# Hemp-lime: highlighting room for improvement

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**Abstract.** Greenhouse Gas Emissions and growing energy demands are global issues that are exacerbated by the construction industry; an industry whose activities make up the majority of most country's emissions, while the Housing Sector alone expends 60% of its total energy consumption on space heating of buildings [1]. Materials are continually being developed to be more environmentally friendly and reduce the carbon foot-print of buildings. Hemp-lime is a natural material that sequesters $CO_2$ during growth of the hemp plant through photosynthesis; this reduces the material's carbon footprint, allowing potential construction of 'zero carbon' buildings. The simple homogeneous construction of a hemp-lime building exhibits a good thermal performance, which can dampen fluctuations in external temperature and passively control internal humidity. This considerably reduces the demand on internal heating and cooling thus reducing the energy consumed within the building. Hemp-lime construction can be conducted in a number of ways including manual placement and spraying. This paper outlines some of the issues arising from differing construction methods, highlighting gaps in the knowledge and understanding of the use of this natural material. The paper concludes by presenting topics for further research in order to improve and promote hemp-lime use within the construction sector.

## 1 Introduction

Natural materials such as stone, clay, lime, wood and Natural Fibre Insulations (NFI) such as wool, straw, hemp and flax are becoming ever more popular for the self-builder, or 'eco-builder'. The benefits of using these natural materials; both in terms of embodied $CO_2$ saving and the energy saving attributed to their performance, have driven the need for better understating and appreciation for their differing construction methods.

With the global energy crisis still a pressing issue in the current climate it is important that the knowledge and understanding of less carbon intensive techniques are shared effectively to raise awareness and help meet current targets.

Hemp-lime is one such NFI, with potential benefits, that is primed ready to move from a niche system into the mass market, but there are some refinements and clarification necessary to make this adoption by main-stream contractors a smooth transition.

## 2 Hemp-lime

Hemp fibre can be used as an insulating quilt material 'Batt' [2], however hemp-lime utilises the soft woody core of the hemp plant, which is of lesser economic value than the fibre. Hemp-lime consists of the chopped up core of the hemp plant (shiv), bonded together, usually, by a lime based binder to form a lightweight concrete-type matrix capable of supporting its self-weight.

### 2.1 Hemp Cultivation

Hemp (Cannabis Sativa) is an annual crop, which grows quickly during the summer to a height of about 4 metres. The plant is made up of two main elements: long outer fibre strands and a woody core. Cannabis Sativa has been grown for thousands of years across the continent and originates, as a cultivated crop, in Asia and China from 2800 BC (Froier, 1960 cited in de Bruijn [3]). Cultivation of the crop spread as the fibre became an integral material in the production of sails and ropes during the sea trade era [4] and found further uses during the Second World War to make parachutes [5].

The hemp plant became somewhat redundant when the cotton trade and labour saving new technologies from America flooded the markets with affordable material [4]. The production and processing of hemp could not keep up with the tropical fibre crops and coupled with restriction on its growth in many countries, [6] hemp was not competitive enough so more synthetic materials dominated the markets. Recently the hemp plant has been rediscovered, with new uses for the seeds of the plant as nutritional foods and oils [7]. The fibres are still used in the production of some sheet materials; clothing and paper, natural rope and as a replacement for the glass fibres in the production of body panels for the automotive industry, which is looking to promote a green edge [7, 8].

### 2.2 Perceived Pros and Cons of Hemp-lime

**Table1.** List of perceived Pros and Cons

| Pro |
|---|
| • Construction<br>→ Simpler construction than traditional timber frame, less stages<br>→ Homogenous structure – airtightness – ideal surface onto which to render/plaster<br>→ low risk of thermal bridging<br>→ No risk of insulation slumping within the wall leaving air voids of un-insulated wall<br>→ Low skilled construction method (NB*) |

| |
|---|
| • Performance<br>→ Good thermal performance<br>→ Damping of temperature fluctuations<br>→ Breathable wall - humidity regulation and passive control of internal environment<br>→ Reasonable acoustical performance [9]<br>→ Excellent fire resistance (chars)<br>• Structural<br>→ Additional stiffness provided to timber frame and protection by alkaline environment [10]<br>→ Lighter construction makes foundation of building less extensive and thus more ecological.<br>• Environmental<br>→ Low embodied energy<br>→ Recyclability of waste materials as well as end of life building |
| Con<br>• Construction<br>→ Short construction season (Feb-Sept)<br>→ Long drying time<br>→ Labour intensive construction - time involved<br>→ Inexperience of contractor can cause complications – some care and training needs to be taken<br>→ Lack of supporting or data in agreement on the protocols of best practice to aid first time users of the material<br>• Structural<br>→ Not load supporting<br>→ Long carbonation time, to reach full strength<br>• Environmental<br>→ Logistics – storage and transport of high volumes of materials |

*see bullet point 4 of construction con list

### 2.3 Environmental Benefit

The Life Cycle Analysis (LCA) of the $CO_2$ emission and sequestration of hemp-lime has been reported in publications [8, 11-13]. However many discrepancies and variability between stated values remain, essentially to do with the inclusion of the sequestered $CO_2$ within the material and the processes by which the binder is formed. Bevan, et al., [8] and Boutin [13] discuss how the Carbon Footprint can be reduced by producing the lime through the burning of biomass; a technique which cannot be adopted for the production of cement, as the high temperatures required cannot be reached [14].

Bevan, et al., [8] state that 108kg $CO_2$ is sequestered in 1$m^3$ of material. Other publications state that the overall $CO_2$ impact of the building is -35kg $CO_2$ [13], however this is assuming that 80% of $CO_2$ [11] given off through the production of lime is reabsorbed through carbonation. Carbonation takes a long time and depends greatly on the thickness of the wall. This provides a prolonged alkaline environment that protects the wooden studs and prevents mould growth, outweighing the need for the material to reach peak strength.

## 3 Constituents

### 3.1 Shiv

Hemp Shiv has historically been a by-product of the fibre production process, used as horse bedding [7] or compressed with the dust into biofuel briquettes [11]. The highly porous nature of the shiv is due to it being the location of the main transport cells, the Xylem and Parenchyma. The shiv serves as a lightweight aggregate, with a low bulk density and a large volume of trapped air within its pores. When mixed with a binder, the shiv adheres together in a random fashion, creating a complex network of voids and gaps containing more air, thus adding to the porosity of the material.

### 3.2 Binder

Binders of hemp-lime can vary depending on the intended purpose, desired characteristics and the location. Usually they consist of a lime base (possibly air lime or formulated lime) mixed with pozzolans, cementitious materials and other additives including additional hydraulic lime. Cement binders were initially trialled but their hydraulic nature competed with the high absorptivity of the shiv, reducing availability of hydration water, resulting in a powdery poor quality material [15]. Lime-based binders were found to work much better for many reasons presented in Evrard and De Herde [16]:

- A hydrated lime sets and hardens through carbonation, a process that requires a much smaller amount of water.
- The permeability of hydrated lime facilitates the drying of the entire wall not just the surface.
- The pH of lime is very high and prevents mould growth on the shiv and the timber frame.
- As with many uses of lime over cement its flexibility allows some distortion of the wall without cracking.
- The thermal conductivity of a hemp-lime wall is lower than if it were made with cement.

The additives mentioned above accelerate the short-term set of the material, allowing faster progress when casting.

Providing enough water is necessary to ensure the initial hydraulic set is achieved. Water plays a vital role in the formulation of hemp-lime, having a significant influence on many factors including consistency, durability, drying, etc. The following section discusses the role of water in the formulation of hemp-lime. Later the performance of the material is considered when the formulations of binder, hemp and water are varied, depending on the method of application or intended purpose.

### 3.3 Water

Water is needed to:

- Ensure thorough mixing of all constituents of the mix, making sure that all the shiv has a coating of binder
- Aid workability, both in mixing and placement of the material

- Hydrate the hydraulic part of the binder to cause the initial set
- Evaporation of excess water leaves air pocket pores (considered a defect in traditional concrete but adds to the porosity and thus the lightweight thermal nature of hemp-lime).

Due to the high porosity of the shiv, much of the water initially added to the mixing process is quickly absorbed by the shiv leaving the material still dry and unworkable. As the binder is added, the workability of the material improves slightly but there is still the concern that there may not be enough water easily available to the binder to cause the initial hydraulic set. Extra water is often added to compensate and ensure the lime is hydrated sufficiently, however after the lime sets the material is left with high quantity of retained moisture. This dry moisture content can be in the region of 70%, which needs to evaporate to approximately 5% [17].

## 4 Performance of Hemp-lime

Research into the performance of hemp-lime materials and buildings have found that the mechanical properties are poor with a compressive strength in the range of 0.5-2MPa [18-20] but the thermal properties of the material make it an excellent insulation material; with conductivity in the range of 0.06-0.18 W/m.K [18, 21].

Collet, et al., 2008 [22] investigated the adsorption desorption properties of the material and observed a hysteresis between the two. The moisture buffering characteristics of the material have also been considered [23], which show potential for the material as an indoor regulator of humidity and comfort. Evrard, de Herde and others discuss the hygrothermal performance of hemp-lime [16, 21, 24-26].

The porosity of the material has found to be very important and has been investigated using Mercury Intrusion Porosimetry and Nuclear Magnetic Resonance and found that the hemp has pores in the range of 1-50 µm. Mesopores of the lime binder can be anything from 0.05 µm [22].

Evrard, et al., 2006 [27] measured heat flux through 25cm wall elements of hemp-lime, cellular concrete and mineral wool and found that the "total amount of energy given from inside environment 24hours after the thermal shock is lower for LHC element ≈ 190kJ/m$^2$." This shows that hemp-lime is capable of retaining heat and requires less energy to maintain a building at a stable temperature. This was also observed in the Haverhill housing project; the hemp houses performed better than steady state predictions; maintaining a temperature of 2 °C above a traditional brick house, despite similar energy consumption [12].

## 5 Methods of Construction

There are many differing forms of construction: prefabrication, moulding of prefabricated blocks and casting or spraying on site. The following will discuss the two most common; cast in-situ and spraying on site into/onto temporary or permanent shuttering, investigating the variations in results.

### 5.1 Cast In-situ

Casting on site into shuttering to form a wall is a simple technique that provides good control over the thickness of the wall and the geometry it follows. Hemp-lime can be cast into any shape or form required, which makes it versatile in many forms of architecture and locations within buildings.

The process of casting hemp-lime follows much the same procedure for casting concrete. Shuttering is erected (in lifts of approximately an arm's depth, to aid filling). The dry components of aggregate and binder are mixed together, and then water is added to activate the binder before being filled into the shuttering. This continues until the shuttering is full, the next layer of shuttering is added and the process repeats. The shuttering is usually removed after 24hours, when the lime has begun to cure and the material can hold its form, allowing air to its surface aiding the carbonation process. Some constructions use an internal permanent shuttering, which acts as an internal finish as well as the mould for casting, this reduces the construction time slightly but may slow down the drying of the hemp-lime. It must be ensured that this permanent shuttering is breathable to allow moisture flow between the hemp-lime and the internal environment. Magnesium oxide or heraklith board is usually used [8].

#### *5.1.1 Water*

More water can be added to the mix 'as required' [8]. This is vague advice and an issue that arises often for first time users of the material who have no reference to base judgement on whether the mix is of the right consistency. There is a tendency to add too much water to the mix as it looks dry or not workable enough, this leads to more problems later on as there is a high quantity of water within the material. This increases the density of the material as it compresses under its own weight, lowering its thermal performance and increasing the time it takes the wall to dry out.

The hemp-lime mix does not need the same workability as a traditional concrete, which is poured in to formwork. Hemp-lime is placed by hand, with the key workability factor being to ensure there is a consistent coating of lime binder on all the hemp shiv particles, which will provide adhesion between the particles when it is cast and the hydraulic set begins to take place.

#### *5.1.2 Placement*

Many of the hemp houses constructed were tamped to compact the material and ensure the shiv formed a consistent matrix, Bevan, et al., [8] suggested tamping the material every 200-300mm. However unlike traditional concrete over compaction is a concern with hemp-lime, causing the material to become too dense; lowering its thermal performance, increasing the time taken to dry and cause problems later on with moisture. If the correct density of material is achieved through ratios and control of water then the weight of the material itself will compact down. It is now generally recognised that the less tamping the better and it is most effective if tamped by hand, ensuring the material fills all parts of the frame, especially below window and floor plates. Care should be taken of sharp or thin edges i.e. door and window revels as the material can be fragile and chip off easily, so more compaction is usually applied here and the area protected during drying.

It is undesirable to have vertical day joints or joints close to openings. At the end of a day's work, casting should be stopped at the top of the shuttering at least one lift below or above a door or window opening [28]. This allows some of the surface material which will dry over night to be removed and the surface roughened before the next day of casting begins.

### *5.1.3 Drying*

Once cast the hemp-lime wall needs to be protected from rain and drying out too quickly: extreme sun, strong winds; because water is integral to the setting of the hydraulic components of the binder. Once this process is complete the full depth of the wall needs to dry out, this can take at least 4 weeks and achieved best if no finishes such as render/plaster are applied. If however a wooden rain-screen cladding is to be applied externally this can be done straight away as it will protect the wall by providing the finished surface but continue to allow drying.

## 5.2 Spraying

Spraying separates the lime and water mixing from the addition of hemp shiv. This ensures all the lime is activated before the shiv are added at the last minute, when the material is placed.

In most systems the lime is made into slurry by adding more water. This slurry is forced under pressure to a nozzle outlet where the shiv, which is blown along a separate hose, is mixed with the slurry. The intention is to coat every particle of hemp with binder, while at the same time using the force of the air flow to project the shiv and binder mixture onto whatever substrate is being covered. However the effectiveness of this method depends heavily on the design of the nozzle to ensure sufficient coating of the shiv in binder to cause the shiv particles to stick together.

### *5.2.1 Homogeneity of material produced*

Considered the actual physical form of the material produced; there is potential for much variability in the material matrix. Hustache, et al., [29] suggested there are two matrix possibilities that can be formed through variations in the ratio between shiv and binder.

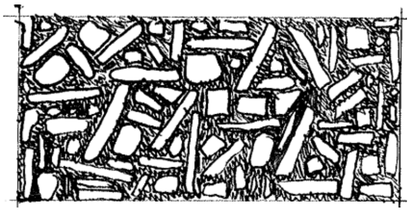

**Fig. 1** High hemp/binder ratio

Figure 1 shows a consistent mix of various size particles of shiv, interlocked and bound together by a thin layer of binder. The binder just coats the surface of the shiv and binds the particles where they touch; leaving air voids in the space between the shiv. This provides a very porous material with strong bonds between the shiv particles, ideally what is desired.

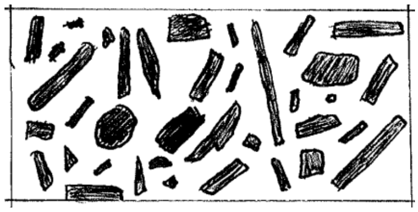

**Fig. 2** Low hemp/binder ratio

Figure 2 shows a heavy binder mass with shiv particles scattered within, caused by too much binder. This produces a material that is very dense with poor thermal performance and a higher moisture content, both of which adversely affect the drying time.

The worst thing that could occur is that the hemp shiv and binder are not mixed in the air at all, but first come into contact with each other on the substrate its self.

**Fig. 3** Layered hemp / binder

This can be a result of spraying too close or a hemp/binder heavy ratio mix at the nozzle i.e. there is not enough binder to coat the hemp, or not enough hemp being provided which results in a layer of pure binder on the wall. Control of the consistency is integral to the quality of the material and influenced by the supply of both parts of the mix to the nozzle. If all the systems are not working in harmony with each other and the appropriate projection distance maintained, there is the possibility of a layered material: with dry shiv in between binder layers. This will also result in a large amount of bounce back of shiv due to the dry shiv not being able to adhere to each other, but only stick to a layer of binder.

#### *5.2.2 Binder / Particle Interaction*

For the shiv that does mix properly in air with the binder there is still some uncertainty how this coating of binder interacts (or not) with the shiv. How does the un-coated or partly coated hemp behave due to its differing porosity of one completely covered in binder? Does this affect the hydric performance?

## 6 Comparison

Both methods of construction have appropriate uses and are versatile in their own right, to pick a preferred method would involve considering all aspects of the project and how the method can be tailored to suit. Bevan, et al., [8] suggest the cast in-situ method for houses smaller than $70m^3$ and a sprayed method for anything larger when considering the time involved. However it is still to be fully understood how the performance of the different materials produced by the respective methods differ.

Collet, et al., 2013 [30] observed very little difference in the materials permeability, moisture diffusivity and moisture buffering value, but the drying rate and in-situ building performance of methods were not considered. It is it this combined with the details of the project which will inform the method that is most suitable for a project.

### 6.1 Versatility

Sprayed techniques are unique to the cast method in that the hemp can be sprayed onto any material and stick to most. This becomes very useful in renovations where it would be hard to cast up to an in-place ceiling. Casting is perceived as slow but as revealed at the Haverhill project it depends on the experience of the contractors [12], the number of labours / mixers and the logistics of the site.

### 6.2 Consistency

Variations in consistency outlined in Figures 1-3 are possible with both methods of application and are attributed to alterations of the hemp/binder ratio as well as a reflection on the skill of the builder. As mentioned above the consistency of the sprayed material is dependent on the spray nozzle mixing the material sufficiently, but a heavy binder matrix (Fig.2) can be achieved through high compaction of the material as a result of the correct spraying distance not being maintained or the cast material being vigorously tamped. It is of paramount importance that a consistent approach is followed in the preparation and placement of the material. Training is advised for the entire team working on the build so that each understands how sensitive the material is to the actions taken. Knowledge and understanding of other wet trades, mortar/concrete mixing are not transferable as this material is not as forgiving.

### 6.3 Water – Setting – Drying

Spraying slightly reduces the need for the large quantity of excess water added to a cast in-situ hemp-lime mix; however this only slightly improves the drying time [31] and it has not been demonstrated that the *rate* of drying improves. Questions arise about the quality of the material produced by the spraying process:

- What happens when dry hemp is added to this lime-water mix?
- Does the hemp suck the water away from the lime, or does it absorb lime too?
- How does this affect the setting of the lime?
- Does shiv dry the lime out rather than provide water necessary for carbonation?

These questions need to be answered by the investigation of cast and sprayed samples.

### 6.4 Fibres

The use of fibres in each method has not been discussed thus far but it is something that must be considered in future. The benefits of adding fibres are minimal in terms of added strength or altering performance [32] and during spraying they can cause difficulties when it comes to delivering a consistent flow of hemp shiv to the nozzle.

## 7 Conclusion

This report has presented an overview of the cast in-situ and sprayed techniques generally implemented in the construction of hemp-lime buildings. Areas where confusion still exists have been highlighted and the author has identified a lack of consistency of published data and current 'correct' protocols.

Spraying is suitable in certain situations but control over the consistency of the material is dependent on the quality of the mixing nozzle and there is minimal control over the density /compaction of the material, whereas cast in-situ materials are able to be tailored to the required purpose through hand placement.

There is still much to be discovered about the differences between sprayed and cast methods, with emphasis on controlling water. A detailed investigation into the drying times and formulation consistency of these methods is being undertaken; exploring the particle/binder interaction of spraying and considering how the formulation of cast methods can be tailored to reduce the amount of water necessary. This will inform the choice of method and provide certainty of the material's performance, in turn promoting the use of hemp-lime as a choice construction material available to a wider community.

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