AN ASSESSMENT OF THE PHYSICAL PROPERTIES OF LIME-HEMP CONCRETE

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Abstract
This work is part of a wider research programme that aims at producing alternatives to conventional building materials. The aim of this project is to investigate several physical properties of a sustainable, carbon-negative, lime-hemp biocomposites which can partially replace existing, non-biodegradable, non-sustainable, building materials of high embodied energy and high CO_2 emissions. The shrinkage, flexural and compressive strengths of these lime-hemp concretes, made with either calcium lime or a commercial binder with a cement content and varying lime:hemp proportions (1:9, 1:1 and 3:1), were investigated according to the relevant European standards. The shrinkage and strength development at 7, 28 and 90 days were monitored. The relationship between shrinkage and binder type, hemp content and water content was observed. The development of the flexural and compressive strengths shared several characteristics but their behaviour departed in relation to increasing hemp content with compressive strength continuously decreasing while flexural strength varied little between 50% and 75% hemp content.

Keywords: lime-hemp concrete, compressive strengths, flexural strength, shrinkage

1. Introduction

The construction industry is non-sustainable. It is responsible for the consumption of non-renewable raw materials and fossil fuels, and for high CO_2 emissions that adversely impact on the environment. In light of this, there is a critical need to develop sustainable alternatives to conventional building materials of high embodied energy responsible for high CO_2 emissions.

Lime-hemp composites, are providing such alternatives and can replace high embodied energy materials for certain applications. They have been used in construction in France since the 1990s, and there are now several hundred hemp buildings in the country. Lime-hemp concrete has also been gaining popularity in Ireland in recent years, and there are now over 20 buildings constructed in lime-hemp concrete and a further 100 that have been thermally upgraded (Pronchetti, 2010) throughout the country.

A lime-hemp concrete is a composite material, comprising of hemp shiv, which is the woody interior of the hemp stalk, and lime. Hydraulic lime, pozzolans and cements may also be added to the binder to reduce setting times. Lime-hemp concrete acts as a CO_2 sink and $1m^3$ of lime-hemp concrete wall can sequester over 100kg of CO_2 (Bevan and Woolley, 2008). Lime-hemp concrete also displays good thermal, acoustic and fire properties.

The physical properties of lime-hemp concrete are still not well known which affects their uptake into mainstream technology. As part of this research, three important physical properties are examined including shrinkage and flexural and compressive strength. Two binders were investigated: a hydrated lime and a commercial binder incorporating cement and other pozzolanic and mineral additions. The hydrated lime will set purely through carbonation while hydraulic additions in the commercial binder will result in a partial hydraulic set which is a faster process. The effect of the different hemp shiv contents, relating to different applications; wall, floor and plaster on the physical properties shall also be examined.

Shrinkage is unlikely to cause problems in properly constructed lime-hemp concrete walls (Bevan and Woolley, 2008). The phenomenon has not been widely investigated for lime and hemp shiv concretes, although hemp fibers (sheath of fiber inside the bark) are widely used to reduce shrinkage in plasters. Shrinkage tests to date, using hemp shiv, have produced varied results that have not proved representative of their performance in real life situations (Evrard, 2003).

The effects of hemp fibers on the flexural strength of lime, cement and gypsum binders has been investigated by Le Troëdec et al (2009), Sedan et al (2008) and Dalmay et al (2010) respectively. A similar flexural loading vs strain curve was observed by all authors in which, initially, the load is primarily supported by the matrix but following the occurrence of the first macroscopic damage, the load is transferred to the matrix/fiber interfaces, with a corresponding slight increase in stress uptake and a reduction in rigidity. Unlike brittle composites, after the peak load is achieved, there is a gradual load decrease on account of the progressive failure of the matrix/fiber bonds. In addition, Elfordy et al (2008) investigated a commercial lime binder and hemp shiv and established the relationship between increasing density and increased flexural strength.

The compressive strength of lime-hemp concretes has attracted more attention than flexural strength and has been investigated by Evrard, (2003); O'Dowd and Quinn (2005); de Bruijn et al, (2009) and Elfordy et al, (2008). Lime-hemp wall concrete is considered a non-load bearing material with compressive strengths typically under 1.2MPa, that is typically cast around a timber frame. It has low rigidity and accommodates major deformations without rupturing (Evrard, 2003).

2. Materials and Methods

2.1 Mixing

Different composites were produced by mixing hemp shiv with either hydrated lime CL90s complying with EN459-1 (2001) or a commercial binder (TH) which included hydraulic and pozzolanic additions. Each binder was mixed with hemp in three ratios by volume (Table 1) in accordance with the specific application. It is noted that the commercial binder is significantly denser than the hydrated lime. The water content was dependent on the amount of hemp in the mix, with 3.3litres of water per litre of hemp as advised by the supplier. The 10% hemp mixes (CL90H10& TH10), on account of the low hemp content required additional water in order to achieve an adequate workability which was determined experimentally.

Table 1 – Mix proportions by volume

Mix Name	Binder	Hemp:Binder:Water By Volume	Application % volume
CL90H75	CL90	1:0.33:3.3	Non-load bearing wall 75% hemp 25% binder
CL90H50	CL90	1:1:3.3	Floor 50% hemp 50% binder
CL90H10	CL90	1:9:22.2	Plastering 10% hemp 90% binder
TH75	Commercial Binder	1:0.33:3.3	Non-load bearing wall 75% hemp 25% binder
TH50	Commercial Binder	1:1:3.3	Floor 50% hemp 50% binder
TH10	Commercial Binder	1:9:22.2	Plastering 10% hemp 90% binder

The binder and hemp were dry mixed for approximately 10 seconds and the water gradually added in 100ml segments at regular intervals. Each batch was mixed for 10 minutes except for the 90% binder mixes which required a further 5 minutes of mixing to achieve workability. After mixing, the samples were transferred into prismatic moulds filled in three layers and tamped 25 times each. The final layer was levelled off with a steel trowel. They were stored under damp hessian for three days at temperature 20°C±2°C and relative humidity 95%±5% and then demoulded and transferred to a curing room at temperature 20°C±2°C and relative humidity 65%±5%.

2.2 Shrinkage

Testing was based on American cement standard ASTM C 596-96 (1996). One sample of each mix was tested. Measurements were recorded, on a daily basis, with gauges accurate to 0.002 mm following removal from the mould on day 3 and were concluded after 30 days by which time, changes in shrinkage for all samples were under 0.0025% per day.

2.3 Flexural and Compressive Strength

Flexural and compressive testing was carried out using a Zwick Testing machine. No standards currently apply to lime-hemp concrete and EN 459-2 (2001) was used to guide the tests. Four samples of each mix were tested. Loading rates of 1N and 10N per second were selected for the flexural and compressive strengths, respectively.

2.4 Modulus of Elasticity

The Young's modulus was used as a measure of the stiffness of the material and was determined by the slope of the linear part of the stress-strain curve both under compression and in flexion.

3. Results and Discussion

3.1 Shrinkage

Shrinkage is primarily due to the evaporation of water during drying, and therefore shrinkage was most significant at early ages (see figure 1). The decrease in length was significant, however, shrinkage was uniform and no significant cracks appeared in any of the samples.

Shrinkage was greatest in the first 10 days. By day 10, the CL90 samples had undergone over 90% of their total 30-day shrinkage while the commercial mix displayed a slower rate of shrinkage, ranging from 70-90% of the total 30-day shrinkage. The total shrinkage at 30 days for the commercial mix was found to be lower than that of the hydrated lime samples for all lime:hemp ratios. This was expected as mortar shrinkage decreases with increasing binder hydraulicity.

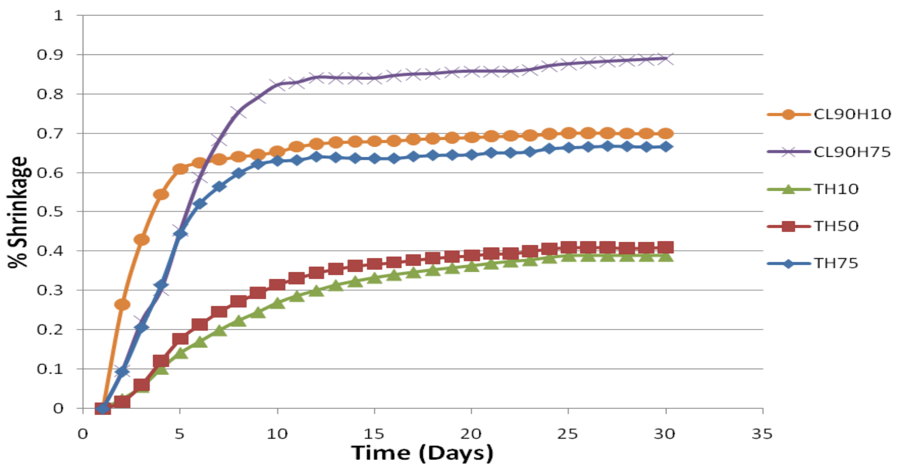


Figure 1 - Shrinkage

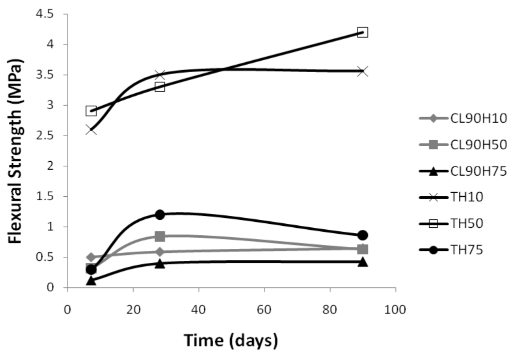
The difference in the 30-day shrinkage of the two 10% hemp mixes is greater than that of the 75% hemp mixes; this suggests that the binder type has a higher impact on the total amount of shrinkage than the hemp content.

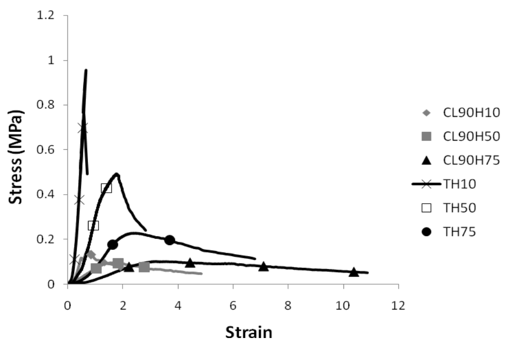
An increase in shrinkage was observed for the 75% hemp mixes partly on account of the increased water content demanded by their higher hemp content. At early stages, the two 75% hemp samples displayed a similar rate of shrinkage as excess water evaporated. However, the commercial 10% and 50% hemp mixes have similar shrinkage despite the 50% mix having lower water content. This suggests that the hemp content must also contribute to shrinkage.

Shrinkage is a complex process that has an interdependent relationship with water content, binder type and hemp content. Binder type appears to have a stronger effect on total shrinkage than hemp content or water content. On site, the drying process can take several months thus shrinkage can also extend over several months. CL90H50 results are not included on account of experimental error.

3.2 Flexural Strength

The flexural strength development and mechanical behaviour of hemp composites in flexion are included in figures 2 and 3. This research found that flexural strength increased with increasing binder content between 25% and 50%. However, a further increase in binder content to 90% had little effect on flexural strength. This suggests a contribution from the lime-hemp bonds towards the flexural strength of the composite. The commercial mix was found to produce samples of significantly higher flexural strength than the CL90s samples. The values obtained are comparable to those from former aurthors: the flexural strength of TH75, which has an equivalent composition to the hempcrete blocks investigated by Elfordy et al (2008), had a similar flexural strength at 28days of 1.2MPa and 1.19MPa, respectively, for an equivalent density.





Figures 2 – Flexural strength development of hemp composites

Figures 3 –Mechanical behaviour of hemp composites in flexion

All samples rapidly attained flexural strength, achieving over 90% of their total 90 day flexural strength by 28 days (with the exception of the 50% commercial mix). The commercial samples developed their early flexural strength marginally faster than the CL90s samples, likely on account of the early formation of hydraulic products. All the low hemp content composites gained their flexural strength significantly faster than the high hemp content samples.

Flexural strength did not continuously increase with time for all mixes. A decrease was recorded for TH75 and CL90H50 between 28 and 90days. Similar behaviour was observed by Hanley and Pavía (2008) in which flexural strength was found to decrease in several hydraulic lime mortars between 28 and 56days. In the case of hydraulic binders, this may be attributed to the evolution of the hydration products formed over time. Behaviour after 90 days was not measured.

Figure 3 shows a representative example of the behaviour of the hemp composites under flexural loading. The 10% hemp mixes with commercial binder act in a brittle manner, and the flexural load vs strain relationship after the point of rupture displays a similar behaviour to that observed by Le Troëdec et al (2009) and other authors (as discussed in the introduction). This suggests that the hemp shiv particles act in a manner similar to hemp fibers at low concentrations.

The 50% and 75% hemp composites exhibit a lower load carrying capacity and progressive failure takes place in a ductile manner. The binder type has the greatest influence on stiffness, with the commercial samples having a greater Young's modulus at higher binder contents. The Young's modulus of the commercial composites was not observed to continuously increase with time, the TH10 and TH50 samples decreasing by 11% and 22% respectively between day 7 and day 90. In contrasts, the CL90s hemp composites (on account of carbonation) increased in stiffness overtime.

3.3 Compressive Strength

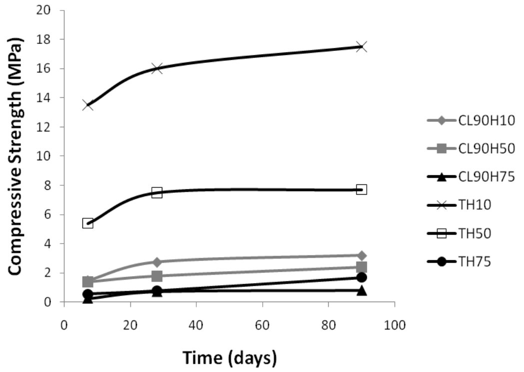
An increase in compressive strength was evident with increasing binder content, as found by Evrard (2003) and other researchers (Figure 4). However O'Dowd and Quinn (2005) noted that increasing the hemp content beyond a 3:1 ratio had little further effect on reducing the compressive strength.

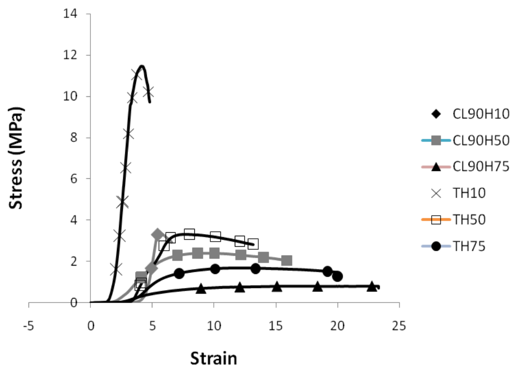
As expected on account of their hydraulic content, the commercial binder composites displayed higher ultimate compressive strengths than the CL90s ones. However, as the hemp content increased, the hydraulic strength of the binder was found to have less effect on the compressive strength of the composite: the 10% hemp commercial samples were approximately 5.5 times stronger than their equivalent CL90 mixes, however the 50% and 75% commercial samples were only 3.2 and approximately 2 times stronger, respectively, than their equivalent CL90s mixes. The low strength samples are approximates on account of variability of the standard deviation in measuring strengths under 2MPa.

The commercial samples, on account of their hydraulic component, had a higher rate of strength gain than the CL90 samples that relied solely on carbonation for strength development. In consequence, the rate of strength gain of the commercial samples increased at higher binder content while the rate of strength gain of the CL90 samples did not.

The compressive strength results obtained are relatively high when compared to other authors (Evrard, 2003 and de Brujin et al, 2009). Elfordy et al (2008) determined a relationship between increasing density and compressive strength and the high compressive strengths is likely linked to a high level of compaction resulting in high density samples.

Figure 5 shows the mechanical behaviour of the hemp composites under compressive loading. As for flexural strength, the 10% hemp samples act in the most brittle manner while at higher hemp contents, the behaviour is more plastic. The behaviour of the 75% hemp mixes is a continuous plastic deformation similar to that described by Evrard (2003), with an initial linear relationship between stress and strain followed by a failure of the binder matrix at a point where the behaviour becomes more ductile. This is likely due to the transfer of stresses to the matrix/hemp interface which allows the sample to continue accommodating load.

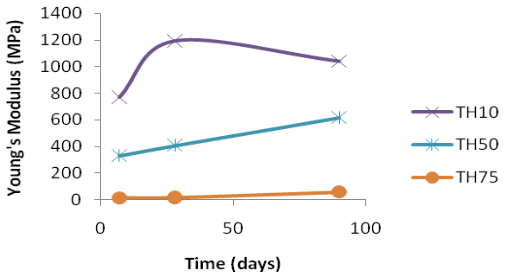


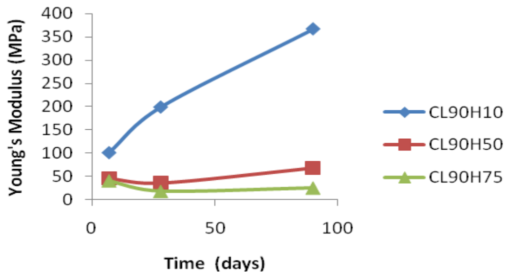


Figures 4 – Compressive strength development of hemp composites

Figures 5 –Mechanical behaviour of hemp composites under compressive loading.

According to the stiffness measured with the Young’s modulus, the commercial hemp composites achieve a much higher rigidity, as also noted by (de Bruijn et al, 2009) however, stiffness greatly decreases at high hemp contents. The results also show a general increase in stiffness over time.





Figures 6 – Average Young's modulus for commercial binder samples subjected to compressive loading

Figure 7 - Mechanical behaviour of hemp composites under flexion

4. Conclusion

Shrinkage is strongly related to drying. It is heavily dependent on the binder nature and influenced in a lower extent by increasing hemp and water contents.

The mechanical behaviour of the hemp composites both in flexion and under compression shows similarities: the composites become more plastic as the hemp content increases. The nature of the binder appears to have a slight impact on mechanical character with the hydraulic component of the commercial binder imparting a more brittle behaviour to the composite at low hemp contents.

The flexural and compressive strength also share several similarities including their dependency on the binder nature at low hemp contents: the faster strength gain and higher ultimate values were observed at low hemp contents for the commercial mix. The composites gained their early flexural and compressive strength at a similar rate, ranging from 30% of the 90 day strength at 7 days for the high hemp content samples to 75% for the low hemp content mixes. The only exception was the CL90s low hemp content mixes which developed compressive strength slower than flexural strength. The commercial binder produced samples of higher stiffness however the effect of the binder was less evident at high hemp contents when the biocomposite's rigidity was significantly reduced.

The main difference between the flexural and compressive strength gain was the compressive strength increased with increasing binder content while the flexural strength achieved a maximum value at 50% hemp content. This suggests a contribution from the lime-hemp bonds towards the flexural strength of the composite.

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