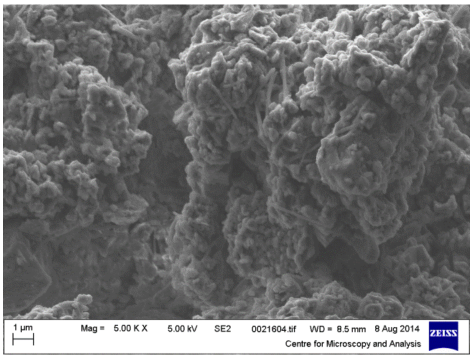

Fig. 4: SEM image of NHL3.5 binder at 1 week showing scarce, large, needle-shaped hydrates and carbonates.

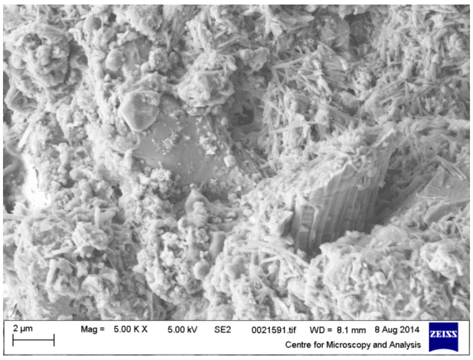

Fig. 5: SEM image of NHL3.5 binder at 1 month including significant hydrates and carbonates.

3.2 Effect of oven drying on compressive strength

As aforementioned, the concretes were oven dried to remove the high moisture content and be able to measure early strength changes. The compressive strength of the concrete is due to carbonation and hydration of the binder together with drying which increases stiffness at early ages. Strength contribution due to drying should be consistent for all samples independent of age or binder type.

The compressive strength of the NHL 3.5 concrete at 1 day is 0.03MPa and the SEM analysis evidenced some hydrates at this stage. This suggests that the contribution of drying towards compressive strength is less than 0.03MPa.

The strength of CL90:CEMII concrete specimens that were oven dried for 24 hours following 28 days of curing was compared with the strength of those not oven dried. The average compressive strength was 0.25MPa and 0.27MPa for the 28 day (non-oven dried) and 28-day oven dried respectively. The difference in results is not statistically significant ($P>0.05$). This suggests that oven drying at low temperatures, does not impact the strength performance of hemp concrete.

3.3 Effect of curing at high RH on strength

Curing the hemp-lime concrete at high RH (>95%) was found to reduce the compressive strength of the CL90:CEMII concrete at 10 weeks (fig 6.). The NHL3.5 concrete shows the same trend, although the results are not statistically significant. The lack of statistical significance may be on account of the little strength of the NHL3.5 concrete (0.07MPa) resulting in low measurement sensitivity of the testing equipment.

The findings are similar to those of Arnaud [2012] who observed that 90% RH during curing reduced mechanical strength of four hydraulic binders.

The CL90:CEMII binder shows significant hydrates at 1 month (fig 3). It is unclear why the presence of water vapour during curing at high RH does not contribute to binder hydration and consequently increase strength as it would in the case of mortars.

3.4 Effect of retention in moulds during curing

Retention of the concrete in its mould will delay drying, as moisture is blocked from escaping through the mould and drying is largely restricted to the uncovered sides.

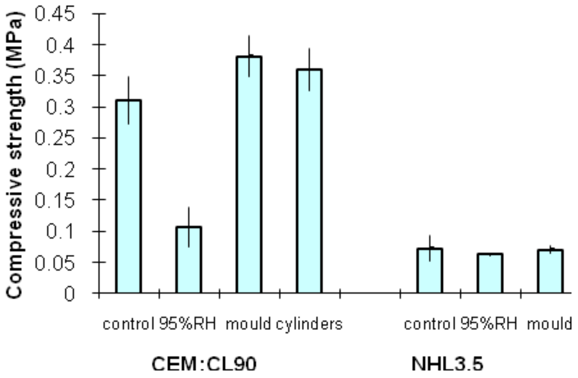

Figure 6. Effect of testing variables on compressive strength of concretes at 10 weeks. Control samples (100mm cube); cubes cured at >95% RH; cubes retained in moulds; cylindrical concrete specimens.

Retaining the hemp-lime concrete in its mould during curing was found to increase the compressive strength of the CL90:CEMII concrete at 10 weeks (fig 6). It is likely that the presence of moisture for longer periods (delayed from drying by the mould) facilitates the formation of additional hydrates.

The effect of retaining the NHL3.5 concrete in its mould during curing is not statistically significant. This may be due to lack of measuring instrument sensitivity at low strength values. However, it is also likely that that the presence of moisture is less beneficial to the NHL3.5 binder on account of its lower hydraulic content.

3.5 Effect of specimen geometry on strength

Specimen size and shape determine the surface area available for drying which may affect binder hydration/carbonation therefore compressive strength. For example, a 100mm cube has a larger surface area than a cylinder with a 100mm diameter and 100mm height and will consequently dry faster. As aforementioned, geometry also determines the ratio of length to height which dictates how strains build up in the specimen and hence its strength.

In order to establish the effect of geometry on strength and exclude the effect of drying, a comparison was made between the performance of a cube and a cylinder of CL90:CEMII concrete cured in their moulds to avoid the influence of drying (table 1).

The results (fig 6) indicate that the specimen geometry does not significantly impact the compressive strength. This agrees with Glouannec [2011] who observed similar compressive strengths for tall and stout specimens.

However, the results evidenced that geometry affects the concrete's behaviour in compression; a summary of the most representative stress vs strain results obtained is included in Figure 7.

As it can be seen from this figure, the cylinders fail following a high stress point or yield point, after which the stress drops (the concrete cannot longer sustain stress). In contrast, following a similar high stress point to that of the cylinders, the cubes continuously deform, showing a large plateau (region of increasing strain for small stress increase) followed by a raising branch where stress increases rapidly in relation to the strain. Elfordy [2008] attributed this to the irreversible compaction of the porous hemp shiv.

As discussed in Walker and Pavía [2014], the final behaviour of the cubes (stress increase) is produced when most hemp cells have collapsed and, as the cells are further compressed, contact between opposing cell walls occurs, resulting in the formation of mechanical bridges which lead to an increase in the stiffness of the material. A similar behaviour has been observed in other cellular solids [Daxner 2010].

Therefore, both geometries typically show three stages in their stress-strain evolution: the first two (linear and plateau stages) are common. However the plateau stage is short for the cylinders and is followed by failure whereas the cubes show a long plateau (increased deformation) followed by a stress increase due to the additional stiffness produced by contact between opposing cell walls.

The variation specimens behaviour is similar to that reported by Glouannec [2011] who observed that tall specimens (height>width) had a clear fracture plain and the maximum compressive strength was followed by a decrease in stress while stout specimens (height<width) crushed continuously. The cylindrical NHL3.5 binder samples crumbled during demoulding and the results are therefore disregarded.

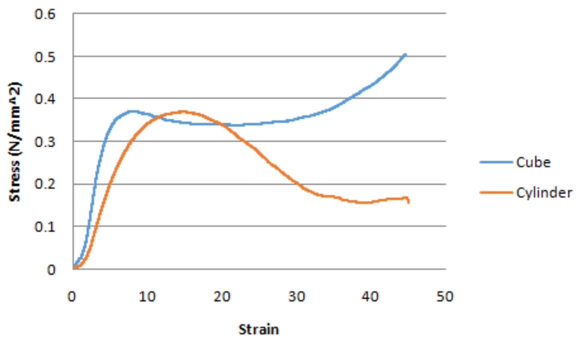

Fig 7. Typical stress vs strain behaviour of hemp concrete varying with specimen geometry.

4 CONCLUSION

Both concretes achieved most of their compressive strength in the first month. The CL90:CEMII concrete achieved a considerably higher strength than the NHL3.5 concrete probably due to its greater hydraulic content (hydrates were much more prolific in the CL90:CEMII binder).

Curing hemp-lime concrete with hydraulic content (50%CL90: 50%CEMII) at high RH (>95%) lowers compressive strength (65.4% drop at 10 weeks). It is unclear why this happens, as the presence of water vapour during curing at high RH should enhance hydration and consequently increase strength. The NHL3.5 concrete shows the same trend although the results are not statistically significant.

Retaining the hemp concrete in *moulds* during curing increases compressive strength of the CL90:CEMII concrete (a 22.9% increase measured at 10 weeks). This is probably due to the presence of moisture for longer enhancing hydrate formation. The NHL3.5 concrete shows the same trend although the results are not statistically significant.

The lack of statistical significance of NHL3.5 concrete results may be due to lack of sensitivity of the measuring instrument at low strength values.

The specimen *geometry* does not significantly impact the ultimate compressive strength of hemp-lime concrete however, it affects the concrete behaviour under a compressive load.

Initially, cylinders and cubes deform on load application up to a similar yield point. Following this yield point, the cylinders fracture whereas the cubes keep crushing to finally experience an additional stiffness produced by mechanical bridges between opposing cell walls.

Drying hemp concrete at 50℃, allows to monitor early strength development and does not impact strength performance. Strength contribution by drying in hemp concrete is small (e.g. less than 0.03MPa in NHL 3.5 concrete).

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