Material Properties and Full-Scale Rain Exposure of Lime-Hemp Concrete Walls

Measurements and Simulations

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Abstract

Lime-hemp concrete (LHC) is a building material consisting of a lime-based binder combined with hemp shiv that is suitable for various building applications. This thesis aimed to elucidate the possibilities for using LHC for exterior walls in a cold, wet climate through investigating mechanical, thermal and moisture-related properties of the material.

The mechanical properties of LHC containing both shiv and fibres of the hemp stalk in combination with different binders were tested in order to find a mixture with increased mechanical strength so that a supporting timber load-bearing structure could be omitted. A larger amount of cement in the binder mix improved compressive strength. However, even when using unseparated hemp (both shiv and fibres) in combination with a high-cement binder, mechanical strength was not sufficient for the material to be load-bearing without additional support.

The moisture properties of LHC were studied in order to determine its robustness and durability in cold, wet conditions. Sorption isotherms and moisture diffusivity were determined over the complete moisture range for two LHC mixes with different lime:hemp ratios. Compared with other building materials (*e.g.* timber, cellular concrete and lime-based render), LHC showed a high moisture diffusion coefficient in the 35-95% relative humidity (RH) range. The sorption isotherm of LHC appeared quite planar up to 95% RH, but steep between 95 and 100% RH.

The thermal properties of specimens with different relative humidities were found to be influenced by RH. At higher RH values thermal conductivity was higher, whereas differences in thermal diffusivity and specific heat capacity as a consequence of differences in RH were less apparent.

Four full-scale wall sections combining different renders and LHC mixes were exposed to a rain scenario in order to fully understand the hygric performance. Moisture properties were used in computer simulations of these full-scale wall sections and the simulation results compared with measured data. It was found that even after prolonged rain exposure, some wall sections had low moisture levels inside the wall. A lime-cement render allowed rain to penetrate the wall more easily than a cement render and also dried more slowly after exposure to rain. LHC with a larger proportion of hemp absorbed moisture more slowly and dried more quickly after construction than a mix with a larger proportion of lime. This indicates that LHC with more hemp in the mix in combination with a cement render would be more suitable for use in a cold, wet climate.

Keywords: hemp, shiv, hydraulic lime, slaked lime, moisture fixation, moisture transport, mechanical properties, rain exposure.

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To my family

"Duurzaamheid duurt het langst"
My variation of a Dutch expression.

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List of Publications

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

I de Bruijn, P.B., Jeppsson, K-H., Sandin, K. & Nilsson, C. (2009). Mechanical properties of lime-hemp concrete containing shives and fibres. *Journal of Biosystems Engineering 103, 474-479*.

II de Bruijn, P.B. & Johansson, P. (2012). Moisture transport properties of lime-hemp concrete determined over the complete moisture range. *Submitted to an international peer-reviewed journal*.

III de Bruijn, P.B. & Johansson, P. (2012). Moisture fixation and thermal properties of lime-hemp concrete. S*ubmitted to an international peer-reviewed journal*.

IV de Bruijn, P.B., Johansson, P., Jeppsson, K-H. & Nilsson, C. (2012). Measured and simulated hygric performance of lime-hemp concrete walls exposed to rain. *Submitted to an international peer-reviewed journal*.

Paper I is reproduced with the permission of the publisher.

The contribution of Paulien de Bruijn (PdB) to the papers included in this thesis was as follows:

I PdB produced the specimens, planned and carried out the experiments and analysed the data. PdB wrote the manuscript in collaboration with the co-authors.

II PdB produced the specimens, planned and carried out the experiments and analysed the data. PdB wrote the manuscript in collaboration with the co-author.

III PdB produced the specimens, planned and carried out the experiments and analysed the data. PdB wrote the manuscript in collaboration with the co-author.

IV PdB produced the test wall in collaboration with laboratory personnel, planned and carried out the experiments and analysed the data. PdB wrote the manuscript in collaboration with the co-authors.

Abbreviations

COMSOL	Simulation software for applications ranging from fluid flow and heat transfer to structural mechanics and electromagnetic analyses.
D_v	Moisture diffusion coefficient, with vapour content as the driving potential [m²/s]
D_w	Moisture diffusivity, with absorbed water as the driving potential [m²/s]
IENICA	European Network for Industrial Crops and their Applications
LHC	Lime-hemp concrete
NHL	Natural hydraulic lime
RH	Relative humidity [%]
THC	Tetrahydrocannabinol
v	Vapour content [kg/m³]
w	Moisture content [kg/m³]
w/b	Water/binder ratio by weight
WUFI	(Wärme und Feucht Instationär) Simulation software for the calculation of the simultaneous heat and moisture transport in multi-layer building components.

1 Introduction

Interest in using lime-hemp concrete (LHC) as a building material has grown in recent years. LHC consists of a combination of hemp shiv and a lime-based binder. It can be used *e.g.* as a building material for walls.

LHC has many beneficial material properties, as well as a low impact on the environment. However, its use in Sweden is still very limited. If LHC is to be used on a larger scale in Sweden, research on the durability of this material in a cold, wet climate is imperative.

Hemp shiv (also called *hurds*) are the woody core parts of the hemp stalk. They were first introduced as a building material in France in the beginning of the 1990s to lighten concrete mixes (Evrard *et al.*, 2006). From there the use of hemp in combination with lime has evolved into a more mainstream material that is marketed by several companies, mainly in France and the United Kingdom. Shiv is mixed with building limes to create a building material that provides good thermal and acoustic insulation (Evrard, 2003), and has a low impact on the environment (Boutin *et al.*, 2005). Furthermore, it provides a building method that allows simplification and reduction of the number of layers and processes involved in timber-frame construction (Woolley, 2006), a building method much used in Sweden. Another advantage compared with timber-frame is that LHC can act as a barrier to moisture and shows good airtightness, in particular when used in combination with a lime-based or cement-based render (Bevan & Woolley, 2008). No polymer-based vapour barriers are needed to create airtightness of the building envelope. In timber-frame construction polymer-based vapour barriers and tapes are used to create an airtight building envelope and to prevent the indoor air (with higher moisture content) from entering colder parts of the construction. This carries the risk that seams and connections cannot be made completely airtight, with moisture being able to enter the construction. This naturally increases the risk of microbial growth arising inside the construction. A report from the Swedish

National Board of Housing, Building and Planning (Boverket, 2010) showed that approximately 36% of all buildings in Sweden (schools not included) suffered from damage related to moisture and microbial growth. Another building method much used in Sweden is the External Thermal Insulation Composite System (ETICS) method, where insulation material is applied on the outside of an exterior wall. However, problems with moisture and microbial growth have also been reported with this system (Johansson, 2011)

A wall of LHC is built up out of one layer of material in combination with a render, and not of different layers as is the case with timber-frame and ETICS. Therefore similar problems might not occur in LHC. According to Bevan & Woolley (2008), LHC "combines the best of masonry and timber frame construction while overcoming many of the problems".

LHC is very lightweight compared with other, more conventional, building materials such as brick and concrete, which is an advantage both when constructing but also when demolishing a building. LHC has low embodied energy compared with other building materials, as it largely consists of a renewable resource from agriculture, namely hemp. During its growth, hemp captures CO_2 and in turn releases oxygen to the atmosphere. When hemp is used in LHC for building, this captured carbon is 'locked up' in the construction of the building. Bevan & Woolley (2008) estimated that 1 m^3 of lime-hemp wall can sequester 108 kg CO_2.

The initial focus in this thesis was on making LHC material load-bearing. Currently, LHC is used in combination with a load-bearing timber structure. If this load-bearing structure could be made redundant, it would be easier to produce prefabricated panels, which would reduce building time and improve material quality as these panels could be produced in a controlled environment.

The thesis also sought to investigate the robustness and durability of the material in a cold, wet climate. For this purpose moisture fixation and moisture transport through the material were studied. Using the data from laboratory experiments as input, a computer simulation was made of a scenario involving rain on an LHC wall. This scenario was also performed on a full-scale LHC wall.

1.1 Objectives

The main aim of this thesis was to investigate the possibilities of using exterior walls of LHC in a cold, wet climate, as well as to investigate possibilities to increase its load-bearing capacity. Specific objectives of the studies reported in Papers I-IV were to:

- Identify mechanical properties of different hemp concretes using both shiv and fibres in combination with various binders. (Paper I)
- Investigate whether compressive strength could be increased so that LHC can be used without a load-bearing structure. (Paper I)
- Identify moisture fixation and moisture transport properties of the material over the complete moisture range. (Paper II and III)
- Evaluate moisture fixation and moisture transport in a full-scale wall subjected to rain. (Paper IV)
- Investigate whether simulations performed using the above mentioned material data correspond with moisture levels measured in the full-scale wall. (Paper IV)
- Determine a suitable LHC mix in combination with a render system that is durable in a cold, wet climate. (Paper IV)

2 Lime-Hemp Concrete

There are many advantages of using LHC as a building material for walls. However, more research needs to be done to define the material and its intrinsic properties in more detail.

Some advantages of using LHC for walls are as follows:

- Lightweight, but with good thermal mass (Bevan & Woolley, 2008)
- Simplification and reduction of the number of layers and processes involved in timber-frame construction (Woolley, 2006)
- Good thermal insulating properties (Evrard & De Herde, 2010; Arnaud, 2009; Elfordy *et al.*, 2008; Cerezo, 2005; Evrard, 2003; Arnaud & Cerezo, 2001)
- Use of a renewable resource from agriculture (hemp)
- Possibility to use locally produced raw materials (hemp and lime)
- Low impact on the environment (Bevan & Woolley, 2008; Boutin *et al.*, 2005)
- Relatively good acoustic insulation (Gle *et al.*, 2011)
- Good airtightness when used in combination with a render system (Bevan & Woolley, 2008)
- Good fire safety (BRE, 2002)
- Unique porosity (Arnaud & Gourlay, 2012; Collet *et al.*, 2008)

2.1 Building Methods

There are several building methods for building walls with LHC, all of which use a load-bearing timber structure. The main building methods currently in use are:

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

Figure 1. Tamped hemp after the removal of temporary shuttering. (Picture: P.B. de Bruijn).

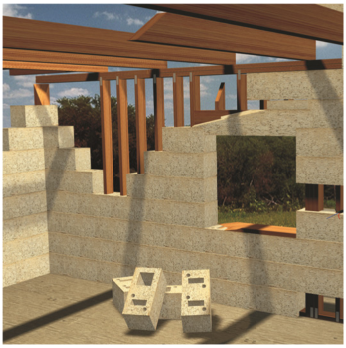

Figure 2. Blocks of lime and hemp. (Picture: R.Robin).

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 LHC (Figure 1). The LHC mix is tamped, either by hand or with a tamping device such as a wooden stave, to eliminate any 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 (Erven, 2007). The plywood sidings can if necessary be removed immediately after the LHC has been tamped in place (Carpenter, 2006).

Spraying

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

Blocks

A load-bearing timber framework is erected. The blocks have slots that fit exactly over studs on the framework (Figure 2). All blocks are placed on the framework and then an upper wall plate is installed (Robin, 2007). In France several houses have been constructed using these blocks, amongst others in Paris, Perpignan and southern Brittany.

2.2 Examples of Lime-Hemp Concrete Buildings

Sweden

Österåker Runö 7-93

A renovation project with LHC on the ground floor of a timber-framed building in Österåker, just north of Stockholm, was initiated by Ronnie Kilman at Vivere Fastigheter AB. It is one of the first known LHC projects in Sweden. The renovation work took place during autumn 2011 (Figure 3).

The walls and floors were stripped on the inside, leaving the wooden structure exposed. Hemp fibre insulation sheets were applied in the floors. LHC was applied on the walls, using a temporary shuttering construction. Small wooden studs were fitted on the walls, on which gypsum boards reinforced with fibres were mounted (Figure 4).

After completion of the project the builder reported that experiences with the materials were good, and that more buildings with LHC should be constructed in the future.

Figure 3. Renovation project Runö 7-93 in Österåker, autumn 2011.

(Picture: R. Kilman)

Figure 4. Inside view of the exterior walls after application of hemp and lime.

(Picture: R. Kilman)

United Kingdom

Adnams Building

The English beer brewery Adnams built a distribution centre/warehouse near Southwold in 2006 (Figure 5). Building blocks of lime and hemp were used to construct diaphragm walls with a cavity that was filled with yet more hemp and lime, giving a U-value of 0.18 W/mK (Lane, 2006). The thermal insulation of the building envelope itself proved to be sufficient, so that no mechanical cooling was needed to achieve the desired storage temperature (Lane, 2006).

Figure 5. Adnams distribution centre. (Picture: P.B. de Bruijn)

Hemp Homes

These houses designed by architect Ralph Carpenter (Modece Architects) are situated in Haverhill, Suffolk (Figure 6). The project consists of four terrace houses; two lime-hemp houses and two masonry houses. The lime-hemp houses were compared to the masonry houses by the British Building Research Establishment (BRE, 2002). Some of the main findings were that the structural qualities and durability of the lime-hemp houses were at least equal to those of the masonry houses. Furthermore, “the external walls of the Hemp Homes appear to retain more heat than those of the […] masonry houses” (BRE, 2002). Another finding was that even though both forms of construction offer equal protection against water penetration, the lime-hemp houses generated less condensation inside the construction. BRE (2002) concluded that the lime-hemp houses perform as well as, or in some cases even better than, the masonry houses when it comes to energy efficiency, acoustic insulation, water permeability and stability.

Figure 6. Hemp Homes in Haverhill. (Picture: P.B. de Bruijn)

France

Montholier

In Montholier two similar houses were constructed; an LHC house (Figure 7) and a straw-bale house. Both houses were built with a load-bearing timber structure. It was concluded that the energy performance of both houses was very good. Unfortunately cracks occurred in the render of the LHC house, and suggestions were made to prevent cracking in future projects (Grelat, 2005).

Figure 7. Hemp House in Montholier, France. (Picture: Grelat, (2005))

Figure 8. Hemp House at the NauHaus Institute in West Asheville, North Carolina, USA. (Picture: Flavall (2012))

USA

The NauHaus Institute

In West Asheville, North Carolina, a 'PassivHaus' and 'Platinum LEED-certified' Hempcrete home was built at The NauHaus Institute (Figure 8). It is made from a timber framework with 406 mm hemp and lime tamped around the framework (Flavall, 2012)

These are just a few of many houses and buildings constructed using hemp combined with lime as a building material. These projects are shown here to give a brief glimpse of the wide variety and possibilities of LHC buildings around the world.

3 Hemp and Lime

3.1 History of Hemp

Hemp (*Cannabis sativa* L.) originates in central Asia and dispersed from there to China (Figure 9), where it was first mentioned as a cultivated crop in 2800 BC (Fröier, 1960). However, even before then hemp was used in South East Asia as archaeologists have found traces of hemp fibre patterns on pottery dating as far back as 10 000 BC, extracted from an excavated ancient village on the island of Taiwan (Abel, 1980).

Fröier (1960) mentions that hemp came from Asia to Europe through two different routes; one through Russia and the Baltic countries, the other further south through the Mediterranean countries.

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Figure 9. The Chinese sign for hemp, symbolising stored hemp stalks.

Hemp became an important fibre crop in Scandinavia during the Viking era. The Vikings probably first came in contact with hemp during their travels eastwards (Fröier, 1960) to the Baltic countries and Russia. Hemp was used *e.g.* for ropes, sails, clothes and fishing lines. Hemp cloths and seeds have been found on the remains of Viking ships dating as far back as 850 AD (Abel, 1980).

From the early Middle Ages up to well into the 20th Century, hemp was a prominent fibre crop. During the prime of world trade by sea, from the 16th to the 18th Century AD, hemp was used for ropes and sails, thus being an indispensable and economically valuable fibre crop (Roulac, 1995).

From Asia to Europe to Northern America, hemp was cultivated to produce fibres for commerce. However, by the end of the 19th Century hemp production declined in the USA and Europe as a result of strong competition from tropical fibres such as jute, abaca and sisal (Johnson, 1999) and cotton grown in the USA (Roulac, 1995). The cotton industry at that time had successfully cut labour costs due to the development of new technologies

(Roulac, 1995) and tropical fibres from developing countries cost little in terms of labour and production (Johnson, 1999).

The hemp industry was less competitive and fell behind due to a lack of mechanisation of its cultivation and processing (Khestl, 2010; Roulac, 1995). At that time the woody core parts of the hemp stalk, the shiv or hurds, were burned in the field as waste, so only 25% of the hemp stalk was used (Roulac, 1995). However, in 1917 there came a turnaround when George W. Schlichten patented a hemp fibre separation machine, improving hemp processing and reducing labour costs tremendously (Roulac, 1995).

Despite this new development, the decline in hemp cultivation that had started decades before was never completely reversed, not even when the demand for hemp fibres increased again during World War II (Roulac, 1995).

In the USA, hemp production was not only counteracted by competition with other fibre crops, but also by federal legislation in the form of the Marijuana Tax Act, which was introduced in 1936 (Johnson, 1999). This legislation was introduced to prohibit the growing of drug hemp, but effectively also undermined the growing of industrial hemp, *i.e.* hemp with a low tetrahydrocannabinol (THC) level.

In the 1950s the hemp industry in Sweden received hard competition from other hemp producing countries, especially Russia (Fröier, 1960). Osvald (1959) also mentions competition with synthetic fibres.

After World War II hemp cultivation in both the USA and Europe declined and in the 1950s and 1960s hemp cultivation was ultimately banned in most European countries and Northern America. Sweden was no exception, and in 1965 the growing of hemp was halted due to its alleged content of narcotic substances (Holstmark, 2006).

As it was never completely abandoned in France (van der Werf, 1994), hemp cultivation revived there in the 1990s. Thereafter, hemp was gradually allowed to be cultivated again in a number of Western European countries. As for Eastern Europe, this is a different story. During the Cold War hemp was grown in fairly large amounts (up to 100 000 ha) in what is now Romania, Hungary, Bulgaria, Poland and the Czech Republic (Karus, 2005). From the 1980s onward this production declined, and in 2005 only a few thousand hectares were left (Karus, 2005).

Following the example of a number of European countries, the ban on growing hemp was lifted in Sweden in 2003. Hemp with a maximum level of 0.2% THC is now allowed to be cultivated (Holstmark, 2006). This kind of hemp is commonly referred to as industrial hemp to distinguish it from pharmaceutical (drug) hemp.

3.2 Hemp Cultivation in Sweden

Since the Viking era hemp has been grown in Sweden. During the 19th century hemp cultivation decreased, but both WWI and WWII gave renewed interest in hemp and an upswing for the Swedish hemp industry. In 1941 two hemp cultivation associations were founded; one on the mainland and the other on the Swedish island of Gotland in the Baltic sea (Fröier, 1960). They both had the capacity to process 1000 hectares of hemp annually. In 1952, however, government support was withdrawn from the mainland facility (Fröier, 1960), and in 1965 all hemp cultivation was banned (Holstmark, 2006). Before this ban, a particularly high concentration of hemp cultivation could be found on the island of Gotland (Figure 10).

Figure 10. Hemp cultivation in Sweden 1952 (Fröier, 1960). A small dot represents an area of 0-5 ha, a medium sized dot represents an area of 5-50 ha, and a large dot represents an area larger than 50 ha.

With the legalisation of industrial hemp growing in 2003, renewed interest quickly arose amongst Swedish farmers. However, to date this interest has not been transformed into establishing large-scale facilities for hemp processing and industrial production of hemp fibre products. Swedish hemp is currently mostly used for combustion purposes.

Smaller initiatives, mainly by Swedish farmers, show an eagerness to learn more about hemp cultivation and its opportunities for the Swedish agricultural sector. An example is briquette production at Jacobsson's farm in Scania, Southern Sweden. Here hemp is made into briquettes right on the farm, producing a bio-energy product that can be burned in fireplaces instead of wood. Another example of a farmer initiative is the start of a hemp fibre separation facility within the project Green4U at a farm in Grästorp, Västergötland.

Table 1. *Hemp cultivation in Sweden 2003-2012 (Rolandsson & Callman, 2012).*

Year	Hectares cultivated
2003	24
2004	141
2005	377
2006	512
2007	792
2008	389
2009	268
2010	263
2011	95
2012	55

The Swedish market for non-food crops very much welcomes industrial products and new possibilities to use hemp, so that hemp cultivation can be promoted to farmers (Eriksson, 2008). Thus far, the limiting factors in the expansion of hemp cultivation in Sweden are the lack of products in which hemp can be used and the lack of a commercial market for these products (Eriksson, 2008). This has made farmers hesitant to start growing hemp. Modern hemp cultivation in Sweden reached a peak in 2007, but has since declined to only 55 hectares of hemp cultivated in 2012 (Table 1). The low and unreliable availability of hemp makes the industry in turn hesitant to invest in hemp as a raw material for its products.

From an European point of view, Evrard *et al.* (2006) claimed that the introduction of hemp shiv into buildings is a new opening for the hemp industry and a way to support the development of industrial fibre crops.

According to Karus (2005), in order to make hemp fibre production profitable, a high-quality application for its by-product (hemp shiv) has to be developed. LHC could serve this purpose. According to the Interactive European Network for Industrial Crops and their Applications (IENICA, 2004), the production of non-food crops is often not profitable until a certain production volume is reached. Using hemp shiv in a large-scale industry such as the building sector would increase the demand for this product. This would allow hemp to be grown on a larger scale, producing fibres as well as shiv for use in industrial products.

In an executive summary on Sweden, IENICA (2004) noted that there are a number of advantages of choosing Sweden for growing non-food crops: Sweden has a political system that supports environmental protection, the Swedish climate minimises the need for insecticides and Swedish farmers are skilled and have a strong farmers' cooperative organisation. Furthermore, Sweden has good research and breeding facilities and a very experienced industry for production of raw materials and products. There is also close cooperation between producers and users and there is a possibility to combine production of industrial products with biomass/energy production. As disadvantages, IENICA (2004) mentions that the Swedish climate gives lower hemp yield, there is no coordinating R&D institution in this particular field, there is a lack of pilot-plant facilities and there are difficulties in obtaining large production volumes.

There seems to be an interest and willingness to explore hemp as a non-food crop for Swedish agriculture and as a raw material for Swedish industry. Cooperation between research, agriculture and industries could push this development forwards towards an increase in hemp cultivation and a profitable industrial hemp business in Sweden.

3.3 The Hemp Plant

Hemp (*Cannabis sativa* L.) is an annual herbaceous plant belonging to the Cannabaceae family (van der Werf, 1994). It produces either male or female reproductive structures (Johnson, 1999). The hemp plant can grow as high as 1.5-4 metres in Sweden according to some sources (Osvald, 1959). According to Fröier (1960), however, hemp in Sweden only grows as high as 2.5 to 3 metres. Further South, in a warmer climate, hemp can grow as tall as 10 metres (Osvald, 1959). The hemp crop requires no pesticides (Bevan & Woolley, 2008) and only little fertiliser. It can even be cultivated as part of a crop rotation scheme in order to prevent weeds from infesting a field (Holstmark, 2006).

The hemp stalk can be divided into fibres, shiv and seeds. Hemp fibres are situated in the bast of the hemp stalk (Figure 11). They have high tensile strength (Bledzki & Gassan, 1999) and can be used to produce *e.g.* textiles, ropes and paper. According to Karus (2005), the main applications for hemp fibres in Europe are in the pulp and paper industry, in building and insulation (*e.g.* insulation mats) and in the automotive industry (*e.g.* natural fibre press-moulded parts).

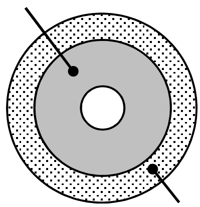

Figure 11. Schematic section of a hemp stalk with shiv in the core and fibres on the outside.

Hemp seeds in Europe are today mainly sold as animal feed. However, because of their nutritional qualities hemp seeds could also be of great interest for the human food sector (Karus, 2005).

Hemp shiv, the woody core parts of the hemp stalk, constitute between 40 and 60% of the mass of the hemp stalk (Evrard, 2003). Historically, hemp shiv was a by-product of the hemp fibre industry. In the USA at the end of the 19th century the shiv was still burned in the field as waste (Roulac, 1995). In Europe, both Evrard (2003) and Fröier (1960) mentioned that hemp shiv historically was used as a combustion fuel for drying the hemp stalks before fibre separation.

Nowadays hemp shiv in Europe is primarily marketed as animal bedding (Karus, 2005). In Sweden, hemp shiv is usually not separated from hemp fibres and the unseparated hemp is mainly sold for combustion purposes (Rolandsson & Callman, 2012). However, since 2008 a hemp separation facility has been operative in Grästorp, Sweden. The separated hemp is marketed as animal bedding, insulation material, oil and briquettes for combustion.

Hemp bast fibres and woody core shiv differ in their chemical composition. Bast fibres have a low lignin content, which makes them very suitable for paper production, *e.g.* (van der Werf, 1994). Shiv has a low pectin content, which makes it more suitable for use in combination with a cementitious binder, as pectin can delay the setting time of the binder (Dalmay *et al.*, 2010).

3.4 Building with Lime

The raw material for lime is usually limestone, but other sources such as chalk, coral rocks or shells can also be used. Limestone contains calcium carbonate ($CaCO_3$) that is heated in a kiln at a temperature of around 900 °C, where it gives off carbon dioxide and forms calcium oxide (CaO), see equation (1). The calcium oxide that is formed is commonly referred to as quicklime; other names are lump-lime or burnt lime. Quicklime combined with water changes to calcium hydroxide ($Ca(OH)_2$), commonly known as slaked lime, aerated lime or hydrated lime, see equation (2). In this thesis calcium hydroxide is referred to as *slaked lime*. Slaked lime reacts with carbon dioxide and thereby forms calcium carbonate in a process known as *carbonatation* (equation (3)). This reaction is extremely slow, as a $CaCO_3$ film forms around the carbon hydroxide particles, making it more difficult for the carbon dioxide to reach unreacted calcium hydroxide.

$$\underset{\text{limestone}}{\boldsymbol{CaCO_3}} \xrightarrow{T = 900\ ^\circ C} \underset{\text{quicklime}}{\boldsymbol{CaO}} + CO_2 \qquad \text{eq. (1)}$$

$$CaO + H_2O \rightarrow \underset{\text{slaked lime}}{\boldsymbol{Ca(OH)_2}} \qquad \text{eq. (2)}$$

$$Ca(OH)_2 + CO_2 \rightarrow \underset{\text{calcium carbonate}}{\boldsymbol{CaCO_3}} + H_2O \qquad \text{eq. (3)}$$

Hydraulic lime is made from limestone that contains fine clay materials, which when appropriately fired in a kiln combine with lime to form active compounds (Holmes & Wingate, 1997). Active compounds in the clay materials, such as soluble silica (SiO_2), alumina (Al_2O_3) and ferric oxide (Fe_2O_3), give a chemical set, in addition to the carbonatation process.

Limestone with a smaller proportion of clay material that is burned to quicklime will give a set that is mainly a carbonatation process. When the limestone contains a larger proportion of clay material, the set shifts to being mainly a hydraulic set. Adding pozzolan to a limestone with a smaller proportion of clay materials will also make this shift to a more hydraulic set. Compared with cement, lime is a less rigid and more permeable material. It has high porosity, creating a light building material. Raw materials, aggregates and additives should therefore be chosen with care, bearing in mind the desired properties of the building material.

3.5 Building with Other Non-Food Crops and Natural Fibres

The building material LHC is reminiscent of other building materials and techniques, both historical and contemporary. These building materials use non-food crops or other natural fibres to create durable and sustainable buildings. Amongst the historical materials are Roman cement and half-timbering.

3.5.1 Roman cement

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 pozzolan and fibrous organic material to improve tensile strength and prevent cracking of the material. This concept has been used and proven durable over millennia. In a translation by Winter (2006), Cato (234-149 B.C.), the author of De Agri Cultura, writes about farm construction as follows "…the builder will cut and make do stone, lime, sand, water, straw, earth from which to make mud." (Winter, 2006). The mix that Cato described over two thousand years 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.

3.5.2 Half-timbering

Another historical building material and building method is that of half-timbering (known as *korsvirke* in Swedish). Here a framework of timber is used in combination with an infill of mud and straw (Figure 12). In Sweden this building technique was mainly used in Scania, a southern province with few forests, as the half-timbering construction method developed as a result of timber scarcity (Aronsson *et al.*, 2002). The geographical spread of half-timbered housing in Sweden is closely related to lack of access to good timber. The wooden framework is load-bearing, while mud and straw create a wall that has reasonable thermal insulation properties and a high thermal mass. Straw improves the durability of the mud wall. There are several similarities between half-

Figure 12. Half-timbered 19th century house, Sweden. (Picture: P.B. de Bruijn)

timbering and LHC. Both have a load-bearing framework of timber, in combination with an infill containing fibrous organic matter (straw and hemp, respectively). In LHC lime is used as a binding agent, whereas mud and dung in half-timbering functioned in a similar binding manner.

3.5.3 Straw bale building

A building technique that also uses a non-food crop is straw bale building. It is a relatively modern building technique, as it arose in the USA in the late 1800s following the invention of the baling machine (Jones, 2007; Woolley, 2006) As is the case with half-timbering, people started building with straw because of a shortage of timber and other building materials. Settlers in Nebraska started building temporary housing with straw, which was for them a waste material from wheat cultivation (Jones, 2007). To build with straw bales they are stacked, usually in stretcher bands, with a wall plate on top. The wall plate is tied down in order to avoid large deformations after construction. The straw bale walls are then plastered on both sides. If necessary, a load-bearing wooden frame can be used, with the straw bales as infill material (Woolley, 2006). The advantages of building with straw bales are good acoustic and thermal insulation (Woolley, 2006). However, special attention has to be paid to detailing so that moisture problems do not occur. In addition to good thermal insulation, straw bale building is sustainable as it uses renewable, locally-grown materials (Goodhew *et al.*, 2004).

3.5.4 Wood-wool cement

A more contemporary building material is wood-wool cement (known as *träull* in Swedish). Wood-wool cement board was patented in Austria as early as 1908 (Rückert, 2000). It consists of wood-wool, cement and water. By the 1930s the material had reached Sweden and was first used as wall insulating boards (Rückert, 2000). Nowadays wood-wool cement is used for its thermal insulating properties, acoustic properties, moisture buffering and resistance to decay and insects (Rückert, 2000; Wolfe & Gjinolli, 1997). With these advantages in mind, the Swedish architect

Figure 13. Wood-wool cement wall elements on a building site in Dalby, Sweden.
(Picture: M. Rückert)

M. Rückert designed and built a detached house in the 1990s in southern Sweden using wood-wool cement blocks. From this project onwards prefabricated wood-wool cement wall elements were developed, and in 2003 a wall element was cast. To date, several houses have been built using these wood-wool cement wall elements (Figure 13).

Edvardsson *et al.* (2008) concluded that a detached house with prefabricated wood-wool cement wall elements uses approx 11% less energy (in kWh/m²·year) than a standard Swedish timber-frame house with mineral wool insulation. Disadvantages mentioned by Edvardsson *et al.* (2008) are the thicker walls and the somewhat higher building costs.

3.6 Sustainable Building

The UN conference on the environment in Rio de Janeiro 1992 was a catalyst for the building industry, the Swedish building industry included, 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. Other terms that are used to describe sustainable building are sustainable construction, green building, eco building, zero carbon, *e.g.* All of these signify approximately the same intent, namely that a building is not an isolated unit that stands by itself, but that it is part of our environment and as such interacts with its surroundings.

When the pioneers in Nebraska found themselves facing a timber shortage, but with an abundance of straw on their hands, they developed a straw building technique (Jones, 2007). When there was a timber scarcity in southern Sweden, the half-timbering technique was developed, saving on timber use (Aronsson *et al.*, 2002). Now that we are trying to build sustainable housing, and the world faces depletion of resources and energy in the future, we should look around and see what the possibilities of our environment are. We could use building materials that we can find in abundance locally; natural building materials that do not need high-tech processing and require little energy for production.

A much quoted definition of sustainable development is this from the Brundtland report (UN, 1987):

"*Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs*".

After having studied different definitions of sustainability, Atkinson (2008) concluded that at the heart of what sustainable development encompasses there is an emphasis on human well-being and how to sustain that well-being over time. There is now a demand from consumers to build more sustainably and this is causing the building sector to change from conventional to sustainable building. As M. Suhr mentioned in the Foreword of the book Hemp Lime Construction (Bevan & Woolley, 2008): "*for far too long, 'eco' building has focussed on energy efficiency in use, with super insulated structures, renewable energy and rainwater collection*".

This development can also be seen in Sweden, where during recent years there has been a tremendous focus on low-energy houses and Passive Houses (well-insulated houses that require little or no energy for heating). However, sustainable building is not the same as building energy-efficiently. Energy efficiency is only one aspect of sustainable building. The development towards energy efficiency is certainly a step towards building more sustainably, but what is needed is diversity. In this perspective LHC can be an alternative to contemporary energy-efficient building methods, adding more diversity to the broad scale of sustainable building.

3.6.1 Sustainable building with hemp and lime

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 *e.g.* non-food crops, in the building sector is imperative. Toledo *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 cost relatively little. Other examples of non-food crops that can be used for construction purposes include flax, miscanthus and cereal straw.

Using agricultural crops in a building material such as LHC 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 lower carbon emissions, because it uses kilns at a lower temperature (Woolley, 2006; Evrard, 2003). Boutin *et al.* (2005) stated that LHC has a low impact on the environment and a potentially favourable impact on the greenhouse effect. Evrard (2003) discussed 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) estimated that one square metre of LHC wall stores between 14 and 35 kg CO_2 over its life span of 100 years. As was mentioned in the introduction, Bevan & Woolley (2008) estimated that 1 m³ of lime-hemp wall can sequester 108 kg CO_2. 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. Those authors also estimated that total fossil fuel use over the life-cycle of LHC walls is comparable to that of other building materials.

3.7 Previous Research on Building with Lime and Hemp

3.7.1 Mechanical properties

LHC has low compressive strength (Arnaud & Gourlay, 2012; Nozahic *et al.*, 2012; Nguyen *et al.*, 2009; de Bruijn, 2008; Elfordy *et al.*, 2008; Evrard, 2003) and therefore a load-bearing structure should be used in an LHC wall. However, if the material could be made load-bearing, this would open the way for new possibilities of use, such as prefabricated wall elements.

A possibility that was investigated in this thesis was to use both shiv and fibres in the mix. According to Li *et al.* (2006) hemp fibre is a good reinforcement material because it has a high tensile strength and a strong tolerance to alkaline environments.

The effects of adding more lime in the mix, or adding more cement, were also investigated in this thesis.

Compressive strength

The compressive strength of LHC varies depending on the exact mix and age of the material. Evrard (2003) studied four different LHC mixtures and recorded compressive strengths of 0.2-0.5 MPa and Young's modulus values of 3-26 MPa. Arnaud *et al.* (2006) found compressive strength values, depending on the mixture, ranging from 0.4 to 1.2 MPa and Young's modulus values of 40-90 MPa. The compressive strength of these LHC is not sufficient for the material to be load-bearing.

O'Dowd & Quinn (2005) reported a compressive strength of 0.71 MPa for a hemp shiv to lime ratio of 3:1 by volume. They also reported that the hemp lime ratio of 3:1 is similar in strength to a 4:1 and 5:1 mix. Slaked 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 slaked lime in the binder mix, the maximum compressive strength is obtained after a period of time ranging from several months up to several decades.

Arnaud *et al.* (2006) also found that one of the specific properties of LHC is that it can be highly strained before failure. They mentioned that the risk of sudden collapse of the building material is rather low, as there is no cracking in the material for a 10-15% compression rate. Compared with conventional building materials, these values are very high. LHC cannot be used as a load-bearing material because of its relatively low levels of failure stress and low elastic modulus. If LHC is to become load-bearing, its failure stress and elastic modulus must be improved.

Splitting tensile strength

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

3.7.2 Moisture properties

Timber frame is commonly used as a load-bearing structure with LHC. However, timber is sensitive to high moisture levels as these can cause rot, decay and growth of fungi. Therefore the hygric properties of LHC and moisture conditions inside an LHC wall should be fully understood. Thus far only a few studies have dealt with the hygric properties of LHC (Colinart *et al.*, 2012). In order to fully understand moisture fixation in LHC in a climate with high moisture loads, more knowledge is needed about the sorption isotherm, including hysteresis.

Moisture transport in the material over the complete moisture range needs to be determined, as knowledge about moisture transport in a building material such as LHC is essential for understanding its behaviour in a climate with high moisture loads and is imperative for performing accurate simulations. Collet *et al.* (2008) measured the sorption isotherms up to 97% RH of lime-hemp mortar and lime-hemp render and found that these are sigmoid with a relatively high standard deviation at the highest moisture level.

Moisture properties were also studied by Cerezo (2005), who produced an absorption and desorption isotherm for a "wall mix" of LHC. These isotherms showed clear hysteresis. The absorption isotherm was produced for relative humidities (RH) up to 95%.

Evrard (2008) studied moisture properties of a wall mix of LHC. With a pressure plate apparatus he measured a sorption isotherm over the complete moisture range, where hysteresis was not taken into account. According to Evrard (2008) equilibrium was considered to be reached when mass varied less than 1% over 24 hours. For small broken samples of LHC it therefore only took a few days up to more than 15 days to reach equilibrium. This is a very short time compared with awaiting true equilibrium (*i.e.* no more weight change).

Other sorption isotherms for LHC have been described by Tran Le *et al.* (2010). However, the sorption isotherm over the complete moisture range (up to 100% RH) was not measured. When studying LHC exposed to high moisture loads, the sorption isotherm at high relative humidity values is of great interest.

Evrard (2008) performed cup tests, using four samples placed in large glass cups over a silica gel. The cups were placed in a climate chamber with 50% RH. With this method the dry vapour diffusion resistance factor could be determined. Using this value, the dry vapour permeability was then calculated.

3.7.3 Porosity

A unique property of LHC is the double porosity of the material. Arnaud *et al.* (2006) mentioned a microscopic porosity in the shiv. In addition there is a macroscopic porosity due to the shiv arrangement. The unique porosity of LHC is made up of several characteristic sizes; macropores due to the imperfect arrangement of the hemp shiv, mesopores within shiv and binder and micropores in the lime-based binder (Arnaud & Gourlay, 2012; Collet *et al.*, 2008).

3.7.4 Thermal properties

One of the advantages of using LHC as a building material is its good thermal insulating properties (Evrard & De Herde, 2010; Arnaud, 2009; Elfordy *et al.*, 2008; Cerezo, 2005; Evrard, 2003; Arnaud & Cerezo, 2001).

Arnaud & Cerezo (2001) tested thermal conductivity for a wall mixture with density 330 kg/m³ and found an average value of 0.135 W/mK.

Cerezo (2005) found that thermal conductivity depends on both the relative humidity and density of the material. A mix with intermediate density (approx. 450 kg/m³) showed a thermal conductivity of 0.10-0.11 W/mK at lower relative humidity values (0-50% RH) and 0.13 W/mK at 75% RH.

Comparisons between thermal conductivity and density were made by Arnaud (2009). Values were found to vary between 0.07 and 0.11 W/mK for densities between 200 and 500 kg/m³. Arnaud (2009) concluded that thermal properties of LHC are very sensitive to water vapour and that thermal conductivity showed a clear increase when the RH of the samples increased.

Evrard (2003) studied thermal properties of LHC at various densities and two different relative humidities. They found that for a wall mix, thermal conductivity was 0.08 W/mK for dry samples and 0.13 W/mK for samples conditioned at 40% RH. They also found that the specific heat capacity of LHC is 1.4 kJ/kgK and the thermal diffusivity 0.14 mm²/s.

Elfordy *et al.* (2008) presented results for the relationship between density and thermal conductivity and found that thermal conductivity increased with increasing density. Evrard & De Herde (2002) showed that this relationship is linear. They found a thermal conductivity of 0.11 W/mK for dry samples and 0.317 W/mK for samples conditioned at 100% RH.

Nguyen *et al*. (2009) studied the direction of compaction of LHC and its influence on thermal properties and found that thermal conductivity perpendicular to the hemp particle direction is lower than thermal conductivity parallel to the particle direction.

3.7.5 Rain scenario

The British Building Research Establishment (BRE, 2002) performed a 96-hour water spray test on LHC in which wall elements (500x500x200mm) with a coating of 10 mm lime mortar render were allowed to rotate around a water spray installation. Water absorption depth was measured after 2, 24 and 96 hours. After 2 hours no water had penetrated the rendered surface. After 24 hours water absorption was observed (visually) up to 20-40 mm from the rendered surface and after 96 hours this had increased to 50-70 mm. BRE (2002) concluded that it is unlikely that rain will penetrate over the complete thickness of the wall.

3.7.6 Simulations

Evrard & De Herde (2010) studied the hygrothermal properties of LHC walls and performed simulations in WUFI, a computer programme that simulates heat and moisture transport in building material. They concluded that LHC appears to have rapid moisture transport in combination with high vapour permeability and high moisture retention.

Evrard (2008) performed material property tests on LHC and introduced these material data in WUFI Pro 4.0. Results from the simulations were compared with measurements and were found to differ from the measured data. Evrard (2008) ascribed these differences to a retarded sorption effect, whereby it takes time before equilibrium water content in sorption tests is achieved. In the simulations this equilibrium was assumed to occur instantly.

Arnaud (2009) studied the hygrothermal behaviour of LHC using a cell of exchange, which consisted of a 30 cm thick wall element placed between a climate box and the laboratory. Temperature and RH were changed inside the climate box and test results on temperature and RH fluctuations inside the wall element were compared with simulations made in COMSOL® Multiphysics, a simulation software that enables modelling and simulation of physics-based systems. When studying a change in temperature, Arnaud (2009) found significant differences between simulated and measured data. He ascribed these differences to coupled heat and mass transfer inside the material and found indications that phase change occurs inside the material.

Accurate simulations of changes in moisture levels inside an LHC wall, caused by rain exposure and/or changes in temperature, would allow studies to be made on different climate scenarios.

4 Materials and Methods

In this thesis, hemp was used in combination with a number of different binders and binder mixes, most of them lime-based. In this section the various materials used are described in more detail. In addition, the research methods used in Papers I-IV are presented.

4.1 Materials

4.1.1 Hemp

Hemp was collected from two different farms throughout the project. **Paper I** focused on mechanical properties, whereas **Papers II-IV** focused on moisture properties. As the project progressed, so did the hemp industry in Sweden. No fibre separation facilities were found in Sweden at the beginning of the project in 2005. However, a few years later a hemp fibre separation facility was put into operation by a farmers' cooperative in Grästorp, Sweden.

For **Paper I** hemp was collected from a farm in Södra Kverrestad in the province of Scania, southern Sweden. The cultivar used was Futura 75. The hemp was sown on 21 April 2005, and allowed to freeze-dry before harvest on 15 April 2006. As the hemp was intended to be processed into briquettes for bioenergy purposes, the hemp crop was harvested, baled and stored in its entirety. The hemp bales were shredded in an industrial shredder; shiv and fibres were not separated. The composition of the hemp by weight was 62% shiv, 35% fibres and 4% dust (particle size <0.5 mm).

The hemp that was used for **Papers II-IV** was collected from a farm in Grästorp in the province of Västergötland, Sweden. The cultivar that was used was Fedora 17. This hemp was sown on 26 April 2009 and harvested on 7 May 2010. The hemp was processed in a fibre separation facility that was developed by the farmers themselves from a combine harvester (Figure 14). This facility effectively separated shiv from fibres.

Figure 14. Fibre separation facility in Grästorp, Sweden.
(Picture: P.B. de Bruijn)

Shiv and fibres

LHC consists of a combination of building lime and hemp. In contemporary LHC commonly only hemp shiv is used, not fibres (Arnaud *et al.*, 2006; O'Dowd & Quinn, 2005; Evrard, 2003; BRE, 2002; Arnaud & Cerezo, 2001) The reason for not using the bast fibres of the hemp stalk vary from economic to physiological and chemical reasons.

First of all, hemp shiv is the by-product of hemp fibre production (Karus, 2005). Hemp fibres can be used in high-quality products such as textiles, biocomposites, building insulation mats and paper. If hemp shiv were to be used in an industrial product/building material such as LHC the profitability of hemp cultivation would increase. To achieve this, separation of fibres from shiv is essential (Skoglund, 2009).

Secondly, hemp shiv differs both physiologically and chemically from hemp fibres. Compared with shiv, hemp fibres have higher cellulose and pectin content, and lower lignin content (Vignon *et al.*, 1995). Hemp shiv has a low pectin content, which makes it more suited for use in combination with building lime. Pectin is known as a chelating agent (Dalmay *et al.*, 2010). It can react with calcium ions in an alkaline environment (Sedan *et al.*, 2007).

Sedan *et al.* (2008) found that when the quantity of hemp fibres added to a cement paste increased, the silica concentration in the cement paste increased as well. This indicates that the silica cannot precipitate with calcium to form calcium silicate hydrate (CSH). Calcium ions are not available as they are bound to the pectin in the hemp fibres. CSH formation is responsible for setting, therefore adding hemp fibres to the mix delays setting time. Dalmay *et al.* (2010) performed an experiment on the delay of setting time for gypsum plaster containing hemp fibres and concluded that this delay was probably due to the pectin content in the fibres.

Thirdly, using shiv and not fibres enables proper mixing (Evrard *et al.*, 2006). Nguyen *et al.* (2009) compared an LHC mix containing shiv and fibres with a mix with only shiv and found that balls of material were more frequently formed in the mix containing both shiv and fibres (Figure 15).

Figure 15. Mixing of LHC. On the left LHC with only shiv, on the right LHC with both shiv and fibres. Balling of the material is clearly visible in the right-hand diagram. (Picture: Nguyen, (2009))

An additional benefit of using hemp shiv in the mix is that shiv under compression is flattened, but not broken (Evrard, 2003). Furthermore, shiv is built up of small veins in which the sap circulates through the plant. This cellular structure is comparable to that of wood and contributes to the favourable insulating and hygroscopic properties of shiv (Evrard, 2003).

A reason for adding hemp fibres to the mix is that fibres have a high tensile strength and would improve the mechanical strength of the mix. However, Sedan *et al.* (2008) and Le Troëdec *et al.* (2009) found that adding hemp fibres to a cement paste gives lower Young’s Modulus and less rigidity.

Another reason for using both shiv and fibres was the absence of a hemp fibre separation facility in Sweden up until 2008. This had an effect on the first part of this thesis. While exploring possibilities for using Swedish hemp in LHC, we came across shredded but unseparated hemp material in the province of Scania, southern Sweden. Because of the unavailability of separated hemp, this unseparated hemp was used in the mix.

During the second part of this thesis a hemp fibre separation facility had become operational in Grästorp, Sweden. As will be discussed later on, the studies in the first part of this thesis showed that the use of both shiv and fibres in LHC did not give higher mechanical strength than results from contemporary studies on LHC mixes where only shiv was used (de Bruijn, 2008). Also, in the meantime studies had come out showing that the pectin content of hemp fibres delays the setting time of the cementitious mix (Dalmay *et al.*, 2010; Sedan *et al.*, 2008)

This explains why in the first studies (Paper I) both shiv and fibres were used, whereas in later studies (Papers II-IV) only hemp shiv was used. It also gives an indication of the rapid developments in both the Swedish agricultural sector and international science when it comes to hemp cultivation and hemp research.

4.1.2 Binders

In the first part of this project the following binders were used: slaked lime (calcium hydroxide), hydraulic lime (NHL5), building cement (CEM II/A-L) and calcinated gypsum (beta-hemihydrate) (Paper I).

In the second part of this project only two binders were used: slaked lime (CL90) and hydraulic lime (NHL5) (Papers II-IV).

4.1.3 Pozzolans

In the second part of the project a pozzolan was added to the binder mix. This pozzolan was a fly ash obtained from Emineral in Denmark (Emineral fly ash Type B4). Fly ash reacts with building lime (calcium hydroxide) in the binder mix and thereby forms calcium silicate hydrate (CSH), (equation (4)):

$$Ca(OH)_2 + pozzolan \rightarrow CSH \qquad \text{eq. (4)}$$

Fly ash is a waste product (or by-product) from coal-fired power stations and is therefore widely available. Using fly ash in a binder mix rather than depositing it reduces the risk of substances from the fly ash leaching into the environment. Furthermore, by using the waste product fly ash instead of an energy-demanding binder such as cement (or in this case less energy-demanding building lime), energy for binder production is saved. Unfortunately, fly ash in itself is not an environmentally friendly product. Direct inhalation of high concentrations of fly ash can cause potential health problems (EPRI, 1998). Pozzolans are added to a lime mix to enable the material to set more rapidly or to regulate the quality of a mortar. By adding a pozzolan, the characteristics of the mix are modified. In a mix with lime, pozzolans accomplish an improvement of the setting of the lime, where lime sets in combination with silicates and aluminates in the presence of water. This is called *hydraulic set* (Holmes & Wingate, 1997). A pozzolan stimulates and improves this hydraulic set.

Fly ash is added to the mix for several reasons. It contains silica which reacts with calcium in the lime binder, forming CSH. It also improves the workability of the mix and reduces the water content needed for workability (Utsi, 2008).

A natural pozzolan that can be used instead of the artificial pozzolan fly ash is volcanic ash, the debris from volcanic activity. In volcanic regions this would mean that a locally available product can be used. Actually the word *pozzolan* is named after the village of *Pozzuoli* in Italy, where the Romans found a volcanic ash that they used as an additive (*pozzolana*) in their building materials. Volcanic ash is currently not available as pozzolan material in Sweden and therefore the fly ash was used instead.

4.2 Lime-hemp Mixes

4.2.1 Binder mixes and specimen production, Paper I

Five different mixes of hemp and binders were used. The materials used for the binder mixes were as follows:

- Slaked lime (calcium hydroxide)
- Natural hydraulic lime (NHL5)
- Building cement (CEM II/A-L)

The composition of the binder mixes is shown in Figure 16. The mixes were prepared using a regular concrete mixer. The ratio of hemp to binder was 3:1 by volume of uncompacted dry material, which equals a hemp/binder ratio by weight of approximately 0.3 (Table 2). The binders were first mixed with some of the water in a separate container before being added to the hemp and the remainder of the water in the concrete mixer. The mix was then allowed to rotate in the concrete mixer for approximately five minutes. Any visible lumps were broken up by hand. The mix was applied to moulds and tamped into the moulds using a wooden stave. After tamping, the moulds were placed on a vibration table (50Hz) for one minute to improve compaction of the material.

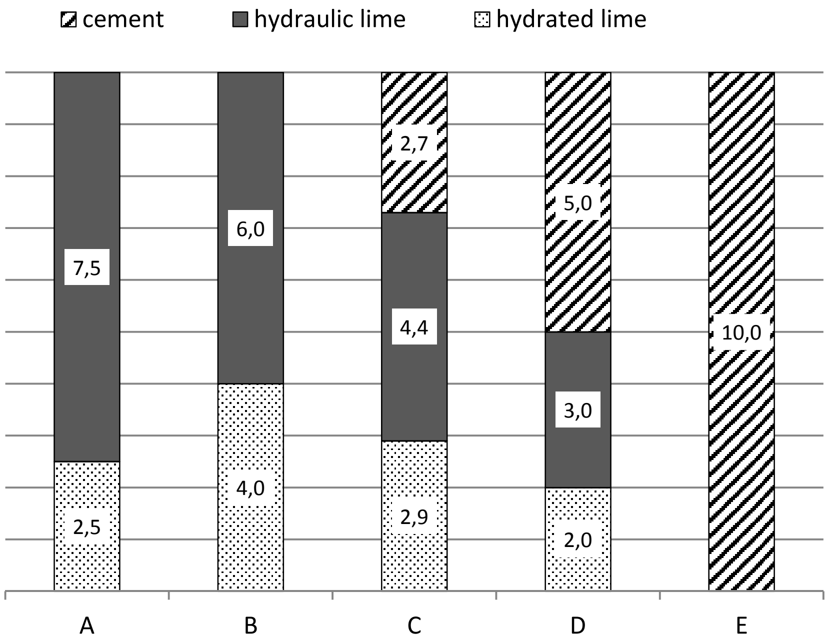

Figure 16. Composition of mixes A-E by relative weight (as fraction of 10).

All specimens were cured for two days in an indoor climate at approximately 20 ºC before they were removed from the moulds. Curing continued for another 12 weeks at 20±4 ºC, after which the specimens were placed in a carbonatation room.

Table 2. *Hemp/binder and water/binder ratio for mixes A-E*

Mix	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

Carbonatation

Specimens were exposed to 4.5% CO_2 for 40 days in order to accelerate the carbonatation process. In the carbonatation room the temperature was kept at 20 ºC and RH 50%. After 40 days the CO_2 levels were lowered again. Specimens were then stored in the carbonatation room at normal CO_2 levels (≈0.038%) until testing.

4.2.2 Experimental mixes of hemp and limes

Prior to commencing specimen production for Papers II and III, experiments were performed to determine a suitable lime mix. Several commercial binder mixes for LHC are available on the European market. The exact contents of these binders are not publicly known. Therefore in the current study, in order to control the exact contents of the mix and its reproducibility, a lime-based binder that can easily be reproduced was used. It was made up of slaked lime, natural hydraulic lime and fly ash.

The main aim of the short experiments was to find a lime mix that has good workability and that can produce representative test samples. In addition, density, water-binder ratio and lime-hemp ratio were considered. The experiments helped determine how to produce the test samples for the moisture property experiments.

The materials used were as follows:

- Slaked lime ($Ca(OH)_2$, Nordkalk SL LA)
- NHL5 (St Astier natural hydraulic lime)
- Fly ash (Emineral fly ash Type B4)
- Hemp (Grästorp, Sweden)
- Bentonite (Weber cement, Malmö, Sweden)
- Wet-slaked lime (Kalkmörtel)

After consulting a cementitious binder specialist, we chose to work with fly ash as a pozzolan. He recommended also using some bentonite for improved workability of the mix, but this was found to be unnecessary as a mix including some 10 vol% fly ash showed good workability in itself (compare mixes A and B in Table 3).

In order to determine the proper amount of fly ash, mixes containing fly ash at levels of 10, 15 and 20 vol% were produced. Two mixes without fly ash were also produced. It was found that a mix with 10 vol% fly ash was best for workability of the mix. The mix was a good slurry, with no problems applying the material into the moulds or getting the samples out of the moulds after hardening. An amount of 15-20 vol% fly ash gave the mix a structure that resembled that of fresh cement. The material lost some of its suppleness. Similar results were found for mixes without fly ash; they were more viscous and did not have the same workability as a mix with 10 vol% fly ash.

Another factor studied was the lime:hemp ratio. Two different lime:hemp ratios were tested; 1:3 and 1:5 by volume. Few noticeable differences were found as regards the workability and appearance of the mixes. However, the density of the 1:5 samples was clearly lower than that of the 1:3 samples. It was found that the samples had to remain in the moulds for a few days to up to 1 week before they could be taken out of the moulds.

Table 3. *Overview of experimental mixes*

Mix	CL90 (vol.%)	NHL5 (vol.%)	Wet-slaked lime (vol.%)	Fly ash (vol.%)	Bentonite (vol.%)	w/b [a]	Lime:hemp ratio (by volume)	Comments
A	75	15	-	10	-	1.75	1:3	Good slurry, good workability.
B	75	15	-	10	0.1	1.77	1:3	Good workability.
C	65	15	-	20	-	2.09	1:3	Viscous and 'cement-like'.
D	70	30	-	-	-	2.33	1:3	Slurry too tough, adding more water did not help.
E	70	-	30	-	-	1.99	1:3	Also tough slurry, but better workability than mix D.
F	75	15	10	-	-	2.56	1:4.5	Like mix E but with more hemp, therefore more water.
G	75	10	-	15	-	1.64	1:3	'Cement-like' and tough, not so good workability.
H	75	15	-	10	-	1.62	1:3	Less water than mix A, good workability.
I	75	15	-	10	-	2.52	1:5	Like mix H but with more hemp, therefore more water.
J	75	15	-	10	-	1.52	1:2.7	In mixes J, K, L the lime mix is the same, but the hemp and water ratios vary.
K	75	15	-	10	-	1.59	1:3	
L	75	15	-	10	-	2.74	1:5	

[a] Water/binder ratio by weight (excluding hemp as a binder).

4.2.3 Binder mixes and specimen production, Papers II-IV

The materials used were as follows:

- Slaked lime ($Ca(OH)_2$, Nordkalk SL LA)
- NHL5 (St Astier natural hydraulic lime)
- Fly ash (Emineral fly ash Type B4)
- Hemp (from Grästorp, Sweden)

LHC mixtures were produced according to the proportions shown in Table 4. Mix A had a lime-hemp ratio of 1:2.5 by volume, mixture B had a ratio of 1:4 by volume.

Table 4. *Composition of mixes A and B*

Material	Mix A (kg)	Mix B (kg)
Slaked lime (Nordkalk SL KÖ)	1842	1842
Natural hydraulic lime (St Astier, NHL5)	368	368
Fly ash (Emineral fly ash Type B4)	244	244
Hemp shiv (hemp variety Fedora 17)	1355	2169
Water	5000	6000

Moisture content of the hemp was determined by weighing hemp samples before and after drying in a heat cabinet at 105 °C. Weight change over time was registered during the course of 7 days. It was found that the hemp had reached its dry weight after 1 day. Moisture content of the hemp was found to be 12%.

Specimens were produced using a rotating pan mixer. After mixing, the LHC was tamped down by hand into steel moulds. Even distribution of the LHC in the cylinders was controlled by weighing the moulds before and after applying the material. Only specimens with a density within a limited interval were accepted. This interval was 830-880 kg/m³ for mix A and 640-690 kg/m³ for mix B. Specimens were cured at ~20 °C and 65% RH for at least 3 months before being subjected to laboratory experiments.

4.3 Construction and Drying of the Full-Scale Wall, Paper IV

A full-scale LHC wall was erected as a dividing wall between two climate chambers. This wall was divided into four sections, with two different LHC mixes and two different renders (Table 5). Mix A contained less hemp and therefore relatively more building lime than mix B (Table 6).

Table 5. *LHC mixes and renders used in the full-scale wall*

Wall section	A1	A2	B1	B2
LHC mix	Mix A	Mix A	Mix B	Mix B
Render	Cement	Lime-cement	Cement	Lime-cement

Table 6. *Proportions of LHC mixes A and B by weight*

Material	Mix A (kg)	Mix B (kg)
Slaked lime	1842	1842
Natural hydraulic lime	368	368
Fly ash	244	244
Hemp shiv	1355	2169
Water	5000	6000

The four wall sections were separated by shuttering plywood, mineral wool and again shuttering plywood. The wall had a thickness of 500 mm. Small wooden studs were installed at 100, 200, 300 and 400 mm from the surface at a diagonal from each other (Figure 17). Electrodes for moisture content measurements were installed in these studs at heights 400 and 800 mm.

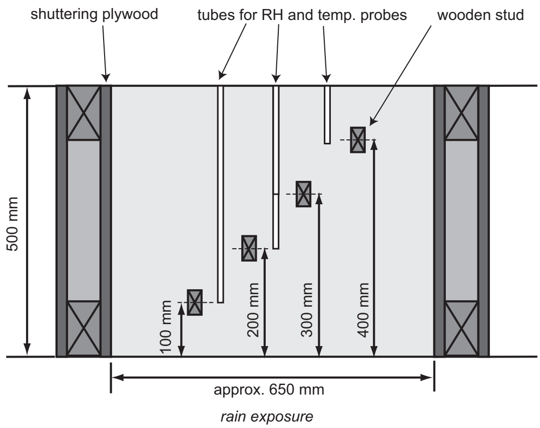

Figure 17. Horizontal section of one wall section.

Figure 18. Mould for the wall, ready to be built. Pieces of masking tape indicated how far one batch should reach.

Figure 19. Probe for RH and temperature sensor (left arrow) and electrodes inside the wooden studs (right arrow).

Figure 20. The mould for the wall, half the wall is built. In the foreground a new batch of LHC.

Figure 21. The wall has been built; plastic film was put on top to prevent the wall from drying too quickly.

Figure 22. The wall after the shuttering plywood had been removed. Probes for RH and temperature sensors in the centre of the walls.

Figure 23. Plastic film was draped over the wall on both sides, leaving an air cavity between wall and plastic. This prevented the wall from drying too quickly.

Batches of LHC were prepared using a pan mixer (125 L, Sandbymaskiner AB[b]). The LHC was compacted manually by tamping to a density value after casting that was established in the moisture property tests. It was important that the wall had the same density as the specimens. Compact density of the wall was regulated by calculating the volume of a wall section and determining the height of one batch of LHC. Masking tape indicated how far one batch should reach (Figure 18).

During casting, probes for RH and temperature sensors were installed on top of the cast LHC, after which LHC was cast around the probes (Figure 18). Masking tape prevented LHC from entering the probes. This masking tape was later removed prior to installing RH and temperature sensors.

The wall was constructed in two days, casting one mix per day (Figures 18-21). The shuttering plywood was removed two weeks after casting (Figure 22). Plastic film was then placed on both sides of the wall at a distance of approximately 100 mm from the wall to prevent the surface from drying too quickly (Figure 23). The film was left on the sides of the wall for 4 weeks, after which it was removed. The wall was then left to dry for approximately four months before a render was applied.

During the drying period, conductance in the studs as well as RH and temperature in the probes were measured and logged regularly. Conductance was initially measured manually using a hygrometer (GANN, Hydromette HTR 300), while RH and temperature were measured using a humidity and temperature indicator (Vaisala HMI41).

Moisture content as well as RH and temperature were measured and logged regularly after construction. Moisture content inside the wall was found to be very high, around 30-40%, and therefore the temperature inside the room was raised. To speed up the drying process, electric heaters were installed in the climate chambers on both sides of the wall. The temperature inside the climate chambers was initially raised to 45 °C during approximately 4 weeks but the drying process inside the wall did not accelerate at the anticipated pace. Therefore the temperature was raised even more, to 55±5 °C, during approximately 3 weeks.

Moisture content inside the wooden studs in the wall was measured using a hygrometer (GANN, Hydromette HTR 300). Figures 24-27 show the drying process during the accelerated drying for the different wall sections. The thick grey lines indicate moisture content before the temperature increase, the thick black lines the situation after the temperature increase had finished. The drying process between

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[b] Since 1986: PEAL AB, Garnisonsgatan 11, 254 66 Helsingborg, Sweden.

start and finish is indicated by the dotted lines, from grey (right after start) to black (right before finishing the accelerated drying).

Wall sections B1 and B2 dried to a moisture content of 6-7% throughout the section of the wall (Figures 26 and 27). However, wall sections A1 and A2 (with a higher amount of lime in the mix) did not dry completely, with moisture contents after accelerated drying of approx. 10-20% (Figures 24 and 25).

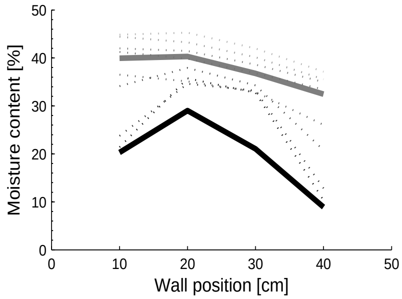

Figure 24. Moisture content in wall section A1.

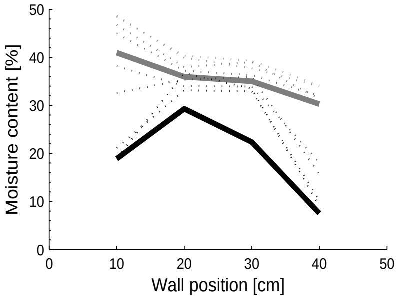

Figure 25. Moisture content in wall section A2.

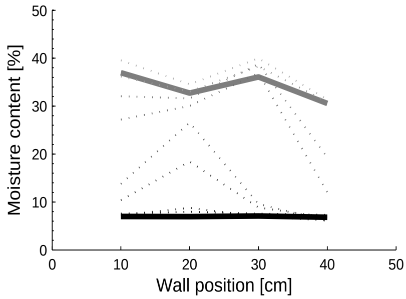

Figure 26. Moisture content in wall section B1.

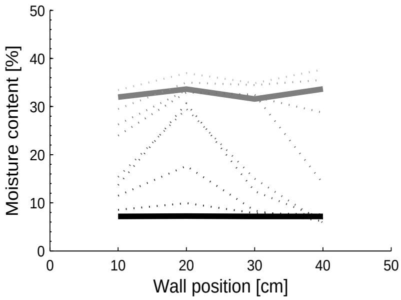

Figure 27. Moisture content in wall section B2.

During the rain scenario moisture content in the wooden studs was logged automatically at 10 minute intervals using a humidity logger (HMG Temp/RF Ver 1-1 041003/TL) connected to a computer with data logging software (Fuktlog Ver 3.0 BML). RH and temperature were logged automatically at 10 minute intervals in wall sections B1 and B2 by connecting the humidity and temperature probes (Vaisala HMP44) to a logger (Pico High Resolution Data Logger ADC-24), which in turn was connected to a computer with data logging software (PicoLog for Windows 5.21.1).

The wall was left to dry during a total of approx. 11 months. After this drying period it was exposed to a rain scenario. For this purpose a horizontal water spray installation was installed at the top end of the wall (Figure 28).

The wall was exposed to a total of five rain episodes. The first three episodes lasted 8 hours each and the final two episodes lasted 1 week each.

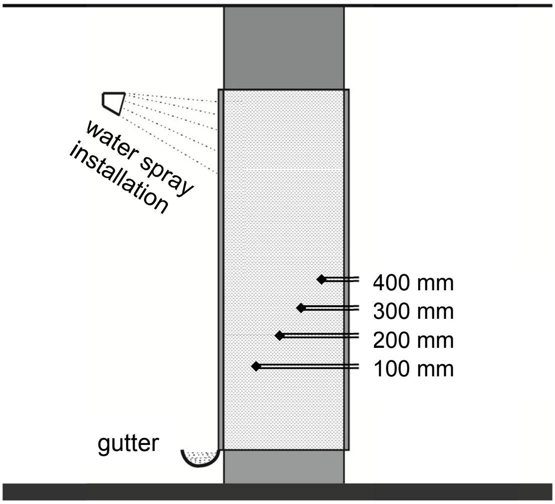

Figure 28. Schematic representation of the water spray installation on the full-scale test wall shown as a section. Probes for measuring RH and temperature and their distance from the rain exposed surface are indicated.

4.4 Overview of Test Methods

The test methods used to determine mechanical, thermal and moisture properties of LHC are shown in the overview in Figure 29.

Mechanical properties of LHC, in which both shiv and fibres were used, were determined in **Paper I**. Compressive and splitting tensile strength both before and after a freeze-thaw regime were determined for five different mixtures of hemp, building lime and cement.

While **Paper I** addressed mechanical properties, **Papers II** and **III** focused on moisture properties. Moisture transport properties for two different LHC mixes were determined in **Paper II**, while moisture fixation of these mixes was studied in **Paper III** and thermal properties were also determined.

In **Paper IV** measurements from a full-scale wall exposed to a rain scenario were compared with results from simulations. Measurements of moisture levels inside the full-scale wall were made using two different methods. For the simulations moisture properties of LHC that had previously been determined in **Papers II** and **III** were used.

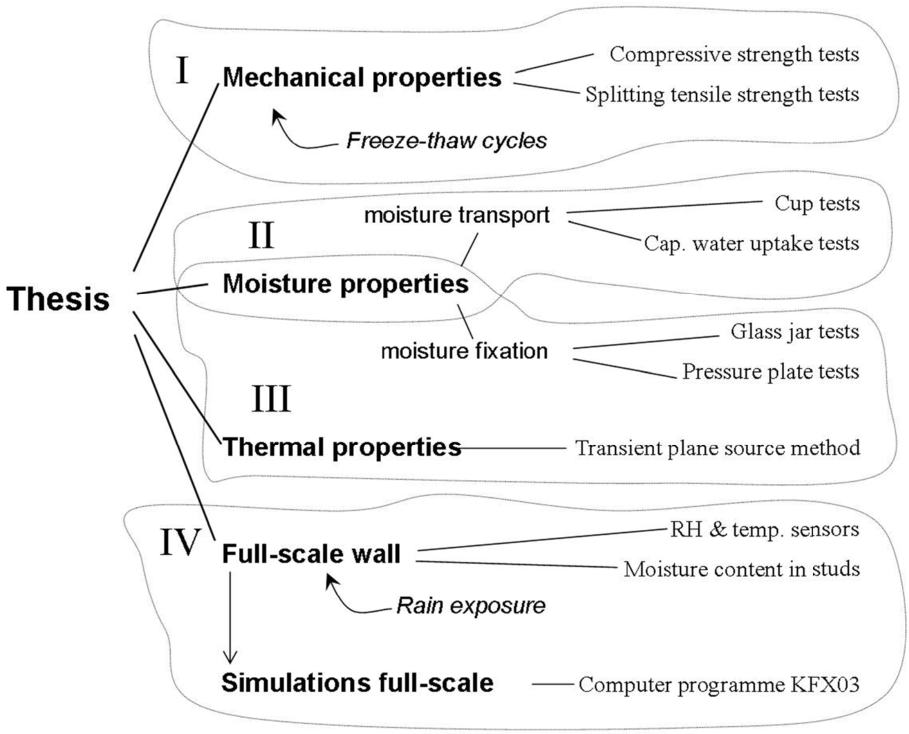

Figure 29. Overview of test methods used in Papers I-IV.

5 Summary of Results and Discussion

5.1 Mechanical Properties (Paper I)

The compressive strength of the different mixtures of building lime, cement and hemp ranged from 0.15 to 0.83 MPa. Mixtures with a high amount of cement showed the highest compressive strength, Young's modulus and splitting tensile strength. However, if LHC is to become load-bearing, compressive strength will have to increase considerably, to values of 3-5 MPa.

Cement seemed to increase mechanical strength, even though using cement as a binder in LHC may have some disadvantages that were not studied in this thesis.

Freeze-thaw cycles did not have a clear negative influence on the compressive strength of the specimens. The mixture where only cement was used as a binder even showed an increase in mechanical strength. This could have been due to the fact that all specimens underwent the same curing treatment prior to being subjected to the freeze-thaw cycles. A lack of access to water during the curing process would have had a negative influence on the final strength of the cementitious binder.

LHC with unseparated hemp did not differ greatly in strength from values found for LHC described in the literature where only shiv was used (Arnaud *et al.*, 2006; Evrard, 2003). This indicates that including hemp fibres in the mix does not significantly improve mechanical strength.

LHC showed high pseudo-plastic deformation at rupture. This pseudo-plastic behaviour indicated that the material was flexible and could withstand an increasing load for a longer time before rupture. On the other hand, a wall built with LHC would settle considerably under its dead weight.

5.2 Moisture Properties (Papers II and III)

The moisture transport properties of LHC were found to be relatively high up to 95% RH when comparing the material to building materials with similar components described in the literature (Nevander & Elmarsson, 2008), such as lime-based render (comparable to lime-based binder) and spruce timber (comparable to hemp shiv). Only cellular concrete (also a porous, cementitious, building material) had a moisture diffusion coefficient of the same magnitude as LHC.

Since the moisture diffusivity as a function of w in the high moisture range is based on capillary water uptake tests, it had to be re-calculated to moisture diffusion coefficient as a function of v using the slope of the sorption isotherm. Therefore moisture transport properties in the high moisture range are to a great extent dependent on the slope of the sorption isotherm. Moisture transport properties in the higher moisture range (>95% RH) required a steep slope of the sorption isotherm in this range. The sorption isotherm was fitted manually in the interval 95-100% RH. The slope of the sorption isotherm in this interval was imperative when deriving D_v (with vapour content as driving potential) from D_w (with absorbed water as driving potential).

A sorption isotherm at both absorption and desorption was produced for the moisture range up to 95% RH. There was some hysteresis, although this was not very distinct. The sorption isotherm for the LHC mix with a larger amount of lime-based binder showed higher moisture content at both absorption and desorption in the moisture range 33-95% RH.

In the range between 95 and 100% RH, the results from the pressure plate tests approximated the fitted sorption isotherm. The results from pressure plate tests described a desorption process; hysteresis between 95 and 100% RH could not be studied.

5.3 Thermal Properties (Paper III)

At both RH levels tested (15 and 65% RH), thermal conductivity was lower for the LHC mix with a larger proportion of hemp in the mix. Even though differences in density between the mixes were apparent, differences in thermal conductivity were not very large. In other words, a larger proportion of hemp in the mix improved the thermal insulating properties somewhat, but not to a great extent. Thermal conductivity for the two mixes at different RH ranged from 0.094 to 0.116 W/mK. This can be compared to values for other building materials such as mineral wool (0.038 W/mK) and cellular concrete (0.15 W/mK) (Nevander & Elmarsson, 2008).

Differences in thermal diffusivity between the two LHC mixes and the two RH levels tested were not significant, and were found to be between 0.25 and 0.30 mm^2/s. Values for specific heat capacity ranged from 0.300 to 0.469 kJ/kgK.

5.4 Full-scale Wall and Simulations (Paper IV)

Two measurement methods were used to measure moisture levels inside the LHC wall sections at different distances from the rain-exposed surface. Measurements of RH and temperature by means of probes inside the LHC resulted in clearer results than measurements of moisture content by means of electrodes in wooden studs inside the LHC. The wooden studs probably had a retarding effect, which meant that a change in moisture levels in the LHC did not cause an immediate response inside the wooden studs. Results from the RH and temperature probes were much clearer, showing an immediate response to the rain exposure.

Simulations of moisture levels inside the wall were made using material data from **Paper II** (moisture transport data) and **Paper III** (moisture fixation data). These simulations showed the same trend as the measured data, but there were some discrepancies. These were probably caused by an underestimation (in the case of cement render) or an overestimation (in the case of lime-cement render) of the transport properties in the lower moisture range. Transport properties for both renders were taken from Johansson (2005), who concluded that additional cup tests should have been performed to ascertain that these properties were correct even in the low moisture range.

Wall sections that contained more lime had not dried completely prior to the start of the rain scenario. The carbonatation process of lime, in which water is formed, could have contributed to this slower drying process. Instead of an increase in moisture levels due to the rain scenario, these wall sections continued to dry. The wall sections with relatively more hemp had dried prior to the start of the rain scenario. In these wall sections a clear response of moisture levels inside the wall due to the influence of the rain exposure was observed. These wall sections had a lower initial RH (60-65% RH). The sorption isotherm was quite flat in this region and thus there was a quick response in RH to an increase in absorbed moisture. Conversions to RH from moisture content measurements showed that even after rain exposure the wooden studs remained in an environment with moisture levels < 70% RH, giving low risk for microbial growth.

Moisture could more quickly penetrate a lime-cement render than a cement render, leading to higher moisture levels inside wall sections with a lime-cement render. Lime-cement render has a coarser structure, and therefore lower capillary force, allowing the underlying LHC to absorb moisture from the render. In addition, wall sections of LHC with a lime-cement render dried more slowly than those with a cement render, probably owing to the weaker capillary forces of the lime-cement render. A cement render has a larger share of fine pores than the coarser lime-cement render. Therefore cement render has a higher capillary force, thus absorbing more moisture from the underlying LHC, thereby facilitating the drying process of LHC.

6 General Conclusions

A load-bearing structure should be used when building with LHC. Even when unseparated hemp (both shiv and fibres) is used, the mechanical strength is not sufficient. Even though hemp fibres were expected to improve tensile strength, the splitting tensile strength of the LHC remains low even with fibres in the mix. In addition, the high pseudo-plastic deformation of the material means that an LHC wall without a load-bearing structure would settle considerably under its own dead weight.

An increase in the amount of hydraulic lime in the binder mix from 50 to 75 weight% does not significantly improve mechanical strength. However, increasing the amount of cement in the binder mix from 29 to 50 weight% doubles the compressive strength. A binder mix containing only cement has a compressive strength close to 3 MPa (the minimum required for the material to be load-bearing), but by choosing only cement as a binder other material properties may be affected. Examination of these was beyond the scope of this thesis. (**Paper I**).

At higher relative humidities the LHC mix with a larger proportion of lime-based binder has a higher moisture diffusion coefficient, indicating that moisture transport through the material increases with a larger proportion of lime-based binder. Compared with other building materials, LHC has a high moisture diffusion coefficient in the interval 35-95% RH. (**Paper II**).

The sorption isotherm of LHC shows some hysteresis between absorption and desorption. A mix with a higher proportion of lime has higher values for both absorption and desorption in the sorption isotherm. The sorption isotherm is relatively planar for relative humidities up to 95%, but in the interval between 95 and 100% RH it is very steep. The latter interval is of importance when studying high moisture loads.

Relative humidity of LHC influences thermal properties. At higher RH thermal conductivity is higher, whereas differences in thermal diffusivity and specific heat capacity as a consequence of differences in RH are less apparent. (**Paper III**).

A larger proportion of hemp in the mix results in lower thermal conductivity and lower specific heat capacity. An LHC with a larger proportion of hemp also absorbs moisture more slowly and dries more quickly after construction than a mix with a larger proportion of lime. This indicates that an LHC with more hemp in the mix would be more suitable for use in a cold, wet climate. (**Papers III** and **IV**)

The simulated data showed approximately the same trend as the measured data, although there were some discrepancies. This discrepancy between simulations and measured data could partly be caused by the fact that hysteresis was not taken into account in the simulations. In addition, transport properties in the simulations could have been underestimated (in the case of cement render) or overestimated (in the case of lime-cement render) in the low moisture range. (**Paper IV**)

Mix B (lower lime-content) dried more quickly than mix A (higher lime content). Wall sections with a lime-cement render absorbed moisture more quickly than wall sections with a cement render. In addition, wall sections with a lime-cement render did not dry as quickly as those with a cement render and relative humidity stayed at higher levels for a longer time. Therefore it could be advantageous to choose a mix with a lower amount of lime in combination with a cement render. (**Paper IV**)

Data on moisture content inside load-bearing wooden studs in the LHC wall are not as easy to interpret as data measured by means of RH and temperature probes. Moisture levels inside the wooden studs do not follow moisture levels inside the wall as accurately and swiftly. When exposed to the rain scenario in this thesis, after initial drying of the wall the wooden studs remained in an environment with low moisture levels, thereby minimising the risk of rot, decay and microbial growth. (**Paper IV**)

7 Future Research

In order to use LHC on a larger scale in a cold, wet climate, further studies of its thermal and moisture properties are required.

- The slope of the sorption isotherm in the high moisture range (95-100% RH) has a large influence on moisture transport properties. A sorption isotherm in this high moisture range including hysteresis is required in order to be able to study water uptake and drying of LHC under high moisture loads. Therefore more desorption measurements should be made in this range by means of the pressure plate method. To obtain measurements for both absorption and desorption (hysteresis) the pressure plate method should be developed further.
- Full-scale tests and simulations should be performed for a longer period of time.
- Full-scale tests and simulations should be performed using temperature gradients.
- Carbonatation speed of LHC should be investigated.
- The risk of microbial growth in LHC should be studied at different RH and temperatures. The influence of the carbonatation degree of building limes and their pH levels on the prevention of microbial growth in LHC should be studied.
- Influences of moisture levels inside an LHC wall on the load-bearing studs should be investigated further, studying possible signs of microbial growth in the wooden studs.
- The possibilities of producing prefabricated wall and roof elements from LHC should be investigated.

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