HEMP MADE

A study on the potential of hemp-lime and hemp-clay components for indoor climate performance and climate impact.

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CHALMERS

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Architecture and Planning beyond Sustainability

“ Plants have enough spirit to transform our limited vision.”

Rosemary Gladstar

Image 1. Hempcrete in wooden formwork

ABSTRACT

We live in a society where people spend most of their time indoors. Buildings should thus provide safe and sound spaces to live, work and sleep in. However, the building industry nowadays is mostly relying on non-renewable, man-made materials that could badly impact the indoor quality of our built environment. Above that, these materials have a non-neglectable negative influence both on resources and on emissions, putting significant pressure on our planet. Natural materials can provide an ecological and healthy alternative to numerous conventional building components. This thesis work investigates hempcrete, a sustainable, natural, biobased material that has great potential as an insulative infill component. Hempcrete is a mixture of hemp hurds with a mineral binder, most often lime-based. The hemp plant is fast-growing, making it a particularly resource-efficient raw material. This work explains what hempcrete is, how it is made and what different construction techniques are applied nowadays. Further on, the work focusses on the material's performances both regarding indoor climate regulation and environmental impact. Various characteristics such as vapor permeability, hygrothermal performances and thermal mass allow for hempcrete buildings to achieve a steady and comfortable indoor climate. Furthermore, hempcrete has a small carbon footprint, mainly thanks to the hemp hurds.

The possibility of associating hemp with clay rather than with lime is also investigated throughout this thesis work. This would enable to create a completely sustainable, safe and sound biomaterial. Lime has non neglectable embodied energy and embodied carbon, whereas clay is a local resource, available everywhere, that does not require processing. Furthermore, hemp-clay is a zero-waste product, as both hemp and clay can be reused or recycled and are both 100% biodegradable.
Both theoretical research and material testing are led to study the potential of hemp-clay, and indoor climate performances are compared.
In the end, guidelines on how to implement hempcrete in design are given and exemplary construction details, with their performance, are elaborated.

KEYWORDS:
hempcrete, hemp, lime, clay, hemp-lime, hemp-clay, bio-based, indoor climate, environmental impact

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During the summer of 2017, I participated in an adobe workshop. Building with earth for a week had spurred my curiosity about natural materials, how much fun it is to work with them, and all the benefits they can bring to the spaces we live in. Since then, my interest in natural materials has been sparked even more during courses and studios I followed.

When choosing a topic for the master's thesis, I came across hempcrete and felt triggered right away. I did not know anything about hempcrete, but the more I read, the more I was intrigued and wanted to explore this material's possibilities. The process and methodology I used during this thesis work have enabled me to gain very thorough and broad knowledge on this material, how it is worked and its potentials as a sustainable building material. I also had the chance to exchange with stakeholders working with hempcrete in different fields, which gave me direct connections to the hempcrete building sector. I have enjoyed exploring new potentials for hempcrete as well, bringing earth into the topic. I see this thesis work as a valuable gain of personal knowledge that I want to continue developing and implement in my further professional work.

THANK YOU!

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TERMS & DEFINITIONS

Biobased material : Animal- or plant-based materials that can be found in nature and are biodegradable.

Binder : A substance that gives cohesion to other substances and makes them stick together in a mixture.

Vapor permeability : Ability of a material to let vapor travel through it.

Relative humidity : The amount of moisture present in the air, in relation to the total amount of moisture that can be held in the air, for a fixed temperature and pressure. Expressed in **%**.

Thermal conductivity (λ) : Physical measure equivalent to the loss of thermal power of a homogeneous material with a thickness of 1m subjected to a temperature difference of 1K. It refers to the material's ability to retain or lose heat. Expressed in **W/mK**.

Thermal transmittance (U) : The rate of heat transfer through an element, it is dependent on the conductivity and the thickness of the element. Expressed in **W/m^2K**.

Embodied energy : Total amount of primary energy used in the production of a material during its life cycle. This includes extraction, processing, packaging, transportation and construction. Expressed in **MJ/kg, MJ/m^2 or MJ/m^3**

Embodied carbon : Total emissions of carbon dioxyde equivalents generated during the production of a material, linked to the embodied energy. Expressed in **$kgCO_2/kg$, $kgCO_2/m^2$ or $kgCO_2/m^3$**

LCA : Life-Cycle Assessment. Evaluation of the environmental impact of a material, based on the energy and materials used, and the waste released. The LCA includes 5 main steps : raw material extraction & processing/ manufacturing - Transport - Construction - Life time of material - End of life.

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Image 2. Hemp-clay samples

01 Introduction

BACKGROUND

> **“Energy-related CO_2 emissions from building operations and construction reached their highest level ever recorded in 2019. Together with manufacturing, transportation, and use of construction materials, they account for 38% of global CO_2 emissions”**
>
> ***United Nations,2020***

The building industry has an important role to play in the global climate crisis. In 2019, buildings and construction accounted for 38% of global CO_2 emissions, with energy and materials taking the biggest share (United Nations Environment Program, 2020). Currently, the building sector is very dependent on non-renewable building materials and construction methods with high embodied carbon. To build sustainably, resource awareness and circularity should be at focus, privileging natural materials and low-tech construction techniques. These materials can be produced locally requiring little processes and therefore have low embodied energy. Most conventional materials are not only harmful to the planet, but also have a possible negative impact on the quality of our indoor spaces. Buildings have become increasingly sealed, constructed with non-vapor diffusive components, to achieve desired thermal performances, and are regulated by high-tech solutions requiring important amounts of energy. Most conventional materials are also highly processed and contain unnatural, chemical components, which largely reduce indoor air quality. These chemicals are radiated in the air releasing small particles (VOCs) that can have noteworthy consequences on our health. Pushed to the extreme, constant exposure to bad indoor air quality and chemicals can lead to “the sick building syndrome (SBS)”, where people get short-term or chronic illness symptoms (Cherney, 2018). Rethinking materials and processes in the building industry is crucial for limiting both the impact on our planet and on ourselves. A shift towards natural and local materials is necessary to achieve sustainable, safe and sound architecture.

Fig.1 Three main sustainable development goals tackled with this thesis work (adapted from © United Nations)

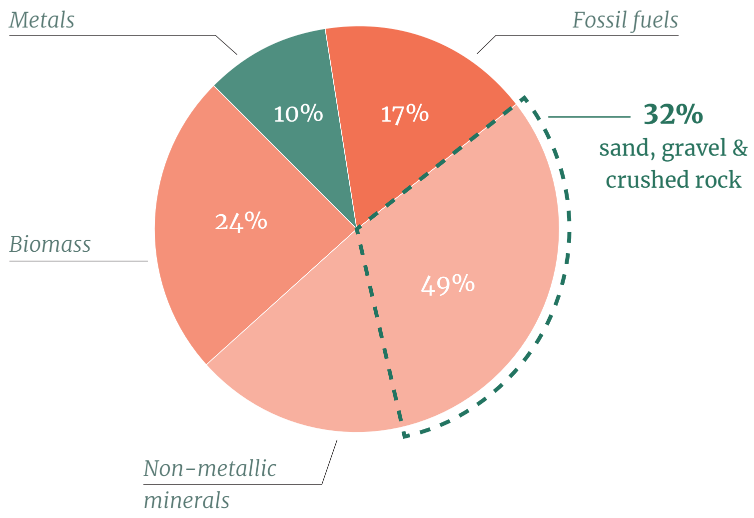


Fig.2 Raw material use for construction in 2017 - Adapted from © OECD

This thesis will focus on hempcrete, a less commonly known biobased material. Hemp is an annual plant belonging to the Cannabis plant family. It is used for various commercial and industrial products, mainly textiles, packaging, and biofuels. Alongside its common use, hemp is a great resource for insulation in buildings. Both the fibers and the shiv (the inner woody stem) of the industrial hemp plant can be used as insulative material. The fibers are mainly used as quilt or board insulation, the shiv is used to make hempcrete by adding a mineral binder. This binder is most commonly lime-based, a natural material sourced from limestone. Hemp is a fast-growing plant with considerable yield percentages, which is mostly higher than its commercial demands. Mainly the seeds and the fibers are valued, making the shiv a big by-product. This gives great potential for the use of hempcrete within the building sector, by turning waste into a resource. Hempcrete found its origin in France, where it has been developed the most. Since then, the biomaterial has gained interest in Europe, the United States and Australia and has been introduced in various projects. Above being a completely natural material, hempcrete offers interesting characteristics for indoor climate performance. Yet, building regulations on the material are still in an early stage, holding back its valorization and development in the mainstream building industry. Hempcrete is most often used in private small-scale projects.

OBJECTIVES

This thesis aims to showcase the potential of hempcrete as a building component. Both hemp-lime and hemp-clay are analyzed and compared. A focus lays on indoor climate performances and environmental impact.

GOALS.

1 Put hempcrete in the picture, contributing to knowledge development of the material and its application in the building industry.

2 Inspire to push the material's potential further, combining hemp and clay

3 Highlight the benefits of hempcrete on indoor climate for health and well-being.

4 Promote natural materials for sustainable resource use within construction.

RESEARCH QUESTIONS.

What is the potential of hempcrete as an insulative building component for indoor climate performance and environmental impact ?

Could clay be a good binder substitute and what indoor climate and environmental performances would hemp-clay have compared to hemp-lime?

DELIMITATIONS.
This work has a clear focus on hemp in association with lime or clay. Many other biobased materials exist and are in development today, but they are not investigated in this thesis work. The purpose is to go deep into knowledge development of hempcrete and explore its contributions within a sustainable building sector. For the same reason, no in-depth research on other applications of hemp in the building industry, for example hemp fiber insulation, is done. The thesis investigates different characteristics of hempcrete regarding indoor climate and environmental performance. The mechanical behavior of the material is mentioned; however, this is not at focus. The research is mainly based on the European context, most references are of French, English and Swedish origin. This sets the work within a more familiar architectural context for the author.

AUDIENCE.
This Master's thesis shows sustainable alternatives to nowadays building techniques and underlines the importance of a shift in material choices in the current building sector. This thesis work aims to become a source of knowledge and inspiration for fellow students and architects.

METHODS

This thesis is developed through background and theoretical research, case studies, experimentations, and design application. As a first step in the process, background research, through literature studies and interviews, gave the context in which hemp is cultivated and used nowadays, and defined hempcrete and its characteristics. The work has a strong focus on theoretical research, which has been an important process all along the work. Several architectural case studies were analysed to understand hempcrete's applications in construction.

Different stakeholders have been interviewed including hemp farmers, researchers, architects and professionals working with hempcrete in construction. Their inputs were valuable contributions to the work and gave new insights during the research. A one-day hemp-lime workshop gave a first hands-on material experience.

Material exploration of hemp-clay was done through experimentations and lab tests. Several samples were made varying proportions, shape, and density. Field tests were also conducted on the raw clay material. The samples were tested on thermal conductivity and moisture absorption.

A design guidebook, giving guidelines on working with hempcrete, and exemplary construction details are the design outcome of this thesis and relate the research back to design principles.

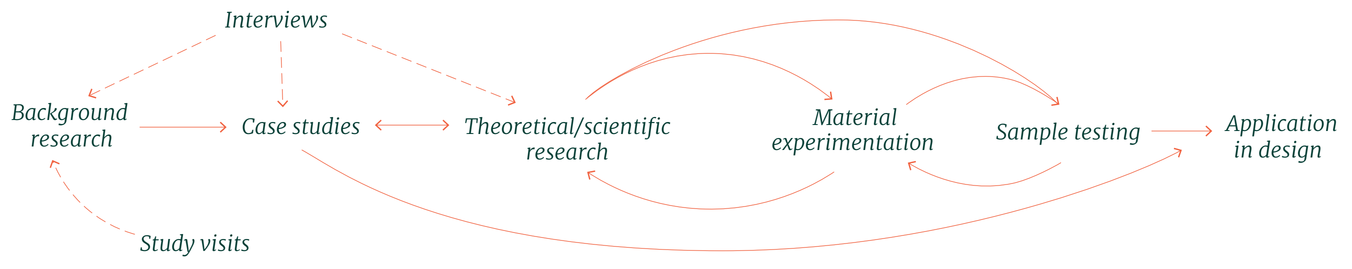


Fig.3 Master's thesis process

02

Hempcrete, an introduction

THE industrial HEMP PLANT

Fig.4 Hemp plant

Industrial hemp (or hemp) is an annual plant belonging to the *Cannabis Sativa* species. It is one of the oldest crops in the world. First records of hemp date back to 2800 BC in China, where it was mainly used for its fibers (Wagner, 2015). Although hemp belongs to the cannabis family, it is not to be confused with recreational cannabis as the plants must contain less than 0.20% of THC (psychoactive substances) to be legally defined as hemp (Wagner, 2015).

The hemp plant is an easy growing plant that thrives in various climates. It is incredibly robust and fast-growing. Hemp can grow at a rate of 30 centimeters per week at its maximum speed (Stanwix & Sparrow, 2014) making it the fastest-growing plant after bamboo. At maturity hemp can achieve more than 4 meters, depending on the variety. The hemp plant has a hollow stem of 4 to 20 millimeters thick. It is composed of bast fibers and shiv (or "hurds"). The stem owes its robustness and flexibility to the bast fibers, which are very strong and hard to break. The inner core of the stem, the shiv, has a high cellulose content, giving it a wood-like structure (Stanwix & Sparrow, 2014). It is also very water absorbent. Hemp has longtime been cultivated only for its seeds and fibers, shivs were merely seen as a waste product sold for animal bedding or burnt (Bevan & Woolley, 2008). However, both hemp fibers and hemp shiv are valuable resources for the building sector.

Hemp can be used or transformed from seeds to roots, every part of the plant can be valued. This makes it a very profitable agricultural crop, generating products for a variety of industries such as food, feed, medicine, cosmetics, textiles, paper, insulation, biofuels, and oils (EIHA, n.d.). In Sweden hemp is mostly valued for energy production through biofuels (Jordbruket i siffror, 2020). With its long, thin rooting network, hemp reaches deep in the ground to reach water, which drains the soil and improves its quality.

Fig.5 Benefits of hemp

CULTIVATION & PROCESSING

Image 3. Sowing of hemp

SOWING. Hemp can be sown as soon as the soil has warmed up to about 8°C (Svennerstedt & Svennson, 2004). In Sweden, this is generally around April[1,2]. The hemp plant grows best in a nutrient-rich loam soil (Svennerstedt & Svennson, 2004). The seeds are put in the ground with a seeding drill whilst at the same time mineral nutrition apports can be given to the soil. These fertilizers will allow for the initial boost to provide better yields but are not necessary for the plant to grow efficiently (Holstmark, 2006; Bevan & Woolley, 2008). Little to no irrigation is needed. According to the European Industrial Hemp Association, hemp can reach full ground cover after three weeks and the dense leaves become a natural soil protector reducing water loss and soil erosion. The fallen leaves also add nutrients to the soil making it healthier.

Image 4. Hemp field

CULTURE. hemp grown for its fibers reaches optimum yield and quality right after flowering, this is generally after 90 to 100 days of growing (Quand récolter le chanvre ?, n.d.). Seed maturation occurs after 120 to 140 days (Svennerstedt & Svennson, 2004). In Europe, the growing season of hemp is generally between March and August, in Sweden this extends untill October. Hemp is a very resistant and competitive crop, naturally suppressing weeds because of its growing speed (Bevan & Woolley, 2008). No chemical treatments whatsoever are needed, hemp naturally repels insects and is pest resistant (Stanwix & Sparrow, 2014, Bevan & Woolley, 2008), making it a clean crop with limited impact on the environment. It can be used as a break crop, in rotation with cereals for example, to clean up the soil and reduce the need for chemicals in agriculture (Stanwix & Sparrow, 2014, Bevan & Woolley, 2008).

Image 5. Retting in Autumn

FIELD-RETTING. After the plant has reached the desired maturity and the leaves have fallen off, the stems undergo a natural digestion process called retting. In most of western Europe, this is done by harvesting the plant in fall and cutting the stalks into 50-60 cm pieces and spreading it in strings across the field (Ahlsten, 2010). It is then left for several weeks to dry, and dew-ret. The action of the sun, rain and microorganisms dissolves the pectin and lignin around the stalks making them easier to be processed afterwards (Wagner, 2015; Ahlsten, 2010). The stalks should be turned at least once to obtain a uniform retting (Nelson, 2000). After retting, the fibers become more workable and have gained strength. Leaving them exposed to dew also improves the water absorbance of the stalks.

Image 6. Hempfield under snow

FROST-RETTING. In Nordic countries hemp stalks are digested by frost, leaving them dry out on the field over winter[1,2](Holstmark, 2006). The stalks are then harvested in Spring, about a year after sowing. This process is necessary in cold and wet countries because the optimal season to obtain dry field-retted stalks is too short, leaving the stalks too wet to be stocked indoors[2]. In this case, there could be a risk of rotting of the straw. The frost-retting technique has however disadvantages. The harvest after winter is more difficult, the fibers have loosened, and it is harder to go through with the cutting machine[2]. Also, the fibers are of lesser quality and due to natural decay, the yield is not as high as in fall (Ahlsten, 2010).

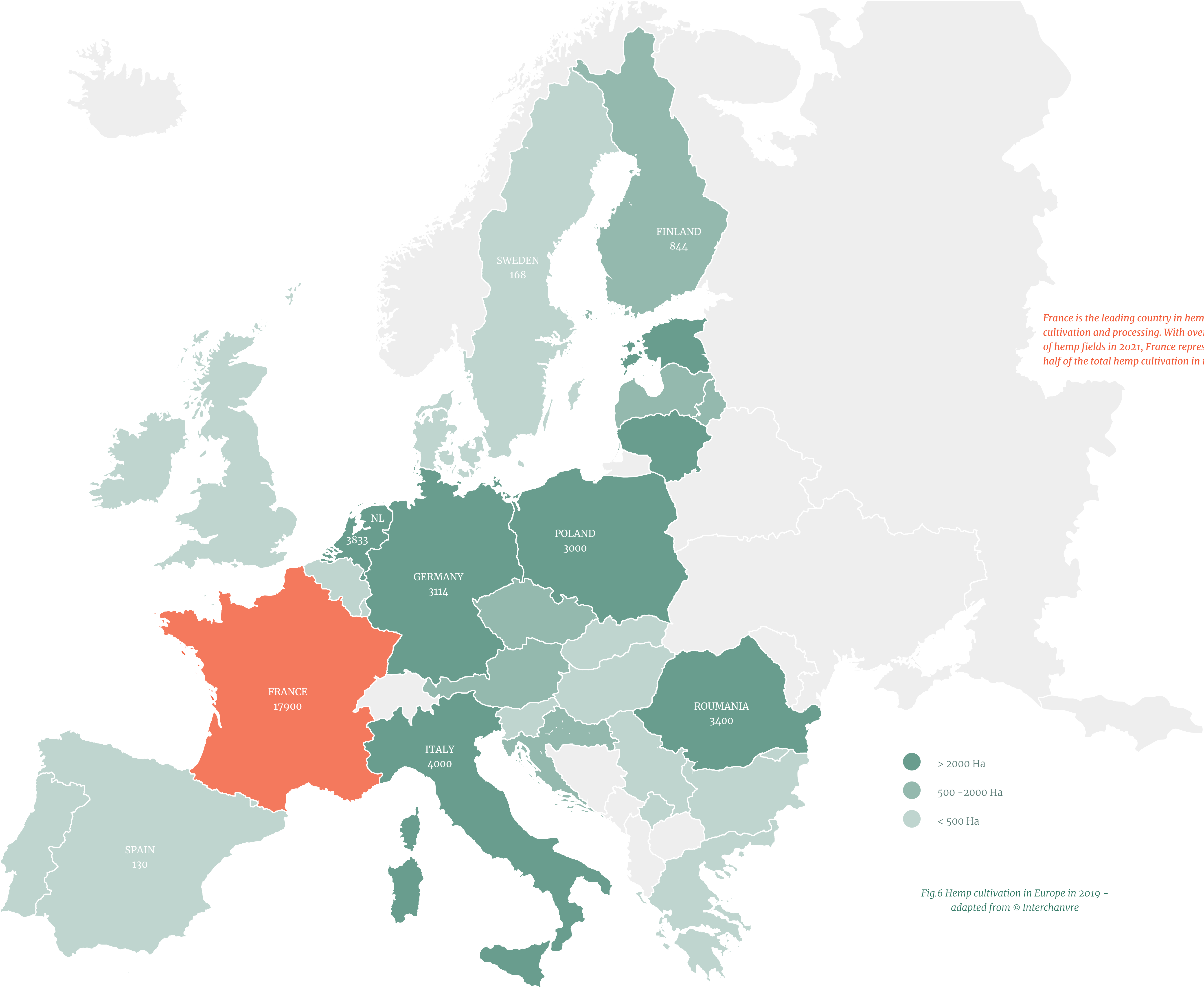
Image 7. Harvesting dried stalks

YIELD. Hemp harvesting is a completely mechanical process, no chemical methods should be used (Terres Inovia, 2020). Cultivation is very easy and does not require many efforts or inputs. The tricky part is the harvesting of the plant as it requires expensive, durable, and qualitative machinery[2]. Especially when the stalks have been left over winter and they have become harder. When the retting process is finished, and the stalks contain less than 15% of humidity (Terres Inovia, 2020), they are collected, pressed into bales and stored before being processed. After Autumn harvest, dry matter yield is around 10 tons per hectare (Jordbruket i siffror, 2020), where the shivs represent 4 to 6 tons (Evrard et al., 2006). According to Bevan & Woolley (2008) this is enough to build one house.

Image 8. Mechanical decorticator

DECORTICATION. The bales are pressed through a mechanical decorticator to separate the fibers from the shiv (Nelson, 2000). This machine crushes and breaks the core of the stalks without impacting the bast fibers (Wagner, 2015). Once separated, the shivs are shredded into uniform pieces and the fibers are refined several times to obtain a clean product. The process is completely dry and non-polluting (Bevan & Woolley, 2008). The only by-product is dust, which can easily be transformed into bricks for biofuel (Bevan & Woolley, 2008). This makes hemp a very profitable crop, as the whole plant can be transformed.

1 : Mail correspondance Thomas Jacobsson | 2 : Visit Göran Andersson



France is the leading country in hemp cultivation and processing. With over 20 000 Ha of hemp fields in 2021, France represents almost half of the total hemp cultivation in the EU.

Fig.6 Hemp cultivation in Europe in 2019 - adapted from © Interchanvre

HEMP IN EUROPE

+70 %
hectares of hemp between 2013 & 2018 in Europe

France produces
40 000
tons hemp shiv per year

170 Ha
grown in Sweden last year*

Hemp was a popular crop in Europe until after World War II. Mainly the hemp fibers were valued for manufacturing textiles. According to EIHA, Russia had the lead of hemp cultivation with about 700 000 hectares, providing up to 40% of European hemp needs in the 1930s. The decline in hemp production came with the invention of synthetic fibers in the 1950s, leading to a shutdown of thousands of hemp manufacturing facilities (EIHA, n.d.). Above that, hemp was falsely considered as a narcotic substance and banned by the United States in the 1960s. Many Western countries followed this new legislation, which has given hemp a bad image and a delay in development ever since. It took decades for hemp to be considered a legal crop again, and sadly by that time important knowledge and machinery were gone.

France, however, never stopped cultivation and developed considerably its resources. It has become the pioneer in hemp cultivation and processing in Europe, followed by Italy and the Netherlands (EIHA, n.d.). In France 40 000 tons of hemp shivs are produced every year (Interchanvre, 2019). Nowadays, there is a rediscovery of the potentials of the hemp plant, and the industry is growing rapidly. From 2013 to 2018, hemp fields in Europe have increased with 70%, with an overall increase of 614% since 1993 (EIHA, n.d.).

Looking at the Swedish context, hemp cultivation was the largest on Gotland Island until the 1950s (Nyström, 2018). At that time, there was also a hemp refinery in Visby, making it possible to both grow and process the plant. Hemp cultivation was forbidden from 1965 until 2003 (Holstmark, 2006), causing important knowledge losses, the shutdown of all refineries and considerable delays in the development of the Swedish hemp industry up till today. Several associations such as Svenkshampaindustri and IHFS (the swedish industrial hemp association) have seen the day to promote the hemp industry and work for its development. Plans for a refinery facility in Skåne are in the making, the goal is to make a process line from seed/stalk to product within a 500 km radius (Test site Steninge, 2020). This will enable to refine the whole plant, increasing its interest and making it a profitable investment for farmers.

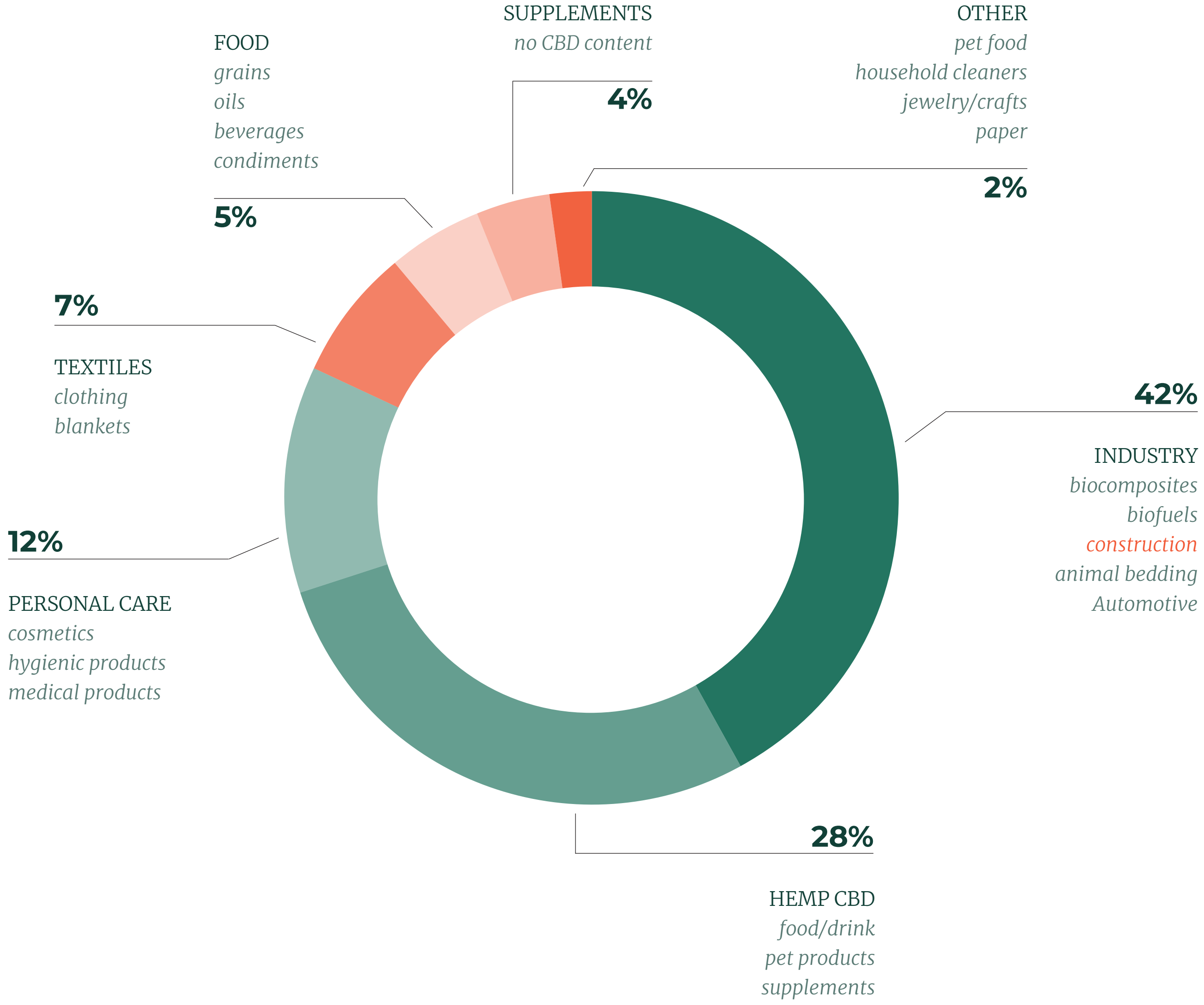


Fig.7 European hemp market in 2017, data from New Frontier Data

** source: Jordburket i siffror*

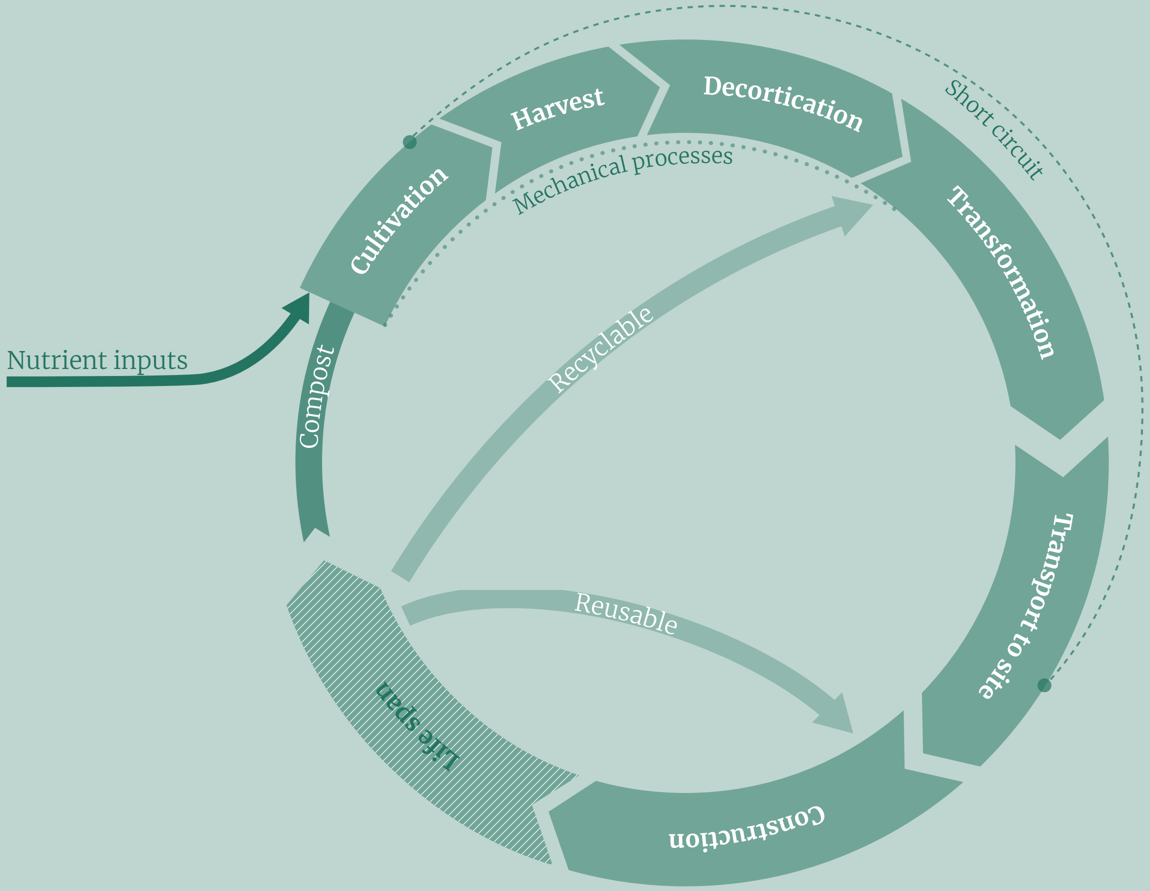


Fig.8 Possible circular cycle of hemp as a building material

HEMP AS A BUILDING MATERIAL

PRODUCT	APPLICATION
Fiber batt insulation	Floor Wall Roof
Loose fibers	Floor Roof
Hempcrete	
binder ratio (− to +)	Roof Wall Floor
Hempblock	Wall Floor
Hemp lime plaster	Finish

Hemp can be transformed into insulative building components both using the shiv and the fibers of the stalk. The fibers can be used in different ways, the most basic being as loose infill. They can also be transformed into soft or rigid batt insulation. This is an environment-friendly composite material containing 92% hemp fibers, 8% polyester fibers, non-toxic bonding agents and a fire treatment (Greenfield, 2020). It is not an entirely natural product due to the polyester binders and fire treatment inside. However, it is by far a better choice than a standard batt insulation, which contains almost 50% of plastics and chemicals for the same percentage of natural fibers (Greenfield, 2020), making it unhealthy and non-eco-friendly. Hemp fiber batt insulation has a thermal conductivity of λ = 0.04 W/mK and performs equally or better than conventional insulation materials (Stanwix & Sparrow, 2014). As a comparison, mineral wool has a thermal conductivity of 0.03 to 0.04 W/mK.

Hemp fibers are very strong giving the insulation a longer durability than standard, synthetic products. Also, the natural fibers' structure and the low density of the batt insulation allow for it to absorb moisture without losing thermal performance ; it can absorb up to 20% of its weight in moisture (Stanwix & Sparrow, 2014). The fibers are open to diffusion and act as a natural filter for condensation, slowly dissipating the humidity that could accumulate inside the insulation (Greenfield, 2020). Builders that have worked with hemp batt insulation find it much more pleasant to install than standard insulation quilts, as they do not experience allergic reactions to its components such as itching or coughing (Greenfield, 2020).

This thesis work will not explore more in detail the various applications of the bast fibers as insulation material. The focus point will be hemp shiv and its application as hempcrete.

Image 9. Fibers

Image 10. Fibers & shivs

Image 11. Shivs

WHAT IS HEMPCRETE ?


Image 12. Wet hempcrete

Hempcrete is a wet mix combining hemp shiv with a mineral binder, most commonly lime-based, and water. Hempcrete, or "hemp-lime", found its origins in France in the 80s when men were searching for an alternative restoration material for wattle and daub infills in historic timber-frame buildings (Stanwix & Sparrow, 2014). It is a non-loadbearing, self-supporting and vapor permeable material, most commonly used as an insulative infill within a loadbearing frame structure (Stanwix & Sparrow, 2014). Hempcrete has gained popularity over the years both in Europe and in other countries such as the United States or Australia. France remains a pioneer in building with hempcrete and has established specific building regulations, owing to in-depth testings of mechanical, insulative and fire performances of the material led by "Construire en Chanvre". No overall EU regulations on hempcrete have been developed yet, therefore making it more difficult to implement as a standardized building component on the larger scale. Knowledge development is an important step towards an easier implementation within construction.

ABOUT THE HEMP SHIV. The shivs represent about 43% of the matter of the plant (Biosys, 2021). To be used in hempcrete, they have to be cut into pieces of about 10 to 25 mm long (Stanwix & Sparrow, 2014; Bevan & Woolley, 2008). The end product should be dry and clean, reducing the amount of dust to the bare minimum (Bevan & Woolley, 2008; Construire en chanvre, 2015). The shiv does not require any chemical treatments, such as fire retardants or repellants, as the lime-based binder will become a natural protection (Bevan & Woolley, 2008). "Constuire en Chanvre" has developed a set of requirements for the shiv to be labelled as certified for the French building industry. The different characteristics analyzed are the granulometry, the density, the humidity rate, the amount of dust, the color, and the yield of the plant (Construire en chanvre, 2015). In France, the building is only certified when the right raw resources are being used. This makes the country a leader in hempcrete construction with solid regulations to rely upon.

ABOUT THE LIME BINDER. Two types of lime exist, air lime and hydraulic lime. Air lime or "pure lime" is made of pure limestone composed of 95 to 99,5% of Calcium Carbonate (BCB Tradical, 2020b). Hydraulic lime comes from limestone containing 6 to 20% clay and silicate impurities. The lime-binder used for hempcrete is mostly composed of air lime. Air lime has been used for thousands of years by mankind and has showcased its potential throughout history as a durable and aesthetic material. Its fabrication follows several precise steps explained by BCB Tradical (2020b). Firstly, the limestone is extracted from a quarry from where it goes to the processing plant. Here the limestone is crushed, washed, and crushed again, after which it undergoes a screening process to keep only the appropriately sized stones. The stones are burned in a kiln at about 950°C until calcination to obtain quicklime. This quicklime is then extinct by hydration, for practical and safety reasons. The right amount of water is added to obtain a dry powder (slaked lime), that does not contain any quicklime anymore, which is the product used to make the hempcrete mix.

Hempcrete has two setting or "curing" steps for which the binder is responsible: the initial set and the re-carbonization of the hydrated lime (Magwood, 2016). The initial set, also called hydraulic set, should be strong and quick (24 to 48 hours) allowing for the hempcrete to be self-supporting and to stay in place. After this initial set the hempcrete will have achieved its full structural properties (Magwood, 2016). During the re-carbonization, the hydrated lime reacts with carbon dioxide in the air and transforms back to its initial form as limestone gaining full strength (fig 9). This chemical reaction [$Ca(OH)_2 + CO_2 = CaCO_3 + H_2O$] releases the energy used during the calcination process (Berge, 2009). This is a very long process that can take up to decades to be fully finished, however it does not influence the functional properties of the hempcrete (Magwood, 2016). Another important aspect is the drying time of the hempcrete, taking several weeks. This drying time has to be considered during construction as it is crucial the hempcrete is enough dried out before applying a finishing layer.

Air lime has a quite slow setting process, which is seen as inconvenient for the construction sector (Evrard & de Herde, 2015). For this reason, two types of lime binder mixes are commonly used nowadays. The first type is composed of about 70 to 85% of air lime to which hydraulic components in forms of lime, cement and/or pozzolans are added, providing a strong initial hydraulic set on site (Walker et al., 2010). The second variety is composed of extremely hydraulic natural cement made from Alpine limestone, which sets quick and strong whilst still maintaining vapor permeability (Stanwix & Sparrow, 2014).


Image 13. Limestone

PROPERTIES OF LIMEBINDER

- Naturally vapor permeable
- Protects from rainwater
- Bactericidal virtues
- Flexible and elastic
- Adaptable to various surfaces
- Patination over time

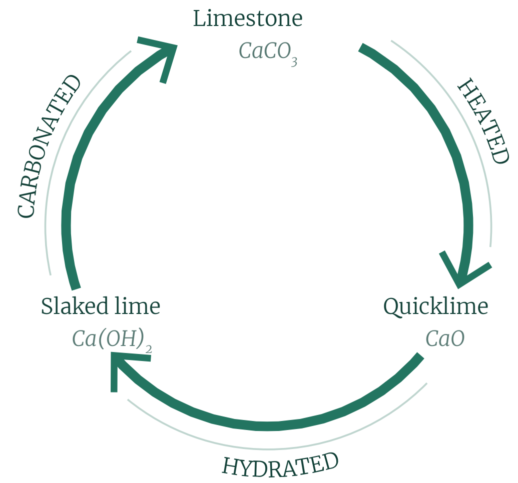


Fig.9 The lime cycle

CONSTRUCTION TECHNIQUES

Image 14. Hand placing method

STEPS FOR HAND-PLACING HEMPCRETE (HC)

1. Place formwork
2. Mix HC
3. Cast HC in 150 mm layers
4. Tamp HC (do not overcompress)
5. Raise slip forms (600 mm height)

CAST-IN-SITU. This is still the most standard hempcrete construction technique, where the hempcrete is mixed on site and cast into a formwork. This formwork can be made of temporary or permanent shuttering and the hempcrete is cast around the structural frame. Temporary shuttering is used when the wall is plastered/rendered or to allow the drying process of the hempcrete before a permanent shuttering is fixed. Most commonly, OSB or plywood boards are used for temporary shuttering (Magwood, 2016), however these are unsuited for permanent shuttering. Indeed, hempcrete is open to diffusion and requires vapor permeable finishes to perform optimally, which is not the case of OSB or plywood (Magwood, 2016). It can be advantageous to have permanent shuttering on at least one side of the wall to reduce labor and material costs.

The mix can either be hand-placed, like pisé, or sprayed in between or onto the shuttering. After the initial set of the hempcrete, the shuttering can be removed. It is best to install as much formwork as possible prior to mixing the hempcrete, to have a more fluid workflow (Magwood, 2016). Usually, the hempcrete is erected layer by layer using slip forms (boards of 600 mm high) on one side for the shuttering. The hempcrete mix is workable 30 to 90 minutes, depending on how strong the initial set is (Magwood, 2016). The hand-placed method is low-tech but more labor intensive. A good organization is required for a steady workflow. Generally, one person is taking care of mixing the hemp, lime and water and controls the quality of the mixture. It is important to have consistency in the mixing process to obtain homogenous hempcrete throughout the construction. One or two persons bring the mixture to the people that are casting, whilst at the same time, others are required to prepare the next wood frames and shuttering elements. The drying time of hand-placed hempcrete is around 28 days, after which finishes can be applied.

Image 15. Spraying method

The spraying technique is a newer method that is often used in France (Stanwix & Sparrow, 2014). It has a fully mechanized application method requiring a special spraying machine. Often, the hempcrete is sprayed directly onto a permanent shuttering board, taking away the need for shuttering on the other side of the wall. This technique is faster and is therefore better suited for larger scale projects. Spraying also enables a more even and lighter application, which reduces the drying time to about 7-10 days (Bevan & Woolley, 2008). This technique is also very suited for renovation projects, as the hempcrete can be sprayed directly onto the existing structure (stonework, wood, bricks...).

PRE-CAST. with a pre-cast method, the hempcrete is delivered in blocks or framed panels directly on site. This means that the drying occurred before arrival on site in a controlled environment, which is a considerable advantage for construction planning and time management. Working with pre-cast elements also gives a dry and clean construction site, independent on the weather conditions. Indeed, casting on site is strongly influenced by temperature and humidity factors; construction can only take place when temperatures are stable above 5°C for the hempcrete to dry out efficiently[1,2] (Bevan & Woolley, 2008).

Making prefabricated wood and hempcrete panels is quick. First, the wood frame with shuttering on one side is made. While determining the dimensions of the wood panel, it is important to consider transport logistics at this early stage. The panels must be easily manoeuvrable during delivery and on site. Their final weight should be pre-calculated, so they do not crush each other while stacked during transport (BCB Tradical, 2019). The wooden studs inside a panel are distanced every 400 to 600mm, and their cross-dimension usually ranges from 100x50mm to 150x50mm. Once the frame is completely assembled the hempcrete is poured in step by step. The panel is worked horizontally to facilitate this process. The panels are left to dry horizontally for a few days after which they can be put vertically, and the back shuttering can be removed if intended. Conduits and piping for technical equipment can be integrated at the casting stage when their placement is pre-planned. This creates a more fluent workflow on site for technicians (BCB Tradical, 2019).

Image 16. Hempcrete prefab panel

STEPS FOR PREFAB HEMPCRETE PANELS

1. Make woodframe and structure
2. Mix HC
3. Pour HC in woodwork
4. Tamp HC removing air pockets
5. Equalize infill

Hempcrete blocks are made in a fairly simple process. The mixture is hand placed in a slip mold, after which it is demolded and left to dry on a drying rack. Standard rectangular shaped hempcrete blocks are not loadbearing and have to be placed within a frame structure on site. They are assembled using a lime or hemp lime mortar. New types of nested hempcrete blocks (male and female part) that could be loadbearing (denser hempcrete mix using natural cement) are in development. Hemp blocks, however, can be problematic regarding cold bridges and if non-loadbearing they are perhaps not the most efficient technique for building with hempcrete.

Image 17. Hempblocs

1 : Phone conversation Thomas Brun | 2 : Interview Peter Holmdahl

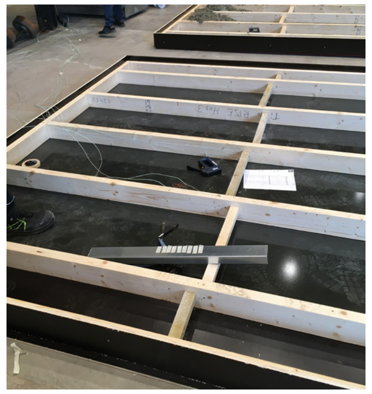
HEMP-LIME WORKSHOP

With House of Hemp @ RISE

During this workshop, two hempcrete wall panels were made at the fire testing department at RISE in Borås. The walls were built using a prefabrication method, where hempcrete was poured into a timber framework. The panels were made in two days. The timber framework was built the first day, the second day the hempcrete was cast. I was invited by Peter to participate the second day so I could experience hempcrete and work the material. It was an exciting day: I saw the mixing procedure and helped at every step of the casting process. It was quite labor intensive, the mixture had to be spread in the framework with a rack than tapped to give an even infill and remove big air pockets. Overall, it took around 2,5h to finish one panel with 2 people. 1 other person was in charge of continuously preparing the mixtures for the workflow to be smooth. An impression of the day is given on the right page (More images can be found in the Appendix). I found hempcrete nice to work with. The downside, however, is the caustic reaction of the lime when it is wetted. Therefore we wore protective wear, goggles and double pair of gloves, because the lime is corrosive to the skin and could give burns. During the mixing of the hempcrete a face mask has to be worn as well to protect from the dust, and avoid it from being inhaled.

This project is led by Gothenburg city, in cooperation with Hoppet and House of Hemp. It aims at making hempcrete available on the Swedish construction market. Different properties of hempcrete will be researched and tested according to Swedish building regulations. The workshop was the start of a thorough research and testing phase of the material's properties regarding fire resistance, thermal performance, acoustics and compressive strength. Hygroscopic and thermal parameters will be analysed via sensors embedded within the hempcrete. Then panels will be subject to acoustic analysis, and fire tests. The results will be compared to Swedish regulations and indoor climate standards and should enable to implement the material within the Swedish building market and contribute to more climate-efficient construction.

1. Making of the panels with pinewood and temporary back shuttering for casting.
Image 18.



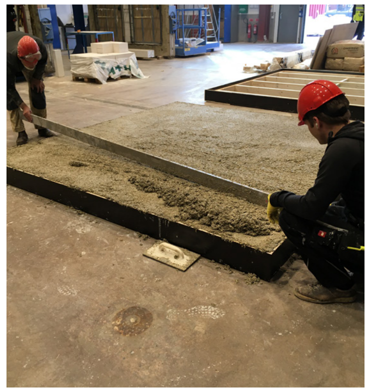
2. Moisture and thermal sensors are added to one panel for analysis.
Image 19.

3. Making the hempcrete: 2 bags of lime binder + 1 bag of shiv + 60L water.
Image 20.

4. The panels are worked horizontally when placing the hempcrete.
Image 21.

5. The mixture is spread in the panels, pushing it onto the wood to remove air in every corner.
Image 22.

6. Step-by-step the framework is filled. The hempcrete is tamped to fit around the wood.
Image 23.



7. When the panel is filled completely, the hempcrete is egalized to obtain a flat infill.
Image 24.

8. The panels are left to dry horizontally for a week. Afterwards, they are placed vertically for further drying.
Image 25.

FIRST CONCLUSIONS

STRENGTHS

Stable indoor climate

Straightforward construction methods

Construction techniques adaptable to climate

Circular use
Recycle - Reuse - Compost

WEAKNESSES

Unequal hemp cultivation at the moment

Transport shiv and lime
CO_2 emissions

Wet construction dependent on weather
drying time hempcrete

OPPORTUNITIES

Reduction carbon footprint building sector
Carbon sink

Simpler construction details
reduction of building layers

Participatory construction
Social interaction
Workforce cost reduction

THREATS

Political legislations on hemp

Lack of mediation and knowledge development

Building regulations

Firstly, the value of hemp as a resource, not only for the building industry, is undeniable. The great potential of the plant lays both in its easy cultivation and in its important carbon storage during growth. Hemp can be cultivated without chemical treatments making it a clean raw resource. The plant could be easily implemented as a break crop with cereal cultivation for example. Hemp would clean and drain the soil before the agricultural cultivation. By doing so, the fields still remain used for their agricultural purposes whilst at the same time cultivating hemp resources.
As mentioned, the plant has regained popularity throughout the last decades, but still struggles with a bad image. This complicates and slows down its development in several countries.

As shown on the figures to the right, hempcrete is a multifunctional material that can be used in different components of a building. The material seems to be so powerful because it manages to combine functionality with performance, enabling to have more straightforward construction methods and component details. It also requires less maintenance being a simple, monolithic element. During the workshop at RISE, I could also experience it is a pleasant material to work with. It should, however, be handled with protective wearing due to the caustic nature of the lime binder.

The building sector is still relying on conventional, man-made materials, making it hard to implement new, biobased materials. Building regulations do not yet follow the pace of natural material development and research, it is a difficult task to convince of their potential and safety. Hempcrete makes no exception. Lot of research is being conducted on its mechanical behaviour, thermal performance, and fire resistance; however, a gap still remains with the possibilities of its implementation in the building industry. Even in France, where hempcrete has been developed the most, regulations are complex and thorough studies and analyses have to be conducted prior to its approval as building material in a given project. This is especially true when the building exceeds 2-story height (David, 2021). Therefore, hempcrete construction still struggles to establish itself in dense urban areas (NXNW architectes, n.d.). Indeed, product certifications and insurance coverage pose a major threat to ecological material development in the building industry.

The next part of the thesis work elaborates the performances of hempcrete, both regarding indoor climate and environmental impact. To start, different construction methods in practice are explored through various case studies.

Fig.10 Personal SWOT analysis

1 Ha hemp = **6 tons** hurds = Walls for **135 m²** house in average

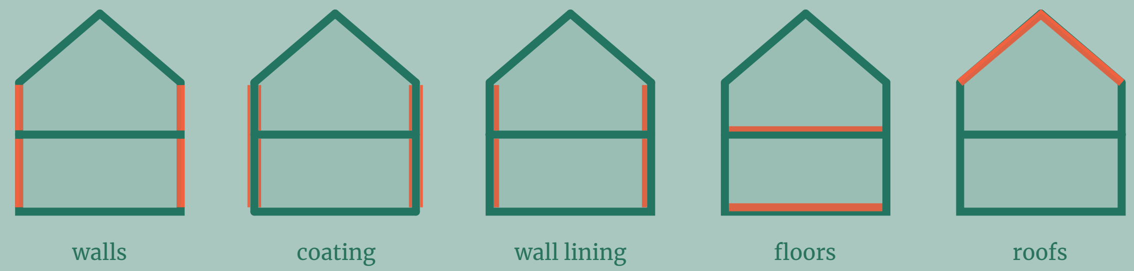


Fig.11 Possible applications of hempcrete within a building

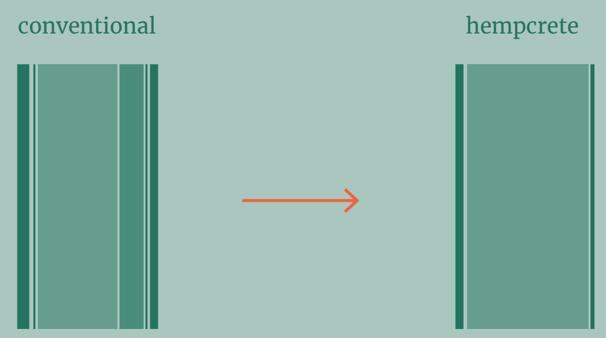


Fig.12 Building layers can be reduced to a minimum

03 Hempcrete performance

CASE STUDIES

PERSONAL ANALYSIS
CHOSEN CRITERIA

PRODUCTION. Factory and worksite conditions. Adaptability and workflow for site management.

SIMPLICITY. Easiness and straightforwardness of the construction technique. New knowledge requirements. Availability of skills and machinery

UP-SCALABILITY. Easiness to upscale this technique, suitability for bigger projects with a tighter construction schedule.

THERMAL. Performance of the building regarding steadiness of indoor temperatures.

AESTHETICS. Appearance of finished result on inside and outside. Material concept made visible. Most subjective criteria.

ENVIRONMENTAL PERFORMANCE. Estimated carbon footprint of the project considering all material choices.

The following case studies analyze 6 selected projects, employing various construction techniques to implement the hempcrete. The projects range in size and function, both public and private buildings. The selected case studies ought to give an outlook on how to make hempcrete a more accessible building technique through upscalability and efficiency on the work site, depending on the type of project.

Currently, hempcrete is mostly implemented in small scale private projects, using a cast-in-situ construction technique in complement with a wood-frame loadbearing structure. Commonly, the biomaterial is worked as a wall infill but can also be used as timber roof insulation or floor infill, varying the mixture's density.

This study intends to understand how the hempcrete construction techniques work and which methods are most efficient depending on the context and the scale of the project. Both wet in-situ construction and prefabrication techniques are presented. The effect of hempcrete on the building's performance is also looked into.

A personal analysis on the use of hempcrete in each specific project's context is given. Six variables were defined and are scored on a scale from 1 to 5. These variables are : Production - Simplicity - Upscalability - Thermal - Aesthetics - Environmental performance. Each term is explained in the orange box to the left.

NATURHUS

Test site Steninge

SPECIFICATIONS
Location: Steninge (SWE)
Year: 2020
Function: Private house
Technique: Sprayed
Construction: Self-built

Image 26. Outside view

Image 27. Spraying the hempcrete

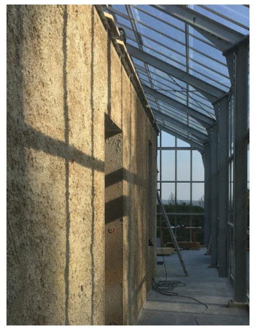


Image 28. Drying of wall

This project follows the concept of the "naturhus", where the heated living space is built within a greenhouse (GH). The heated space is 70m² big, about half the size of the GH. Its walls are made of hempcrete sprayed onto a wooden structure. The house both has facades inside the GH (South-East) and facades directly exposed to the outside (North-West). The hempcrete is casted in a 350mm layer, giving it considerable thickness for thermal performances. Indeed, according to Patrik Bengtsson, the owner and builder of the house, the indoor climate inside the house is very stable and reaches a comfortable 22°C with not much heating required[1]. The house is also rather small making it easy to heat. "It feels like a stonework house, you feel the heaviness of the walls"[1]. Initially, the hempcrete facades inside the GH would remain bare, but a lime plaster had to be applied to make them more even. Several temperature and humidity meters are incrusted in the walls. The hempcrete walls work in symbiosis with the GH, balancing the humidity levels and maintaining steady temperatures inside the house. However, humidity levels inside the GH are not excessively different from outside because of little vegetation present yet.

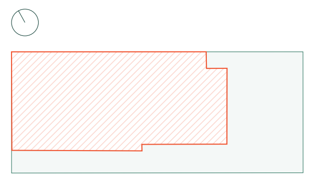


Fig.14 Floorplan scheme

WALL COMPOSITION
Lime render
Hempcrete 350mm
Woodwork 45x170mm
Clay plaster

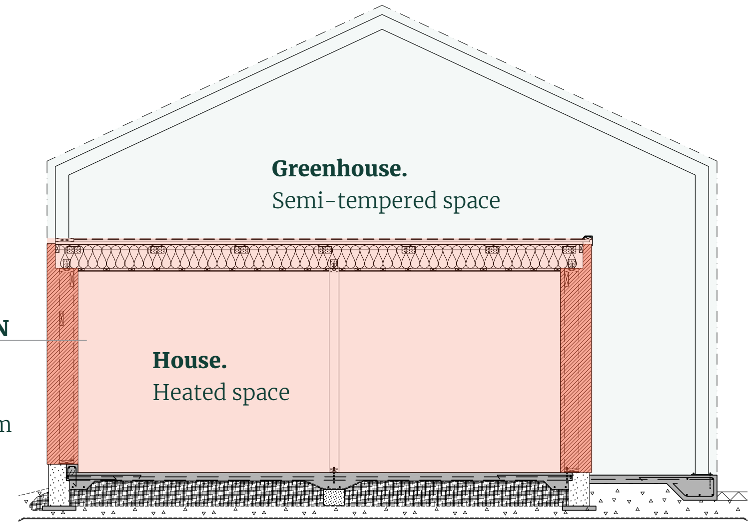


Fig.13 Transversal section -Courtesy of © Patrik Bengtsson

SPRAYED HEMPCRETE
personal analysis of the concept used in the project

1: Phone conversation Patrik Bengtsonn

REGIONAL HOUSE EDEGEM

BC Architects

SPECIFICATIONS
Location: Edegem (BE)
Year: 2015
Function: Public facility
Technique: Cast-in-situ
Producer: BC Studies

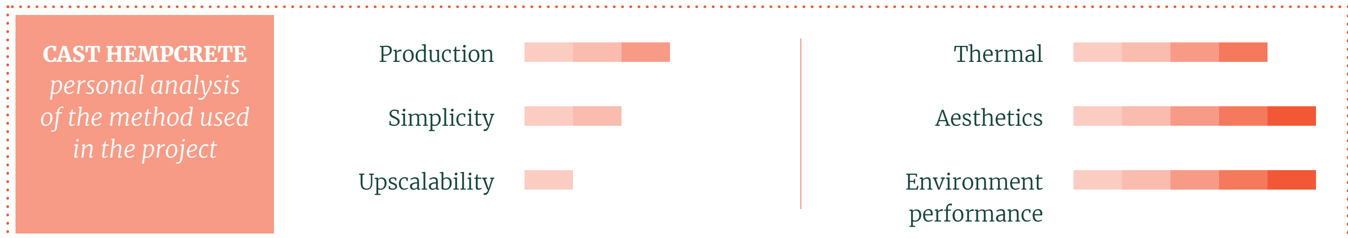

Image 29. Outside view


Image 30. Placing hempcrete on walls


Image 31. Placing hempcrete on the roof

Set within the particular context of the Fort V site, a former military unit now transformed into a public park, the building is placed inside one of the old hangars responding to a Hortus Conclusus concept (BC Architects, 2016). The project is an educational space where children and adults can learn about ecology and nature. The building is 350m² big and its typology is inspired on the military architectural arched masonry language of the surrounding (BC Architects, 2016). The educational program of the project is also reflected in its material and construction choices; a combination of structural earth masonry and hempcrete insulation (BC Architects, 2016). The project showcases sustainable, both ecological and social, building techniques working with local and low-impact materials in a participatory approach.

The construction is based upon self-building and participatory techniques using locally sourced materials, knowledge and workforce. The masonry structure of the project is made from Compressed Earth Blocks (CEB) using clay, called “Boomse Klei (clay from Boom), sourced from a nearby quarry (BC Architects, 2016). The blocks were made on site, inside the hangar, during a 3-week workshop. An insulative hempcrete layer is cast on the outside of the masonry structure, used both for the walls and the roof insulation. The hempcrete was hand-placed during a 2-week workshop. Owing to a participatory construction approach, with volunteer architecture students and youth, building costs were lowered whilst at the same time providing knowledge exchange over local materials and sustainable building techniques. Around 150 volunteers helped to build the project (BC Architects, 2016).



CONSTRUCTION. The project uses participatory construction approaches both for the CEB production and for the hempcrete casting. The workshops gave hands on practical knowledge during the built and theoretical knowledge during lectures held over lunch every day (BC Studies, 2017).

The structural masonry walls use 19 000 CEB made on site during the first 3-week workshop. Clay was extracted from the quarry and spread inside the hangar to dry for 4 to 5 days. This was repeated 6 times giving approximately 3000m² raw clay material to work with (BC Studies, 2017). Prior to the workshop, the compressive strength, and structural performances of the CEB were thoroughly tested. The bricks achieve a compression force of 4 MPa, achieving Eurocode 3 for masonry works (BC Studies, 2017). 312m² hempcrete was hand-placed to become the insulative layer on the outside (BC Architects & Studies, n.d.). The worksite is non-dependent on outside weather, making it possible to build over winter without drying problems of the hempcrete. The hempcrete was cast onto supporting wooden frames attached to the façade. No additional layers between the CEB and the hempcrete were needed, both materials are vapor permeable allowing for the walls to be open to diffusion and balance moisture content. Hempcrete is used both for the walls and roof. The roof has a timber structure with a vapor permeable ceiling board on which the hempcrete is cast. The building stands protected from rain making it possible to use the hempcrete as the apparent finish of the building.


Fig.16 Exploded axonometric ©BC Architects

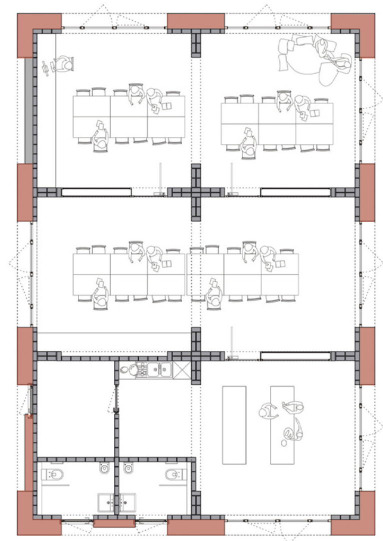


Fig.17 Floor plan ©BC Architects

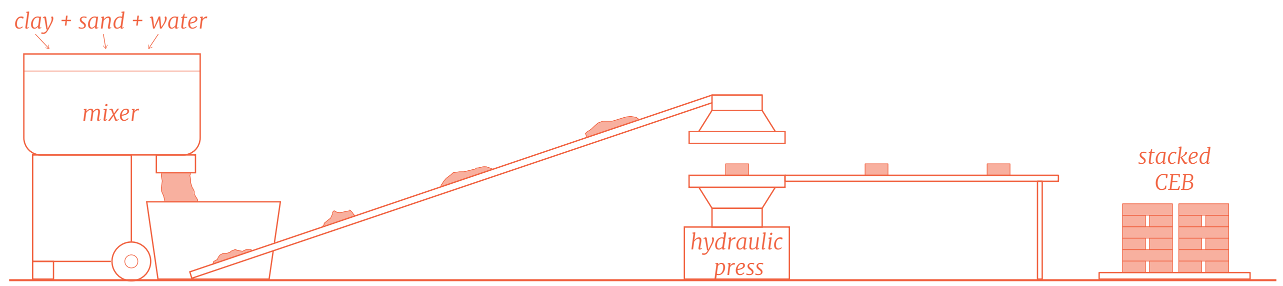


Fig.15 CEB production chain

MARX DORMOY

Barrault & Pressaco

SPECIFICATIONS
Location: Paris (FR)
Year: 2020
Function: Social housing
Technique: Sprayed
Structure/thermal: LM ingénieur


Image 32. West façade

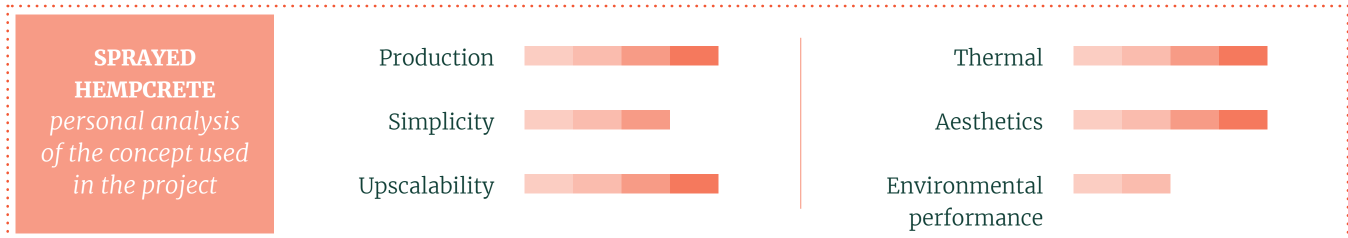

Image 33. East façade

This social housing project won the first prize of the competition for Paris Habitat. The building is 6 stories high and offers 15 apartments, 3 per floor. On the ground floor are shops, making it part of the public space of the street. The building stretches over the whole plot size, one façade is on Marx Dormoy Street, a wide, busy, and noisy street, the other one is on a narrower and quieter street. The architects designed small courtyards to break up the center of the building providing ventilation, natural light and views to the apartments (Griffiths, 2022). According to Barrault, the choice of hempcrete was made both for environmental issues but also for architectural purposes; the hempcrete is used as a tool to translate a Parisian tradition of thick facades with bow windows (Griffiths, 2022). Building with hempcrete is still more expensive than standardized materials, therefore becoming a niche market making it riskier in urban development (David, 2021). Also, regulations are still complex and generally limited to 2-story buildings, even though France is the leader in hempcrete construction. Thorough engineering studies and analyzes had to be presented to allow for the building permit of this project to be accepted (David, 2021).


Image 34. Interior


Image 35. Construction


Image 36. Construction



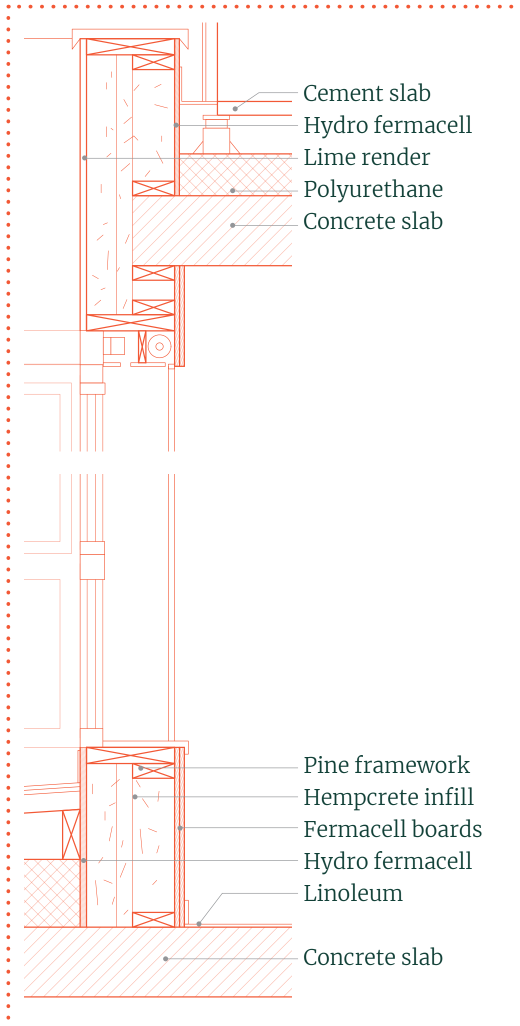


Fig.18 Detail section on facade © Barrault & Pressacco

CONSTRUCTION. The building uses a pillar and slab reinforced concrete main structure. According to Mouly (2020) the structural and thermal engineer of the project, using a fully wood structure was not possible for economic reasons (Nilsson, 2020).
The choice of bio-sourced materials was made for the façade construction. Here, a pine wood framework is placed on the concrete slabs. Fermacell boards are fixed to the inside of the wooden structure and become the formwork on which the hempcrete is sprayed. These boards, made of 80% gypsum and 20% recycled cellulose fibers, are a certified healthy and ecological material that allow for permeability of the wall. The hempcrete is sprayed in several layers to achieve a regular and even application, the thickness varies between 23 and 30cm depending on the façade section (Barrault & Pressacco, 2021). A vapor permeable lime render becomes the exterior finish.

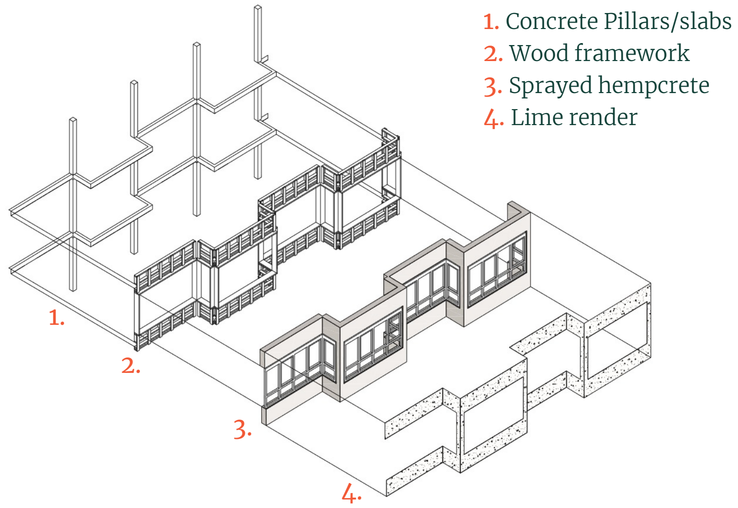


Fig.19 Exploded facade axonometry © Barrault & Pressacco

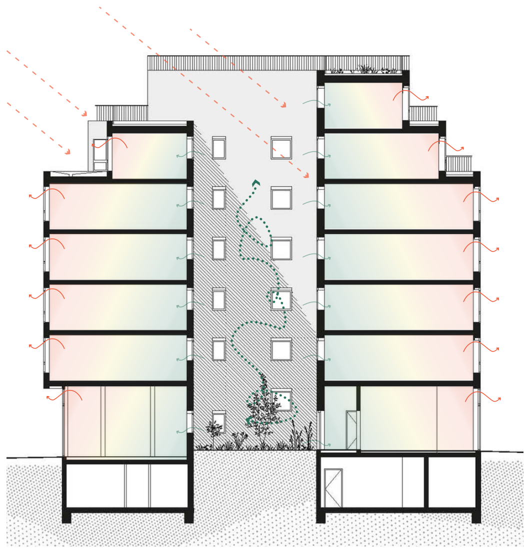


Fig.20 Section, cooling performance- Adapted from © Barrault & Pressacco & LM ingénieur

PERFORMANCE. The choice of hempcrete provides comfort to the occupants in several ways. The hempcrete enabled to have very wide window ratios, about 40% of the façade is glazed because there was no need for extra insulation around the windows (David, 2021). This provides additional light to the indoor spaces. The wall sizes are also reduced thanks to a limited number of components, giving more usable space in the apartment. This is very appreciable in a dense Parisian urban context. According to Mouly (2021) form follows performance in the case of hempcrete; the material has low thermal conductivity and is able to store and release energy when needed thanks to its thermal mass. The energy use of the building is notably lower despite the very large windows in the living areas (David, 2021). Each apartment is cross ventilated by windows both on the street side and towards the courtyard. Thanks to their small size and dense vegetation, the courtyards provide cooling in summer which enhances the natural ventilation of the apartments.

FLAT HOUSE

Practice Architecture

SPECIFICATIONS
Location: Cambridgeshire (UK)
Year: 2019
Function: Demonstrator project
Technique: Prefabricated panels
Organisation: Material Cultures


Image 37. Outside view

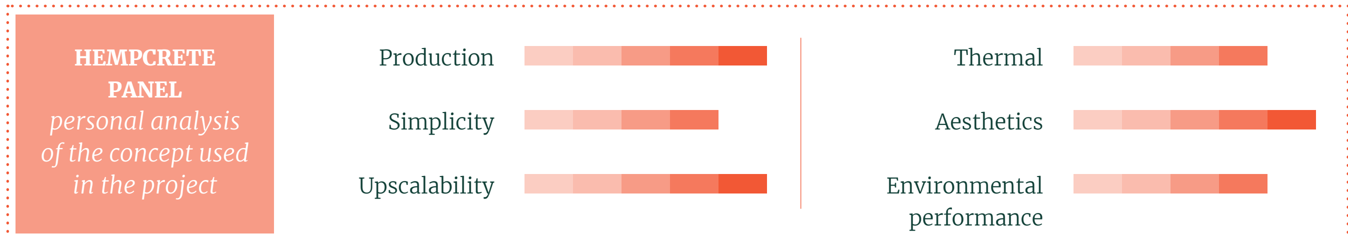

Image 38. Inside view

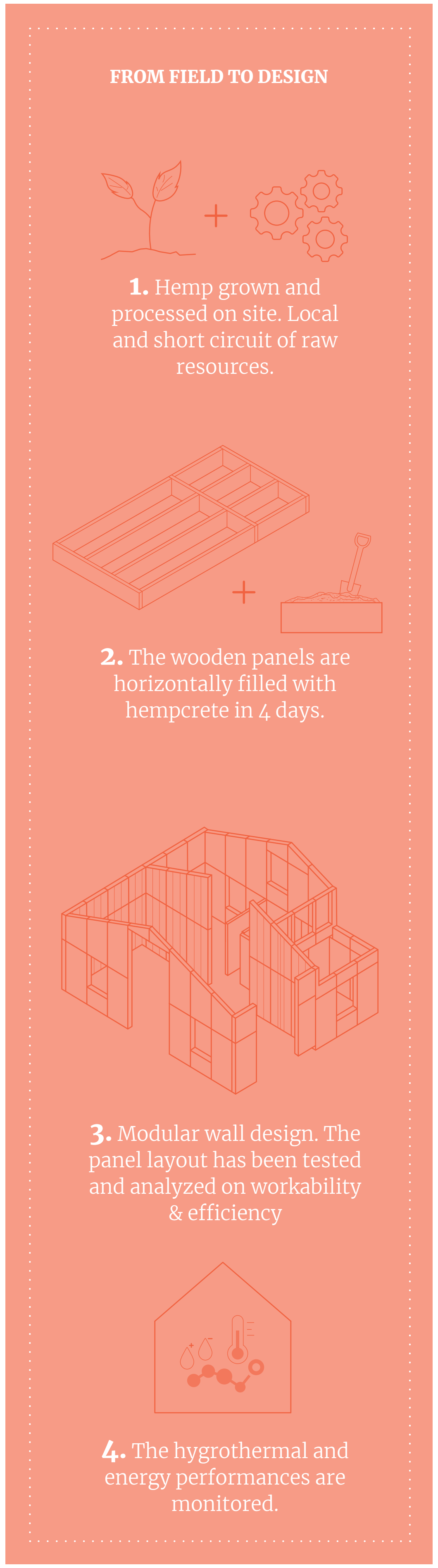

Image 39. Construction site

Flat house is a demonstrator project that investigates the scalability of hempcrete construction. It is situated in a rural area at Margent Farm, a research and development facility working on hemp and flax bioplastics (Practice Architecture, n.d.). The house has a simple floorplan, 3 bedrooms on two stories and a double height living room with open kitchen. A single glazed greenhouse is attached to the living area. Facing south, the greenhouse accumulates solar gains and radiates them back into the house[1].

The house is designed as a testbed for prototyping prefabricated hemp panels (cassettes) and how to upscale them to larger housing construction. For this, a 4-step methodology was developed. Firstly, the cultivation and processing of the hemp was investigated. Thanks to the rural context of the project, it was possible to grow 20 acres of hemp on the site's farmland to be used specially for the building. The crop was sown at the start of the growing season, harvested 3 months later, and refined on site[1]. Both the shiv and fibers find an application in the building; the shivs are used for the hempcrete and the fibers are used for the façade cladding. Prior to system design, 1:1 testing has been conducted were the dimensioning and the layout of the cassettes were researched. The walls of the house are designed like a puzzle, making the most efficient use of material. Also, different wall finishes were explored such as lime plaster and water paint, and whether they are best applied before or after assembly[1]. The façade cladding, a combination of hemp fibers and sugar-based resin, was developed on site by Margent Farm.

The hygrothermal and energy performances of the project are monitored, providing a post-occupancy analysis for further research and improvement.





CONSTRUCTION. The key materials in this project are hempcrete cassettes, timber, and hemp fiber cladding. The desire was to keep construction techniques simple and low-tech. The hempcrete cassettes for the walls are prefabricated, built in 10 days by one person[1]. Before casting the hempcrete, all the electrical conduit were fitted. The casting took 4 days (Stanwix, n.d.). All the drying sessions of the hempcrete were before arrival on site, making the worksite dry and quick. A total of 20 days were needed for the built, it took 5 days to place the cassettes on site with a small crane (Stanwix, n.d.). The architects used UK pine wood and avoided chemicals inside the house[1]. Wood fiber insulation is used for the ceiling, the floor and as permanent shuttering of the cassettes on the exterior wall side[1]. For this, hemp fiber boards could have been a possible alternative. The hemp walls are complemented with woodwool boards on the ceiling, made of shredded timber and cement.

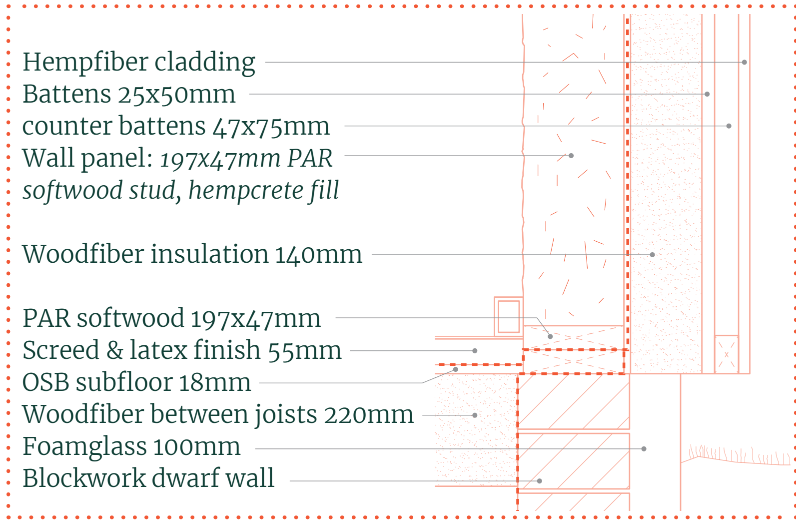


Fig.22 Detail section, adapted from © Practice Architecture


Image 40. Hemp fibre corrugated sheets

- Hemp fibers & sugar-based resin
- Thermal compression
- Exterior cladding (rainscreen)
- Interior finish (ceiling, wall, acoustics)
- Very low carbon footprint
- Strong and durable

The panels change color when exposed to outside weather and UV rays. Adds vibration to façade.

PERFORMANCE. The interior is left raw on most walls of the house with only a thin clay paint coating on the hempcrete. This gives a soft and light ambiance to the space and makes the acoustics warm and subtle (Stanwix, n.d.). The house has an A-grade for the EPC (Energy Performance Certificate), with a score of 104 out of 107 points, and an A-ranked Environmental Impact rating (Material Cultures, n.d.).

◁ Fig.21 Methodology (building axonometry adapted from © Practice Architecture)

1: Acan Conference - Paloma Gormley

PIERRE CHEVET SPORT CENTER

Lemoal Lemoal Architectes

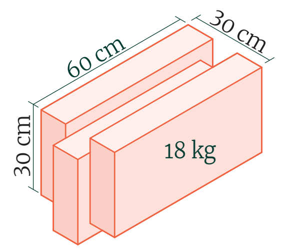
SPECIFICATIONS
Location: Croissy-Beaubourg (FR)
Year: 2021
Function: Public facility
Technique: Loadbearing hempblocks
Producer: VICAT Biosys

Image 41. Outside view

Image 42. Inside view

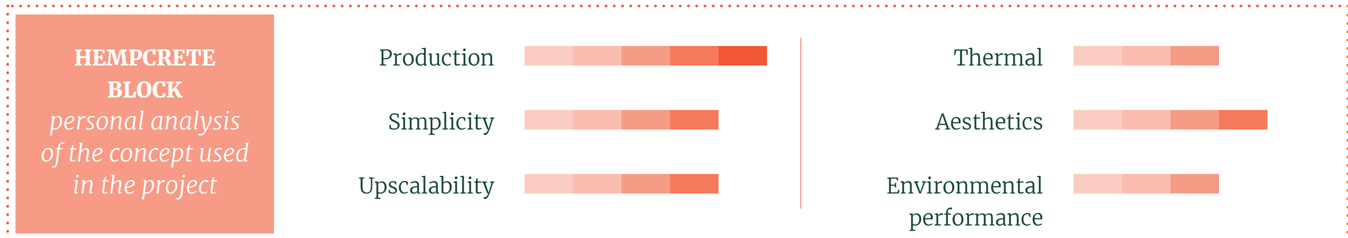
Image 43. Hempcrete block

This small-scale sport center is located in a residential area of Croissy-Beaubourg, near Paris. The project has the intention to become a focus point of the area, with other public facilities nearby. The floor plan is very open and has a straightforward distribution; there is a main large space around which, on the lower part, are the changing rooms, storage, and technical rooms. The available implantation space was limited, so the architects looked for a construction technique that would enable to keep as much usable space as possible for the floor plan[1]. Structural hemp blocks were chosen, which reduced the number of components in the wall to a strict minimum. This is a very new construction technique, compact hemp blocks made of hemp shiv and natural Prompt VICAT cement™ are used as loadbearing construction for the walls[1]. The natural cement comes from Alpine stones, extracted from underground quarries and burned at 1200°C[3]. The blocks were prefabricated and delivered to site enabling a fast, dry and clean construction process; the walls were built in 10 days[2]. The hemp blocks were processed about 400 km from the site, with locally grown hemp. This project is the first public equipment to be built with hemp blocks in France. The blocks are bigger than regular concrete blocks but can be worked with the same techniques and are easy to cut[1]. The bricks are calculated to have a life span of 100 years and are 100% recyclable afterwards[3].



Compressive strength	2.2 MPa
Thermal conductivity	0.0710 W/mK
Phase shift	10h
Acoustic reduction	43 dB
Fire resistance	30 REI

Fig.23 Characteristics Biosys hempblock[3]



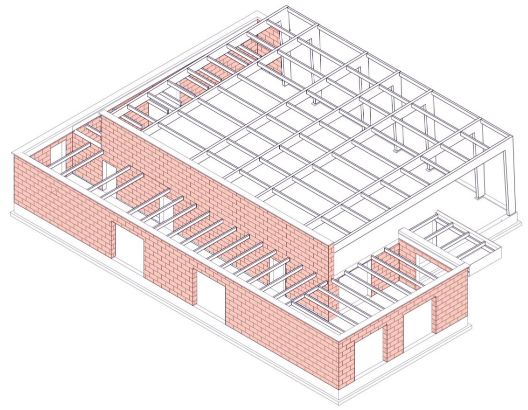


Fig.24 Isometric view © Lemoal Lemoal

CONSTRUCTION. The hemp block walls form a U-shape of 3m high, the central wall is 5m high[2]. This construction technique is similar to a masonry construction with concrete blocks, with the difference that the hemp blocks are nested on each other without any mortar[3]. The base of the wall consists of a cellular concrete footing, to raise the hemp blocks from the ground and protect it from capillary water rise[1]. At the corners and at critical parts of the wall a built-in metallic chaining brings additional support. This is filled with concrete to assure structural reinforcement of the wall[3]. The top of the wall is finished with a thin concrete beam providing additional resistance. The roof structure is made of wooden semi porticos placed on the hemp block walls. Biobased materials were only used in the wall construction; the roof is finished with standard insulation and metal roofing[1].

PERFORMANCE. The hemp block walls are oriented towards the south, to take full advantage of the thermal mass properties of the walls. The blocks do not fully avoid cold bridges. However the thermal requirements (RT2012) of the project were lower because of its use as sports equipment[1]. Regardless, the indoor climate is comfortable thanks to the warm sensation of the walls[1]. On the inside of the building, the blocks were either finished with a lime plaster or left untouched to showcase its materiality, and to benefit fully from the acoustic performances of the hemp blocks[1].

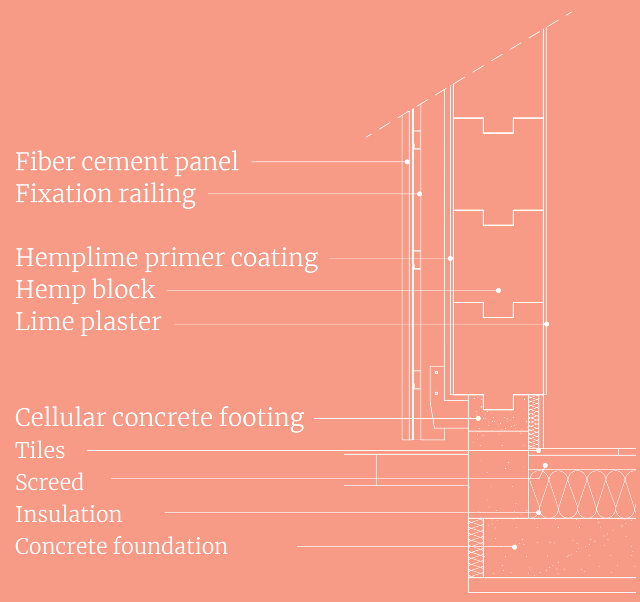


Fig.25 Wall section © Lemoal Lemoal

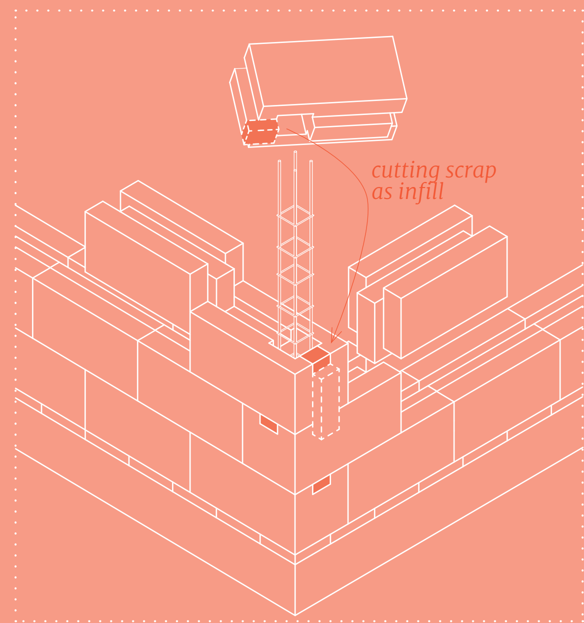


Fig.26 Diagram of hemp block construction[3]

1: Interview with Sonia Sifflet - Head architect | 2: Acan Conference - Sonia Sifflet | 3: Biosys VICAT brochures

LA HUCHETTE

Dumont Legrand Architectes
LM ingénieur

SPECIFICATIONS
Location: Paris 5e (FR)
Year: 2015
Function: Public facility
Technique: Renovation
Fibra Award Laureat 2019

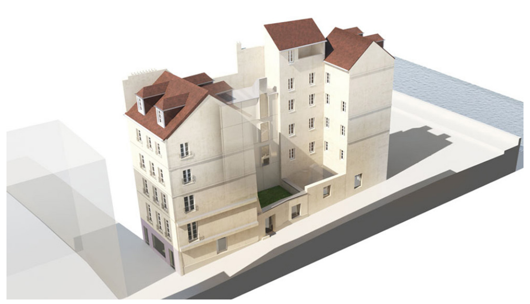


Image 44. Axonometric view

Image 45. Before renovation

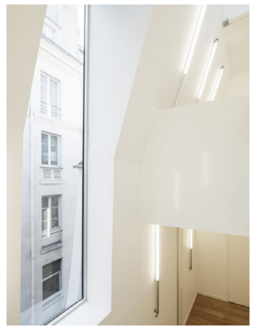


Image 46. After renovation

This renovation and extension of a residential historical building uses hempcrete as insulation material. The building belongs to the Parisian architectural heritage, so it was important to valorize its materiality without constraining its durability. The Huchette building is characterized by its natural stone masonry with a lime render. This gave the building good hygroscopic properties, thanks to the permeability of the materials. The project team looked for a renovation concept that matched the breathable walls in place. Most insulation materials advocate against vapor permeability, making the project "question nowadays conventional techniques" (Dumont Legrand Architectes & LM ingénieur, n.d.). Hempcrete became an obvious choice, it is both sprayed onto the stonework as interior lining and used as exterior render. This double insulation, both on outside and inside of the wall enables to enhance thermal performance of the building (Dumont Legrand Architectes & LM ingénieur, n.d.). The interior insulation provides hygrothermal inertia similar to the inertia of the original stonework, the exterior insulation reduces cold bridges of the envelop without drastically increasing the facade thickness (Dumont Legrand Architectes & LM ingénieur, n.d.). Fig. 27 shows the performance after renovation of the facade. The indoor temperature reaches a comfortable 20°C with a more even increase inside the wall.

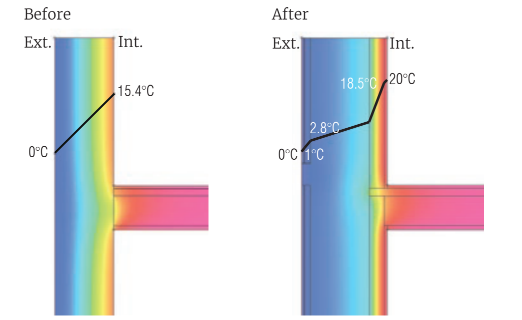


Fig.27 Thermal performance facade © LM ingénieur

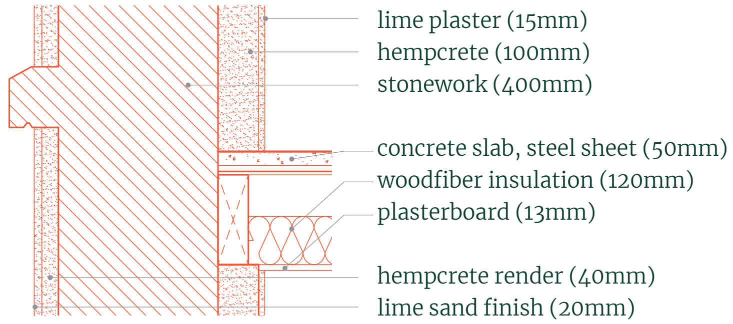
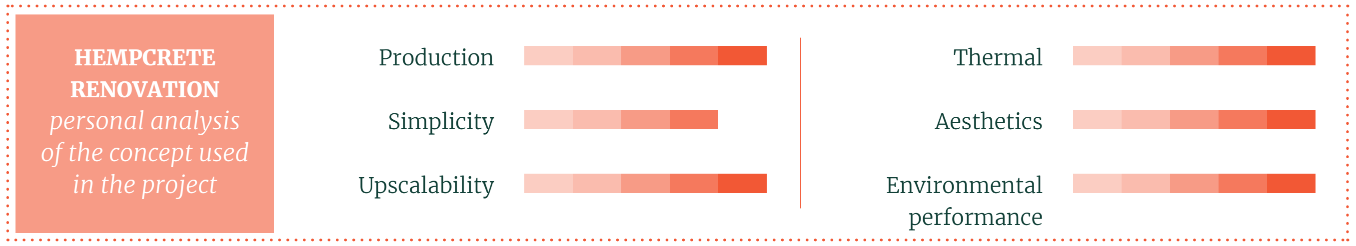
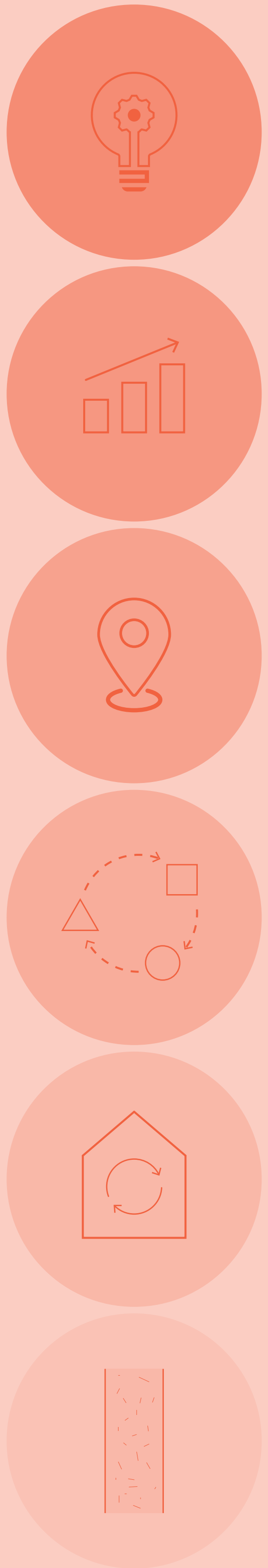


Fig.28 Detail section - adapted from © Dumont Legrand Architectes



CASE STUDIES CONCLUSION



KNOWLEDGE development is required for natural building materials. The more know-how, tools and machinery are available, the better the new building techniques become accessible and attractive. It also would take hempcrete out of the "niche market" it is currently in.

UP SCALING AND PREFABRICATION are important for the material to become an obvious choice in construction. It would make hempcrete applications easier and more feasible in the building industry. The construction will not be bound to weather conditions and can gain considerable speed.

CONTEXT should be considered during construction planning. Hempcrete can be both wet and dry applied, thus taking into account the climate and season in which the built is going to occur will facilitate the process. This to avoid delays and difficult site managment.

ADAPTABLE both in big and small scale, hempcrete has the potential of being developed in city-scale projects but can also be used in a self-built context. It could become a reference material for various construction methods.

RENOVATION really shows the potentials of hempcrete, as it can be easily added to the existing structure. With little intervention and no superfluous additional layers, the performances of the building are considerably increased.

Hempcrete is most used as a **WALL ELEMENT** in current projects. It can just as easily be worked as roof or floor element. Inside the roof, its density can be lower to improve insulative qualities. As floor element density is increased to be able to stand the loads.

Fig.29 Main considerations from case studies

HEMPCRETE & INDOOR CLIMATE

INDOOR CLIMATE DEFINING FACTORS

THERMAL

Air movement
Temperature
Heat radiation
Humidity

ATMOSPHERIC

Air quality
No chemicals
Fresh air

ACOUSTIC

Noise
Sound perception

ACTINIC

Lighting
Radiation
Electrical/magnetic fields

MECHANICAL

Ergonomics
Vibration
Anti-slip protection

Definition according to WHO

Indoor climate is essential for the well-being of the users of a space. It impacts comfort, health, and productivity, where vulnerable individuals such as elderly or children could be affected the most. Its main physical influential factors are thermal climate, indoor air quality, sound, and light (P.E. Nilsson, 2003). All defining factors of indoor climate according to the WHO are listed to the left. It shows that both perceptible elements, such as air movement or temperature changes, and imperceptible elements, chemicals or radiation, are to be considered. This chapter analyzes which parameters hempcrete has a beneficial impact on and how it does this.

Human comfort is the most obvious effect of indoor climate. It refers to the degree of satisfaction of the users in the space. This is influenced by various factors such as thermal climate, sound, light, odor and aesthetics. Comfort, however, is subjective and strongly depending on physiological and behavioral variables (P.E. Nilsson, 2003). Energy transfers together with humidity fluctuations influence the way we perceive our environment. People are very sensitive to such variations which can lead to a sensation of discomfort. The human body is constantly in communication with its environment, generating and dissipating energy. Thus, maintaining steady perceived temperatures and humidity levels is crucial for thermal comfort. Hempcrete has the ability to do this.

Secondly, the built environment affects human health. Various factors such as thermal climate, noise and light are considered, however, indoor air quality has the greatest impact on our well-being (P. E. Nilsson, 2003). Indoor air pollutants can radiate from the materials we use and can have a bad effect on our health. This is called the "Sick Building Syndrome". Most of the time we do not link common symptoms, like headaches, allergic reactions, or irritations to the quality of the indoor spaces we are living/working in.

Also, users' productivity is linked to the indoor climate. This aspect refers to the ability to perform both mental and physical tasks (P.E. Nilsson, 2003). Mostly thermal climate, acoustics, and indoor air quality influence productivity (P.E. Nilsson, 2003).

As shown on fig. 30, the strongest asset of hempcrete is controlling the thermal climate, both considering temperatures and humidity. The material also contributes to improving the air quality of the room. Overall, it provides a comfortable atmosphere.

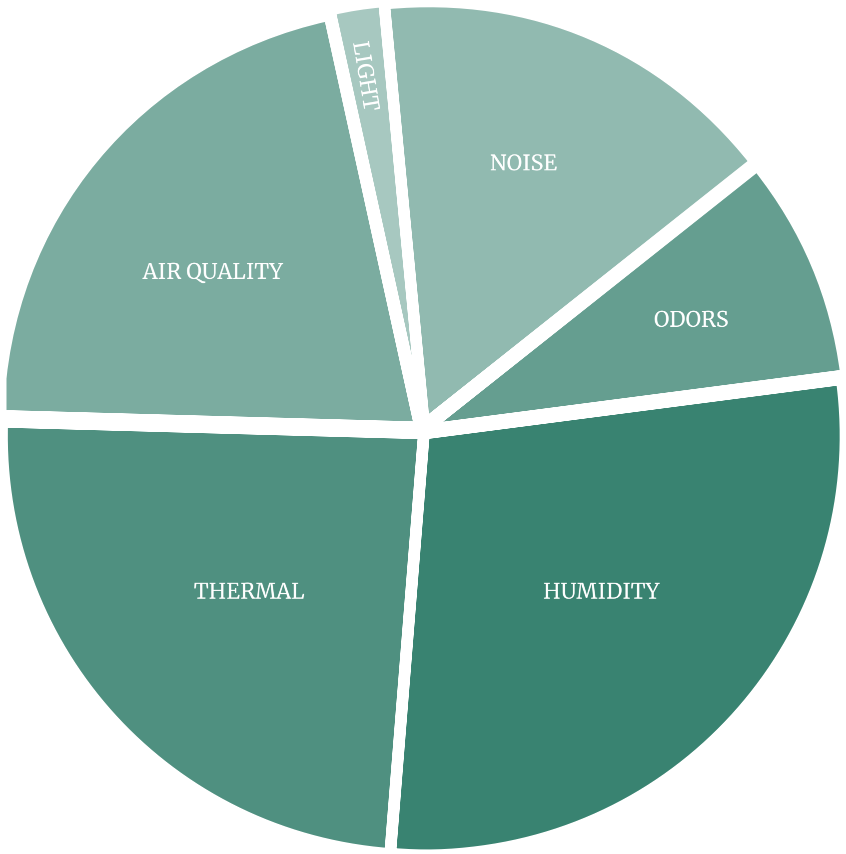


Fig.30 Indoor climate parameters positively impacted by hempcrete

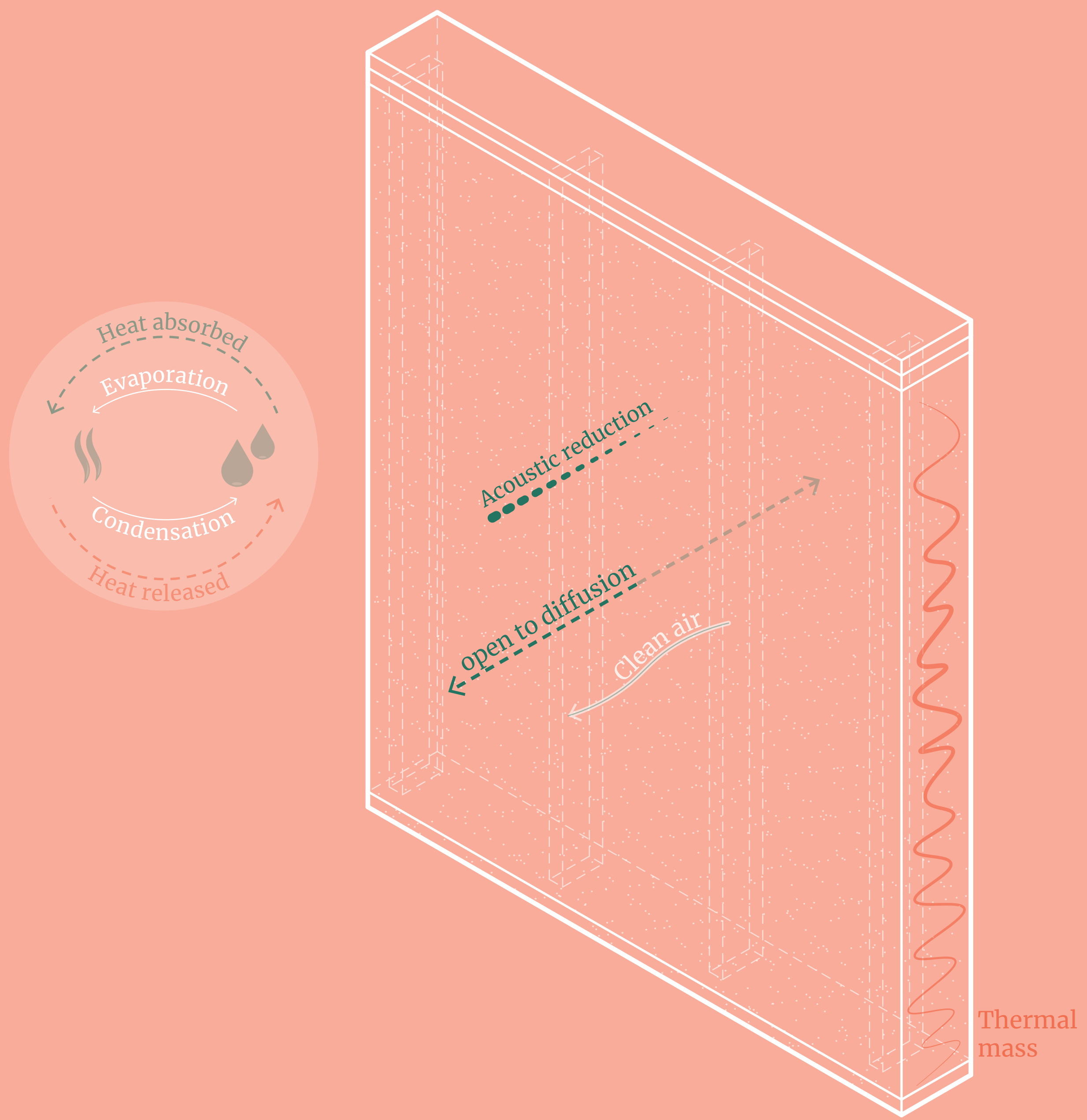


Fig.31 Indoor climate performance of a hempcrete wall

THERMAL PERFORMANCE

Hempcrete is an infill material with insulative qualities that can be used in the wall, slab, and roof. It is denser than other insulation materials due to the mineral binder, increasing its thermal conductivity (λ). Generally, a good performing insulation material has a thermal conductivity between 0.025 and 0.05 W/mK. The thermal conductivity of hempcrete is linked to its density, the degree of compaction and the water content (Stanwix & Sparrow, 2014; Collet & Pretot, 2014). Therefore, its lambda value ranges from 0.07 to 0.3 W/mK (Collet & Pretot, 2014), so it is not an exceptional insulator. However, hempcrete, unlike conventional lightweight insulation, fills the whole structure which gives it usually 30 to 40cm thickness and makes it meet insulative performances that meet building standards (Stanwix & Sparrow, 2014). So, it can achieve low thermal transmittance, without the disadvantages of synthetic high-performance insulation that require a lot of energy in production and contain unnatural, chemical components.

Hempcrete's thermal performance is linked to more than its conductivity only. Because hempcrete is a medium density material, 10 times denser than lightweight insulation, it acquires thermal mass and the ability to store heat. The material both traps the air, creating air pockets in the hemp-lime matrix that become a barrier to heat transfer, and absorb some of the heat inside its fabric (ACAN, 2021). Its thermal diffusivity, the capacity of a material to transmit a temperature variation, is low (Evrard et al., 2006), making it an excellent thermal damper (Interchanvre, 2019). In a study by Collet and Pretot (2014) is stated that 300mm hempblocks can achieve a heat delay of about 15h. Sparrow says a classical 200mm hempcrete and wood frame wall can delay heat for about 12h (ACAN, 2021). This makes hempcrete buffer the indoor temperature variations and gives a steady perceived temperature (fig. 35). The users will feel little variations, creating thermal comfort. According to Strandberg-de Bruijn (2020), hempcrete reaches optimal performance after drying out, so usually, the first year the thermal performance still needs to regulate.

Hempcrete buildings provide a steadier indoor climate, reducing temperature variation, which drops energy demands on heating, cooling and ventilation (Strandberg-de Bruijn et al., 2019; Cerema, 2021). Indeed, according to Lawrence, researcher and professor at Bath University, people have reported to feel comfortable at 18°C in a hempcrete house, which is about 3°C lower than standard (Bringing hemp home, 2021). Also, hempcrete's surface temperature changes fast (low thermal effusivity), it adapts its surface temperature to the ambient temperature, giving a warm feeling when touching the material (Evrard et al., 2006).

Hempcrete	λ : 0.07 - 0.3 W/mK
Hemp fiber	λ : 0.04 W/mK
Strawbale	λ : 0.045 W/mK
Glasswool	λ : 0.035 W/mK
Rockwool	λ : 0.035 W/mK
Polyurethane	λ : 0.029 W/mK

Fig.32 Thermal conductivity of both natural and synthetic insulative materials. Values obtained from Bachelor's lecture.

	250	300	350	400 (mm)
Cast[1]	0.23	0.20	0.17	0.15
Block[2]	0.27	0.22	0.19	0.17

Fig.33 U-values (W/m²K) of cast hempcrete and hempblocks for varying thicknesses.

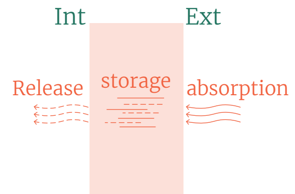


Fig.34 Thermal mass

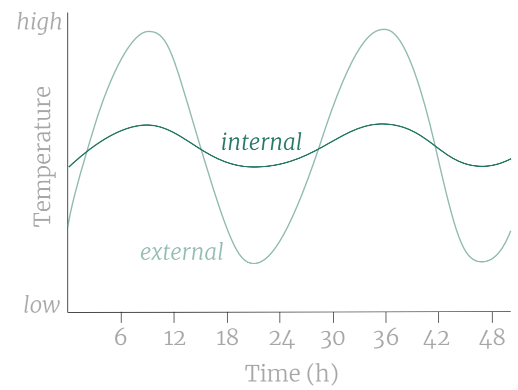


Fig.35 Buffering of temperature variations (day-night). Adapted from © Sparrow, ACAN conference

1: Stanwix & Sparrow (2014) | 2: Sparrow (2021) ACAN Webinar

HYGROSCOPIC BEHAVIOR

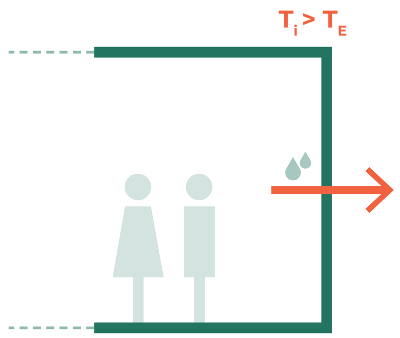


Fig.36 Water vapor is pushed through the structure from the inside to outside

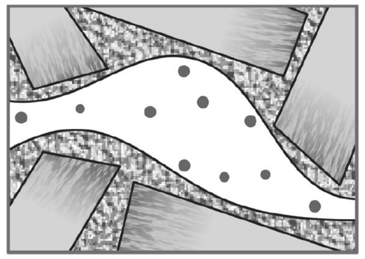


Fig.37 Hygroscopic region ©Evrard & De Herde. This scheme shows the normal state of hempcrete up to about 90% relative humidity. The pores of the material show some water presence, inceasing the material's mass. (Evrard & De Herde, 2006, Bevan & Woolley, 2008).

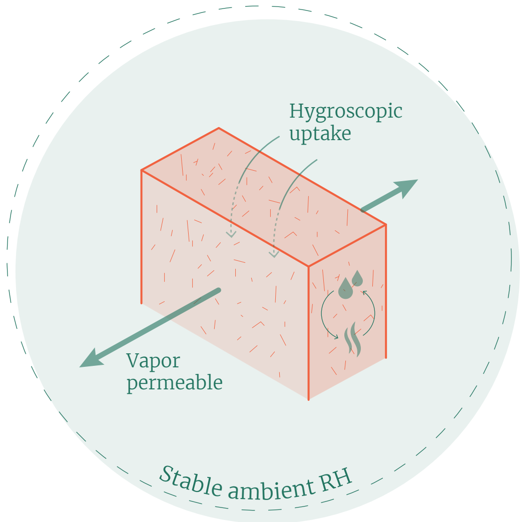


Fig.38 Humidity performance of hempcrete

In moderate and cold climates such as the one in Gothenburg, outdoor air temperatures are often much lower than indoor air temperatures. This generates differences in vapor pressure between the interior and the exterior (Minke, 2012). Above that, the users' activities also contribute to increasing vapor content in the inside atmosphere. This vapor pressure differences push vapor to travel through the wall from inside to outside (Fig.36). Traditional building techniques relied on natural, vapor permeable components such as stone, wood, earth and lime. These materials have shown to be very durable, keeping the building in a good state for decades even centuries. Vapor could travel through each layer, constantly regulating moisture content inside. Conventional buildings, however, are designed to be vapor impermeable, wanting to refrain any moisture from entering the building with a vapor barrier. But by doing so, it also impedes accumulated moisture from escaping the building (Stanwix & Sparrow, 2014). This can result in cold, damp, and unhealthy indoor environments with possible mould formation. Buildings have become strongly dependent on heating/cooling systems to regulate this. Therefore, permeable components are key for good indoor climate and durability of the building, as they are able to balance vapor pressure differences naturally. For this to work efficiently, a breathable building component requires for all layers to be vapor permeable and let vapor travel through from inside to outside.

The hygroscopic behavior of a material is its ability to absorb moisture from the surrounding air. Both the hemp shiv and the lime are hygroscopic materials. hemp shiv is porous, it is naturally open to water vapor and can absorb/desorb moisture infinitely without quality loss (Stanwix & Sparrow, 2014). Hempcrete is also vapor permeable on a macroscopic level (see fig. 37). Indeed, its internal matrix structure is open and composed of interlocking shiv trapped in the binder, making it porous (Stanwix & Sparrow, 2014).

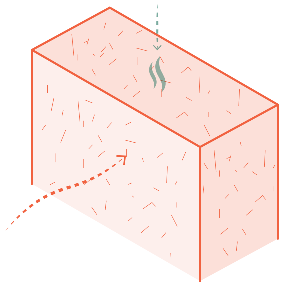
Hempcrete's response to humidity is a reaction of its vapor permeability in combination with a high hygroscopic uptake (Evrard & de Herde, 2015). Indeed, hempcrete is in active interaction with the ambient humidity, constantly absorbing or desorbing moisture (Bringing hemp home, 2021), until an equilibrium is reached. Its ability to buffer the moisture present in the atmosphere leads to a stable indoor relative humidity, constant between 40 and 60%, which is at the desired comfortable rate. When humidity increases in a room, for instance after a shower or during cooking, it is absorbed into the material's fabric. This process is reversed when the relative humidity drops, evaporating the water. Stable humidity levels create more regular temperatures, they have an important impact on indoor climate and on how people perceive the ambiance (Bevan & Woolley, 2008). Above that, because moisture is regulated constantly, no condensation appears on the inner walls, avoiding mould formation or material destruction. This makes the material durable and lengthens its lifespan.

HYGROTHERMAL PERFORMANCE

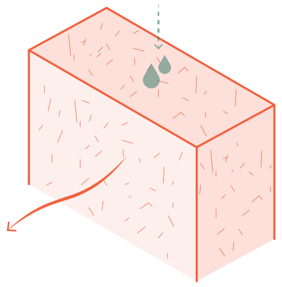
Hempcrete balances the thermal and hygroscopic fluctuations inside a building. This is called hygrothermal performance. The material's thermal performance is positively impacted by its vapor permeability and hygroscopicity. Water vapor is absorbed by the hempcrete when moisture levels increase in the ambient air. By doing so, the inner structure of the material changes by taking up water in its pores. This occurs both on macroscopic level, in the wide-open pores between the coated shiv particles, and on microscopic level, in the thin open pores of the shiv particles and in the binder matrix (Evrard, 2006). Water has a 20 times higher thermal conductivity than air and has a greater ability to store heat (Stanwix & Sparrow, 2014). The changes in water vapor content, moving into, through and out of the material, correspondingly change the thermal reaction of hempcrete. Likewise, the moisture content inside hempcrete adds a phase change property to the material (Bevan & Woolley, 2008).

When ambient temperature decreases condensation forms in the material's porous structure. This phase change of water, from vapor to liquid, generates energy through latent heat which compensates the temperature decrease and maintains a steady, comfortable perceived temperature (Evrard et al., 2006, LB Eco habitat, 2019). On the contrary, when evaporation occurs inside the material's matrix due to an increase in ambient temperature, the phase changing, from liquid to vapor, will consume energy and maintain the surface temperature.

The phase changing constantly effects heat storage and transfer of the material in reaction to the ambient atmosphere. This capacity to buffer temperature changes creates a steadier, comfortable indoor climate, which in terms reduces heating and cooling demands (Bevan & Woolley, 2008, Collet & Pretot, 2014, Strandberg-de Bruijn et al., 2019).



SUMMER. Water evaporation inside the wall absorbs heat. Wall temperature steady but sensation of coolness.



WINTER. Water condensation inside the wall releases heat. Wall temperature steady but sensation of warmth.

Fig.39 Hygrothermal performance scheme

AIR QUALITY

Indoor air quality is crucial for the health and well-being of the occupants of a space. It refers to the cleanliness of the air, both influenced by relative humidity levels and polluting substances radiating from material surfaces. As mentioned before, hempcrete controls humidity levels inside the building, avoiding condensation. Relative humidity is preferably maintained between the 40-60% RH band. Too dry or too moist air can lead to health problems. As shown on fig. 40, when RH values are outside this optimum range mould, rot and bacteria can proliferate, causing damage to the building or illnesses. Also interesting to mention is that alongside the hygroscopic capacity of the material, lime, being a natural biocide, has a beneficial impact on pests and moulds (Bevan & Woolley, 2008).

A valuable fact about hempcrete is that it does not contain any volatile organic compounds or chemicals. No pesticides are used neither during the growth of the hemp plant, nor within the hempcrete mixture. There is no need for chemical treatments or fire retardants whatsoever. For this reason, it is a safe material without any risk of toxic pollutant emissions during its lifespan and/or demolition (Sparrow & Stanwix, 2014). This provides it with great qualities for use in building. Caution however must be taken during construction. The lime powder is very volatile and becomes caustic in reaction with water.

Because hempcrete has a positive effect on indoor air quality, and can regulate it passively, ventilation needs are reduced. The building's ability to store heat enables natural ventilation without drastic heat losses. Hereby, fresh air can circulate, increasing the air quality. Hempcrete could easily be associated with low-tech, passive ventilation systems, reducing the energy demands of the building, thereby reducing its carbon footprint in use.

Fig.41 Factors impacting indoor air quality

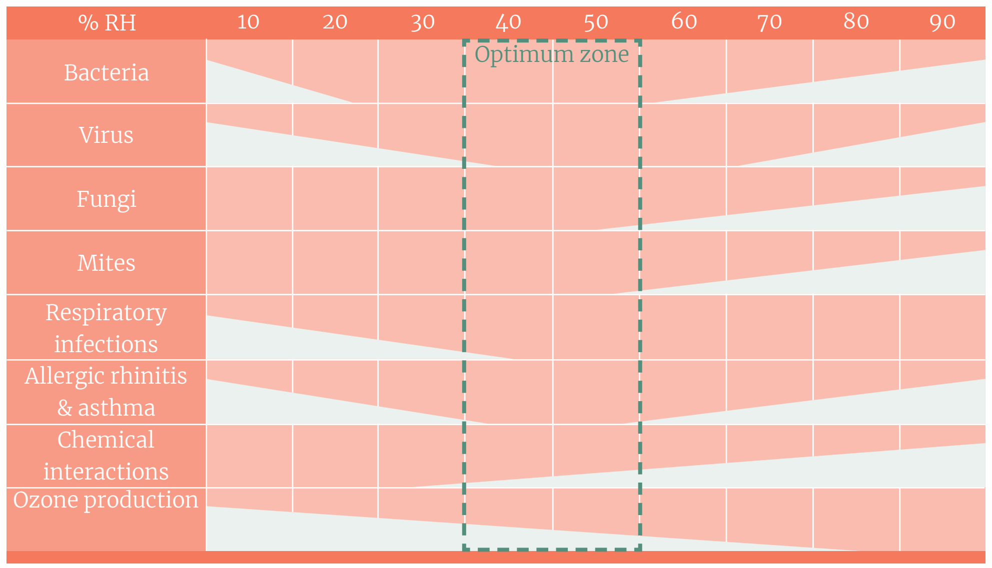
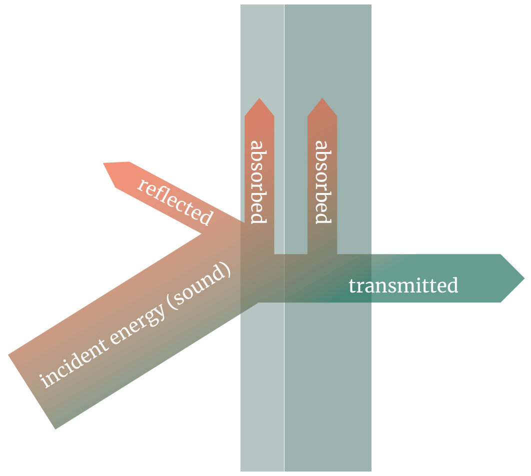


Fig.40 The health impacts of indoor relative humidity. The optimum RH level is between 40 and 50%. Adapted from © Bevan & Woolley, 2008

ACOUSTICS

The acoustics of a room refers to the transmittance and absorbance of sound. Good acoustics enables for reduction of undesired noise whilst at the same time allowing wanted sounds to be clear and intelligible. The main sources of disturbing noise is through the building envelope, through shared walls and from building services and appliances. Too much disturbance could interfere with the mental well-being of the users. Therefore, acoustic materials aim at reaching good indoor sound quality by balancing the sound levels, the reverberation time and the frequency distribution (P.E. Nilsson, 2003). A material is characterized by its Sound Absorption (α) and its Transmission Loss (TL). Soft, porous materials will absorb sound whilst hard materials will reflect it. Too much absorption leads to a feinted sound, too much reflection leads to echoing. The amount of energy left after absorption by the material is the transmitted energy, which passes through the element.

Mainly the hemp shivs in hempcrete are allowing for acoustic reduction. The shivs are porous, anisotropic (varying in size and thickness) and vary in direction within the hempcrete matrix. Although the binder has no effect on the acoustic qualities of the material, the mixture's density is important (Glé et al., 2018). The denser the mix, the fewer pores and the more sound will be reflected. Hempcrete allows for good sound absorption and lowers reverberation times. This could reduce the need for additional acoustic treatment, but this strongly depends on the function of the building. The thickness of the material as well as how the materials's finishes have an impact on the acoustic performance. According to Kinnane et al. (2016), unrendered hempcrete shows good acoustic absorption ranging between 40-50%. However, adding a lime render reduces this value significantly because the porosity of the surface changes.



α = absorbed energy/ incident energy
TL= transmitted energy/incident energy

Fig.42 Sound passage through element

ODORS

Hempcrete has a pleasant smell. It is mainly the lime that gives the odor, the shiv has a similar smell than straw. The scent is stronger when the hempcrete is wet and then softens whilst drying. However, hempcrete is rarely left bare without internal finish, so it is not affecting the smell of the inside air. This being said, according to Angélica Karlsson[1], a contact person from the Hoppet preschool project, hempcrete does seem to handle bad smells quite well. The Hoppet project aimed to achieve a carbon negative construction. The project includes a recycling house next to the preschool, which is made of hempcrete prefabricated panels, built and delivered by House of Hemp[2]. It is the first construction with hempcrete in Gothenburg. The recycling house is an unheated space and the built is quite recent. However, Angélica describes it to be "less smelling than other recycling houses [up till today]".

1: Email correspondance concerning the Hoppet project | 2: Interview with Peter Holmdahl - House of Hemp

HEMPCRETE & CLIMATE IMPACT

*Fig.43 Greenhouse gas impact of hemp**

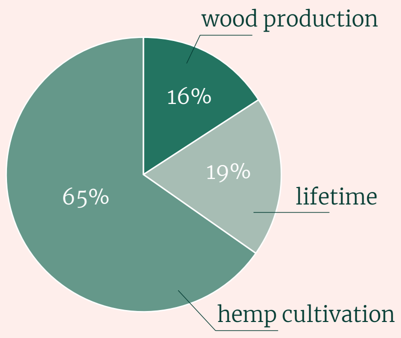


*Fig.44 CO_2 absorption hempcrete**

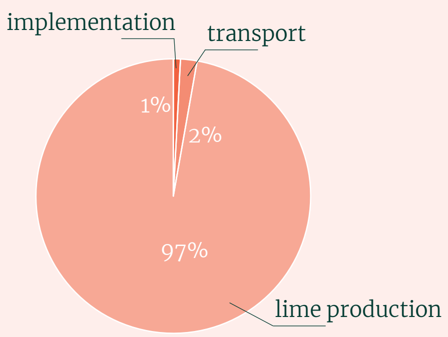


*Fig.45 CO_2 emisisons hempcrete**

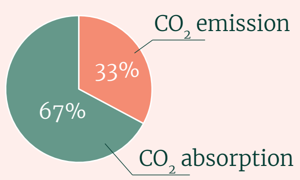


Fig.46 Greenhouse gas impact hempcrete 100-year lifespan

I have mainly focused on carbon emissions to analyse the climate impact. Hempcrete sequesters carbon dioxide in three carbon sinks that are the hemp shivs, the wooden framework, and the lime binder (during carbonization). Its life cycle analysis is referenced to a 100-year life span, also showcasing the durability of the material. At its end of life, hempcrete is biodegradable. At this stage, the part of carbon dioxide absorbed in the shivs will return to the atmosphere (INRA, 2006)

THE HEMP PLANT is a big carbon sink. It sequesters about 1.6 times its weight in carbon while growing. Therefore, hemp is the main reason for the positive climate impact of hempcrete. The main negative effect of hemp on the environment is the nitrogenous fertilizers used for cultivation (INRA, 2006), which has a consequence on emissions, non-renewable resource consumption and water pollution. These nitrogen inputs are still lower than classic agricultural cultures, and hemp requires less irrigation and no chemical treatments. According to the report of INRA (2006) lowering fertilizers by 20% would reduce the potential environmental impacts of hemp cultivation by 10%.

THE LIME BINDER has the biggest climate impact of the hempcrete components. Lime is burned in a kiln at about 950°C, which is emitting important amounts of Co_2. The lime will carbonate during the lifetime of the building (about 70%), absorbing carbon dioxide from the air. This however will not balance the full emissions of the production processes. Air lime binders have a lower impact than natural cement binders burned at 1200°C.

TRANSPORT is also of considerable impact on the climate performance of hempcrete. Shortening transport distances from field/mine to factory/site will have a non-neglectable effect on the life cycle analysis. Hemp and lime are not available everywhere and processing plants are scarcely developed, meaning the traveled distances are quite important. Looking into short-circuits would be important for further development.

At end of life, hempcrete can be easily demolished and could be biodegradable. This, however, is depending on the amount of cement present in the lime binder. The lime binder also represents the biggest share of embodied energy and embodied carbon in hempcrete. Looking at an alternative binder, that has lower climate impact, would make hempcrete even more performing. The next part of this thesis explores the potential of a clay-binder. Clay has identical qualities regarding vapor diffusion and is 100% natural and biodegradable. Can it reach similar performances than lime ?

** Data retrieved from INRA (2006)*
*** Rapport sur la filière chanvre construction (2019)*

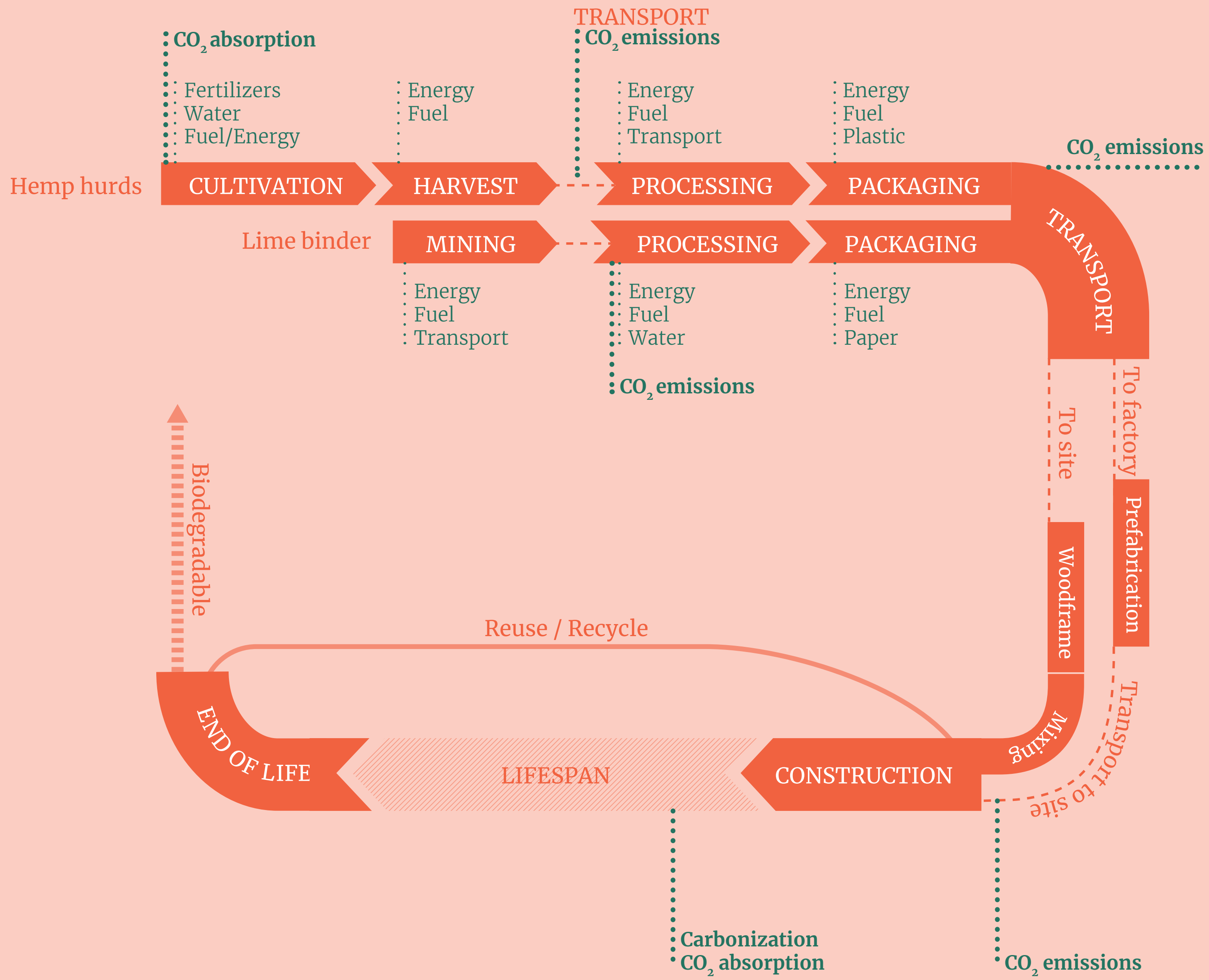


Fig.47 Personal Life Cycle diagram of hempcrete. The impacting factors during hemp and lime production are mentioned. The important carbon dioxide emissions/absorptions are highlighted.

04

Hemp-clay investigations

PROPERTIES OF CLAY

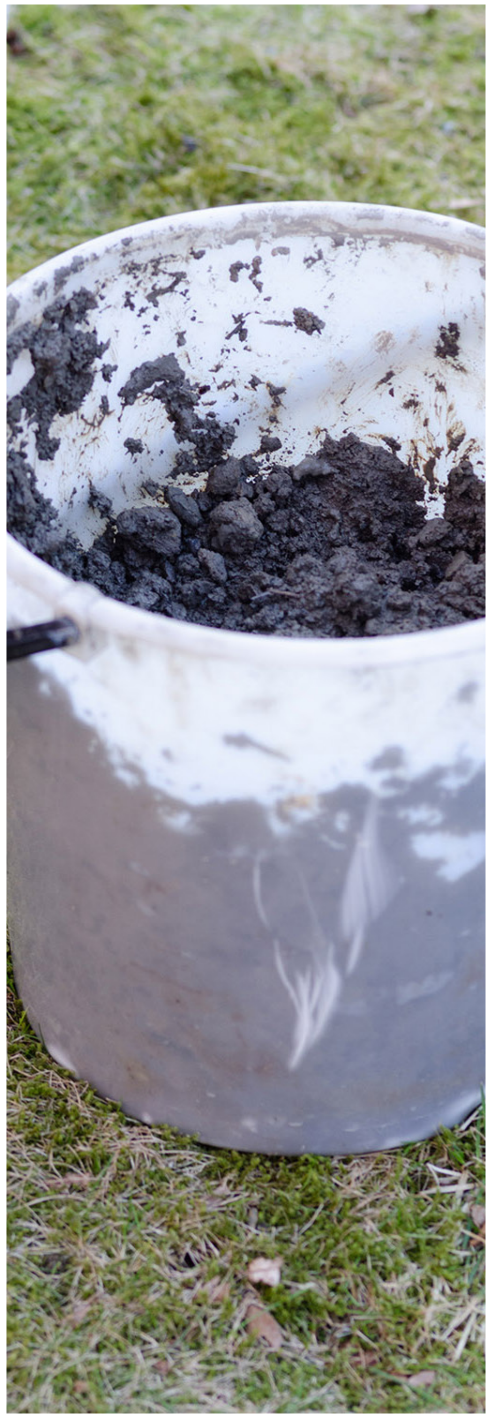


Image 47. Bucket of clay material

Earth is one of the oldest building materials of mankind's history, rooted in traditional building cultures globally. It is a locally available and cheap resource, easy to implement. It is estimated 1/3 of the world's population lives in an earthen house (Practical Action, n.d.). Earth is composed of clay, sand, silt, and gravel. This composition varies from place to place, and soils are classified in four main categories : clayey – silty – sandy or gravelly. It is recommended to have a minimum of 15% clay content for the soil to be suitable in construction (Practical Action, n.d.).

Clay is a natural mineral coming from silicate rock (Feldspar, Mica) erosion (Gaia Architects, 2003). Clay provides the cohesion of the soil, acting as a natural binder. Cohesive soils, also called "rich" or "clayey", are best suited as binder for natural fiber aggregates (Gaia Architects, 2003). It is prefered to have above 30% of clay by volume. If suitable clay is available on the site of the project, the excavated soil for the foundations can be directly reimplemented in the building. The clayey soil must be free from humus or any organic material, this to increase cohesive properties and avoid mould formation (Volhard, 2016; Gaia Architects, 2003). Therefore,it is preferably excavated from lower soil layers. Several field tests exist to identify the composition of the excavated earth.

Earth hardens by drying in the air, no chemical reaction takes place as is the case for lime. Binding properties of clay are considered to be lower compared to lime or cement. However, fully dried, clayey earth becomes a strong, hard mass. An important difference between clay and lime lays in its reaction to water. Lime chemically cures in contact with air and hardens back into limestone. Earth materials do not have the same property, and unless fired above 400°C, they will remain vulnerable to water. Indeed, dry earth softens when wetted, making the binding properties reversible (Volhard, 2016). Therefore, it is important to always protect earthen components from prolonged water exposure. Above that, earth swells in contact with water and shrinks again when drying. This is a considerable disadvantage as cracks or gaps can appear inside the building. The type and clay content is an influential factor for the shrinkage/swelling ratio (Minke, 2012). Fibres, hemp shiv in the case of hemp-clay, can prevent shrinkage. Adding fibers both reduces the proportion of clay in the material, and allows for water to be absorbed. According to Minke (2012) fibers also reduce the appearance of cracks, because the binding force is increased. Shrinkage tests have been conducted in the thesis work and are described on p. 75

On a microscopic level clay is composed of crystalline sheets called "lamellae". These are stacked on each other. Fig. 48 shows the internal structure of clay depending on the water content. Clay becomes malleable or liquid in contact with water. Thin water films form between the lamellae, making them slide over one another (Volhard, 2016). This gives the slippery feel of clay once it is wet. After drying, the material regains its cohesive strength as the lamellae bond back together. Once dry, the material becomes a strong, compact mass. Clay particles are very small (< 2 µm), in comparison sand is between 0.06 and 2mm (Busbridge, 2009; Volhard, 2016).

THE CLAY MATERIAL used in this thesis work was excavated at Olskroken, Gothenburg. Laboratory test[1] for suitability as building material had been conducted. The clay is described as soft-plastic. A binding force test classified the clay as "almost fat" with good cohesive and compressive strength. The soil is defined as "clayey silt" and contains natural lime. It is also concluded that fibers could be a good means to reduce shrinkage ratios of the material[1].

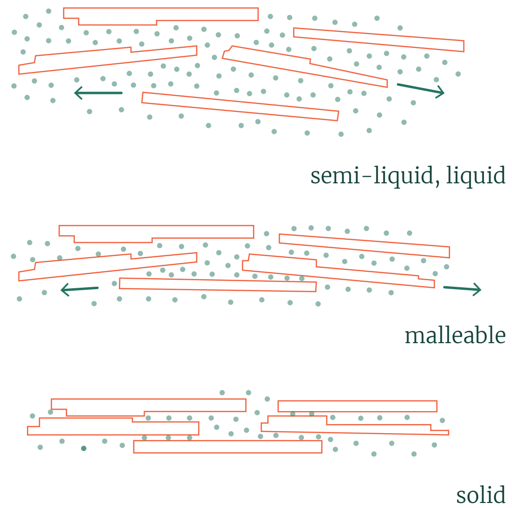


Fig.48 Consistency of clay particles depending on water content. Adapted from © Hamer, 1975

LIME	CLAY
Rarer resource	Local resource
Corrosive - dusty	Safe to work
CO_2 emissions (During production)	No CO_2 emissions (No processing)
Pest resistance	Possible mould when humidity > 20%

Natural resource

Chemical free

Vapor permeable

Lime and clay are both natural minerals that are among the oldest building materials in history. Both have similar indoor climate contributions: they are diffusion permeable, able to store heat and absorb harmful particles.

Since clay is available almost everywhere, its material costs are relatively low. Lime is rarer and more processed thus more expensive.

The main relevant difference, however, lays in the embodied energy of the materials. As mentioned before, limestone is processed, calcinated and hydrated to become workable. This implicates the use of non-renewable resources and carbon dioxide emissions in the atmosphere. Clay, on the contrary, is directly workable once excavated, limiting emissions to a bare minimum.

Fig.49 Comparison between lime and clay

1: ZRS Ingenieure GmbH - Prof. Dr.-Ing. Christof Ziegert, personal communication, 01.09.2019

HEMP-CLAY IN THEORY

Image 48. Hemp-clay wall sprayed-applied

The hemp- clay technique is an adaptation of light earth construction or “LEC”. Light earth is defined by Gaia Architects (2003) as “a mix of clay with fiber or other fill material such as straw, woodchip or minerals forming a solid yet insulative wall within a structural framework”. It originally comes from the German term “Leichtlehm”. A combination of very wet clay (“clay slip”) and straw is most commonly used for LEC. The clay provides the cohesive strength and acts as a binder for the aggregates. LEC is always worked as an infill material within a loadbearing structure.

Hemp-clay or "hemp-earth" is a mix of clayey soil and water (“clay slip”), to which shivs are added. This alternative technique wants to take the benefits of hempcrete even further, taking away the lime-binder. It is only in its early stages of development, with research and testing being conducted in very small scale. The biggest struggle hemp-clay will probably face for larger development in public and urban contexts is to be recognized as safe and durable. Although earth was a common material in traditional building, the material is seen nowadays as “new” and “unconventional” and has difficulties to claim its rightful place within the sector. Light earth construction, for example, is very little referenced in the public building sector. In Germany, however, it has been recognized as an official building technique since the late 80s with corresponding regulations and norms.

Today, hemp-lime is starting to gradually claim its place in the building industry. Its implementation is more or less recognized and regulated, depending on the country. Replacing lime with clay means this process needs to start over again and new research is needed to prove its suitability.

In France, several associations have launched the Eco-Terra research project. This project was conducted between 2016 and 2019 and aimed to perform scientific and technical research on hemp-clay components. Comparisons with hemp-lime were made on thermal and acoustic performance, and the environmental impact was assessed. The goal of the research is to showcase circular, short-circuit light earth construction options in France. This is a first, and important step in developing the recognition of eco-construction. This thesis aims to contribute to knowledge development for this newer technique. Several material experimentations and tests were conducted to assess the potential of hemp-clay components.

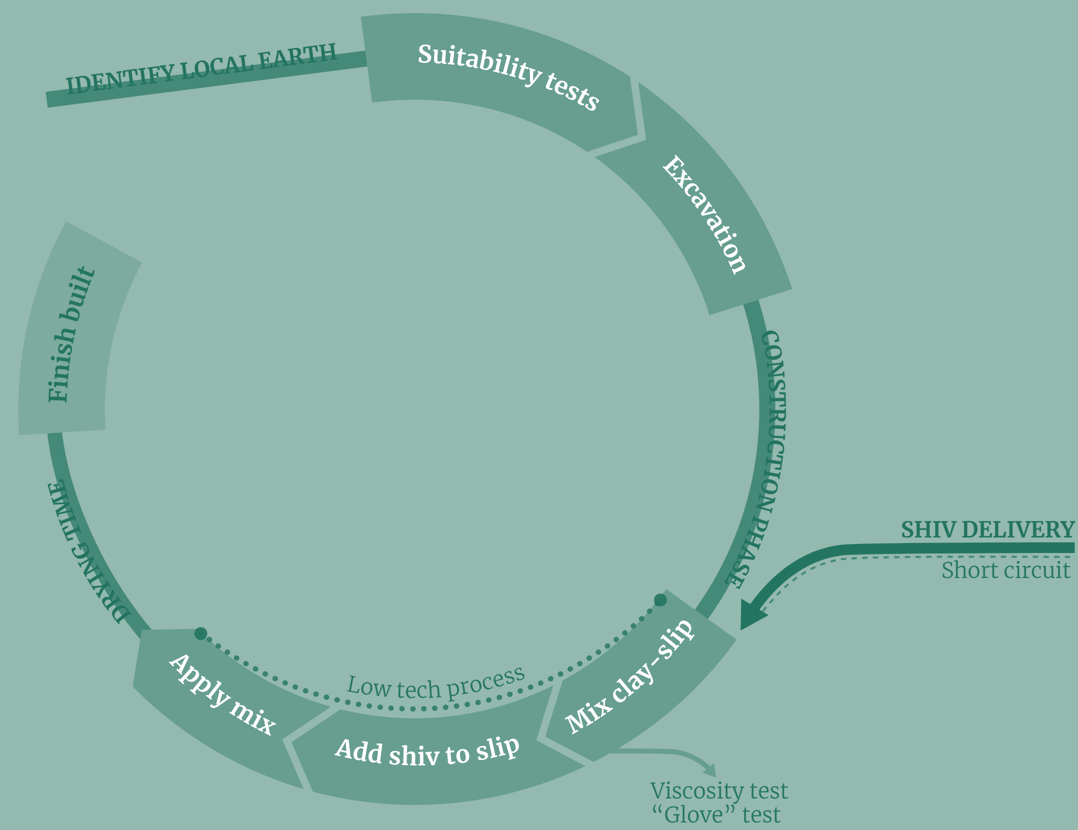


Fig.50 Possible hemp-clay construction cycle (local - wet applied)

INDOOR CLIMATE PERFORMANCE

THERMAL CONDUCTIVITY. Earth, and especially clay, is very dense and heavy so it is not an insulating material. Just as with hemp-lime, it is the association with bio aggregates that creates the insulating capacities. The mixture of earth, water, and hemp gives lightness to the material, increasing its thermal insulation. Solid earth at a density of 800 kg/m³ has a thermal conductivity of λ = 0.3 W/mK, whereas lightweight straw earth at a similar density has a value of λ = 0.18 W/mK (Minke, 2012). This shows the influence of the straw aggregate in the insulating properties of the material.

Looking more specifically at hemp-clay thermal performance, a study of Mazhoud et al. (2017) found that hemp-clay composites have similar thermal conductivities than hemp-lime composites. Their research measured thermal conductivities ranging from 0.089 to 0.111 W/mK for different hemp-clay samples with densities varying between 346 to 470 kg/m³ (Mazhoud et al., 2017). The thermal conductivity of the material is very dependent on the density of the mix, lighter materials give better insulative values. This indicates thermal conductivity is closely linked to the clay-slip proportion, the shivs are of less impact. Clay is generally denser than lime, thus the thermal intertia could be improved with hemp-clay.

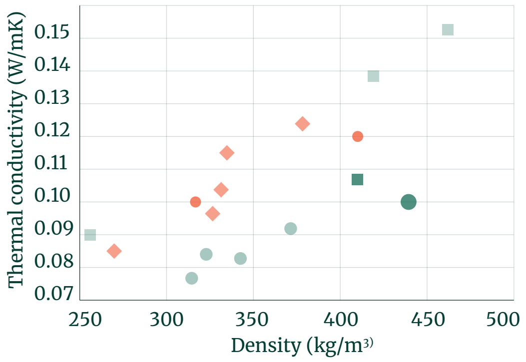
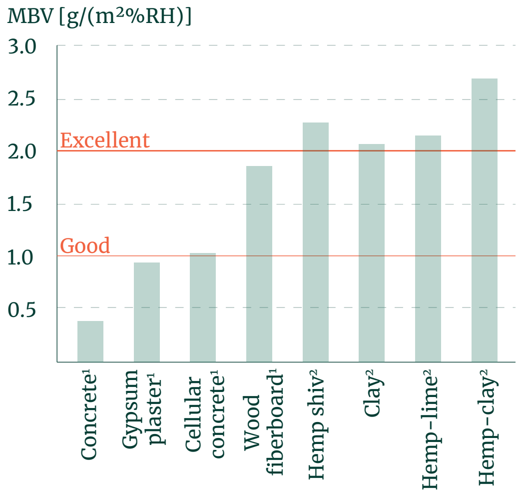


Fig.51 Thermal conductivity measurements based on density.

HYGROSCOPIC BEHAVIOR. Like mentioned before, earth becomes malleable in contact with water, vapor however does not affect its solid, dry state. This is because earth, just like lime, is open to vapor diffusion and can absorb humidity without changing its morphological properties (Minke, 2012). Clay has an excellent hygroscopic behavior and is often used as an inside plaster for regulating moisture content in the air. Research has found hemp-clay to perform even better on a hygric level than hemp-lime. Moisture buffer value (MBV) measurements performed by Mazhoud et al. (2017) found an increase of 24.6 % between hemp-lime and hemp-clay. The moisture buffer value of a material represents the amount of its moisture absorption/desorption when exposed to controlled daily relative humidity variations between two determined levels. Fig. 52 summarizes moisture buffer capacities of different materials. Classic materials such as concrete and gypsum plaster have a much lower hygric performance. Hemp-clay reached a MBV of 2.68 /(m²%RH), ranging it high in the excellent rate. For thermal comfort, hemp-clay reaches similar performances than hemp-lime.



1: Amziane & Sonebi(2016) | 2: Mazhoud et al. (2017)

Fig.52 MBV of various materials.

INDOOR AIR QUALITY. Clay is a healthy material being a 100% natural and unprocessed. Because of its higher hygroscopic qualities than lime it shows a greater ability to absorb pollutants in the surrounding atmosphere, reducing the amount of VOCs and other toxins. Clay is also able to remove ozone from the inside air. Ozone accumulates in our buildings and, when in contact with certain materials such as carpets and furniture, creates toxic pollutants. These can cause irritations both for skin and lungs.

Clayey soil is usually basic, with a pH-value between 7 and 8.5 (Minke, 2012). This forms a good defense against fungus, who thrive in acid environments. However, it is important to let the hemp-clay wall completely dry, reaching less than 20% relative humidity inside the element, before applying finishes. Otherwise, decay or fungal proliferation could occur over time.

ACOUSTICS. Clay is a plastic material, which makes it able to absorb and soften sound. When used as a plaster, clay reduces reverberation and noise levels in a room. The combination with hemp's porosity enhances these qualities. Hemp-lime and hemp-clay, at a given density, show similar acoustical performances concerning sound insulation (transmission loss) and sound absorption. According to Glé et al. (2018) both materials show three levels of porosity contributing to sound balancing: intraparticle (porosity within the shiv), intrabinder (porosity within the binder) and interparticle (porosity of the hemp-binder matrix). The intraparticle porosity because of shiv concentration has the most influence on acoustic performance. The clay type or clay-slip viscosity does not seem to have a determining influence (Glé et al., 2018). Both hemp-lime and hemp-clay have a change in performance with density increase, resulting in an absorption peak at lower frequencies and lower amplitude (Glé et al., 2018). The compaction rate of the material is directly linked to its porosity, bigger compaction leads to reduced absorption however increases transmission loss. However, because clay is denser than lime, hemp-clay shows a higher sound transmission loss with an average observed difference of 3dB for a given frequency range (Glé et al., 2018).

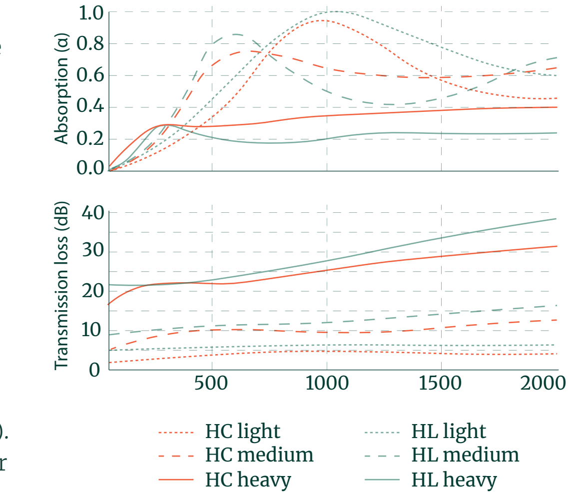


Fig.53 Hemp-lime (HL) and hemp-clay (HC) comparison on sound absorption and transmission loss depending on density. From © Glé et al. (2018)

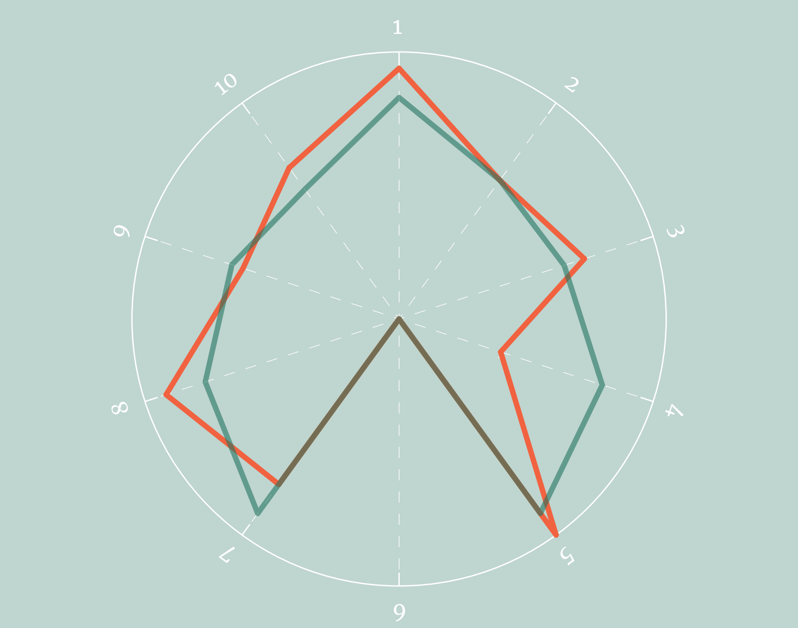


Fig.54 Comparison of indoor climate performance hemp-lime/hemp-clay

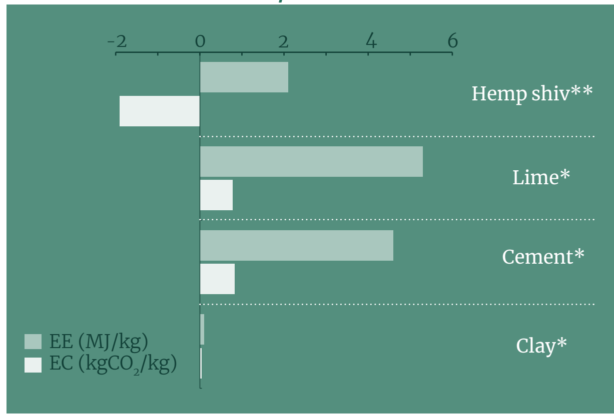
CLIMATE IMPACT

The main advantage of clay is it can be found right under our feet, making it a locally available resource that is abundant on a global scale. Large amounts of earth are excavated every day for foundations of buildings. Sadly, this earth is often seen as waste and is only rarely reused in construction. Indeed, earth represents one of the biggest construction wastes in our current building sector. This resource, however, could be a valuable asset for the industry, leading towards climate-efficient building. indeed, earth does not require processing to be usable within construction. In general, when looking at the Life Cycle Analysis of a material, the transformation from raw resource to building material requires the most processing and thus the most energy. The earth material used for hemp-clay does not need processing (no stabilizers are required, and it is unfired). It is only important to test the suitability of the soil to see whether it fits with the desired construction techniques for the built. This means earth materials have very low embodied energy. It is even more true if the excavated soil comes directly from the building site where it will be used. In that way, carbon emissions from transport are also cut, giving the material little embodied carbon.

In association with hemp, which already represents a huge carbon sink, clay pushes the environmental performance even further. Replacing lime with clay would enable to divide carbon impact by 5 and embodied energy by 20 to 25 (ECO-TERRA, n.d.).

Hemp-clay fits entirely in the circular economy. At the end of life of the building, the hemp-clay components could be recycled or reused. Because the clay is used unfired, it would regain a malleable/liquid state in contact with water and the mixture could be refreshed and transformed to be used again without change of its properties. Both hemp and clay are completely biodegradable, making it also possible to crush the hemp-clay components on site and let them return to soil. Earth is 100% compostable, indefinetely reusable and recyclable as long as it has not been stabilized with cement or lime.

EMBODIED ENERGY/EMBODIED CARBON



According to Bevan & Woolley (2008), 1 m³ of hemp-lime (330kg/m³) requires:

110kg hemp shiv
220kg lime binder (85% hydrated lime & 15% cement)

Hemp-clay would use similar proportions of hemp and clay binder.

Fig.55 Embodied energy & embodied carbon values for different hempcrete raw materials.

** Data retrieved from ICE database v3.0, Bath University (2019)*
*** Data retrieved from INRA (2006)*

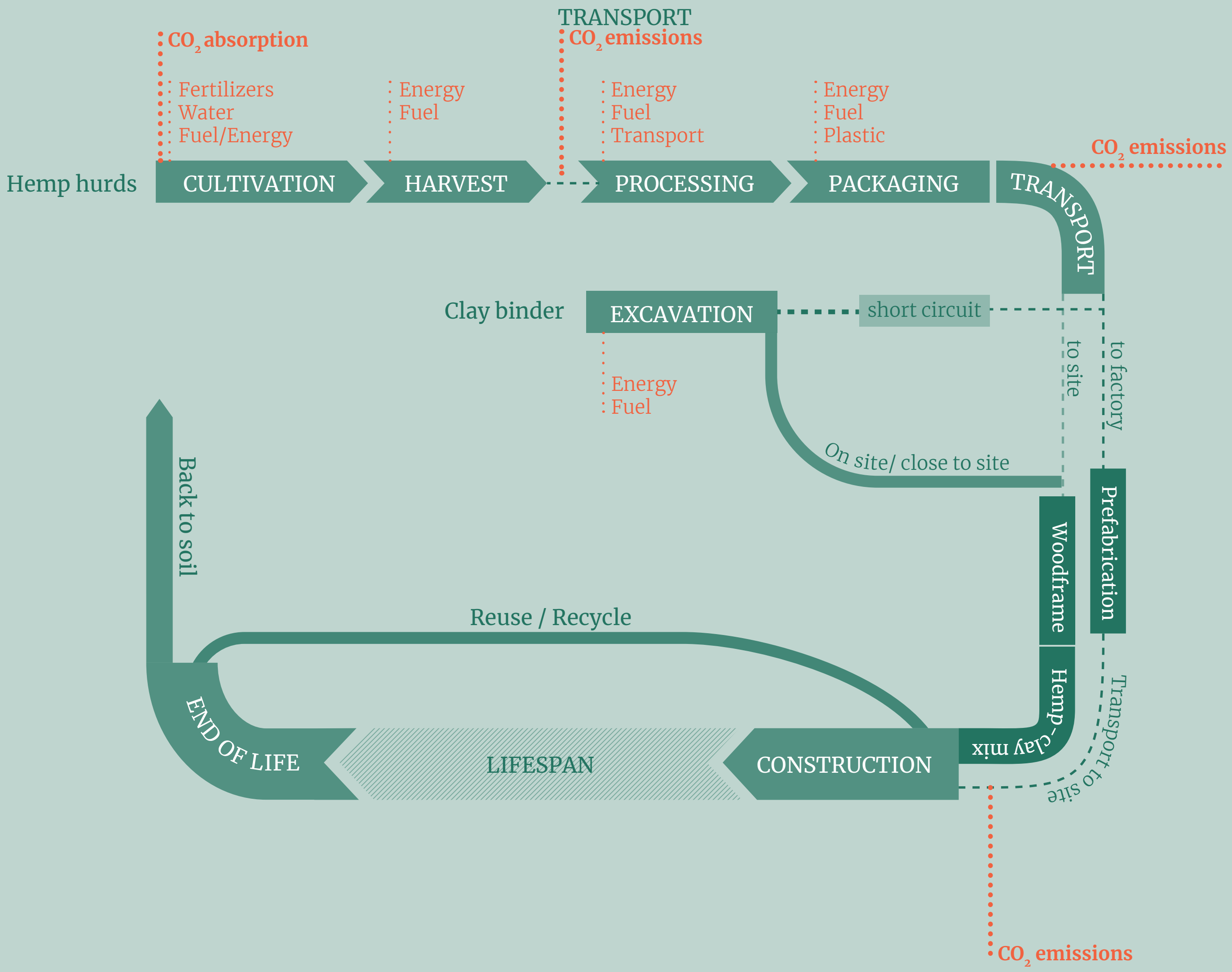


Fig.56 Life Cycle diagram of hemp-clay, echoing the previous hempcrete Life Cycle diagram.

MATERIAL EXPERIMENTATIONS

Image 49. Hemp-lime sample made during workshop at RISE. Its mass ratio (shiv:binder) is (1 shiv: 2 binder). The lime binder used is from Tradical.

During the Master thesis, hands-on material experimentations were done as a tool to discover the material, feel how it works and try out different clay and shiv ratios.

As a starting reference, I looked at the work of Ruth Busbridge (2009) who has investigated hemp-clay through sample testing. From her work, I understood the procedure for manually making hemp-clay blocks and had a first reference of the proportions clay:hemp. First the clay and water have to be mixed to make the clay-slip (explained below), then the hemp shivs are added and mixed until fully coated. This process is different than for making hemp-lime, where first the hurds and lime are mixed together before the water is added. Hemp-lime is mixed in a mechanical mixer (cement-mixer or bigger) because the material is caustic for the skin. Hemp-clay does not irritate; therefore, I could use my hands for the mixing. I have worked with small batches, so it was a feasible method and went quite fluently. During construction, hemp-clay can be mixed mechanically or within a spraying machine, similar to hempcrete.

The clay I received from Earth Lab Studio was in a very wet state, which helped speed up the process considerably as it was much easier to mix with the water. The tested shiv:clay volume ratios range from 1,5:1 to 3:1, with varying slip consistencies. This is comparable to hemp:lime weight proportions.

RESEARCH QUESTIONS FOR SAMPLE TESTINGS

Experimenting proportion variations of clay:water & slip:hemp

Workability hemp-clay?

Drying time of hemp-clay?

Could clay reach similar/ better thermal and hygroscopic performances than lime?

Strength of the material?

CLAY-SLIP

1. Clay slip is a slurry of clay and water. Its consistency can go from “milky liquid” to “custard thick”.
2. Clay is easier to mix when wet – Letting clay rest in water before making the slip can be helpful.
3. Two on site tests exists to evaluate slip consistency : Glove test & viscosity test (see Appendix).
4. Once the slip prepared it can be easily stored for a longer time, the clay will remain in solution.

FIRST SET OF SAMPLES

Image 50. Small sample 1

SPECIFICATIONS

Slip: 400g clay + 60g water (7:1)
Slip appearance: Custard-like
Proportions : **1 vol slip + 2 vol shiv**

Dry weight: 143g

Density: 540 kg/m³

Image 51. Clay / shiv sample 2

SPECIFICATIONS

Slip: 900g clay + 300g water (3:1)
Slip appearance : Liquid
Proportions : **1 vol slip + 2 vol shiv**

Wet weight: 540g
Dry weight: 279g -48,33%

Density: 463 kg/m³

Image 52. Clay / shiv / fiber sample 3

SPECIFICATIONS

Slip: idem sample 2
Proportions :
1 vol slip + 1 vol fiber + 1.5 vol shiv

Wet weight : 760g
Dry weight : 385g -49,34%

Density: 396 kg/m³

Image 53. Cylinder sample 4

SPECIFICATIONS

Slip: 800g clay + 200g water (4:1)
Slip appearance : Thick cream
Proportions : **1 vol slip + 2,5 vol shiv**

Wet weight: 580g
Dry weight : 299g -48,45%

Density: 631 kg/m³

COMMENTS FIRST EXPERIMENTS.

The clay used for making the samples was already quite wet, making it difficult to assess the amount of water to add. The first intention was to try different proportions (clay:water) from very thick to liquid slip. Thick slips gave very dense materials (main weight comes from clay). For the next set of samples, a viscosity test was performed to evaluate the slip consistency (see Appendix). Sample 3, with shiv and fibers, is the biggest sample of the first set. Yet it is the least dense of all. The fibers make it more aery, less compact. Sample 4 has the highest density due to bigger compaction and a thick clay-slip. After 3 days, the surfaces of sample 1, containing little water, were dried out, color changed from dark brown to light grey. Samples 2 and 3 (same slip consistency), showed a net difference in drying. Sample 3, containing fibers, took significantly more time to dry. Fibers do not absorb as much water as shivs.

SECOND SET OF SAMPLES

Image 54. Sample 5

SPECIFICATIONS

Slip: viscosity test performed
Proportions : **1 vol slip + 2 vol shiv**

Wet weight: 52g
Dry weight: 24g -53,85%

Density: 429 kg/m³

Image 55. Sample 6

SPECIFICATIONS

Slip: viscosity test performed
Proportions : **1 vol slip + 3 vol shiv**

Wet weight: 39g
Dry weight: 18g -53,85%

Density: 296 kg/m³

Image 56. Sample 7

SPECIFICATIONS

Slip: viscosity test performed
Proportions : **1 vol slip + 2,5 vol shiv**

Dry weight: 570g

Density: 320 kg/m³

GENERAL CONCLUSIONS MATERIAL EXPERIMENTATIONS

1. It is not possible to predefine the amount of water that needs to be added to clay as the raw clay can be in a more or less wet state. Therefore, the best way of testing the consistency of the clay-slip is by doing the glove test systematically. This is an easy way of checking the mix.

2. Mixing the clay-slip and shiv is very easy. No dust or chemical reactions occur so it is a safe and pleasant process. There is no particular need for protective wear.

3. It is important to mix the slip and shiv thoroughly so that all the shiv is coated with binder.

4. Hemp-clay seems to be longer workable than hemp-lime. During the workshop at RISE, I noticed that hemp-lime hardens quite quick, and the material was easier worked when freshly mixed. After 30min the mixture had already hardened considerably due to the curing of the lime in contact with air. Clay does not cure in contact with air. Hemp-clay is wetter and stays wet longer.

5. The samples could be demoulded immediately, the clay-slip holds everything together. The texture of hemp-clay is much stickier than hemp-lime, which has a drier feel.

6. When wet, the samples are very flexible and shapable. With water evaporation, the material gains strength and becomes a solid mass. After a day, the samples already gained considerable strength even though they were still wet.

7. All the samples have lost more or less half their weight after drying. The second set of samples, where the slip viscosity was checked, lost more weight than the first set.

8. Once dry, the external surface of the material becomes brittle and shiv particles get loose when handling the sample. It seems not advisable to have hemp-clay directly exposed as an internal wall finish without a thin coating finish.

9. The shrinkage test below shows that a proper mixed clay-slip in combination with hemp is stabilized during drying. Shrinkage does not occur, or only in very small ratios that should not affect the built.

10. The drying time of the hemp-clay samples seemed longer than for the hemp-lime sample. The hemp-clay samples showed only light drying after a week. Also, a sample developed mould during drying. It was placed on a glass support, and could not breath properly (see Appendix).

SHRINKAGE TESTS

During the drying of clay the water layers evaporate which causes shrinkage. The initial sample was a 100% clay soil, with no aggregates. This was made malleable and left to dry. The sample lost about 1cm in diameter after 72h of drying. Cement or lime stabilizers are often added to avoid shrinkage. It is stated in litterature that fibers also have the ability to stabilize and reduce the shrinkage of clay. This was tested with two other samples. The first sample contained an important amount of clay for a small amount of fibers. After drying, a shrinkage of 1mm on the edge was observed. The sample did show cracks, which was not the case for the pure clay sample. The second sample contains 2 volumes of shiv for 1 volume of adequate clay-slip, this is the usual proportion for hemp-clay. This sample does not present any remarquable shrinkage nor cracks.

Image 57. wetted clay

Image 58. After 72h

Image 59. Hemp<<clay

Image 60. After 72h

Image 61. Hemp:clayslip (vol 2,5:1)

Image 62. After 72h

SAMPLE TESTS

The first part of the material experimentation looked into proportions, quantities, mixing processes, drying and material consistency. In this part of the experimentation, the samples are used to analyse moisture uptake/release and thermal conductivity with scientific methods. Also, a quick, simplified strength test was performed on 2 of the samples (see Appendix).

The list of samples used for the tests is given in the blue box to the left. These samples are the same as the ones mentioned on the previous pages, only their name indication was changed for practical reasons. Samples 1, 2 and 7 correspond to the samples of the second set. Samples 4,5 and 6 are from the first set. Sample 3 is a small piece of the hemp-lime sample made during the RISE workshop. The aim was to compare samples with different hemp:clay and clay:water proportions, and different densities. At the same time, sample 3 (hemp-lime) was a reference sample.

Both the hygroscopic behaviour and thermal conductivity tests were performed at the Building Materials Lab at Chalmers. Because of available time and material, comparative measurements rather than absolute measurements were taken. Also, the results are subject to several uncertainties such as the precision of the weighing (weighing ought to be repeated several times to increase precision), some possible material loss during manipulation (dusty, brittle samples). The time span for the hygroscopic measurements was also too short to achieve a precise outcome, nevertheless comparisons between samples could be made. At the Lab I have used the climate chamber, furnace and Hot Disk device for the testings.

LIST OF SAMPLES

SAMPLE 1:
shiv + clay
vol ratio (2:1)
density **429 kg/m³**

SAMPLE 2:
shiv + clay
vol ratio (3:1)
density **296 kg/m³**

SAMPLE 3:
shiv + lime
weight ratio (1:2)
density **402 kg/m³**

SAMPLE 4:
shiv + clay (thick slip)
vol ratio (2:1)
density **463 kg/m³**

SAMPLE 5:
shiv + clay (thick slip)
vol ratio (2.5:1)
density **631 kg/m³**

SAMPLE 6:
shiv + fiber + clay
vol ratio (1.5:1:1)
density **396 kg/m³**

SAMPLE 7:
shiv + clay
vol ratio (2,5:1)
density **320 kg/m³**

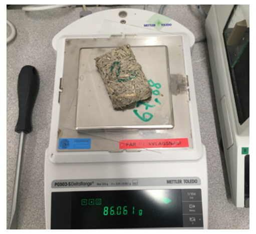
MOISTURE BALANCING MEASUREMENTS

Sample 1 -Hemp-clay (vol 2H:1C)
Sample 2 -Hemp-clay (vol 3H : 1C)
Sample 3 - Hemp-lime (weight 1H: 2L)

TEST PROCEDURE. After initial weighing, the samples are placed in a climate room at fixed 20°C and 50%RH (**phase 1**). In order to assure minimal weight loss due to material loss (the samples are very brittle), they are placed on holders. The moisture uptake is measured, according to weight increase of the samples. The samples have been weighed a total of 3 times at an interval of 3-4 days. For **phase 2**, the samples are placed inside a furnace at 105° and RH0%. Here the moisture release is investigated by weight loss. The samples have been weighed 3 times, at +6, +24 and +48h. Normally, for each phase the weighing should continue until a steady state is reached to achieve absolute values. However, due to a short amount of time, I have conducted a comparative method, stating an initial set of days for phase 1 and hours for phase 2. The weight increase/decrease is analysed comparatively between the samples.

PHASE 1. Samples placed in room at 20°C and 50%RH

Image 63. Samples placed in climate room



Initial weight of samples: Ambient RH/°C
sample 1 : 23.36g
sample 2 : 18.04g
sample 3 : 36.24g

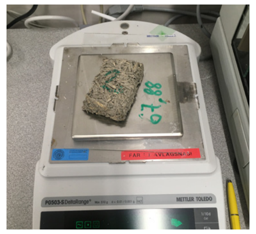
Weight of samples after 4 days:
sample 1 : 23.528g +0.71%
sample 2 : 18.181g +0.78%
sample 3 : 36.540g +0.83%

Weight of samples after 7 days:
sample 1 : 23.529g +0.01%
sample 2 : 18.176g -0.03%
sample 3 : 36.580g +0.11%

Weight of samples after 11 days:
sample 1 : 23.531g +0.01%
sample 2 : 18.184g +0.04%
sample 3 : 36.62g +0.11%

PHASE 2. Samples placed in oven at 105°C and 0%RH

Image 64. Furnace, interior and exterior



starting weight of samples (without holder):
sample 1 : 23.531g
sample 2 : 18.184g
sample 3 : 36.62g

Weight of samples after 6h:
sample 1 : 22.301g -5.23%
sample 2 : 17.194g -5.44%
sample 3 : 33.754g -7.83%

Weight of samples after 24h:
sample 1 : 22.263g -0.17%
sample 2 : 17.156g - 0.22%
sample 3 : 33.577g -0.52%

Weight of samples after 48h:
sample 1 : 22.221g -0.19%
sample 2 : 17.118g -0.22%
sample 3 : 33.482g -0.28%

CONCLUSIONS MOISTURE MEASUREMENTS

1. The HL sample balances moisture quicker. This, however, is contradicting with the found research. An explanation can be that the HL sample was made before the HC samples. It was probably in a drier state. Also, it seemed the lime content was higher than usual for HL (the sample was made with leftovers from the workshop and it probably contains too little hemp in the end).

2. All samples have the biggest moisture release/uptake gap during the first third of the test. It could be concluded that the samples react quick to moisture variations, before steadying moisture content gradually.

3. Comparing the two HC samples, sample 2, containing more shiv, had a higher moisture uptake/release than sample 1. Both samples are made from the same clay-slip in identical amount, thus it could be concluded that the main impact here has been the shiv moisture performance.

4. The weight increase was slower than the weight decrease. The samples released quicker moisture content than was absorbed. It would have been necessary to increase the number of days of the first phase of the test to achieve more significant results.

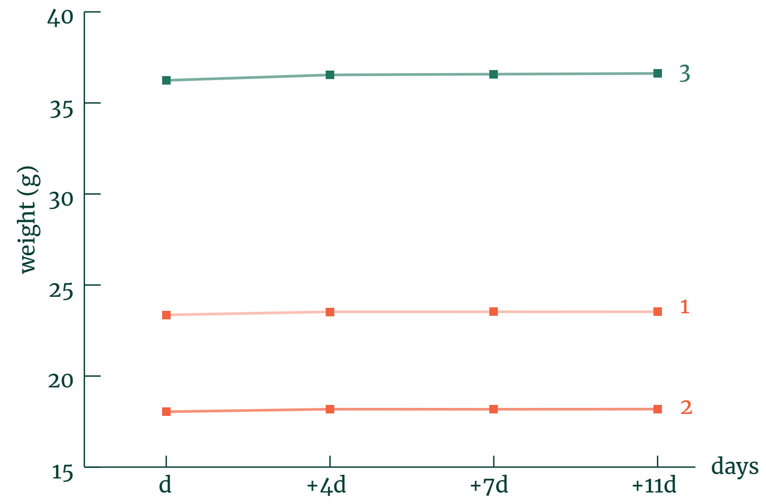


Fig.57 Weight increase by moisture absorption over time

Fig.59 Weight increase of each sample seperatively

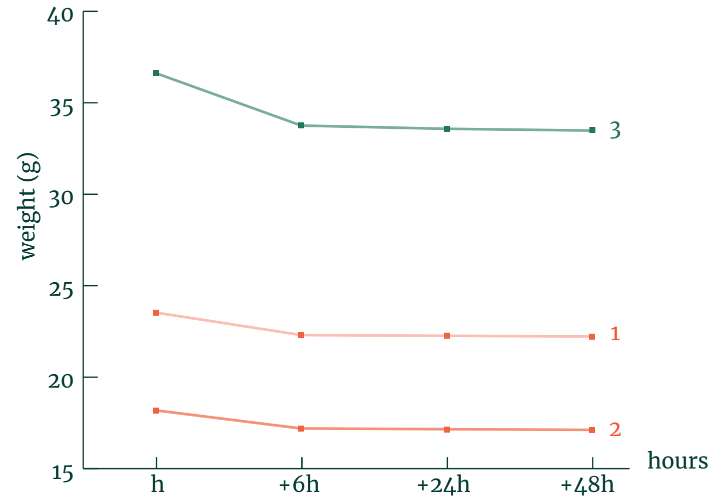


Fig.58 Weight decrease by moisture release over time

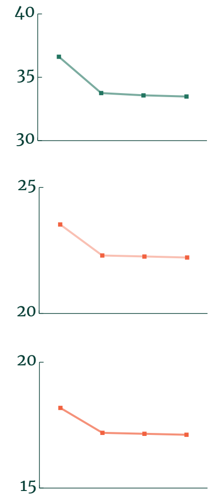


Fig.60 Weight decrease of each sample seperatively

THERMAL PERFORMANCE MEASUREMENTS

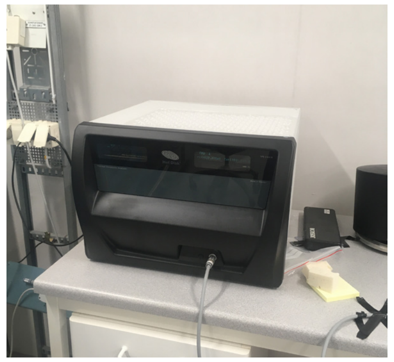


Image 65. Hot disk device

TEST PROCEDURE. The thermal performance was measured with the single side Transcient Plain Source (TPS) method. The Hot Disk machine stands in the climate room at 20°C and RH50% to work in a stable environment. First the sample was placed, on top, a 5mm sensor, sandwiched between the sample and an insulation material with known thermal conductivity (white material). A weigh is placed to press everything together. The device sends electricity to the sensor. This electricity is transformed into heat inside the sensor. The sensor is doing two actions at the same time : heating up the sample and measuring the temperature elevation.
The device is linked to a software on pc, where the measuring time and heating power were chosen (10sec, 40mW in my case).

FOLLOWED SCHEDULE
Delay before first measurement: 2min
Number of measurements: 3
Delay between measurements: 5min

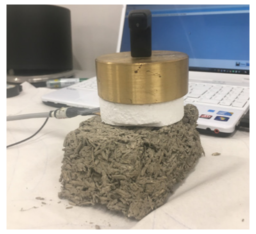
The single sided TPS method does not give absolute values. For this to be the case, the sensor should be sandwiched between two identical samples (rather than one known insulator), which I did not have. Therefore, the measurements should be interpreted as comparative values between the samples.

Samples 3 to 6 were stored at ambient temperature and ambient RH before TPS measurements.

SAMPLE 3
Thermal conductivity: 0.1644 W/mK

SAMPLE 5
Thermal conductivity: 0.1207 W/mK

SAMPLE 4
Thermal conductivity: 0.1478 W/mK



SAMPLE 6
Thermal conductivity: 0.1312 W/mK

Samples 1 & 2 were used for moisture measurements before TPS measurements (initial state - dried at 104° during 48h).

SAMPLE 1
After drying 104° - RH 0%
Thermal conductivity: 0.1014 W/mK

After 7 days storage at ambient temperature & ambient RH
Thermal conductivity: 0.11 W/mK

SAMPLE 2
After drying 104° -RH 0%
Thermal conductivity: 0.098 W/mK

After 7 days storage at ambient temperature & ambient RH
Thermal conductivity: 0.095 W/mK

CONCLUSIONS THERMAL MEASUREMENTS

1. Thermal conductivity is closely linked to density and clay:hemp proportions. This is visible in the test results. Samples 4,5 and 6 have too thick slips, with an important clay content, therefore the thermal conductivities are rather high. The HL sample, as mentioned before, seems to contain too much lime, therefore its lambda value is very high.

2. Sample 5 is the densest sample but also has the highest shiv content in its mix. Also, this sample is cylinder shaped, which also increases the weight. This could explain the lower conductivity value of 0.1207 W/mK, even though the material's density is very high.

3. Samples 1 and 2 are both made with a clay-slip that was tested on viscosity. Their thermal conductivity is the lowest of all results. The proper proportions of clay and water are crucial to achieve good performance. Sample 2, being less dense and containing more shivs performs best.

4. The conductivity measurements of samples 1 and 2, after 7 days in ambient atmospheric conditions, do not seem to be conclusive. Sample 1 showed an increase in conductivity, sample 2 showed a decrease. According to the read scientific research, conductivity increases with humidity content. The single sided TPS method is probably not accurate enough.

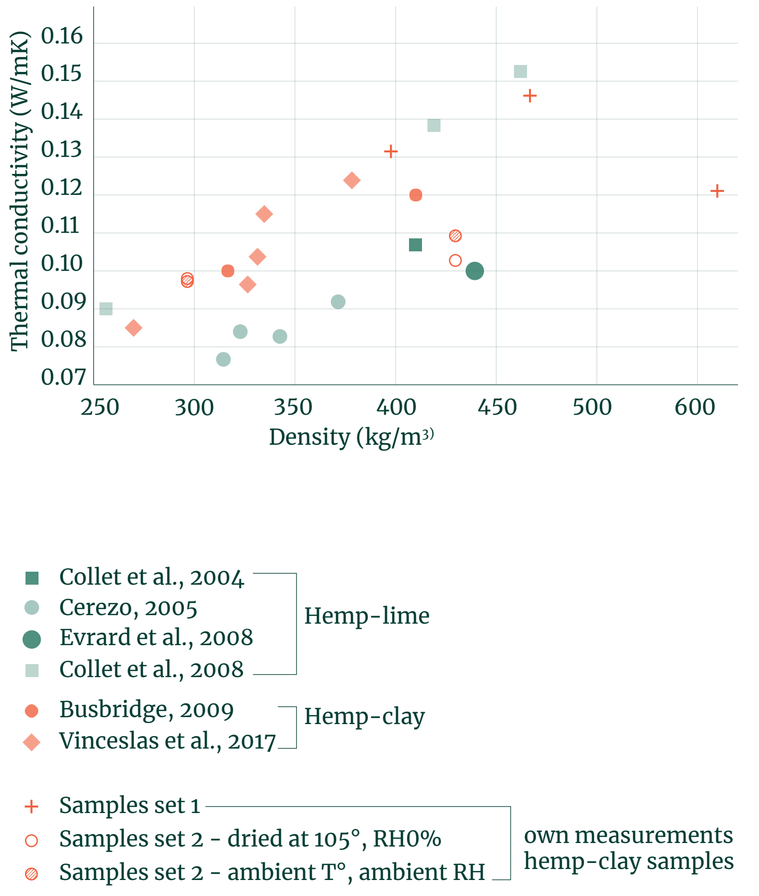


Fig.61 Thermal conductivity values of different hemp-lime and hemp-clay values from research, compared to own measurements.

PERSONAL REFLECTIONS ON LAB TESTS

Performing tests in the Building Materials Lab at Chalmers allowed me to link this architectural thesis to the engineering side of material development. It was interesting to exchange with scientists and see their processes and methods, having a rather rational outlook on things.

The choice of investigating moisture performance and thermal conductivity only was due to time management and available help. As I never performed such tests and am not allowed nor able to use all lab equipment on my own, the choice of conducting simple tests was made.

For me, the testing phase of the thesis was a completely new experience. I had only heard and learned about moisture and thermal conductivity during theoretical lectures and never measured this in practice. It was interesting for me to understand which tools are used, how they work and what the required conditions are to achieve workable results. It is, indeed, not that straightforward to achieve the desired outcome without expert help, as many factors influence the initial conditions or the conditions along the experiment. For example, I was not able to determine the water content of the samples prior to the moisture test, which ofcourse adds already a big uncertainty to the equation.

The values and conclusions I obtained are bound to uncertainties. But within the framework of this work, brought insights on the properties of the material samples and helped me to understand the theoretical research I conducted beforehand.

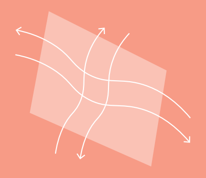
05

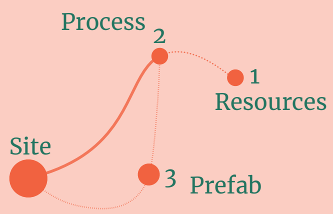
Application in design

A HEMPCRETE GUIDEBOOK

As a personal synthesis of the conducted research, several hempcrete design principles are listed below. Here,"hempcrete" refers to the method hemp + mineral binder. Most of the guidelines are applicable both for hemp-lime and hemp-clay, as both materials have similar properties and requirements. The guidelines are divided in 4 main themes : Context - Construction - Waterproofing/Weatherproofing - Performance. These principles aim to increase the efficiency and durability of hempcrete.

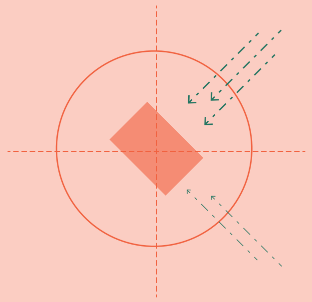
CONTEXT





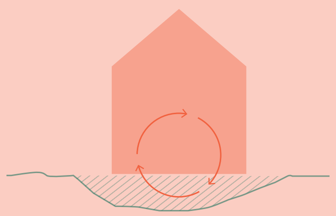
Short distances between raw material supply, manufacturing and construction site are an important factor of sustainable design. Hemp-clay has a greater potential as a short circuit material as it could be locally sourced nearby the site and requires little processing.

Fig.62 Local circuits



Hempcrete's optimal performance is linked the site conditions. The drying time during construction and its exposure to wear and tear along its lifespan are important to consider for durability of the material. In rainy, windy contexts such as the climate of Gothenburg, it is advisable to orient the built to minimize direct impact of dominant winds and heavy rainfall on the facades. This is especially true for hemp-clay, which is fragile to excessive water exposure.

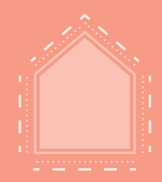
Fig.63 Site conditions



Hempcrete is easily dismantled and can be reused/recycled without problem. Hemp-clay is 100% biodegradable as long as it has not been stabilized with lime or cement. Indeed, hemp-lime is often referred to as biodegradable, but the (small amount of) cement and pozzolans within the lime binder make this questionable.

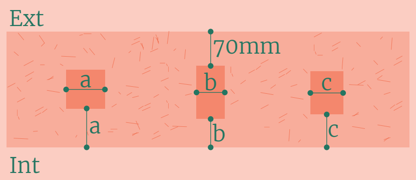
Fig.64 Circularity

CONSTRUCTION



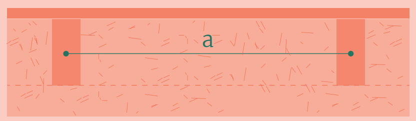
When working the hempcrete, the roof structure can provide a good weather protection during the built. This is especially good for wet construction. In this case, first the framework is built on which the roof structure is added and made weather sealed. After this, the hempcrete is added.

Fig.65 Built-up



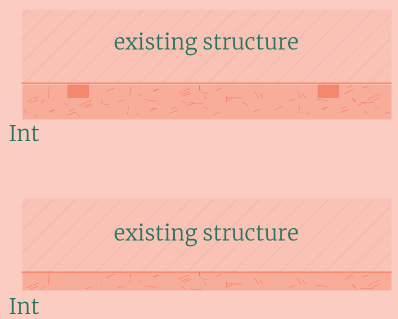
Hempcrete is a plastic, flexible material. It is able to absorb the shocks of the user's activities. However, a minimum coverage around the structural wall framework is required to avoid cracking. On the interior, this coverage thickness is equal to the thickness of the vertical structure. On the exterior, this coverage is advised around 70mm, to avoid water ingress (Sparrow & Stanwix, 2014).

Fig.66 Structure coverage wall - Section in plan



The permanent sheathing is placed onto the timber structure. The hempcrete is cast or sprayed onto the framework and can either be flush to the structure, or extend and burry the timber inside. This is also the method used for prefabrication panels.

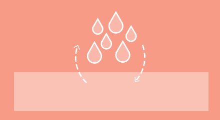
Fig.67 Permanent sheathing - Section in plan

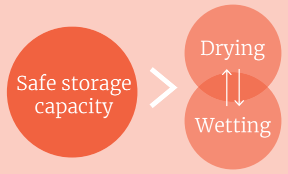


Hempcrete can be directly applied to an existing, permeable structure (brick masonry, stonework, pisé...). This is a good technique for renovation, allowing to increase the indoor climate performance of the building with only a small addition. Up to 11cm, the hempcrete can be directly sprayed onto the existing structure. Above 11cm, a small wooden sub-structure is required for adherence and strength.

Fig.68 Wall lining - Section in plan

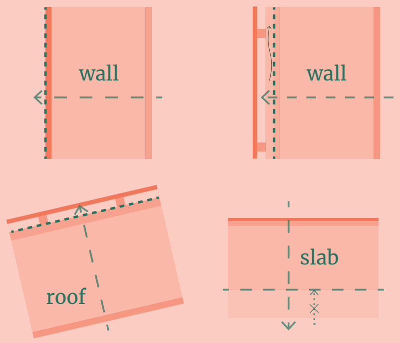
WATERPROOFING/WEATHERPROOFING





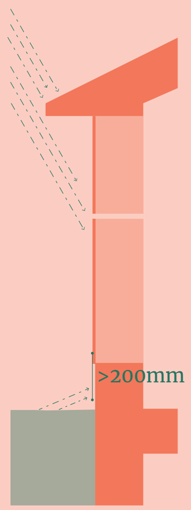
The material is hygroscopic and vapor permeable. However, this does not mean it is insensible to excessive water exposure. For the durability of hempcrete and its performance, it is crucial to allow for good drying. During a wet construction, it is important to wait for the material to have dried out before applying the next components (avoid mould formation). During the lifespan, the building should be able to let vapor travel freely to balance the moisture within the hempcrete components.

Fig.69 Moisture/water buffering



The facade finish is both an aesthetic feature and aims to protect the wall of water exposure. Two types of facade protection can be applied: a surface coating (typically a lime-sand render) or a ventilated rainscreen (cladding, stone...).
A hempcrete slab should be protected from rising dampness.
All components surrounding the hempcrete (for roof, wall or slab) should be open to vapor diffusion (arrow).

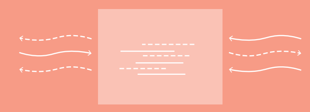
Fig.70 Vapor diffusion

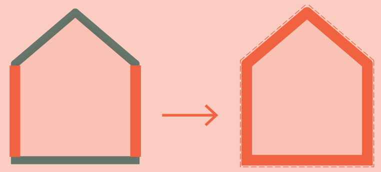


A foundation toe-up of minimum 20cm protects the wall from water splashing or capillary uptake. If using a surface coating facade finish, a roof overhang can form a good protection from wind and rainfall. This will prevent too much water ingress through the render.

Fig.71 A good hat and boot

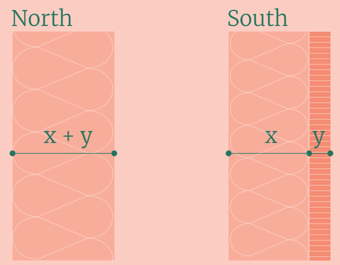
PERFORMANCE





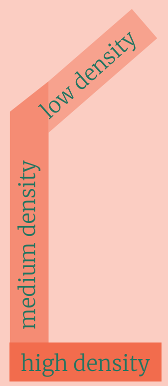
Hempcrete is mostly used for walls but can also be applied in roofs and floors. The material effectively prevents air flow and contributes to the airtightness of the building, especially if it becomes the insulative envelope of the building. Both the inside finish and the exterior vapor membrane ensure the airtightness further.

Fig.72 Airtightness



On the sun exposed facades, a thick hempcrete plaster added to the hempcrete wall can increase thermal inertia. Hemp-clay especially would perform good for thermal inertia and allow to clean the indoor air. Likewise, a thicker hempcrete wall infill can increase the insulative value to compensate for cold exposure.

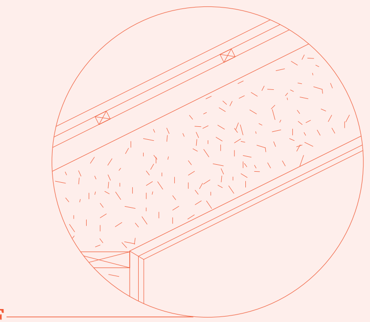
Fig.73 Cold/warm exposure



Low density (200-250kg/m^3) as roof infill to increase insulative performance.
Medium to medium-high density (250-350kg/m^3) as wall infill for required insulative performance whilst at the same time providing structural strength.
High density (350-500kg/m^3) as floor infill to increase strength and withstand load shocks.
Hemp-clay is denser than hemp-lime.

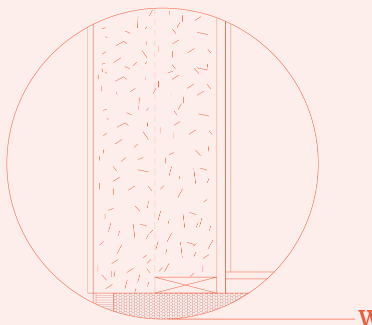
Fig.74 Density

EXEMPLARY DETAILS & PERFORMANCE



ROOF

Roof finish
Tongue & groove wood fiber board (60mm)
Hempcrete light ≈200 kg/m^3 (300mm)
Wood rafter (300mm)
Wood wool board (25mm)
Clay plaster (15mm)
U-Value: 0,151 W/m^{2}K



WALL

Lime-sand render (15mm)
Wood stud (175x45mm)
Hempcrete medium-dense ≈330 kg/m^3 (350mm)
Wood wool board (25mm)
Clay plaster (15mm)
U-Value: 0,228 W/m^{2}K

Fig.75 Principle detail 1

DETAIL 1. With this principal detail, the hempcrete is the only insulation material used, so the wall thickness is increased to higher insulative performance. Different hempcrete thickness variations were tried and the following thermal transmittance values were obtained:

200mm - 0,363 W/(m^{2}K)
250mm - 0,303 W/(m^{2}K)
300mm - 0,260 W/(m^{2}K)
350mm - 0,228 W/(m^{2}K)
400mm - 0,203 W/(m^{2}K)

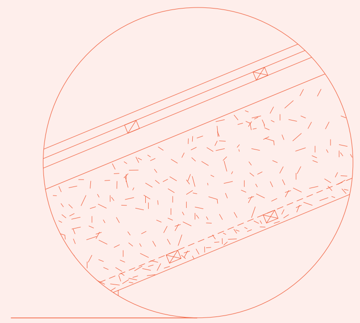
The hempcrete infill in the roof should be minimum 300mm thick, a wood fiber board gives additional insulation, and is also the airtight layer and vapor membrane for the roof.

The following thermal conductivities were used for the details:
Hempcrete light (≈200 kg/m^3) : **λ = 0,06 W/mK**
Hempcrete medium-dense (≈330 kg/m^3) : **λ = 0,09 W/mK**
Hempcrete dense (≈400 kg/m^3) : **λ = 0,11 W/mK**
This represents a mean value of the different results found during research and sample testing. The values do not differentiate hemp-lime and hemp-clay, as they reach sensibly similar values, and are depending on mixture conditions.

.**DETAIL 2.** The wooden framework is placed on the outer side of the wall. In this case the wall is thinner (250mm), but this is compensated by a hemp fiber insulation board on the outside. The facade is finished with a ventilated rainscreen that allows for weatherproofing. A dense hempcrete lining can be added on the inside of the wall, providing extra thermal inertia. The ceiling can also be made of a denser hempcrete mixture. Having hempcrete as a finish material also adds interesting textures and vibrations to the interior. During the material experimentations, I obtained different materialities. The material can be more or less grainy and interact with light infall to create depth on the interior finish and add patterns. Depending on the density and amount of binder, the material is rather brittle, so a thin clay coating can be useful to avoid dust and material loss when touched. The amount of binder changes the compactness and the texture of the material. This can give aesthetical value to the interior space and adds a sensorial experience to the finish.

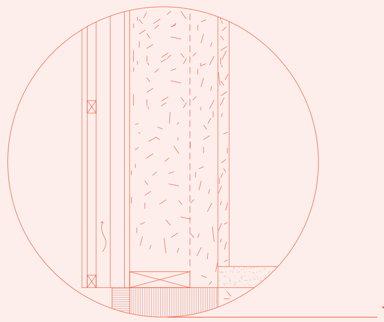
Image 66. Different textures can be obtained. The more shiv, the rougher the texture but also the more brittle the material is.

Image 67. Clay has a varying color pallet, depending on its location. This links the interior finish to the context of the built and allows for variations in interior atmosphere and vibrance.



ROOF

Roof finish
Tongue & groove wood fiber board (60mm)
Hempcrete light ≈200 kg/m^3 (300mm)
Wood rafter (300mm)
Wood battens (25mm)
Hempcrete ceiling ≈350 kg/m^3 (40mm)
Thin clay coating (5mm)
U-Value: 0,149 W/m^{2}K



WALL

Thin clay coating (5mm)
Hempcrete plaster ≈400 kg/m^3 (40mm)
Hempcrete medium-dense ≈330 kg/m^3 (250mm)
Wood stud (175x45mm)
Panelvent sheathing (15mm)
Hempfiber board (40mm)
Ventilated facade finish
U-Value: 0,224 W/m^{2}K

Fig.76 Principle detail 2

CARBON IMPACT CALCULATION. Many factors influence the carbon impact of hempcrete, especially the composition and the amount of binder. Indeed, depending on the desired density (roof – wall – slab) the amount of binder is lower/ higher and thus the climate impact varies in consequence.

To be able to compare hemp-lime and hemp-clay at 200kg/m³, 330kg/m³ and 400kg/m³, a personal, simplified calculation is made. For this, official figures both from the LCA of hemp shiv (INRA,2006), and the ICE database v3.0 (2019) were used. Therefore, the calculations take primarily into account the material production stage. However, it is at this stage the biggest difference of impact is noticeable. During construction the same tools would be used, transport impact would be lower for hemp-clay, as clay could be from site. But this is not considered in the study. A fixed amount of shiv is used in the calculation, and the amount of binder was adapted to increase/decrease the density of the material. Exactly the same proportions were used both for hemp-lime and hemp-clay. For this reason, the carbon absorptions are the same for hemp-lime and hemp-clay as it is the shiv that is considered to absorb CO_2.

The details of the calculations can be found in the Appendix.

CLIMATE IMPACT

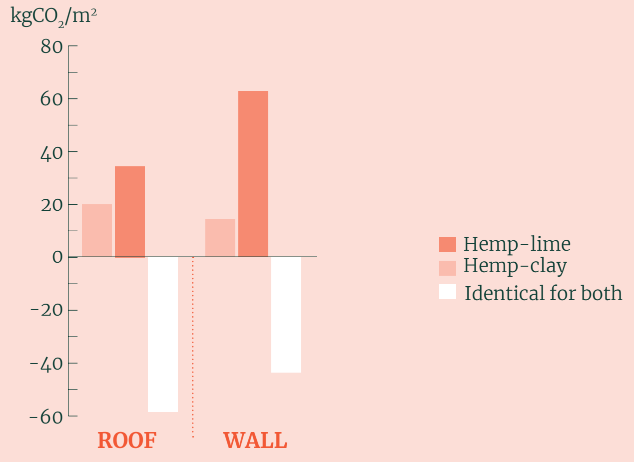


Fig.77 Comparative carbon impact detail 1

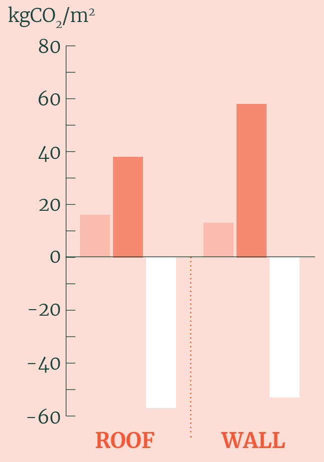


Fig.78 Comparative carbon impact detail 2

CONCLUSION & DISCUSSION

There is a need for more sustainable building materials and construction methods to change the impact of our sector on the environment. Natural and biobased materials have already proven their potential for decades, even centuries. The main issues lay in their recognition regarding building norms and regulations. It is thus important to research and talk about natural materials, to open the discussion and allow for knowledge development.

This thesis work has focussed on hempcrete, to highlight its potential and raise awareness about the material. Indeed, during my education I had never come across this material, and it was never mentioned. This shows a lack of knowledge and awareness about hempcrete. Although this biobased material is not brand new and has been used for several decades, especially in France, its implementation and recognition remain very low. I have enjoyed researching this, to me, unknown biobased material in depth and finding all the great possibilities it offers. The thesis had a double relevance. Firstly, hempcrete as it is most known, hemp in association with lime, was researched and analysed. Then, a more personal investigation was made on hemp and clay, allowing to link scientific and theoretical research to field tests and material experimentations.

The following research questions were investigated during this master's thesis: **What is the potential of hempcrete as an insulative building component for indoor climate performance and environmental impact? Could clay be a good binder substitute and what indoor climate and environmental performances would hemp-clay have compared to hemp-lime?**

During the first part of the thesis work, the analysis of hempcrete's various interesting properties have allowed to assess its great potential as a clean and environmentally friendly building component. Its hygrothermal properties, relatively good thermal conductivity, and porous structure, amongst others, allow for great performances regarding thermal comfort, indoor air quality and acoustics. The case study analysis also showcased these potentials, and above that highlighted the simplicity of construction and detailing. Hempcrete allows to reduce the number of required layers and components, making construction more straightforward and logic.
The second part of the thesis assessed the possibility of substituting lime with clay. Both the theoretical research and the personal experimental and scientific research have shown that hemp-clay reaches similar, or better, indoor climate performances. Clay has a neglectable climate impact, thus hemp-clay also outperforms hemp-lime on an environmental level.

Although this thesis work highlights the many advantages of hempcrete (both hemp-lime and hemp-clay), various challenges still remain.
The most impacting challenge is the relatively bad image hemp has undeservedly developed during the late 50s. Because hemp is often confused with cannabis its development and recognition are difficult in some countries, and hard legislation refrains its easy cultivation. For the interest of developing hempcrete more easily in the building sector, it could be interesting to investigate the possibilities of replacing hemp with another bio aggregate. Could the same properties be reached?
Another challenge is the drying time of the material during construction. This step is crucial to gain optimal performance and durability of the material, but it slows down the construction phases. Research on how to upscale hempcrete is starting to being developed. This is also an important domain to further investigate and will allow for hempcrete to become a more obvious choice in construction. Looking more specifically into hemp-clay, this thesis has not worked on mechanical behaviour or structural strength. Clay is less strong than lime and has a different mechanical behaviour. Lime turns back into limestone while curing, thus gaining considerable strength. This is not the case for clay, which hardens into a strong solid when dry but remains fragile to excessive water exposure. Above that, clay is denser than lime. This means that less dense hemp-clay mixes would be used to achieve similar thermal conductivity as a hemp-lime mix, this also influences its mechanical strength. More research would enable to understand the limits of the material and its best applications.

The followed methodology has allowed me to do in depth research on the important aspects of hempcrete, looking into raw resources, working methods, performances, and climate impact. On a personal level, this thesis also allowed me to gain deeper knowledge about indoor climate factors, especially concerning thermal comfort. Hempcrete's interaction both with relative humidity and temperature was interesting to investigate on a scientific level, this was very new to me. Likewise, looking into Life Cycle Assessment also gave me knowledge on what aspects are important to consider for material and construction choices. The thesis work had a very theoretical approach, allowing to link architecture to engineering and scientific research. This was a very interesting way of researching for me and gave me insight on both the creative and rational side of material development. I feel my personal learning curve is very high, I found the master's thesis process stimulating and inspiring to continue this research work in my professional career.

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Skype meeting 30.11.2021

Peter Holmdahl - Co-founder House of Hemp, hempcrete builder, develops hempcrete in Sweden
Meeting 18.01.2022

Thomas Brun - Founder ab²c Conception, hempcrete builder
Phone conversation 24.01.2022

Göran Andersson - Hemp farmer Grästorp
Phone conversation 04.02.2022
Meeting 26.02.22

Sonia Sifflet - Partner Architect at Lemoal Lemoal
Skype meeting 14.02.2022

RISE workshop - With House of Hemp 22.02.2022

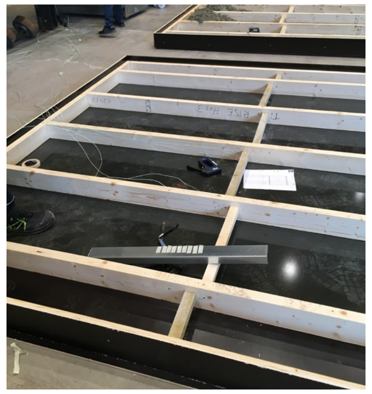
Patrik Bengtsson - Interior Architect, Designer & Self-builder
Phone conversation 12.03.2022

APPENDIX

WORKSHOP 22nd of February: MAKING WALL PANELS FOR TESTING

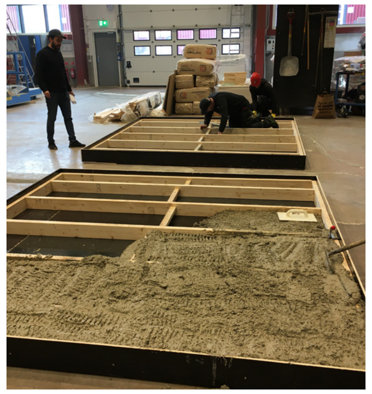
With House of Hemp @ RISE, Borås


Panel made with pinewood and temporary back shuttering for casting.


Two panels were made. Worked horizontally for placing the hempcrete.

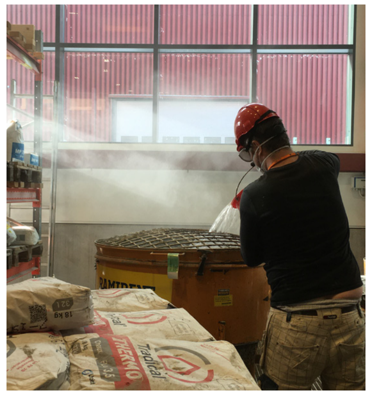

Pouring 1 bag of hemp shiv in the mixer (20kg).


The hempcrete is tamped, important not to apply too much pressure.


Step-by-step the framework is filled (1 layer of 2)


Humidity and thermal sensors were added to one panel for analysis.


Pouring 2 bags of lime binder in the mixer (2x18kg).


Adding about 60L water to the mix.


Testing the mixture: A small ball of hempcrete breaks in the middle.


First layer of hempcrete is placed, nicely tamped and fitting around the wood.


Zoom on material aspect.

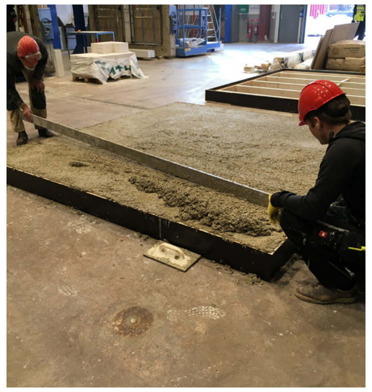

New batches of hempcrete are added to form a second layer.


The mixture is poured in the framework.


It is spread, pushing it onto the wood to remove air in every corner.


Zoom on spreading of hempcrete. A rack was used.


Spreading and tamping the mixture again, making it fit all around the frame.

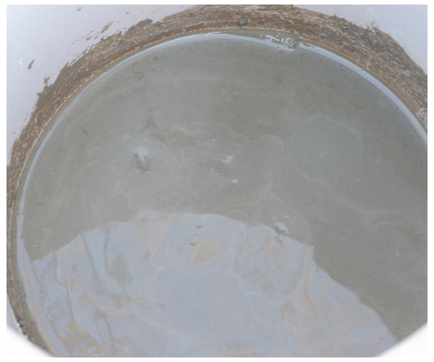

The hempcrete is egalized to obtain a flat infill.


Finished panels. Left to dry for a week before put vertically.

MAKING THE FIRST HEMP-CLAY SAMPLES

Preparation of clay and water in one bucket, hemp shivs in another bucket.

First mixing clay and water together. The mixing was done by hand, in small amounts. It is a rather intensive procedure, using a paddle mixer would be advisable.



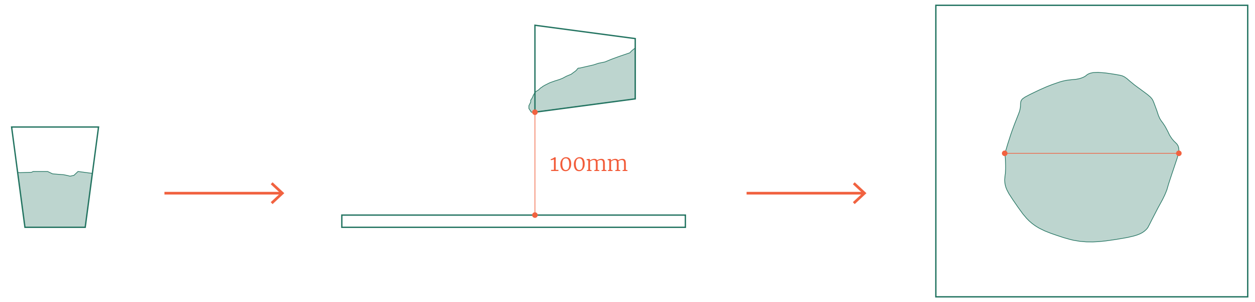
Zoom on clay-slip. This was a thick slip of proportions 4:1 (clay:water).

Adding the hemp shivs to the clay-slip.

Zoom on hemp-clay mix, the mixture is rather sticky because of the clay-slip.

Mold the hemp-clay into a form. The sample can be demolded immediatly and left to dry.

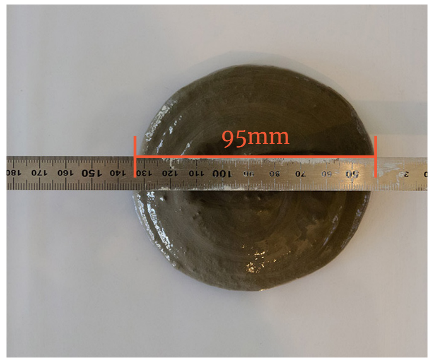
CLAY SLIP VISCOSITY TEST



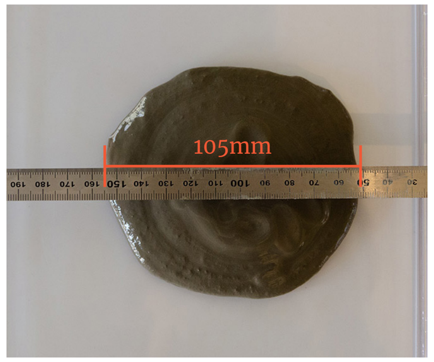
1. Fill a recipient with 100ml clay slip.

2. Pour the slip from a 100mm distance on a flat, non absorbing surface (glass, plastic...).

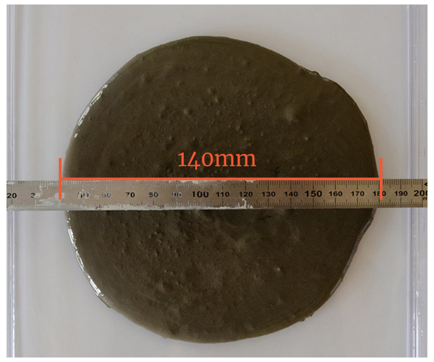
3. The puddle should mesure between 125 and 175mm. If too small, add water. If too large, add clay.



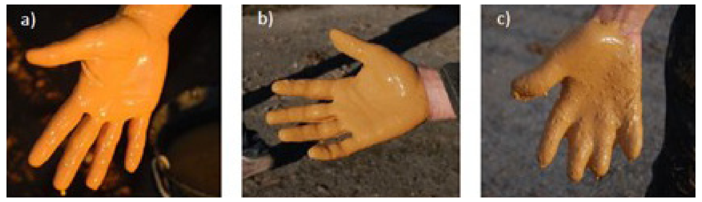
Test 1 : The slip is too thick, water must be added



Test 2 : The slip is still too thick, water must be added



Test 2 : The slip is of good consistency



Glove test © Vinceslas (2019), Caractérisation d'éco-matériaux Terre-Chanvre en prenant en compte la variabilité des ressources disponibles localement. Doctorial thesis.

The glove test is an efficient way to test viscosity on site.
a) The clay-slip is too thin and liquid, the hand is visible through transparency.
b) The hand is covered with a thin "glove". clay-slip of good consistency.
c) The slip is too thick and does not shape the hand.

HEMP-CLAY SAMPLE SECOND SET

Wooden mould used to make the sample.

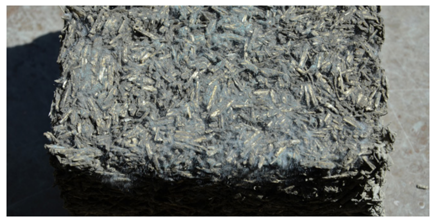
The clay-slip was prepared before-hand and used only several weeks after. It was still perfectly workable after stirring the slip. This slip is the same as the viscosity test on the previous page. 1 volume of slip is mixed with 2,5 volumes of hemp shiv.

Mixing the shiv and clay-slip thoroughly , all the shiv must be coated with slip and a homogenous mix is to be prepared.

Putting the hemp-clay mixture in the mould, layer by layer, and tamping everytime to remove air gaps.

The sample can be demolded immediatly. It is left to dry.

After 3 days, the corners are dried out. The surface while drying is quite fragile and brittle. Pieces can come of if handled without care.



Mold appeared on one sample that was placed on a glass surface to dry. It could not properly breath...

FLEXURAL/COMPRESSION STRENGTH

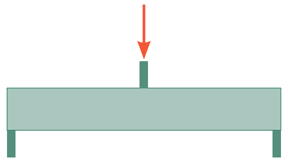


Fig.79 Flexion test scheme

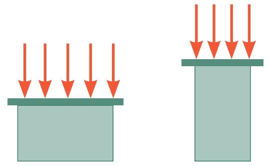


Fig.80 Compression test scheme

TEST PROCEDURE. 2 simple tests were performed to investigate the flexural and compression strength of sample 4 and sample 7. The aim is to give a rough first impression on how the material reacts to load, depending on density and clay content. Sample 4 has a density of 463kg/m³, and has a higher clay content, proportion wise. Sample 7 has a density 320kg/m³, it is very brittle and contains more shiv.

For the 3-point flexural test, the samples were placed on two wooden pieces that represent the span length. Another wooden piece, placed in the centre of the sample, transferred the load to one point. The load (water in a bucket) was gradually increased until rupture of the sample.

For the compression test, a person of 80kg stood, first on the biggest surface section, then on the biggest height section. This test was performed on the sample after the flexural test, on a smaller piece of each sample.

FLEXURAL TEST.

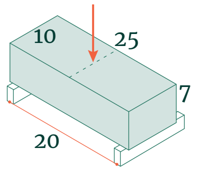


Fig.81 set-up sample 7

Image 68. Initial set-up

Image 75. After rupture

After pouring water gradually in the bucket, sample 7 broke with 7.5kg weight on top. The rupture was not very neat and a large part of the material was broken in smaller pieces.
After pouring water gradually in the bucket, sample 4 broke with 12.5kg weight on top. The rupture was neat and made a clear cut of the sample in two pieces.

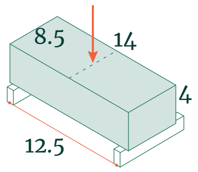


Fig.82 set-up sample 4

Image 69. Initial set-up

Image 76. After rupture

Sample 7 is lightweight and less compact than sample 4. Sample 4 contains more clay and is therefore more solid, when it breaks it does so in a neater rupture than sample 7. The conducted test highlights that density and clay content increase flexural resistance. Hempcrete, however is more subject to compression than flexion.

COMPRESSION TEST.

Image 70. Compression sample 7

Image 71. Broken sample

Image 72. Sample 4 - First compression

Image 73. Sample 4 - Second compression

Image 74. Broken sample

After compression with 80kg on the larger surface section, sample 7 showed signs of desintegration and no longer held correctly together.
After compression with 80kg on the larger surface section, sample 4 stayed intact. When subject to 80kg compression on the highest section, the sample broke and crumbled. Clay content is obviously determing the compressive strength of the sample.

These tests are only stating briefly the impact of density, compactness and hemp:clay proportions on flexion and compression.

U-VALUE CALCULATIONS

DETAIL 1

2 HC Roof

No Building assembly description

Heat transfer resistance [m²K/W] inner Rsi : 0,10 outer R_{sa} : 0,04

Section 1	λ [W/(mK)]	Section 2 (if any)	λ [W/(mK)]	Section 3 (if any)	λ [W/(mK)]	Total widht thickness [mm]
CLAY PLASTER	0,800					15
Wood wool board	0,080					25
HC light	0,060			Rafter	0,110	300
sarking board	0,042					60

Section 2 percent 0,5% Section 3 percent 8,0% Sum 40,0 c

U-value: 0,151 W/(m²K)

DETAIL 2

2 HC Roof

No Building assembly description

Heat transfer resistance [m²K/W] inner Rsi : 0,10 outer R_{sa} : 0,04

Section 1	λ [W/(mK)]	Section 2 (if any)	λ [W/(mK)]	Section 3 (if any)	λ [W/(mK)]	Total widht thickness [mm]
CLAY PLASTER	0,800					5
HC medium dense	0,090	Battens	0,110			40
HC light	0,060			Rafter	0,110	300
sarking board	0,042					60

Section 2 percent 0,5% Section 3 percent 8,0% Sum 40,5 c

U-value: 0,149 W/(m²K)

1 Wall

No Building assembly description

Heat transfer resistance [m²K/W] inner Rsi : 0,13 outer R_{sa} : 0,10

Section 1	λ [W/(mK)]	Section 2 (if any)	λ [W/(mK)]	Section 3 (if any)	λ [W/(mK)]	Total widht thickness [mm]
Clay plaster	0,800					15
Wood wool board	0,080					25
HC medium dense	0,090	WOOD BEAM	0,110			350
Lime-sand render	0,800					15

Section 2 percent 10,0% Section 3 percent 1,0% Sum 40,5 cm

U-value: 0,228 W/(m²K)

1 Wall

No Building assembly description

Heat transfer resistance [m²K/W] inner Rsi : 0,13 outer R_{sa} : 0,10

Section 1	λ [W/(mK)]	Section 2 (if any)	λ [W/(mK)]	Section 3 (if any)	λ [W/(mK)]	Total widht thickness [mm]
HC plaster	0,110					40
HC medium dense	0,090	WOOD BEAM	0,110			250
panelvent sheathing	0,100					15
Hemp fiber board	0,040					40

Section 2 percent 10,0% Section 3 percent 1,0% Sum 34,5 cm

U-value: 0,224 W/(m²K)

LCA CALCULATIONS

EC hemp: -1,9 $kgCO_2$/kg
EC Pure lime: 0,78 $kgCO_2$/kg
EC Cement : 0,83 $kgCO_2$/kg
EC Clay : 0,05 $kgCO_2$/kg

The lime binder was assumed to contain:
85% pure lime
15% cement

1m3 of hemp-lime at 330kg/m³ contains about:
110kg of hemp
220kg of lime
These are the reference proportions for the following calculations. The same proportions are used for shiv+ lime and shiv+clay.

The amount of shiv was assumed fixed. So,

200kg/m³:	330kg/m³	400kg/m³
110kg shiv	110kg shiv	110kg shiv
90kg binder	220kg binder	290kg binder

Example for 330kg/m³ calculation:

Hemp-lime 330kg/m³:
220 * 0,15 = 33 (amount of cement)

110 * (-1,9) = -209 -> -209 $kgCO_2$/m³

33* 0,83 = 27
187*0,78 = 145 -> 172 $kgCO_2$/m³

Total emitted: - 37 $kgCO_2$/m³

Hemp-lime 330kg/m³:
110 * (-1,9) = -209 -> -209 $kgCO_2$/m³

220* 0,05 =11 -> 11 $kgCO_2$/m³

Total emitted: - 198 $kgCO_2$/m³

The same calculations were made for 200 kg/m³ and 400kg/m³

DETAIL 1/ hemp-lime

Roof — Area 1 kvm

Type	Material	Thickness	cc	Trp km	Emissions [ton CO2]	Storage [ton CO2]
Mortar.Gypsum.	clay plaster	0,015	1		0,0006	0,0007
Wood	Wood wool lig	0,025	1		0,0047	0,0062
Wood	Lumber tech d	0,3	0,1		0,0032	0,0245
Add.your.own.e	Hemp-lime lig	0,3	0,9		0,0192	0,0113
Insulation.mat	Wood fiber in	0,06	1		0,0087	0,0164
					0,0000	0,0000
					0,0000	0,0000
					0,0000	0,0000
					0,0000	0,0000
Climate emission roof					**0,0364**	**0,0591**

Outer wall — Area 1 kvm

Type	Material	Thickness	cc	Trp km	Emissions [ton CO2]	Storage [ton CO2]
Mortar.Gypsum.Boa	clay plaste	0,015	1		0,0006	0,0007
Wood	Wood wool l	0,025	1		0,0047	0,0062
Add.your.own.epd	Hemp-lime m	0,35	0,9		0,0542	0,0217
Wood	Lumber tech	0,175	0,10		0,0018	0,0143
Mortar.Gypsum.Boa	lime plaste	0,015	1		0,0038	0,0000
–					0	0
–					0	0
					0	0
–					0	0
–						
Climate emission Outer wall					**0,0651**	**0,0430**

DETAIL 1/ hemp-clay

Roof — Area 1 kvm

Type	Material	Thickness	cc	Trp km	Emissions [ton CO2]	Storage [ton CO2]
Mortar.Gypsum.	clay plaster	0,015	1		0,0006	0,0007
Wood	Wood wool lig	0,025	1		0,0047	0,0062
Wood	Lumber tech d	0,3	0,1		0,0032	0,0245
Add.your.own.e	Hemp-clay lig	0,3	0,9		0,0030	0,0113
Insulation.mat	Wood fiber in	0,06	1		0,0087	0,0164
					0,0000	0,0000
					0,0000	0,0000
					0,0000	0,0000
					0,0000	0,0000
Climate emission roof					**0,0202**	**0,0591**

Outer wall — Area 1 kvm

Type	Material	Thickness	cc	Trp km	Emissions [ton CO2]	Storage [ton CO2]
Mortar.Gypsum.Boa	clay plaste	0,015	1		0,0006	0,0007
Wood	Wood wool l	0,025	1		0,0047	0,0062
Add.your.own.epd	Hemp-clay m	0,35	0,9		0,0046	0,0217
Wood	Lumber tech	0,175	0,10		0,0018	0,0143
Mortar.Gypsum.Boa	lime plaste	0,015	1		0,0038	0,0000
–					0	0
–					0	0
					0	0
–					0	0
–						
Climate emission Outer wall					**0,0155**	**0,0430**

DETAIL 2/ hemp-lime

Roof — Area 1 kvm

Type	Material	Thickness	cc	Trp km	Emissions [ton CO2]	Storage [ton CO2]
Mortar.Gypsum.	clay plaster	0,005	1		0,0002	0,000
Add.your.own.e	Hemp-lime med	0,04	1		0,0069	0,003
Wood	Lumber tech d	0,025	0,1		0,0003	0,002
Add.your.own.e	Hemp-lime lig	0,3	0,9		0,0192	0,011
Wood	Lumber tech d	0,3	0,1		0,0032	0,025
Insulation.mat	Wood fiber in	0,06	1,0		0,0087	0,016
					0,0000	0,000
					0,0000	0,000
					0,0000	0,000
Climate emission roof					**0,0384**	**0,057**

Outer wall — Area 1 kvm

Type	Material	Thickness	cc	Trp km	Emissions [ton CO2]	Storage [ton CO2]
Mortar.Gypsum.Boa	clay plaste	0,005	1		0,0002	0,0002
Add.your.own.epd	Hemp-lime	0,04	1		0,0091	0,0033
Add.your.own.epd	Hemp-lime m	0,25	0,9		0,0387	0,016
Wood	Lumber tech	0,175	0,10		0,0018	0,0143
Wood	MDF board f	0,015	1		0,0056	0,0144
Insulation.materia	Hemp insula	0,04	1,00		0,0017	0,0016
Wood	Lumber tech	0,025	0,1		0,0003	0,0020
Wood	Lumber tech	0,025	0,1		0,0003	0,0020
–					0,0000	0,0000
–						
Climate emission Outer wall					**0,0578**	**0,0535**

DETAIL 2/ hemp-clay

Roof — Area 1 kvm

Type	Material	Thickness	cc	Trp km	Emissions [ton CO2]	Storage [ton CO2]
Mortar.Gypsum.	clay plaster	0,005	1		0,0002	0,000
Add.your.own.e	Hemp-clay med	0,04	1		0,0006	0,003
Wood	Lumber tech d	0,025	0,1		0,0003	0,002
Add.your.own.e	Hemp-clay lig	0,3	0,9		0,0030	0,011
Wood	Lumber tech d	0,3	0,1		0,0032	0,025
Insulation.mat	Wood fiber in	0,06	1,0		0,0087	0,016
					0,0000	0,000
					0,0000	0,000
					0,0000	0,000
Climate emission roof					**0,0159**	**0,057**

Outer wall — Area 1 kvm

Type	Material	Thickness	cc	Trp km	Emissions [ton CO2]	Storage [ton CO2]
Mortar.Gypsum.Boa	clay plaste	0,005	1		0,0002	0,0002
Add.your.own.epd	hemp-clay d	0,04	1		0,0002	0,0033
Add.your.own.epd	Hemp-clay m	0,25	0,9		0,0033	0,016
Wood	Lumber tech	0,175	0,10		0,0018	0,0143
Wood	MDF board f	0,015	1		0,0056	0,0144
Insulation.materia	Hemp insula	0,04	1,00		0,0017	0,0016
Wood	Lumber tech	0,025	0,1		0,0003	0,0020
Wood	Lumber tech	0,025	0,1		0,0003	0,0020
–					0,0000	0,0000
–						
Climate emission Outer wall					**0,0134**	**0,0535**