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Characterisation of Low Density Hemp-Lime Composite Building Materials under Compression Loading

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ABSTRACT

Hemp-lime (HL) is a sustainable low carbon composite building material that combines hemp shiv with formulated lime based binders. It was developed for use as an insulating material in solid walls as well as for floors and roofs. This paper reports on the testing of 45 HL cylinders in order to compare their strength and stiffness properties at three different densities and at different ages up to 91 days, using three binders of differing composition and strength. Although strength and stiffness of the HL are low, the study showed that the strength properties of HL composite are not directly related to the individual strength of the binder, but rather are a function of complex interaction between the hemp and lime. Strength and stiffness of the HL increases with mix density and age.

INTRODUCTION

The UK has set a target for moving towards zero carbon housing by 2016. This ambitious target can be achieved by reducing energy consumed during building use and through the adoption of materials with lower embodied carbon levels and higher recyclability during construction. The use of HL is slowly growing in the UK as the level of environmental awareness increases within the construction industry, in recognition that buildings contribute around 50% of the nation's CO_2 emissions and in response to legislative changes such as the Code for Sustainable Home [CSH 2007].

During the 1980’s and 1990’s the use of HL developed primarily in France, where the practice is now well established with over 200 buildings having been constructed using HL in 2007 [Arnaud Evrard, pers. comm.]. In the Champagne region of France, there are numerous historic oak framed buildings that were infilled with lime, straw and rubble when originally built [Allin 2005]. The use of HL originated from the need to mimic the behaviour of these materials since repairs carried out during the 1950’s and 1960’s with inappropriate materials had lead to damage [Allin 2005]. HL’s inherent flexibility and vapour permeability, due to the porous structure of both the hemp and the set binder [Arnaud and Cerezo 2002, Arnaud 2000, Evrard et al. 2006] complimented the requirements of old buildings.

HL is composed of three main constituents:

- **Hemp shiv** - Making up 40-60% of the Cannabis Sativa L. plant by mass HL composites use the woody core of the plant stalk known as Shiv. Hemp is grown as a break crop and harvested after 3-4 months. Once collected and bailed, the hemp is introduced into a processing plant which separates the shiv from the fibre and removes any dust, dirt and other particulates. The main markets for hemp fibre are currently within the automotive, paper and the textile industries. The shiv is primarily used as horse bedding but has recently experienced an increasing demand within the construction industry.

- **Binder** – This creates a matrix connection between the particles of shiv. Although predominantly composed of lime, binders have been specifically developed for use with HL through the addition of hydraulic components and other additives to create a relatively fast initial hydraulic set on site. Once mixed within the composite, carbonation of the lime takes place, converting calcium hydroxide into calcium carbonate. This absorption of CO_2 partially offsets the CO_2 released during production of the binder.
- **Water** - Potable water. Essential in activating the reactive elements within the binders.

Hemp plants store carbon during their growth as a result of photosynthesis. This carbon remains locked within the plant material until it decays. Combined with the relatively low carbon emissions of lime production, HL is marketed as a 'better than zero carbon' footprint material. Approximately 103 kg of CO_2/m^3 is absorbed for a typical medium density HL wall [Lime Technology 2008].

The primary function of HL in construction is to create an insulative layer against the cold, heat, noise and humidity of the outside world. But in addition HL has also been reported to passively regulate the interior of buildings within acceptable boundaries of temperature and relative humidity [Roaf et al. 2007]. The main use of HL is within non-structural applications, where the material is cast or sprayed around a primary structural frame of timber generally [Figure 1]. Once cast or sprayed in place, to a thickness usually between 250 mm to 500 mm, the material is left initially to set for a few days before a compatible (usually lime based) render finish is applied directly onto the HL. Alternatively, as with the Renewable House at BRE, the walls can be cast with a permanent breathable shuttering layer on the inside face, which also receives a lime plaster.

Fig. 1. . HL Cast Around Timber Primary Structure (Lime Technology 2008)

By reducing lime binder content it is possible to reduce material costs, carbon footprint and density (improving thermal insulation) of HL. This paper reports on performance of novel low density mixes. In addition there have been recent changes to the formulated lime binders in order to shorten the labour time on site and improve the initial hydraulic set during colder temperatures, further reducing costs. There is currently no published data on these binders. The objectives of the study reported in this paper have been to characterise HL composites to further optimise their performance. Concurrently, an initial investigation into optimising density of the material has been undertaken.

EXPERIMENTAL INVESTIGATION

A total of 45 cylindrical specimens of HL were fabricated in order to compare the strength and stiffness properties of HL at three different densities (200, 275 and 300 kg/m^3) at ages of 28 and 91 days using three different binders. Although a non load-bearing material, compression testing was used as an effective comparison tool between different binders. Furthermore, the material must display a certain amount of robustness for use on site; the process of specimen fabrication, testing preparation and testing offered hands-on comparison and analysis between the different densities.

Materials

The hemp used within this study is distributed under the trade name Tradical™ HF and was processed by Hemp Technology in the UK.

Three binders were compared. Two binders that are available in the UK under the trade name Tradical™ Hemp Binder (THB) and a natural hydraulic lime based binder produced by French lime producers St. Astier called Batichanvre™ (BC).

Tradical™ binders are based on CL90 Air Lime with the addition of hydraulic components and other additives to improve porosity and workability. The THB binders used within this study were blends previously used within the UK but are now more commonly on the continent (THB-A) and a development of this first binder in which changes have been made to reduce the initial hydraulic setting time and make it more suitable for use in colder temperatures (THB-B). The strength of all three binders measured in accordance with BS EN 196-1:2005 are given in Table 1. BC gave the highest strength of all binders with a 28 day mean compressive strength of 30.2 N/mm^2, which was up to three times greater than that of the THB binders. It is postulated this may be down to a higher proportion of hydraulic components within the BC binder.

Table 1. 28 day Compressive and Flexural Strength of THB and BC Binders

	THB-A	THB-B	BC
Compressive strength (N/mm^2)	9.3	13.9	30.1
Flexural strength (N/mm^2)	3.5	4.5	7.2

Mix proportions

In practice, hemp is delivered to site as 20 kg bales and the binder is supplied in 22 kg bags. Until recently mixes used two bags of binder to every bale of hemp and 60 litres of water. This mix, when correctly introduced on site, would produce a density of around 330kg/m^3. The binder and water are the two densest constituent parts. By reducing the proportions of binder and water the final density of the material can be reduced. Current industry mixes use 1.5 bags of binder to every bale of hemp and 40-50 litres of water. This mix creates densities of approximately 275 kg/m^3. This paper also reports tests carried out on mixes of one bag of binder to every bale of hemp and 40 litres of water creating a set material with a density of approximately 220 kg/m^3. The specimens using BC were mixed to the same mix proportions as those using THB.

The most developed blend of binder, THB-B, is currently in use in the UK construction industry. For the purpose of this study, this binder was set as the control binder. Accordingly, only this binder was used to compare mechanical differences due to changes in density. Specimens using BC and THB-A were only tested at densities of 275 kg/m^3 and at ages of 28 and 91 days. Specimens using THB-B were also tested at 14 days.

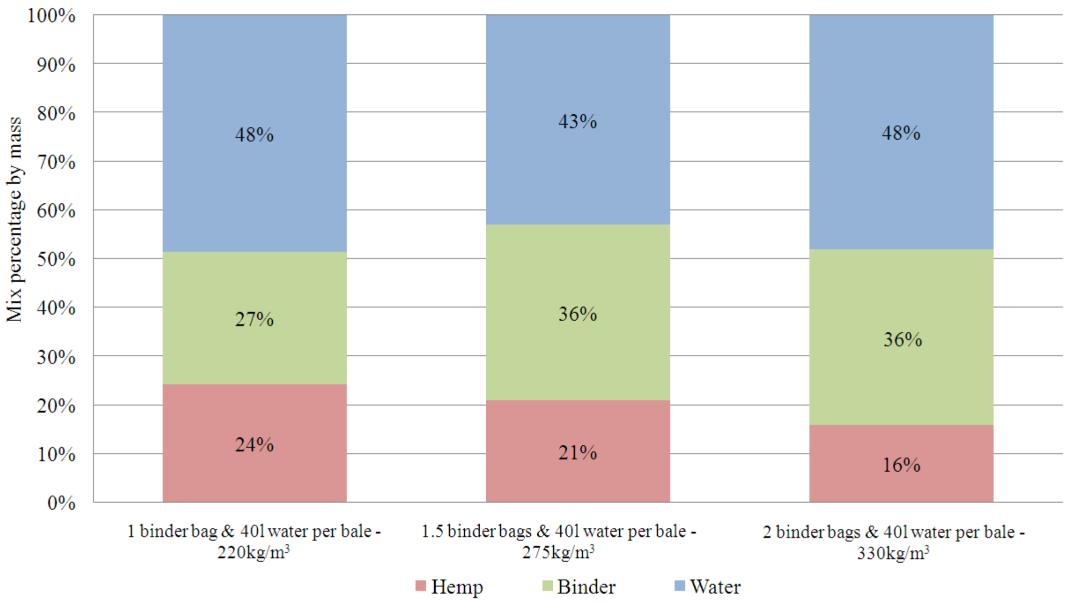

Fig. 2. Mix Proportions by Percentage Mass

Specimen densities

In order to fabricate specimens to a required 'dry' density the corresponding 'wet' density at fabrication needed to be established. Within this study the 'dry' density was defined as the density of the specimens after 91 days of curing in a conditioning room (set at 20˚C ±1˚C and 60% ±5% RH). As part of an initial test series, nine specimens were fabricated, three for each density being compared, using differing amounts of compaction for each of the three specimens to create three different wet densities. These were then placed in an oven at 105˚C and removed once no further mass changes were observed. A nominal moisture content (MC) of 7% was then added to this anhydrous mass of the specimens as this is the mean MC of HL after 91 days of curing under laboratory conditions [Evrard 2003]. The relationship between the wet and the dry densities then allowed calculation of the wet mass of material needed to produce specimens with densities of 220, 275 and 330 kg/m^3 at 91 days.

Specimen manufacture and curing conditions

The material was mixed using a pan mixer. The water and dry lime binder were mixed together first, to create a uniform slurry. The shiv was then added and mixed uniformly. Mixing took no longer than five minutes, from the addition of the lime to the water, to complete.

Fig. 3. Moulded Specimen

The required initial wet mass of fresh material was introduced into wax dipped cylindrical cardboard moulds of dimensions 150mmØ x 300mm length. The 2:1 height:diameter ratio was the same as previous tests carried out in France and the UK [Cerezo 2005, Evrard 2003, Gibbs 2006, Stella 2005]. The wax coating ensured no moisture was absorbed by the cardboard. Both ends of the specimen were then sealed with plastic ends to prevent moisture loss from the specimen and to ensure satisfactory hydration of the binder, Figure 3. All specimens were then placed in a conditioning room at a temperature of 20˚C ±1˚C and relative humidity of 60% ±5%. The plastic caps were removed after 24 hours and the specimens laid horizontally for a further six days until the cardboard moulds were stripped by use of a small circular table saw. Once de-moulded the specimens were placed vertically on shelving supported on mesh that allowed air to circulate around the entire surface area of each specimen.

Specimen preparation and testing

At the appropriate age, the specimens were removed from the conditioning room and prepared for testing. To ensure flat and parallel end surfaces, and to ensure even distribution of loading, rapid-hardening dental plaster was used to cap both ends. Although this introduces a small amount of water to the ends of the specimens, this was found to be the best technique. Saw-cutting the specimen ends was trialled but proved unsuccessful; the low density material was too friable to cut. Prior to capping, all specimens were weighed and dimensions measured in order to calculate their density. Testing was carried out using a DARTEC machine complete with automatic data acquisition software. The rig was set to monotonically load at a displacement rate of 3 mm/min until failure had occurred. Previous work has shown there to be little difference in mechanical behaviour when using different loading rates (Arnaud and Cerezo 2002).

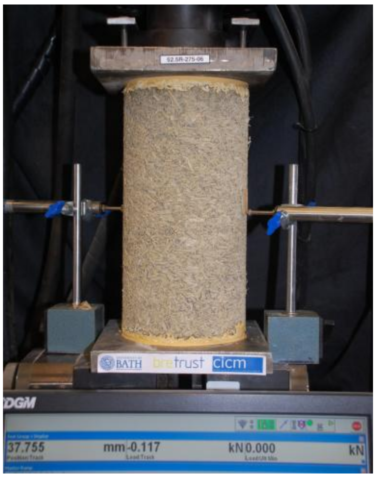

Fig. 4. Typical Testing Setup

Figure 4 shows a typical testing layout complete with steel platens that ensured even loading across the whole cross section. The top platen was articulated to allow rotation during testing. After testing 100 g of material from each specimen was removed and placed in an oven to determine the MC at the time of testing.

RESULTS AND DISCUSSION

Specimen density

The aim during testing was to compare three different densities of HL. The required wet mass of material at fabrication was calculated in order to create the desired densities at an age of 91 days. Table 2 displays the mean measured 91 day densities compared to the target densities. The initial tests and calculations proved to be successful in calculating the required wet mass of material required to achieve the ‘dry’ density required. Standard deviations (and range) for 91 day 220, 275 and 330kg/m^3 THB-B specimens were 1(2), 3.2(6.0) and 2.5(5)kg’s respectively showing an acceptable level of repeatability and result reliability from the fabrication, curing and testing techniques.

Table 2. Mean THB-B Specimen Densities at 91 days

Target ‘dry’ density (kg/m^3)	Achieved ‘dry’ density (kg/m^3)	Difference (%)
220	221	+0.5
275	278	+1.1
330	342	+3.6

Compressive strength development of HL

Figure 5 shows the stress/strain relationship of specimens mixed with the three different binders tested at 28 days. The low ultimate compressive strengths (less than 0.1 N/mm^2) and initial tangent moduli (3-22 N/mm^2) are comparable with other synthetic and natural insulation products. Ultimate compressive strengths were developed at between 2 and 13% axial strain. Although performance confirms that HL is probably best used as a non-load bearing material, load bearing applications similar to straw bale (which has even lower strength and stiffness) remains feasible. The HL specimens made with BC gave a higher initial stiffness but a lower ultimate strength than the THB-A specimens. In terms of strength specimens made with THB-A performed 37% better than specimens made with THB-B and 33% better than specimens made with BC.

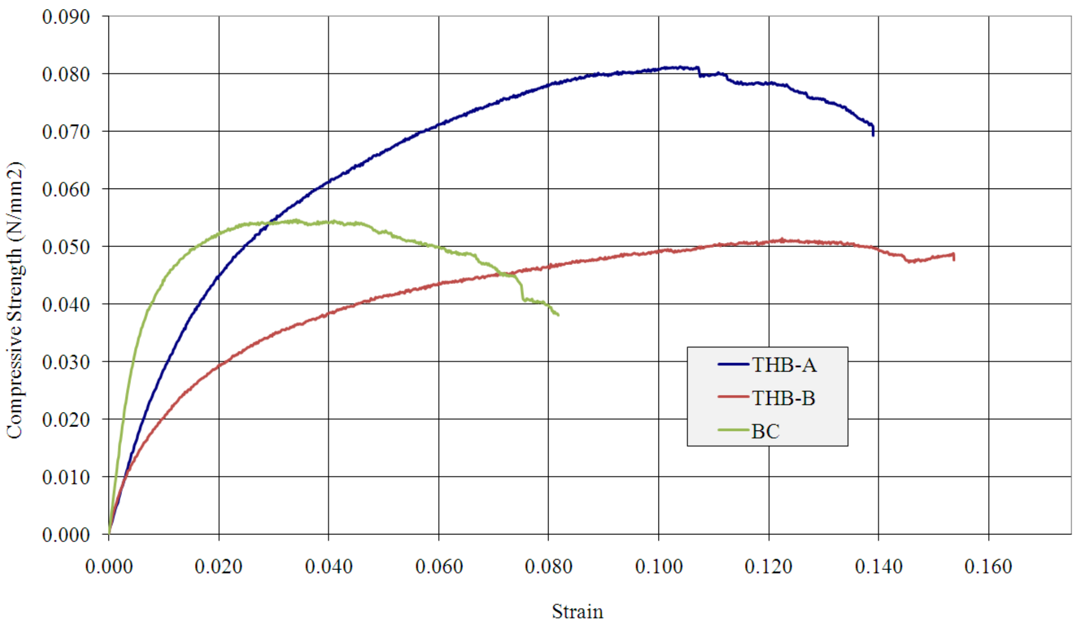

Fig.5. 28 day Stress-Strain Relationship of Specimens Mixed with Different Binders

Table 3 shows the development of strength over age for the specimens mixed with the different binders. There was little further strength development beyond 28 days.

Table 3. Strength Development of Specimens Mixed with Different Binders

Binder	Average 28 day strength (N/mm^2)	Average 91 day strength (N/mm^2)
THB-A	0.081	0.093
THB-B	0.051	0.052
BC	0.054	0.057

Figure 6 shows the compressive strengths of the HL specimens made using THB-B, at all three densities and testing ages. The compressive strength is shown against the percentage mass of the slurry when fabricating took place i.e. the percentage mass of the water mixed with the binder. The observed increase in strength from 14 to 28 days may be attributed to the development of hydrate minerals within the hydraulic phase of the binder. From 28 to 91 days there was almost no appreciable gain in strength. At this age the hydration phase of setting within the binder had probably finished. Any further gain in strength was most likely due to the carbonation of the air lime content within the binder. On-going work is mapping progress of carbonation with time.

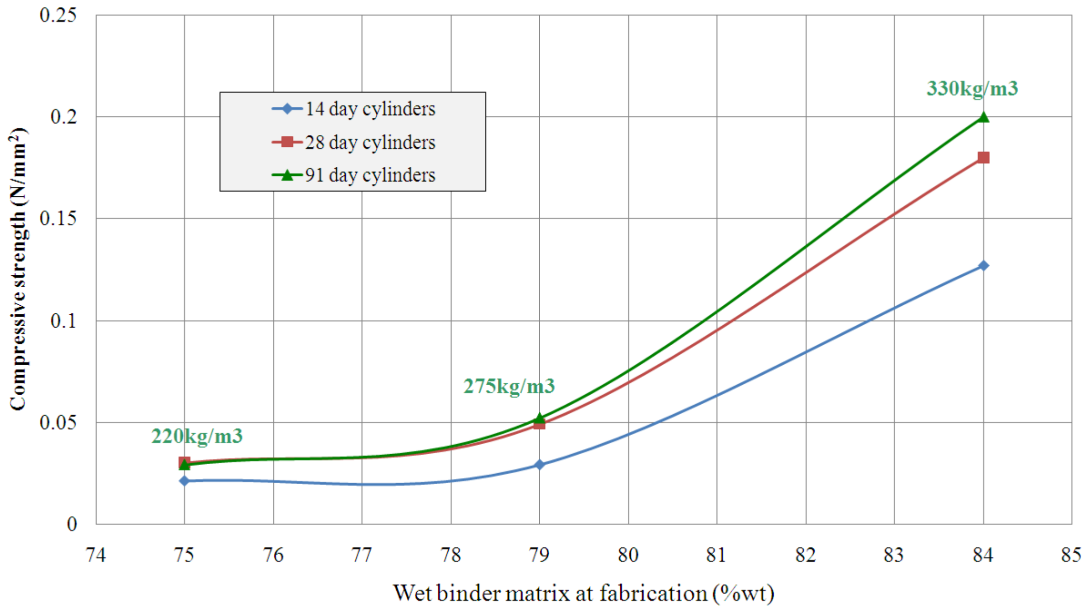

Fig. 6. Compressive Strength vs. Wet Binder Percentage of THB-B Specimens

The testing technique used proved reliable in producing repetitive and reliable results with a consistent performance. The standard deviations for 28 day THB-A, THB-B and BC specimens were 0.0031, 0.0025 and 0.004 respectively. Although compressive strengths were low, a degree of inter-particle integrity is required within the material in order to allow plasters and renders to be applied. Although the mix proportions used for specimens at a density of 275 kg/m^3 do not show a significant increase in strength or stiffness compared to specimens of density 220 kg/m^3, there was a noticeable improvement in specimen integrity during handling and specimen preparation, a level of integrity which would be suitable for on-site plastering and rendering. This has been confirmed by past and current on-site projects which have successfully used the mix with no reported problems from lack of integrity.

Table 4 gives the elastic moduli and strain at failures of THB-B HL specimens. As expected elastic modulus increased with specimen density. The elastic modulus of 330 kg/m^3 specimens were similar to work published in France [Evrard 2003]. The stiffness of lower density HL was poor at early ages but improved as carbonation took place.

Table 4. Stiffness and Strain at Failure of THB-B Specimens

Density (kg/m^3)	Mean initial elastic tangent modulus (N/mm^2)			Mean peak strain at failure		
	14 Day	28 Day	91 Day	14 Day	28 Day	91 Day
220	4.8	3.3	15.3	0.094	0.059	0.053
275	5.6	3.7	12.9	0.094	0.133	0.125
330	22.4	12.0	20.9	0.115	0.084	0.057

Upon visual inspection of the different densities, it became clear that the differing percentages of slurry at mixing changed the way the shiv particles were interconnected within the composite. Figure 7 shows how particles had a low level of inter-particle connectivity in 275kg/m^3 specimens as opposed to the encapsulated shiv particles in 330kg/m^3 specimens giving them a much higher degree of inter-particle connectivity. This higher degree of connectivity translates into higher levels of initial stiffness. As loading was applied, the hardened binder carried the load and was the major cause for the initial elastic modulus. As the binder matrix began to fail the shiv particles moved closer together and inter-particle friction began to have a dominant effect until ultimate failure occurred.

Fig. 7. Shiv and Binder Matrix of 275 and 330kg/m^3 Specimens

Specimen failure

All HL specimens were tested in the same vertical orientation as when they were fabricated to see whether the casting orientation had any effect on the position of failure within low density specimens. Figure 8 shows three specimens at failure, all made with the same binder but at different densities

Fig. 8. THB-B: 220, 275 and 330 kg/m^3 Specimens at Failure

All of the specimens tested exhibited failure within the upper half of the cylinder. It is postulated this may have been down to slumping of the material during casting and initial stages of curing creating a slightly denser lower half of the specimen. This aspect is subject of on-going study.

Moisture content of HL

At each age of testing the MC of the specimens was determined by removing 100 g of material and placing in an oven at 105˚C until no further mass loss was recorded. Based on previously published data [Evrard 2003] an initial assumption of 7% had been made for the MC of HL at 91 days; this value had formed part of the calculations in determining the mass of wet material needed to achieve the required density after 91 days. The MCs of the specimens at each age as a percentage of the specimen mass are given in Table 5.

Table 5. Moisture Content of THB-B HL Specimens

Specimen density (kg/m^3)	**220**			**275**			**330**		
Specimen age (days)	14	28	91	14	28	91	14	28	91
Mean moisture content (% mass)	24	10	6	19	9	6	26	11	6

Results show a MC of 6% at 91 days compared favourably to the 7% value assumed. The 7% value used was an upper bound value within the range of 4-7% of 'normal' moisture contents previously reported by [Evrard 2003].

CONCLUSIONS

The following conclusions can be made following this study:

- Low density HL walls are a viable option for the construction industry. However, due to the low strengths and stiffness, it is not generally recommended for load bearing applications.
- Results indicate the ultimate strength of the material to be dependent on the percentage of wet binder used during mixing.
- The stiffness of the material increases and the strain at failure decreases with time.
- The stiffness is dependent on both the percentage of wet binder used and the density of the specimen.
- The ultimate strength of HL as a composite is not directly related to the strength of the binder.
- Failure positions within the specimens are dependent on the casting orientation.
- Testing methodologies have produced representative and consistent results.

Use of HL in building construction causes a reduction in the use of high energy intensive materials such as bricks and concrete. This reduction, along with the hemps ability to absorb and lock in CO_2 during its growth results in a reduction of CO_2 emissions and earning of carbon credits.

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