Hemp Concretes

Mechanical Properties
using both Shives and Fibres

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Cover: Hemp concrete specimens.
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Abstract

Hemp (*Cannabis sativa*) is an agricultural crop that can be used as a building material in combination with lime and cement. A composite building material that combines a cementitious binder (building limes and cement) with hemp shives, the woody core of the hemp stalk is generally referred to as hemp concrete (HC). However, industrial facilities to separate hemp shives and fibres are currently not available in Sweden. HC has many advantages as a building material but it is not load-bearing and must be used in combination with a load-bearing wooden frame.

The aim of this research was to elucidate the feasibility of using both hemp shives and fibres in a HC to determine an optimal mix of the different binding agents and to investigate if adding undensified microsilica to the mix and using calcinated gypsum as a binder would improve mechanical strength of the material. The effects on compressive strength of pre-mixing the binder or creating perforations in the test specimens were also investigated.

Cube and cylinder specimens cured for 40 days in a carbonation room (4.5 vol% CO_2) were tested for mechanical properties, water sorption and frost resistance. Including more hydraulic lime or undensified microsilica in the mix did not significantly affect mechanical strength, whereas adding more cement to the mix increased mechanical strength. Calcinated gypsum as a binder gave mechanical properties of the same magnitude of a contemporary HC. Pre-mixing the binder created a more homogeneous material but it did not seem to play an important role in final mechanical properties. The perforations created in some of the test specimens produced a material with a lower Young's modulus and higher deformation at rupture.

Using both shives and fibres in a hemp concrete may be a suitable approach in Sweden until facilities for separating hemp fibres from shives become available.

Keywords: hemp, building material, lime, cement, gypsum, carbonation, shives, silica, lime-hemp concrete.

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To my family

Een goed begin is 't halve werk,
Dutch proverb.

en het halve werk is'n goed begin.

Contents

List of Publications

This thesis is based on the work contained in the following papers, which are referred to in the text by their Roman numerals:

I. de Bruijn, P.B., Jeppsson, K-H., Sandin, K. & Nilsson, C. (2008). Mechanical properties of lime-hemp concretes containing shives and fibres. *Submitted to an international peer-reviewed journal.*

II. de Bruijn, P.B., Jeppsson, K-H. & Nilsson, C. (2008). The effect of silica, gypsum, pre-mixing and perforations on mechanical properties of hemp concretes. *Submitted to an international peer-reviewed journal.*

My contributions to the papers included in this thesis were:

I. Planning of the study in collaboration with my co-authors. Responsible for producing test specimens, sampling, data collection, analysing the data, and writing the paper.

II. Planning of the study in collaboration with my co-authors. Responsible for producing test specimens, sampling, data collection, analysing the data, and writing the paper.

Abbreviations

DM/ha	Dry matter per hectare
HC	Hemp concrete
LCA	Life cycle analysis
LHC	Lime-hemp concrete
RH	Relative humidity
w.b.	Wet base

Introduction

Hemp concrete

The introduction of hemp (*Cannabis sativa* L.) into building materials is relatively recent. Hemp shives were first introduced in the early 1990s in France in order to lighten concrete (Evrard, 2006). Hemp concrete is the term used in this thesis to describe a building material that combines a binder and shredded hemp.

A hemp stalk can be separated into fibres, located in the bark, and shives, located in the core of the hemp stalk. Hemp shives are the woody core parts of the hemp stalk, referring to their appearance and cellular structure, which resembles that of wood (Evrard, 2003). In the literature, a combination of a lime-based cementitious binder and hemp shives has been referred to as hemp concrete (translated from the French, Evrard, 2003), lime-hemp concrete (Evrard *et al.*, 2006; Evrard, 2006), hempcrete (Elfordy *et al.*, 2008) and vegetable concrete (Arnaud *et al.*, 2006). The binders investigated in the present study were not necessarily lime-based, so the term hemp concrete (HC) is used in this thesis in combination with the term lime-hemp concrete (LHC).

At present, several products such as hemp shives and pre-mixed limes are readily available to create a HC. Companies in Europe that market HC products are mainly situated in France and the UK and include Atelier de Chanvre, Cannabric, Canosmose, Chanvribat, Construire en Chanvre, EasyChanvre, Hemcore, HempFlax, Lhoist, Limetechnology and Tradichanvre.

Hemp

Hemp is a fast growing annual plant. It is a member of the family Cannabaceae in the order Urticales (which includes the nettle family). A hemp plant can reach a height of 1.5-4 m in northern Europe, while further south it can reach up to 10 m (Osvald, 1959). Hemp fibres have high tensile strength (Bledzki & Gassan, 1999) and are advantageous for use in a number of products such as paper, textiles and natural fibre composites. Fibres and shives are usually separated for these purposes. Historically, hemp shives were a by-product of the hemp fibre industry and were sold as horse bedding (Karus, 2005) and for combustion (H. Rolandsson, pers. comm. 2008). However, hemp shives can be used in a more high-quality product such as hemp concrete. Unlike other concretes that use only vegetable fibres (Gram *et al.*, 1984; Tolêdo Filho *et al.*, 2003), a hemp concrete generally uses the hemp shives, not the fibres.

Hemp yield in Sweden as reported by Holstmark (2006) ranges from 14.1 to 17.8 tonnes dry matter per hectare (DM/ha). Bernesson (2006) reported 6 to 11 tonnes DM/ha and Nilsson & Olsson (2008) mentioned 12 tonnes DM/ha. In the Nordic climate hemp can either be harvested in autumn or in spring. Spring harvesting requires a short period of frost before harvest. Frozen hemp is easier to harvest because it breaks more easily.

According to the Swedish Board of Agriculture, the hemp currently grown in Sweden is mostly used for bioenergy (H. Rolandsson, pers. comm. 2008). Of the more than 500 hectares of hemp grown in 2006, around 200 hectares were used for bio energy (Table 1). The hemp is pressed into briquettes before combustion for energy purposes. Another fraction of the hemp grown is used in trials and research projects. Not all of the hemp is harvested, and some is therefore ploughed under in the field. Only a few hectares of hemp are grown per farm in the absence of a commercial market to sell the product (H. Rolandsson, pers. comm. 2008).

Table 1. *Area of hemp cultivation in Sweden in recent years (H. Rolandsson, pers. comm. 2008)*

Year	Number of hectares cultivated
2003	24
2004	141
2005	377
2006	512
2007	792
2008	389

The Swedish market for non-food crops very much welcomes industrial products and new possibilities to use hemp, so hemp cultivation can be promoted to farmers (Eriksson, 2008). A limiting factor in the expansion of hemp cultivation in Sweden is the lack of products in which hemp can be used, and the lack of a commercial market for these products (Eriksson, 2008). No commercial fibre separating facility is currently operating in Sweden (H. Rolandsson, pers. comm. 2008). However, there is a facility in Vallberga, southern Sweden, which is currently not in use as there is no hemp fibre market in Sweden. In the future, hemp could be separated at Vallberga. This would promote Swedish hemp cultivation and the possibilities to market hemp fibres. From a more international point of view, Evrard *et al.* (2006) claimed that the introduction of hemp shives into buildings is a new opening for the hemp industry and a way to support the development of industrial fibre crops.

Cementitious binders

The lime-based cementitious binder used in HC consists of the following main components:
- Hydrated lime
- Hydraulic lime
- Cement

The raw material for lime is usually limestone, but other sources such as chalk, coral rocks or shells can also be used (Holmes & Wingate, 1997). Limestone contains calcium carbonate ($CaCO_3$), which is heated in a kiln at a temperature of around 900 °C where it gives off carbon dioxide and forms calcium oxide, CaO. The calcium oxide formed is commonly referred to as quicklime. Quicklime combined with water changes to calcium hydroxide $Ca(OH)_2$, known as hydrated lime, aerated lime or slaked lime (Holmes & Wingate, 1997). In this study it is referred to as hydrated lime.

Hydraulic limes are made from limestones that contain fine clay materials, which when appropriately fired in the kiln combine with lime to form active compounds. These active compounds in the clay materials, such as soluble silica (SiO_2), alumina (Al_2O_3) and ferric oxide (Fe_2O_3), give chemical setting in addition to the carbonation process (Holmes & Wingate, 1997). Older hydraulic limes consisted of a hydrated lime and a certain amount of clay. Hydraulic limes nowadays are blends of hydrated lime, blast furnace slag (silica), unfired ground limestone (often a mix of $CaCO_3$ and $MgCO_3$), a little cement and additives (Verver, 1998).

Woolley (2006) reported that lime is relatively weak in both compression and tension, which gives masonry walls constructed with lime mortar a certain amount of flexibility. Cement, by contrast, is quite strong in tension and acts to resist movement. Lime is a more permeable material and it has lower mechanical strength. During the hardening process of hydrated lime, the material takes up carbon dioxide. Over time, the lime carbonates and hardens while forming calcium carbonate.

Cement consists of different compounds that are formed out of these principal oxides, namely calcium oxide, silica, alumina and ferric oxide. They set more quickly than lime, and change chemically while hardening. Cement is completely hydraulic – as it sets, it takes up water (Verver, 1998).

Evrard & de Herde (2005) believe that rich lime (calcium oxide) is more appropriate for use in HC than cement. The main reason they give for this is that the slow carbonation process of the lime is more compatible with the fast water uptake of the hemp shives compared with the reactions of a hydraulic binder such as cement. They also claim that the high pH of lime protects the hemp shives from mould and bacteria for a long time.

Historical context

Hemp cultivation in Sweden

Hemp originates from Central Asia and has been grown there for thousands of years. Abel (1980) states that hemp is mentioned in Roman literature from around the year 100 B.C., indicating that the plant was grown in what is now southern Europe. Hemp was most probably not known in central and northern Europe until the beginning of the Christian era. Sweden probably became familiar with hemp during the Viking era, when Swedish Vikings explored parts of Russia (Osvald, 1959).

During World War II hemp cultivation expanded very rapidly, and during the period 1940-1960 hemp fibre production remained relatively constant. However, in 1965 the growing of hemp was banned in Sweden due to its content of narcotic substances (Holstmark, 2006). This ban on hemp lasted around 40 years and was only lifted in Sweden in 2003. The highest level of tetrahydrocannabinol (THC) permitted in Swedish hemp is 0.2% (Holstmark, 2006). This kind of hemp is commonly referred to as industrial hemp to distinguish it from pharmaceutical hemp.

Historical building materials

Hemp concrete shows some similarities to other building materials and methods that have been used throughout history, including Roman cement and half-timbering.

Roman cement is an ancient building material where a bonding agent such as lime is combined with an aggregate such as sand (Delatte, 2001). The lime is combined with pozzolans and fibrous organic material to improve tensile strength and prevent cracking of the material. This concept has been used and proven durable through time over the last millennia. Cato (234- 149 B.C.), the author of *De Agri Cultura*, writes about farm construction thus (translation by Winter, 1979): "…the builder will cut and make do stone, lime, sand, water, straw, earth from which to make mud.". The mix that Cato described over 2 millennia ago combines lime, aggregates such as stone, earth and sand, and straw as fibrous organic material in a mix with water. The use of lime in building structures dates back even further than that. According to Adam (1994), lime was already used in plaster in Asia Minor in the sixth millennium B.C..

Another building material and building method is that of half-timbering (Swedish *korsvirke*), with a framework of timber and an infill of mud and straw, see Figure 1. In Sweden this building technique was mainly used in Scania, a southern province with few forests. The wooden framework was load-bearing, while the mud and straw created a wall that had reasonable thermal insulation properties and a high thermal mass. The straw improved the durability of the mud wall.

Figure 1. Half-timbered house from the 19th century , Sweden.

There are several similarities between half-timbering and HC. Both have a load-bearing framework of timber, in combination with an infill of fibrous organic matter (straw and hemp, respectively). In HC limes are used as binding agents, whereas in half-timbering mud and dung functioned in a similar binding manner.

These three building techniques arose independently. However, the use of the agricultural crop hemp in combination with a binder in hemp concrete is reminiscent of both Roman concrete and half-timbering. HC could be regarded as the return of older building techniques in a modern shape.

Building with hemp concrete

Sustainable building

The UN conference on the environment in Rio de Janeiro 1992 was a catalyst for the Swedish building industry to focus more on a sustainable future, with an accompanying sustainable built environment (Bokalders & Block, 2004). The paths towards a more sustainable built environment are very diverse. The main themes of the 2010 Environmental Programme of the Swedish Ecocycle Council are (Kretsloppsrådet, 2003):

- Energy conservation
- Efficient use of building materials
- Phase-out of hazardous substances
- Secure and healthy indoor environment

Using renewable agricultural crops as raw materials for the building industry is in line with the development towards a more sustainable built environment. The way in which the built environment consumes natural resources means that it is one of the most significant contributors to global and local environmental problems (Woolley, 2006). Therefore a shift to using renewable materials, such as non-food crops, in the building sector is imperative. Tolêdo Filho *et al.* (2003) emphasise the importance of the use of vegetable fibres in concretes, especially in non-industrialised countries. They point out that vegetable fibres are cheap and readily available, require only a low degree of industrialisation for their processing and a small amount of energy for their production, and thus costs are low. Other non-food crops that can be used for construction purposes include flax, miscanthus and cereal straw. The latter two, like hemp, have a woody core that can be used in construction biocomposites (NNFCC, 2008).

Using agricultural crops in a building material such as HC creates a material with a lower density, thus reducing the energy needed for transportation (Evrard, 2003). Lime requires less energy to produce than cement, with much lower carbon emissions, because it uses kilns at a lower temperature (Evrard, 2003; Woolley, 2006).

In a LCA report written for the French Ministry of Agriculture and Fishery, Boutin *et al.* (2005) state that lime-hemp concretes have a low impact on the environment and a potentially favourable impact on the greenhouse effect. Evrard (2003) discuss carbon dioxide storage in hemp concrete construction. As hemp grows it takes up carbon dioxide and when it is harvested and used in a building material, this carbon dioxide is stored inside the material during the lifespan of the building. Boutin *et al.* (2005) estimate that one square metre of LHC wall stores between 14 and

35 kg CO_2 over its life span of 100 years. This is due to CO_2 storage in the hemp and the construction wood, but also in the lime, which takes up carbon dioxide as it sets. They also estimate that total fossil fuel use over the life-cycle of lime-hemp concrete walls is comparable to that of other building materials (370-394 MJ per m^2).

Advantages of building with hemp concrete

The main advantages of building with HC are:

- Good thermal insulation (Evrard, 2003)
- Good acoustical insulation (Evrard, 2003)
- Low impact on the environment (Boutin *et al.*, 2005)
- Simplification and reduction in the number of layers and processes involved in timber-frame construction (Woolley, 2006)

Building methods

There are several building methods for building walls with HC, all of which use a load-bearing timber structure. These methods are:

- Tamping (R. Carpenter, pers. comm. 2006)
- Spraying (Elfordy *et al.*, 2008)
- Blocks (R. Robin, pers. comm. 2007)

Tamping

Boards, for example plywood sheets, are temporarily attached to both sides of a load-bearing timber structure, creating a mould that is filled with HC, (Figure 2). The HC mix is tamped, either by hand or with a tamping device such as a wooden stave, to avoid large air voids in the material. It is important not to tamp too hard, as this produces a material with poorer thermal insulation properties. On the other hand, the tamping has to be hard enough to eliminate large air voids (H. Erven, pers. comm. 2007). The plywood sidings can be removed immediately after the HC has been tamped in place (R. Carpenter, pers. comm. 2006; SEBTP, 2007).

Two hemp houses have been constructed in Haverhill, UK, using the tamping method. Reports by the British Building Research Establishment (BRE, 2002; BRE, 2003) have concluded that the qualities of these hemp houses are at least equal to those of traditional constructions.

Spraying

Plywood sheets are attached to one side of the load-bearing timber structure and the HC is sprayed evenly onto these boards. The HC adheres sufficiently to the boards to stay in place. This spraying method is described by Elfordy *et al.* (2008).

At the Centre for Alternative Technology in Wales, UK, a new building is currently being constructed using the 'hempcrete spraying method' (CAT, 2008).

Blocks

A load-bearing timber framework is erected. The blocks have slots that fit exactly over studs on the framework (Figure 3). All blocks are placed on the framework and then the wall plate is installed (R. Robin, pers. comm. 2007).

In France several houses have been constructed with these blocks, amongst others in Paris, Perpignan and southern Britanny.

Figure 2. Tamped hemp after the temporary siding has been removed.

Figure 3. Blocks of lime and hemp. (Picture: R. Robin)

Material Properties

The combination of hemp shives and a cementitious binder creates a building material with mechanical, thermal and acoustic properties that differ from those of conventional concrete. It has a lower density, a lower thermal conductivity and better acoustic insulation properties and is thus advantageous for use in construction (Cerezo, 2005; Evrard, 2003; O'Dowd & Quinn, 2005; Arnaud *et al.*, 2006). However, it is not load-bearing.

Some material properties of a LHC mixture for walls and those of other building materials, as reported by Evrard (2003) and Avén (1984) are presented in Table 2.

Table 2. *Some material properties of lime-hemp concrete (wall mix) and other building materials (sources: Evrard, 2003 and Avén, 1984).*

Material	**Young's modulus** **E (MPa)**	**Compressive strength** **σ (MPa)**	**Density** **ρ_{norm} (kg/m³)**	**Thermal conductivity** **λ_{norm} (W/m·°C)**
Steel	210000	350-1000	7500-8500	52
Concrete	20000	12-80	2300	1.5
Cellular concrete	1000-2500	5	420-1250	0.14-0.23
Brick	10000-25000	25-60	1300-1700	0.27-0.96
Wood	230–20000	$4_{\perp}$ - $34_{\parallel}$ [1]	350-900	0.12-0.3
LHC (wall mix)	24	0.4	445	0.17

[1] ⊥ perpendicular to the wood grain, || parallel to the wood grain.

For producing a LHC wall mix Evrard (2003) used 19% (weight) hemp shives, 31% (weight) lime binder and 50% (weight) water. They used a pre-formulated lime binder mix that consists of 75% hydrated lime, 15% hydraulic lime, 10% pozzolans and <5% additives.

Even though generally a high portion of hydrated lime is used in conventional LHC, according to Woolley (2006) companies experimenting with hemp in the UK have successfully used hydraulic limes and other mixes. For example, O'Dowd & Quinn (2005) used a lime binder that consists of hydraulic lime (NHL 3.5).

Compressive strength

The compressive strength of HC varies depending on the exact mix and age of the material. Reported compressive strength values for HC vary from 0.02 to 1.22 MPa (Arnaud & Cerezo, 2001). Evrard (2003) reports compressive strengths varying from 0.2 to 0.5 MPa, depending on the composition of the mixture. This is not enough for the material to be load-bearing and an additional load-bearing structure is needed. O'Dowd & Quinn (2005) reported a compressive strength of 0.71 MPa for a hemp shive to lime ratio of 3:1 (volume). They also reported that the hemp lime ratio of 3:1 is similar in strength to a 4:1 and 5:1 mix.

Hydrated lime takes up carbon dioxide while it sets, but this is a very slow process. According to Arnaud & Cerezo (2001), depending on the amount of hydrated lime in the binder mix, the maximum compressive strength is obtained after a period of time ranging from several months up to several decades.

Splitting tensile strength

O'Dowd & Quinn (2005) report splitting tensile strengths, depending on the mixture, varying from 0.12 to 0.23 MPa. They found that a mixture with a hemp shive to lime ratio of 3:1 by volume had a splitting tensile strength of 0.15 MPa.

Thermal insulation

Arnaud & Cerezo (2001) tested thermal conductivity for eight different mixtures and found values ranging from 0.07 to 0.11 W/mK. Evrard (2003) report thermal conductivity of 0.17 W/mK for material placed in a 'normal' environment but do not describe conditions in this normal environment, although they are most likely a temperature of 20 ºC and a relative humidity of 60-70%.

Increasing mechanical strength

There are different ways to create a HC with higher compressive strength than that of HC reported in other research. This could be achieved by modifying the composition of the matrix, *e.g.* by using different mixtures of the binding agents and by adding suitable pozzolans or additives. Pozzolans that are much used in concrete are fly ash and silica fume. They contribute to the improvement of mechanical strength of concrete (Almgren *et al.*, 2007). Undensified microsilica has an extremely small grain size and therefore high reactivity with free lime in concrete, forming a strong and non-permeable paste (Asrar *et al.*, 1999). Consequently, using undensified microsilica in combination with lime may improve the mechanical strength of HC.

Using gypsum as a binder in combination with hemp could result in increased mechanical strength. Karni & Karni (1995) report a compressive strength of 12.0 MPa for unretarded gypsum. Calcinated gypsum (plaster of Paris) is a binding material produced from gypsum, with the chemical notation beta-hemihydrate (β-$CaSO_4 \cdot 0.5H_2O$). Using gypsum in combination with hemp could result in a building material with higher compressive strength than when using limes.

Aims of the thesis

The aim of this thesis was to determine some important material properties of different hemp concretes, using varying binder compositions in combination with the entire shredded hemp stalk as currently available in Sweden.

Specific objectives were to:

- Identify mechanical properties of different hemp concretes using both hemp shives and fibres and varying binder compositions.
- Investigate whether adding undensified microsilica to the mix improves compressive strength.
- Investigate the compressive strength when calcinated gypsum is used as a binder for hemp concrete.
- Investigate whether pre-mixing the binding agents with water before adding it to the hemp affects the final strength of the material.
- Investigate whether creating perforations in the material, in order to increase its relative surface area, increases compressive strength.

The overall aim was to identify a mixture of binders that was optimal from a mechanical point of view. Our starting assumption was that the above-mentioned measures would improve the mechanical strength of hemp concrete.

Materials and Methods

Hemp

The hemp used in this research was the cultivar Futura 75, acquired from a local farm in the province of Scania, southern Sweden, where it was sown on 21 April 2005 and allowed to freeze-dry before being spring-harvested on 15 April 2006. The entire hemp plant was harvested, baled and stored. The hemp bales were processed in an industrial shredder where the shives, fibres and dust were not separated. The composition of the hemp material by weight is presented in Figure 4.

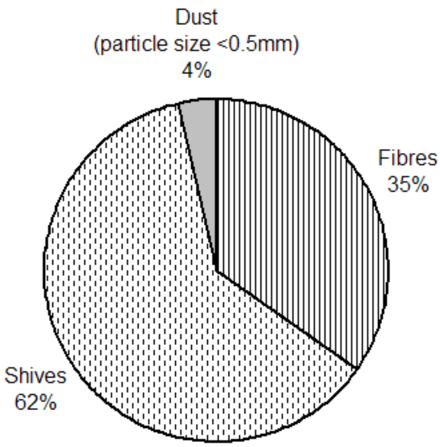

Figure 4. Composition of hemp material by weight%.

Binding agents

The binders used in this study were hydrated lime (calcium hydroxide), hydraulic lime (NHL 5), building cement (CEM II/A-L) and calcinated gypsum (beta-hemihydrate). The material density values as established by laboratory measurements are presented in Table 3. The density of the materials was determined and calculated by taking the mean value for five measurements of 1 litre of uncompacted dry material.

Table 3. *Density of hemp, binders and additive*

Material	**Density, kg m^{-3}**
Uncompacted shredded hemp	98
Hydrated lime ($Ca(OH)_2$)	528
Hydraulic lime (NHL 5)	1590
Cement (CEM II/A-L)	1330
Calcinated gypsum (beta-hemihydrate)	892

Binder mixtures

In Paper I, five mixtures of the binding agents were prepared, designated A, B, C, D and E. In Paper II mixtures with the same binder composition as B, D and E in Paper I were prepared. Mixture N consisted of hydrated and hydraulic lime. Two mixtures designated P and R contained the additive undensified microsilica, while a mixture designated S contained the binder calcinated gypsum (Figure 5).

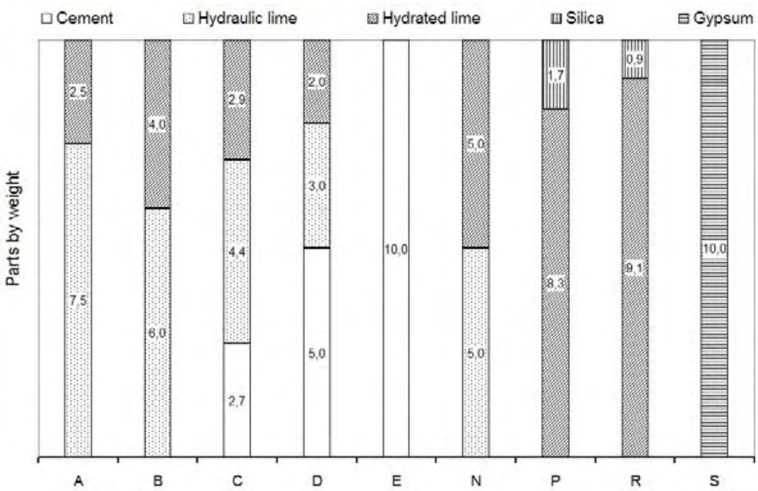

Figure 5. Composition of mixtures A-E, N, P, R and S by relative weight (as fraction of 10).

For each mixture, a series of cube and cylinder specimens were prepared. Standard steel moulds measuring 150×150×150 mm were used for preparation of the cube specimens. For the cylinder specimens in paper I, cylindrical ø150 mm steel moulds with a length of 300 mm were used. The moulds were lined with plastic household film for ease of extraction of the specimens from the moulds after preparation (O'Dowd & Quinn, 2005). The binder-hemp mixtures were prepared using a concrete mixer. For mixtures A-E in Paper I, the hemp/binder ratio and the water/binder ratio excluding hemp as a binder were as indicated in Table 4. The ratio of hemp to binder was 3:1 by volume of uncompacted dry material, resulting in a value of approximately 0.30 for hemp/binder ratio by weight. The binders were mixed with water in a separate container, using an electric with agitating attachment, before being added to the hemp and additional water in the concrete mixer.

Table 4. *Hemp/binder ratio and water/binder ratio in mixtures A-E in Paper I*

Mixture	**Hemp/binder (kg/kg)**	**Water/binder (kg/kg)**
A	0.28	1.06
B	0.33	1.33
C	0.30	1.20
D	0.28	1.11
E	0.22	0.89

The hemp/binder ratio and water/binder ratio for mixtures used in Paper II are presented in Table 5. As the mixtures were found to be rather dry after production in Paper I, water/binder ratios in Paper II were higher than those in Paper I. Also, the binders were not pre-mixed with water before being added to the hemp, with the exception of mixtures P and R to activate the silica. Specimens of mixture P were prepared both with and without pre-mixing the binders and designated P_{mix} and P respectively.

Table 5. *Hemp/binder ratio and water/binder ratio in mixtures used in Paper II*

Mixture	**Hemp/binder (kg/kg)**	**Water/binder (kg/kg)**
E	0.22	1.47
D	0.28	1.81
B	0.33	1.87
N	0.37	1.71
P	0.64	3.75
R	0.61	3.73
S	0.33	2.10

The binder mix was added to the hemp in the concrete mixer and allowed to rotate for five minutes. Any visible lumps were broken up by hand. The mix was applied to the moulds and tamped into the moulds using a wooden stave (45×45 mm). A layer of approximately 50 mm was applied, then tamped. After this another layer was applied and tamped, then a third and tamped. At that point the mould was filled with the mix. Cylinders were filled in a similar way. After tamping, the moulds were placed on a vibration table (50 Hz) for one minute. Specimen preparation was different for mixture S, as gypsum sets very quickly. One specimen was prepared at a time, blending gypsum and water by hand before adding the hemp.

For Paper II an insert was made of plywood and plastic tubes (ø32 mm). It was used in combination with the steel cubic moulds (150×150×150 mm) with the aim of creating perforations in some of the specimens of mixtures B, N P and R (Figure 6).

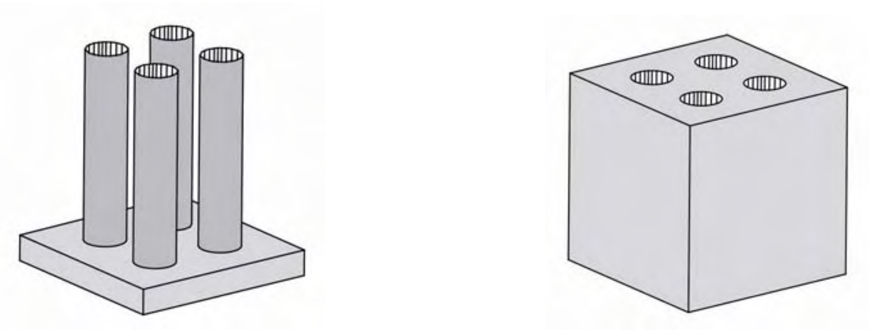

Figure 6. Left: Insert used for creating perforations in test specimens. Right: Test specimen with perforations.

All specimens were cured for two days in an indoor climate at approximately 20 °C and then removed from the moulds. In Paper I curing continued for another 12 weeks at room temperature (average temperature 19.7 °C within the range 17.3-23.9 °C. The specimens were then placed in a carbonation room. In Paper II specimens were placed in the carbonation room as soon as the last specimens had cured for two days, which was three weeks after preparation of the first specimens. In total, specimens were cured for 18 weeks in Paper I and 12 weeks in Paper II.

Carbonation

Specimens were exposed to 4.5% CO_2 for 40 days in the carbonation room to accelerate the carbonation process. In the carbonation room the temperature was kept at 20 ºC and relative humidity at 50%. Arnaud & Cerezo (2001) found that these conditions were optimal for the curing and carbonation of HC. Gram *et al.* (1984) concluded that during the carbonation process of concrete, the higher the relative air humidity rises above 50%, the more slowly the carbon dioxide is transported in the pore system.

Specimens of all mixtures were placed in the carbonation room in order to keep curing conditions equavalent for all specimens. After the carbonation process, the specimens were kept in the carbonation room at normal CO_2 levels (≈ 0.038%) until testing.

Testing material properties

A compressive strength test was performed on the test specimens, both before and after exposure to 25 freeze-thaw cycles of 12 hours of +20 ºC followed by 12 hours of -20 ºC. The cylinders underwent a splitting tensile test. Additional cube specimens were tested in a water sorption test. The following values were determined: stress (σ in MPa), strain (ε), Young's modulus (E in MPa), splitting tensile strength (T in MPa) and water sorption coefficient (A_w in kg m^{-2} $s^{-½}$), see Paper I and II.

Methods to determine compressive strength and splitting tensile strength were according to Swedish standards SS-EN 12390-3 and SS-EN 12390-6 respectively. However, they were modified in order to be suitable for HC. This modification involved adjusting strain velocity in such a way that the specimens were strained for at least 30 seconds before rupture occurred.

Statistical analyses

Statistical analyses were carried out using the software package Minitab 15 for Microsoft Windows (Minitab Inc., State College PA, USA). Appropriate t-tests, analysis of variance and Tukey's tests were carried out to determine whether differences between the test mixtures were statistically significant ($P<0.05$).

Results

Compressive strength

The results of compressive strength tests in both papers are presented in Table 6. In Paper I, mixture D showed the highest values for compressive strength, but after exposure to the freeze-thaw treatment mixture E clearly showed the best results. In both cases mixture E, which contained only cement as a binder, had the highest values for Young's modulus. Mixtures A and B were not significantly different when comparing results before and after the freeze-thaw treatment (data not shown).

In Paper II, the Young's modulus values of mixtures B and E before and after freeze-thaw treatment did not differ significantly. Mixture E clearly had the highest Young's modulus. Mixtures B, D and N, all of which contained approximately 50% hydrated lime, showed similar results. However mixture D, which also contained cement, had significantly higher compressive strength before the freeze-thaw treatment. Mixtures P and R, which contained silica, not only had low compressive strength, but also a low Young's modulus. Furthermore, they were negatively affected by the freeze-thaw treatment.

Undensified silica as additive

Mixtures P and R (and P_{mix}) contained hydrated lime and some undensified microsilica. This did not create a mechanically stronger material in comparison to mixtures B and N in Paper II, which contained a combination of hydrated lime and hydraulic lime. Mixtures P and R had low values for compressive strength and Young's modulus, both before and after the freeze-thaw treatment.

Table 6. *Composition of mixtures used in Papers I and II and their mechanical properties before and after freeze-thaw treatment*

Paper I **(binders pre-mixed)**

Mixture	Composition, fraction by weight	Before freeze-thaw treatment σ (MPa)	Before freeze-thaw treatment E (MPa)	After freeze-thaw treatment σ (MPa)	After freeze-thaw treatment E (MPa)
A	7.5 / 2.5	0.20_{a}	13.41_{a}	0.23_{a}	14.79_{a}
B	6.0 / 4.0	0.15_{a}	12.65_{a}	0.19_{b}	12.49_{a}
C	2.9 / 4.4 / 2.7	0.44_{b}	17.40_{b}	0.30_{a}	$25.87_{a,b}$
D	5.0 / 3.0 / 2.0	0.83_{d}	28.01_{c}	0.66_{c}	39.19_{b}
E	10	0.55_{c}	49.40_{d}	2.78_{d}	323.89_{c}

Paper II **(B-N and S not pre-mixed, P and R pre-mixed)**

Mixture	Composition, fraction by weight	Before freeze-thaw treatment σ (MPa)	Before freeze-thaw treatment E (MPa)	After freeze-thaw treatment σ (MPa)	After freeze-thaw treatment E (MPa)
B	6.0 / 4.0	$0.42_{a,b,c}$	$23.90_{a,b,c,d}$	$0.27_{a,b}$	19.33_{a}
D	5.0 / 3.0 / 2.0	0.80_{d}	†	0.38_{a}	17.73_{a}
E	10.0	2.14_{e}	173.90_{e}	1.79_{c}	165.80_{b}
N	5.0 / 5.0	0.53_{a}	$36.69_{a,f}$	0.25_{b}	17.05_{a}
P	8.3 / 1.7	0.33_{b}	$14.38_{b,g}$	0.13_{d}	4.42_{c}
R	9.1 / 0.9	0.42_{c}	$16.62_{c,g}$	0.12_{d}	4.50_{c}
S	10.0	0.71_{d}	$60.50_{d,f}$	†	†

Hydraulic lime   Hydrated lime   Cement   Gypsum   Silica

†No data available due to computer failure.

Different letters (a, b, c, *etc.*) within columns indicate significantly different values (P<0.05).

Gypsum as binder

For mixture S, where gypsum was used as a binder, both compressive strength and Young's modulus were higher than that of the other mixtures, with the exception of mixture D and E.

Pre-mixing the binder

Compressive strength was affected more by pre-mixing the binder than Young's modulus. This indicates that the brittleness of the material was less affected by pre-mixing the binder. Mixtures B, E and P all had higher compressive strength when not pre-mixed. This also applied for the Young's modulus of mixture E (Table 7).

Table 7. *Results of compressive tests on the different mixtures used in Papers I and II*

Mixture	**Compressive strength, σ (MPa)**	**Young's modulus, E (MPa)**
B_{mix}	0.15	12.65
B	0.42 *	23.90
D_{mix}	0.83	†
D	0.80	†
E_{mix}	0.55	49.40
E	2.14 *	173.90 *
P_{mix}	0.33	14.38
P	0.45 *	17.04

† No data available due to computer failure.

* Significant difference in relation to pre-mixed specimens of the same mixture ($P<0.05$).

Solid versus perforated specimens

Comparisions of solid specimens with perforated specimens showed that solid specimens had slightly lower compressive strength and higher Young's modulus (Table 8).

Table 8. *Results of compressive tests for solid specimens and specimens with perforations for mixtures B, N, P and R*

Mixture	Compressive strength, σ (MPa)	Young's modulus, E (MPa)
B_{solid}	0.42	23.90
B_{perf}	0.60	7.60
N_{solid}	0.53	36.69
N_{perf}	0.60	7.82 ⋆
P_{solid}	0.33	14.38
P_{perf}	0.73 ⋆	5.69 ⋆
R_{solid}	0.42	16.62
R_{perf}	0.66 ⋆	4.17 ⋆

⋆ Significant difference in relation to solid specimens of the same mixture ($P<0.05$).

Splitting tensile strength

The splitting tensile strength of the cylinder test specimens as reported in Paper I did not exceed $113 \cdot 10^{-3}$ MPa, which was the value found for mixture D (Table 9). Mixtures A and B had the lowest splitting tensile strength. These mixtures contained only building limes.

Table 9. *Splitting tensile strength of mixtures A-E used in Paper I*

Mixture	Splitting tensile strength, T (MPa)
A	$23.5 \cdot 10^{-3}$ a
B	$21.6 \cdot 10^{-3}$ a
C	$36.7 \cdot 10^{-3}$ b
D	$113 \cdot 10^{-3}$ c
E	$58.3 \cdot 10^{-3}$ d

Different letters (a, b, c, *etc.*) within columns indicate significantly different values ($P<0.05$).

Water sorption

In Paper I, the mean water sorption coefficient was 0.15 $kg/m^2\sqrt{s}$ for the mixtures A–E. No statistically significant differences between the mixtures could be observed. Water sorption of specimens with a lime render will be tested in a later stage of this research project.

Discussion

Hemp

One of the objectives of this research project was to determine the mechanical properties of different hemp concretes using both hemp shives and fibres. Unseparated hemp was used in both studies (Papers I and II). In contemporary HC only hemp shives are used, not fibres (Arnaud & Cerezo, 2001; BRE, 2002; Evrard, 2003; O'Dowd & Quinn, 2005; Arnaud *et al.*, 2006).

The use of both shives and fibres did not seem to give different mechanical properties compared with other research where only hemp shives were used. Contemporary HC where only shives, not fibres, are used have a compressive strength of 0.4-1.2 MPa (Arnaud *et al.*, 2006) or 0.4 MPa for a 'wall' mix (Evrard, 2003). Furthermore, Young's modulus ranges between 20-90 MPa (Arnaud *et al.*, 2006) or 24 MPa for a wall mix (Evrard, 2003).

The use of both shives and fibres probably affects the material mechanically and in other ways. Fibres are thin and have a different porosity from shives and they also have a different chemical composition (van der Werf, 1994). Compared to other HC this could have created a difference in material properties that were not tested in this research, such as thermal insulation properties and moisture buffering properties.

Compressive strength and Young's modulus

Different compositions of hydrated lime, hydraulic lime and cement were compared. An increase in hydraulic lime in the mixture did not increase the compressive strength of the material as shown by a comparison of mixtures

B and N in Paper II, with N containing more hydraulic lime than B. Any differences observed between these mixtures were not statistically significant.

Lime is soft, permeable and (pseudo-)elastic and has a high capillarity. Cement is hard, less permeable and inflexible and has a low capillarity. Therefore lime-based and cement-based materials can perform quite differently (Woolley, 2006). More cement in the mixtures in Paper I did not increase mechanical strength greatly compared with other mixtures without cement. Even so, the Paper II mixtures that contained more cement (D and E) clearly had higher mechanical strength. In order to keep curing conditions equivalent for all mixtures, the cement in Paper I was not watered. In Paper II this was reconsidered, and specimens that contained cement were regularly watered during the first two weeks of curing. This most likely caused the difference in mechanical strength between cement-containing mixtures C, D and E in Paper I and those in Paper II (D and E).

After producing specimens for the first study it was noted that water/binder ratio in the mixture might have been low. Therefore more water was added to the mix in paper II. This could have influenced the mechanical strength of mixtures in paper I and II.

Woolley (2006) noted that it is not easy to give detailed instructions on the correct proportions of hemp and lime. Furthermore, Nguyen *et al.* (2008) reported that the water exchanges between the hemp shives and the lime paste are not predictable because of a lack of data concerning hemp shive characteristics and the best granular size distribution for hemp concrete.

Arnaud (2000) pointed out that the mechanical properties evolve slowly during the first year, and that setting continues even after that. Carbonation was accelerated in the present study by means of a carbonation room. Even so, the setting of the lime-containing mixtures probably continued for a long time.

Undensified microsilica is often used in concrete to create a stronger material (Almgren *et al.*, 2007). However, in the present study hydrated lime mixtures with undensified microsilica as an additive had low mechanical strength, both before and after freeze-thaw treatment. Mixtures P and R which contained the additive undensified microsilica were particularly affected by the freeze-thaw treatment.

Calcinated gypsum in combination with hemp and water as a building material showed good results for compressive strength before freeze-thaw treatment, see mixture S in Paper II. Gypsum has a strong sensitivity to humidity (Evrard, 2003), which means that caution has to be taken when using it as a building material for walls. Protecting it from high humidity is very difficult. For this and other reasons Evrard (2003) did not recommend using calcinated gypsum as a binder in combination with hemp. However, using a suitable render on the material might at least protect the gypsum from water damage.

Splitting tensile strength

Paper I determined splitting tensile strength for the mixtures A–E. Mixture D, which was a combination of hydrated lime, hydraulic lime and cement, was the only mixture that had a splitting tensile strength of more than 0.1 MPa. van der Werf (1994) mentioned the high tensile strength of hemp fibres. We had expected that the splitting tensile strength of HC with both fibres and shives would be higher than that of other HC, but this did not seem to be the case. For a shive:lime mix of 3:1 by volume, similar to proportions used in this research, O'Dowd & Quinn (2005) found a tensile strength of 0.15 MPa, which is a value of the same magnitude as found in this research.

Water sorption

Water sorption analyses of the different mixtures as determined in Paper I revealed no significant differences between mixtures A–E as regards water sorption coefficient. An average of 0.15 $kg/m^2\sqrt{s}$ was found for the HC. This was similar to that of other cementitious building materials such as brick (ρ=1900 kg/m^3) and cement mortar, both of which have a water sorption coefficient of 0.1 $kg/m^2\sqrt{s}$ (Sandin, 1996).

Water sorption of specimens with a lime render was not investigated but will be examined in the continuation of this research.

Freeze-thaw treatment

Freeze-thaw treatments seemed to improve the mechanical strength of some of the specimens, particularly mixture E in Paper I. It is likely that this was because mixture E, which contained only cement, was not watered during curing to keep curing conditions equivalent for all mixtures. When mixture E was later immersed in water for 24 hours to prepare for the freeze-thaw treatment, it gained strength. In Paper II, mixtures containing cement were watered during curing. This gave different results after freeze-thaw treatment compared with those in Paper I. Compressive strength for mixture E in Paper I was higher after exposure to freeze-thaw treatment. For mixture E in Paper II, the value was lower after freeze-thaw treatment. Both compressive strength and Young's modulus decreased as a result of the freeze-thaw treatment.

It is apparent that both mixtures P and R, which contained undensified microsilica, lost much of their original strength as a result of the freeze-thaw treatment.

Pre-mixing

For pre-mixed specimens generally compressive strength was higher and Young's Modulus lower. However, conclusive results regarding the influence of pre-mixing the binder with water before adding it to the hemp on final mechanical strength were not obtained. Evrard (2006) concluded that violent mixing does not have an important impact on drying, final density and final vapour permeability. It should be noted that pre-mixed specimens (B_{mix}, D_{mix} and E_{mix}) were produced for Paper I, while unmixed specimens (B, D, E and P) were prepared for Paper II. P_{mix} was prepared for Paper II. As mentioned earlier, mixtures D and E were not watered during curing in Paper I, whereas they were watered in Paper II. However, a direct comparison can be made between mixtures P and P_{mix} as they were both prepared in Paper II. They showed the same tendency as mixtures B and E, namely lower compressive strength for the pre-mixed specimens. This was not the case for Young's modulus, for which values were not significantly different between P and P_{mix}.

Standard deviation was lower for specimens with pre-mixed binders than for those with unmixed binders, with mixture D as the exception. This indicates that pre-mixing the binder led to the creation of more homogeneous material. One reason for pre-mixing the binder with water would be to reduce the risk of lumps of binder in the final mixture. In this study, any visible lumps of binder were broken up by hand.

Perforations

When preparing the test specimens for Paper I, it was observed that the specimens had a 'hard shell' with a softer core. This generated the idea of creating perforations in the test specimens in order to increase the surface of the hard shell, and to reduce the amount of soft core material.

Creation of perforations in a test specimen reduces its weight and creates air cavities. This will most likely also affect its thermal insulation properties, an aspect not studied in this research. It is interesting to note that while the total amount of material in the test specimen decreased due to the perforations, the compressive strength stayed the same. That is to say even though less material was used it gave similar compressive strength results.

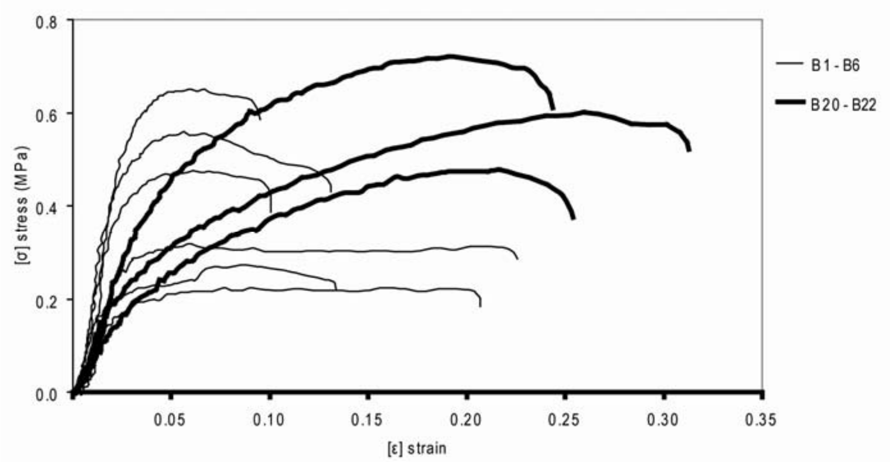

Figure 7. Graph of compressive test results. Specimens B1-6 are solids, B20-22 are specimens with perforations.

On the other hand, Young's modulus was lower in perforated specimens (Figure 7). A material is created that deforms considerably before rupture. Arnaud *et al.* (2006) reported that a 'vegetable concrete' can be highly strained before rupture and mentioned the lower risk of a sudden collapse of houses made with this material. This is an interesting material property specific to HC. Future research could examine the appropriateness of increasing the relative surface area of the material even further, and its influence on mechanical strength and thermal insulation properties.

Conclusions

Unseparated hemp, with both shives and fibres, is suitable for use in a HC when no fibre separating facility is available, as is the case in Sweden at the moment. Mechanical properties of a HC with unseparated hemp have the same magnitude as contemporary HC where only hemp shives are used. Even though fibres were present in the unseparated hemp material, the splitting tensile strength of the HC was low.

The amount of hydraulic lime, 50 to 75% (weight) present in a binder mixture of hydrated and hydraulic lime did not significantly affect the mechanical strength.

Cement in the binder affects the mechanical properties of a HC. An increase of cement from 29 to 50% (weight) doubled compressive strength. A binder mixture with only cement that was watered during curing had the highest compressive strength and Young's modulus. Cement may affect other material properties of HC but these were not included in this study.

Different binder mixtures containing hydrated lime, hydraulic lime and cement did not significantly affect water sorption properties of the HC.

Undensified microsilica as an additive of 9 to 17% (weight) to a hydrated lime binder in a HC gave low mechanical strength both before and after freeze-thaw treatment.

Calcinated gypsum as a binder combined with hemp gave mechanical properties of the same magnitude as contemporary HC. However, because of its sensitivity to humidity it may not be a good building material for walls.

Pre-mixing the binder with water before adding it to the hemp created a more homogeneous material. Conclusive results regarding the influence of pre-mixing the binder with water before adding it to the hemp on final mechanical strength were not obtained.

Perforations in the material gave a greater surface area of ‘hard shell’ around a softer core. Young’s modulus for specimens with perforations was lower, deformation at rupture was higher.

Future Research

Future research is needed to examine the appropriateness of increasing the relative surface area of the material even further, and its influence on mechanical strength and thermal insulation properties.

Water sorption of the mixtures A–E without a render was 0.15 $kg/m^2\sqrt{s}$. Future research will address the water sorption of the mixtures B–S with a lime render.

The moisture buffering properties and porosity of HC are other interesting topics for future studies, in the light of creating healthier indoor environments.

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