

# **PROTOTYPE OF HEMPCRETE NOISE BARRIER WALL**



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#### ABSTRACT

The main aim of this Bachelor's thesis was to examine and to propose a prototype design of a highway noise barrier wall, which is made from Hempcrete, a hemp-lime composite material. The thesis was commissioned by the company Hemprefine Oy, with the participation of HAMK University of Applied Sciences.

The possibility of constructing such structure was assessed and evaluated. In addition, advantages and disadvantages of a Hempcrete noise barrier wall prototype were discussed. Hempcrete and concrete were also compared.

The prototype design of the Hempcrete noise barrier was made according to the concept of environmentally friendly green structures. It consists of a timber load-bearing frame; four Hempcrete blocks, connected to each other; and foundation, which is chosen according to the geotechnical aspects of construction site. Based on the various researches, it was concluded that the construction of the Hempcrete noise barrier in the targeted area (Finland) is difficult due to the excessive water absorption by Hempcrete. Its implementation requires deeper studies and testing of the durability and resistance of the material in the Finnish climatic conditions.

As a conclusion, it can be stated that the presented prototype of Hempcrete noise barrier wall is an eco-friendly, sustainable structure with the ability to sequester CO<sub>2</sub> and unique sound absorption properties, that can be successfully used in countries with a dry climate. Such structure can contribute to the development of environmental and sustainable road construction.

**Keywords** Noise barriers, Hempcrete, noise pollution, green noise barrier

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## **1 INTRODUCTION**

The main aim of this Bachelor's thesis is to conduct a study on Hempcrete and propose a prototype design of a highway noise barrier wall made from a Hempcrete. Hempcrete is a new bio-composite building material with low embodied energy generally consisting of hemp, binder and water. Combining great acoustic performances and ability to store and sequester carbon dioxide in its structure, this material can be used in many different ways, especially it can be applied as the main material for a highway noise barriers.

Hemp is one of the oldest cultivated plants in our planet, which has played a significant role in people's lives, and traditionally was used for textile fiber, paper production and preparation of medicines and confections. Nevertheless, in the last century due to constant comparison and ascribing of industrial hemp to a drug plant, and because of the several laws ordained in the USA and in many European countries, the cultivation of hemp became illegal in many places of the world. Nowadays, the situation is gradually changing with the growing concern and uprising trends related to the environmental conservation and protection, cultivation, harvesting and use of hemp resumed and now legally happens in Asia, Canada and many European countries. Historically, hemp was a versatile plant in Finland. It was separated, according to fineness and quality, and used in different ways such as material for ropes, fishing nets, sacks, raw material for soap and lamp oils etc.

With already existing and upcoming environmental problems, which humanity will meet in the nearest future, main aims of construction turned towards sustainability, energy efficiency and use of "green" eco-friendly materials. The use of such material as Hempcrete can meet the demands of modern building activities and conduce the development of eco-innovations in the field of road construction.

## **2 NOISE POLLUTION PROBLEM**

Noise pollution is a fast growing concern, which is becoming a major problem in many cities all around the world, as noise affects and influences the human health, and is claimed to be one of the most important environmental risks (World Health Organization, 2018). The term environmental noise is commonly defined as any unwanted sound, except sounds emitted or originated from the industrial or any other workplace activity. Thus, the main sources of environmental noise, or also called community noise, are road, rail or air traffic.



Road traffic plays a dominant role and affects more people than any other form of transportation (Park, et al., 2018). According to the World Health Organization (WHO), noise generated by traffic has pernicious influence on every third person in Europe (World Health Organization, 2018). Transport noise is usually generated by the interaction of tires with the pavement, and sounds produced by car engines. That is why it is possible to form several generalized influence factors on which noise levels depend (excluding terrain of the road and weather conditions):

- Type and quality of road pavement

Quality and type of road greatly influences the generation of noise levels. The material of road pavement and its quality directly impact and determine the noise which appears due to tire friction and surface. With the development of technologies, rubberized asphalt possesses unique properties and is a noise reduction pavement material. This kind of pavement is the most efficient and produces less noise than others: asphalt, large sett, masonry and gravel paving (materials are indicated in accordance with the production of noise). Furthermore, the condition of pavement is important. Road surface, which has different kind of defections such as hollow spots, incoherencies and ridges, always create increased unwanted noise levels (Mahadev N. Harkude, 2015).

- Traffic Speed, intensity and flow composition

Most of the noise produced by vehicles is generated from working engines. When a car accelerates or gain its speed, engine performance increases as well as its noise. Various researches point out that sound energy emitted from the car engine approximately doubles for each increment of speed in 16 km/h. Also, during an increase in speed noise levels rise due to air resistance and enhanced friction between tires and road pavement (Marianna Jacyna, 2017) (Mahadev N. Harkude, 2015),.

In addition, intensity (traffic flow) and traffic composition factors are significant. Traffic composition is implied by the relation of number of different types of cars. As, for example, trucks, buses and old vehicles produce and exert much more noise, comparing to modern light motor cars, not only due to their engine capacity and quality, but also because of its specific structure and displacement, which influence the aerodynamic drag (Marianna Jacyna, 2017) (Mahadev N. Harkude, 2015),.

Excessive noise has a strong impact on people resulting in numerous socially significant and medically serious problems related with physical and mental health. It also influences the environment which surrounds us. Under the influence of noise, the natural biological processes and animal's and bird's life might be affected and violated. The total influence of noise on living organisms, especially on humans, is complex and ambiguous and always differs by the degree of perception, as its main objective indicator

factors are pitch, sound intensity and exposure duration. Nowadays, as unwanted noise consists almost in every daily activity, it usually influences sleep, provokes annoyance, can affect the behavior, and lead to cardiovascular and psychophysiological effects.

This issue has a strong impact on people's daily lives. With the population growth, urbanization and increased usage and development of different kind of transport facilities, this problem will only grow and gain its danger level.

## 2.1 Possible effect on health and solutions

A small research and overview of possible problems and impact of the environmental noise on people's mental and physical health and conditions are presented below, in order to expand and deepen the main topic of this thesis. As it is important to know all consequences, which are related to noise pollution, to the end that the further solution of the issue can be better understood.

As it is known, noise creates direct and indirect (cumulative) harmful and adverse actions, which impact and damage the social environment and working occupation. As was mentioned above, the main effects of noise pollution result into hearing impairment, sleep disturbance, negative behavior and annoyance, cardiovascular problems.

Hearing loss or hearing impairment is a partial or total inability to hear. It is also defined as an increase in the threshold of hearing as clinically assessed by audiometry (Jairwala, Syed, Pandya, & Gajera, 2017). This problem can occur due to many reasons, but the major cause of it is occupational exposure of noise. As a consequence, hearing impairment can be followed with buzzing in ears (also called tinnitus), aberrant sound perception, etc. The duration of those effects can be temporary or even can become permanent, depending on the exposure time and its power.

The following issues like sleep disturbance, annoyance and negative social behavior represent a combination of followed-up actions, and arise, mainly, because of the impact of community noise. As it was mentioned before, traffic is one of the main causes of noise pollution inasmuch as roads are usually located directly next to living areas and buildings. That is why noise level thresholds can exceed up to 30 dB. Such over limits, in long term, lead to serious consequences. Firstly, excessive noise disturbs night time sleep and violates sleeping stages regime that usually results into fatigue, annoyance and anger. Furthermore, during sleep noise can contribute and affect blood pressure and heart rate (Stansfeld & Matheson, 2003). Inadequate night's sleep has other after-effects, which accumulate and come out in every day behavior. Signs and evidences of such changes can be traced in aggressiveness, unfriendliness, disengagement, frequent changes in mood etc. (Park, et al., 2018).

Behavioral and health effects caused by traffic noise are considered complex and indirect. Nevertheless, the influence of noise pollution exposure on human health should not be diminished and must be seriously taken into the account. In order to solve and minimize the consequences of traffic noise several different approaches are proposed:

- Development of road management
- Development in road construction technologies
- Improvements and implementation of new motor vehicles technologies
- Improvements of noise barriers

In such a manner, in the following sections of this thesis a new possible solution for minimizing traffic noise will be presented and described. This solution is a prototype of a noise barrier wall, in which environmentally friendly and efficient material is used.

### 3 NOISE BARRIER WALLS

Noise barriers are the structures erected along highways, major avenues and railway tracks, whose major aim is to mitigate the noise exposure effect and reduce it as much as possible, in order to prevent its impact on surrounding communities. They have become frequent features along many roads due to the arising problem of excessive noise and its influence on people's health. Another important aim of the noise barrier structures is to block the views of traffic; thus, they must be designed in a way to fit into the local environment. Because of such objectives many factors and both acoustic and non-acoustic considerations must be taken into account during the planning and design phase of the structure. Figure 1 below shows an example of a noise barrier wall.



Figure 1. Noise barrier wall fitted into local environment (Bendtsen, 2010)

Acoustic factors include barrier materials, shape and dimensions of the structure and its location, while non-acoustical considerations refer to structural integrity or visual design, accessibility and maintainability, safety factors. All of the above mentioned elements are connected to each other and must be considered because in many cases problems related to non-acoustical factors may have a negative effect on acoustical properties of the barrier (CEDR, 2017).

To give a proper and complete understanding of the main topic of the thesis, the basics of sound and its characteristics related to the design and planning of a highway noise barrier walls are firstly described, and after that information about noise walls is presented.

### 3.1 Basic characteristics of sound

Sound is vibration, which passes thorough different substances. In other words, sound represents the propagation of mechanical oscillations in the form of elastic waves in solid, liquid or gaseous media. In the narrow sense and from the perspective of human psychology and physiology, the sound is various movements of molecules in air, which are perceived by humans (Foley, 2017).

Regarding the topic of this thesis, highway traffic noise is formed by three sources: vehicle engines, truck exhaust stacks, and interaction between road pavements and tires. The energy of sound, produced from the above-mentioned sources, due to the movements of source lead into small fluctuations in atmospheric pressure, which are expressed as sound pressure and measured in units of micro Newtons per square meter ( $\mu\text{N}/\text{m}^2$ ), or micro Pascals ( $\mu\text{Pa}$ ). The amplitudes of sound pressure ranges from 20 to 200 million micro Pascals. Therefore, this level is usually measured on a logarithmic scale, called decibel (dB) scale, where a value of 0 dB is equal to a sound pressure level of 20  $\mu\text{Pa}$ . This value is generally accepted as a threshold of hearing for most people (U.S Department of Transportation Federal Highway Administration, 2000). Figure 2 shows a scale of relating sounds encountered in daily life and their approximate decibel values.

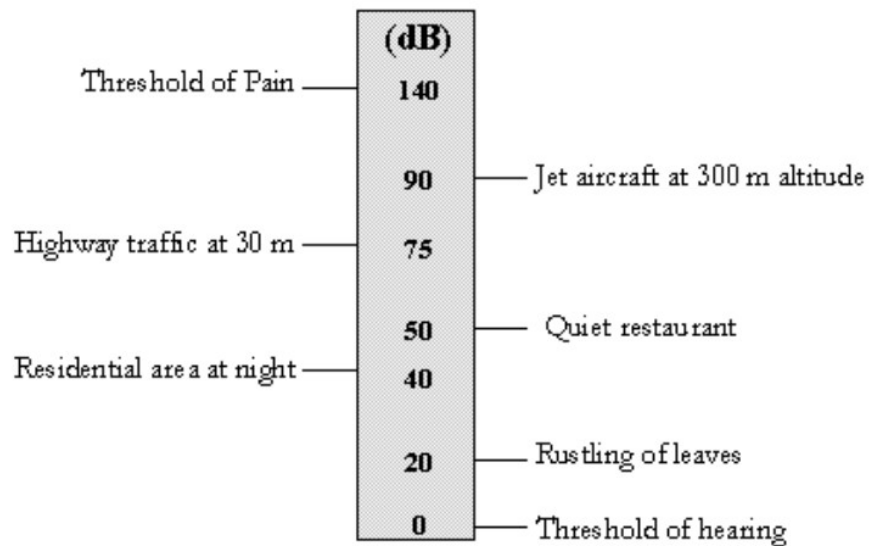


Figure 2. Decibel scale (U.S Department of Transportation Federal Highway Administration, 2000)

As sound is a wave, it has another characteristic, which is called tonality or frequency. Frequency of sound is defined as the number of wave cycles that occur in one second, and is measured in Hertz (Hz). Most people can hear in a range from 20 Hz to 20 000 Hz, but nevertheless not all frequencies are differently perceived by a human ear. Hereby, traffic noise is measured with the use of “A-weighted” system (Figure 3) (U.S Department of Transportation Federal Highway Administration, 2000).

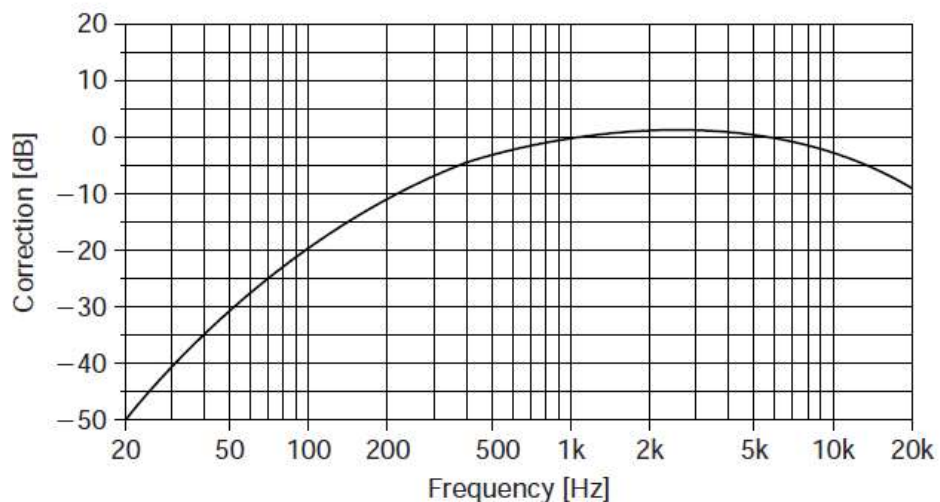


Figure 3. The “A” frequency Weighting (Brixen, 2011)

Generally, in such a system, lower frequencies, as they do not have large impact on the final result of the measurement, are suppressed, while frequencies in the range of 1000 and 6000 Hz are slightly emphasized. With

the help of such a scale, it is possible to define the human perception of sound during the specifications of internal noises (Brixen, 2011).

### 3.2 Sound measurements

The main goal of any noise barrier is to reach the maximum reduction of noise and sounds. In order to define the effectivity of the structure, the Insertion Loss (IL) must be calculated. Insertion Loss – is the difference in sound levels at a receiver location, which is under influence of the same source of sound with and without the existence of a barrier (Figure 4). The only presence of the barrier between road and the receiver gives a 5 dB(A) attenuation of noise, and with every another 1 meter in wall height can provide approximately 1,5 dB(A) of sound reduction (U.S Department of Transportation Federal Highway Administration, 2000).

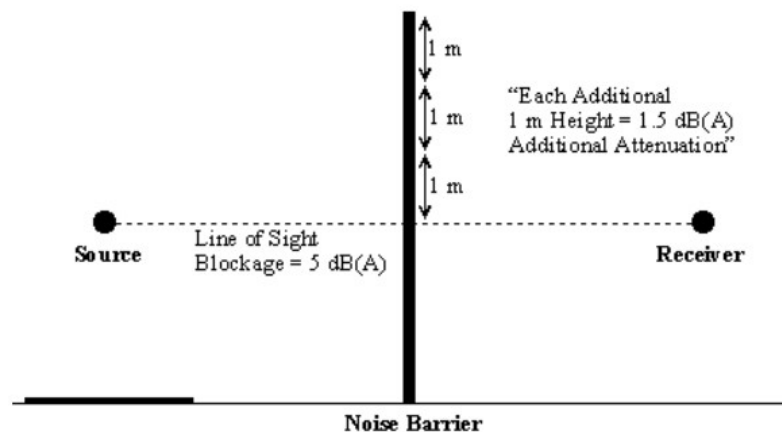


Figure 4. Insertion loss (U.S Department of Transportation Federal Highway Administration, 2000)

Sound Reduction Index ( $R_w$ ) is a measurement used in many countries to define the level of sound insulation of the material, and it is determined in the range of 50 to 5000 HZ and expressed in decibels. In order to define the efficiency of sound reduction properties of the structure, special tests must be conducted, during which one side of the material or wall is exposed to sound, and after sound level difference between two sides of the wall is calculated.

Another parameter for measuring sound insulation is Noise Reduction Coefficient, and it shows the amount of absorbed sound by the material. This value is ranged from 0 to 1, where with the greatest number, more sound will be absorbed. Noise Reduction Coefficient for a usual noise barrier is usually around from 0.6-0.8 (U.S Department of Transportation Federal Highway Administration, 2000).

### 3.3 Types of noise barriers

Noise barriers can be categorized in different ways. But most of the times they are classified by acoustic behavior and can be absorptive, reflective and reactive.

Absorptive noise barriers are usually made of or contain porous material that absorbs any sounds and noise. Such absorptive materials are mineral wool, foam plastics, or special absorptive slabs. Most of the times, absorptive noise barriers are covered with a perforated sheet, in order to improve the entry of the sound into the barrier with the following absorption of its kinetic energy (Serdyukov, 2016). These coverings are usually made from aluminum, steel or timber plates. With the greater sound absorption ratio of the material used in a barrier, the less sounds incoming from traffic is reflected back to the opposite side. This makes absorptive noise walls perfect tool for solving excessive traffic noise problem. Figure 5 is an example of an absorptive noise barrier.



Figure 5. Absorptive noise barrier (FHWA, 2001)

Reflective noise barriers (see Figure 6) are metal sheet or any other rigid material single panels, which reflects, or bounce sounds back to its source. Usually, reflective barriers are located on both sides of the road opposite to each other (such barriers are called parallel barriers), and reflected noise starts to reverberate between the barriers and vehicles. This effect cause deterioration in each noise walls performances. As it is stated in technical report by CEDR (CEDR, 2017), such quality losses can be from 2 to 6 dB(A). Due to multiply reflections, which are diffracted over an individual barrier, negative effect is created and, most of the times, the source of the sound receives an increased noise load. Due to this issue, the

application area of this type of barriers is limited (Serdyukov, 2016). But their main advantage is the relatively cheap cost comparing to the other types of noise barriers.



Figure 6. Reflective concrete noise barrier (CEDR, 2017)

Reactive barriers are those, which include cavities or resonators designed to attenuate particular noise frequencies (Kotzen & English, 1999). This kind of technology can be combined with other types of noise barriers. The most frequent combination is the use of reactive barrier with absorptive material.

The choice of the material for the barrier, in terms of acoustic considerations, lead to the range of possible visual design. Noise barriers can be divided according to their light transmittance. Thus, they can be transparent, opaque, tinted or panels with transparent inserts. Absorptive and reactive barriers are always opaque by their nature, while reflective noise screens can play a role of visual barriers (Kotzen & English, 1999).

Transparent barrier may be completely integrated and fitted into the local environment, without derogation to the city architecture and its appearance, improving traffic safety due to improved viewing angle and illumination of the road (Serdyukov, 2016).

### 3.4 Functioning of a noise barrier

The main aim and application target of sound barriers is to lower the noise level and minimize the effects of traffic activities on local communities. Noise barriers create an obstacle in the course of sound waves by blocking



the direct path line from the source to the receiver. Thus, the barrier creates an acoustic shadow zone, through which noise waves cannot pass and propagate. In order to increase the efficiency of this effect and significantly decrease or completely remove perceived noise, a barrier should be long and tall enough. Therefore, a wall must be designed in a such manner that the receiver is placed lower than this shadow line in vertical projection (see Figure below) (CEDR, 2017) (Serdyukov, 2016).

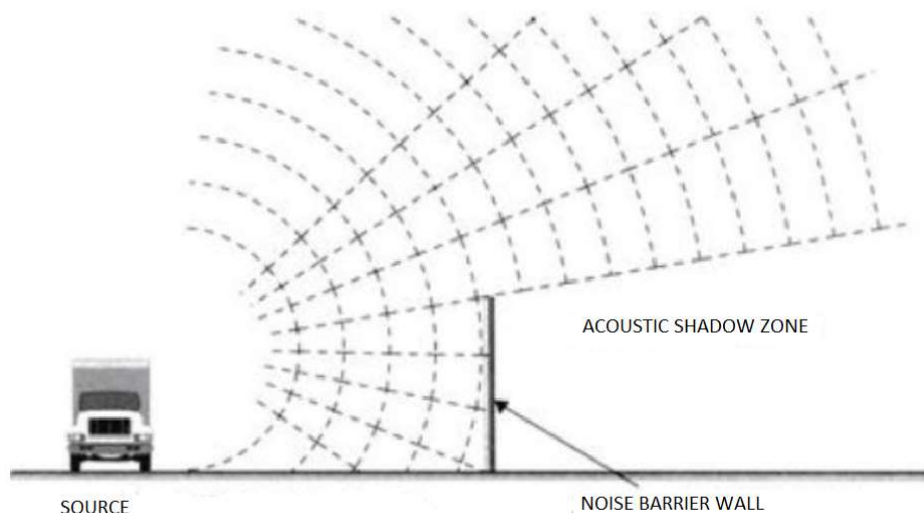


Figure 7. Acoustic shadow zone (Serdyukov, 2016)

As it was mentioned before, due to various materials and technologies used in noise wall structures to reduce as much sounds as possible, barriers either reflect sound back across the traffic, absorb it, transmit it or forcing it to take a longer path to the receiver (FHWA, 2001). This extended path of sound is always described as diffracted path (U.S Department of Transportation Federal Highway Administration, 2000). With this principle, the receiver is subjected to the diffracted and transmitted noise (noise, transmitted through the barrier, reaches the receiver with a 'loss' of acoustical energy). The diffracted noise depends on the shape, dimensions and location of the barrier, while the transmitted noise relies on materials of the wall (CEDR, 2017). In Figures below, the basic working principles of noise barriers are presented.

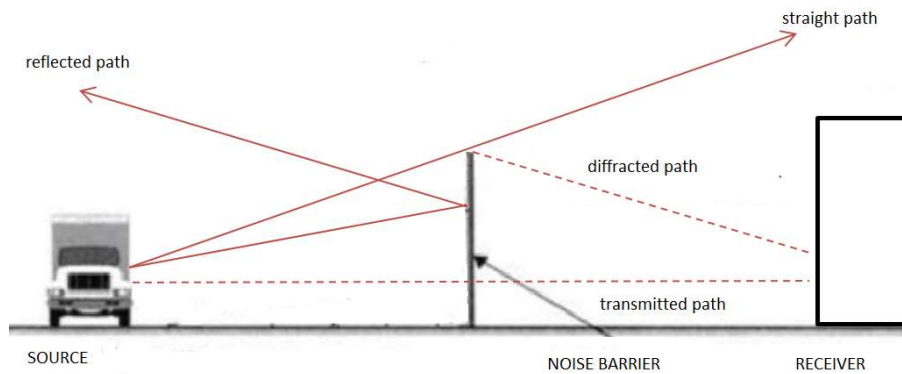


Figure 8. Noise paths altered by a noise barrier

As sound energy has an ability to spread and pass through different materials and superficies, the amount of such transmitted noise is usually described by such parameter as Transmission Loss (TL). It depends on the sound frequency emitted on the surface and material properties of the barrier. Following the book published by U.S Department of Transportation Federal Highway Administration (2000) anything can be used as a highway noise barrier if it has a Transmission Loss at least 10 dB(A). Furthermore, if the material has a TL equal or greater than 33 dB(A), it means that it has a satisfactory property and capable of meeting all the requirements for noise barriers in any case and situation.

### 3.5 Visual considerations

Visual design of any noise barrier plays an important role and must be designed for each individual location, in order to fit into the surrounding area. If this term is not observed, the noise barrier will remain an “alien” dull structure diminishing landscape quality and character, which can lead to several subsequent issues.

Noise walls create a visual effect, which affect both drivers and people, the receivers of excessive noise from the roads. The height of the barrier, the surface relief pattern, the distance of the wall from the roadway, and the speed of the vehicle, all these factors influence the perception of the driver on the barrier. For example, if two parallel barriers are located closely to the road, a disturbing and irritating psychologic effect can arise as drivers can feel themselves in enclosed space surrounded by the walls. Almost in the same way, a visual effect of the barrier refers to the receivers, and depends on the height, color, surface texture and the distance of the barrier from the receiver. Such structure as noise wall can block the view or spoil the landscape (Klinger;McNerney;& Busch-Vicniac, 2003).

In order to avoid such issues related to a visual design of the wall, two methods can be implemented (Klinger;McNerney;& Busch-Vicniac, 2003). In the first approach, the noise barrier is designed in a way to dominate the landscape, be monumental, so its details and materials are chosen in such manner that the structure becomes a part of the landscape. While in the second method, the structure is fully integrated into the local environment.

Because of those methods, acoustic and non-acoustic requirements and future installation location of the noise barrier, a visual design of modern noise barriers walls is now provided with a broad range of variants and combinations, which can be grouped according to their shapes and application area as shown in figure below:

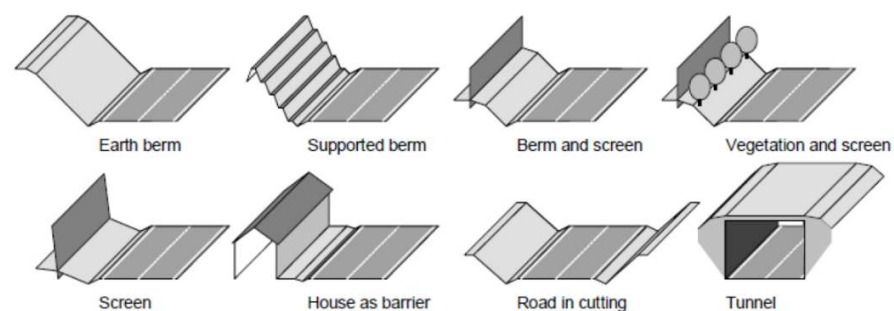


Figure 9. Examples of noise barrier wall shapes (CEDR, 2017)

- Earth berms and embankments (can be used in a combination with a convectional barrier)
- Vegetative barriers (noise barrier walls, which are made partly or completely from vegetation)
- Screens (can compose a configuration with any other type of barrier or with a building)
- Covering barriers (a road in a cutting or tunnel)  
(CEDR, 2017)

Combining different kinds and types of shapes of noise walls, it is possible to come to the best possible solution for an individual area, conjoining not only the best acoustic performance, but also a great visual design.

## 4 HEMPCRETE AND ITS CONSTITUENTS

Hempcrete is a lightweight, biodegradable, non-toxic breathable building material, which can be used in different kinds of structures. In this thesis, it is a bio-composite mix of hemp shives or herds, fibers, lime binder and water (see Figure 10).



Figure 10. Hempcrete (Isohemp natural building, 2019)

Typically, Hempcrete is used as a non-load bearing material, and usually need a supporting bearing structure. It was firstly used in France in the early 1990s, in order to improve the properties of concrete and make it lighter. Nowadays, Hempcrete has been mainly used as thermal insulation in different parts of buildings. But many researches have been conducted lately, which have discovered the great potential use of the material as noise insulation.

Hempcrete, itself, is very similar material to concrete. The have very common consistency and almost the same application.

The core of hemp has a unique characteristic. Hemp shiv has a low pectin content, which allows it to work better with a binder, as pectin can delay the setting time of a binder (Bruijn, 2012). Hemp shives and lime are blended with water in a special formwork or timber shuttering. Sometimes special aggregate is added to “standard” mixture, in order to accelerate up the following processes or to change the properties of the final product. During this mixing phase, a chemical reaction takes place between water and binder, which let ingredients to bind and set together (Magwood, 2016). The proportions of hemp and lime are usually specified and designed with the desired application (Bevan & Woolley, 2008).

After this process, the mixture is left for drying. At that time the binder is set and cured, as well as additional water content is dried out. This phase can take from one to several months to reach the final consistency and properties of Hempcrete.

With the upcoming environmental related problems, the need of energy efficient solutions has rapidly ascended. Hempcrete can be one of possible solutions which can be used in many various ways. The main key and success factor of this material is that it has “carbon negative” impact on the environment due to the specific nature of hemp, and chemical

reactions, which occurs during the drying process of lime, hemp and water. This topic will be discussed more precisely in further sections.

#### 4.1 Hemp

Hemp or Cannabis Sativa is a herbaceous plant (see Figure 11), which belongs to the Cannabaceae family (Suman Chandra, 2017, s. 263). The plant can be grown very fast without any additional fertilization inputs and pesticide applications (Bevan & Woolley, 2008), and can reach a heights from 1 up to 5 meters, depending on the seeding location.



Figure 11. Hemp (*Cannabis sativa*) (Britannica)

Sometimes hemp is confused with the cannabis plants that serve as a source of drug marijuana. However, hemp, also called industrial hemp, refers to cannabis varieties that are primarily grown as an agricultural crop and contain low THC content. THC, delta-9 tetrahydrocannabinol, is a compound chemical that is responsible for psychoactive effects. THC levels for industrial hemp are much less than 1%, and considered as a threshold value for cannabis to have intoxicating potential or psychotropic effect (Clark, 2011). Following the current legislation and rules in the European Union, only varieties with a THC content not exceeding 0.2 % may be cultivated and used (European Monitoring Centre for Drugs and Drug Addiction, 2018).

The stalk of the plant is thin and hollow and can be separated into shiv and fibers (Figure 12).

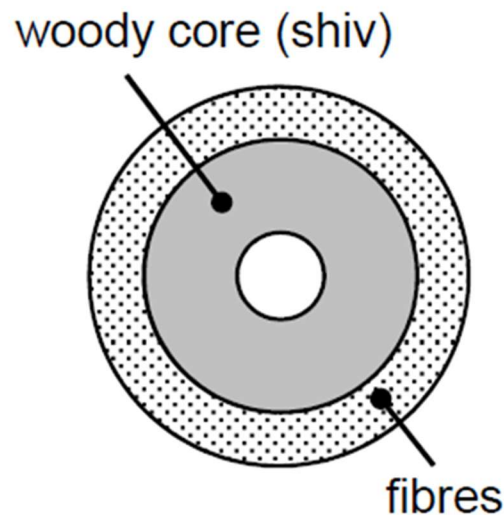


Figure 12. Schematic section of a hemp stalk (Bruijn, 2012)

Hemp shiv (hurd) is soft inner woody part of the stem which has great acoustic and thermal properties. But historically, it was used as a by-product of the hemp-fiber industry and as a combustion fuel. Nowadays, hurds are usually used as insulation material and animal bedding (What is hemp, 2018).

Fibers are situated in the bark of the stalk and have a high tensile strength. The properties of fibers are highly dependent on timing and quality of the harvest. Hemp fibers are mainly used not only for textile, paper and rope production, but also as a construction and insulation material (What is hemp, 2018).

The seeds of hemp can also be used in many different ways. They contain about 30% of oil and can be an alternative source of protein and magnesium (Britannica). Hemp seeds are typically used in different products for humans such as cosmetics, foods, pharmaceuticals, and as a fodder for animals.

Hemp is used in many different branches and fields, and is a beneficiary plant to grow for farmers (see Appendix 1). Hemp is an unpretentious plant, which requires only basic care. It grows in very dense clusters and does not need herbicides and pesticides at all. Furthermore, hemp is usually used for crop rotation, and has a potential even to heal and improve soils.

#### 4.1.1 Hemp as a main component of hempcrete



Hemp shives or hurds are commonly used and act as the main component in Hempcrete. The hemp shiv is very durable and has low pectin content (Bruijn, 2012). Due to its porous structure, shives have an ability to absorb and store a big amount of mixing water, which is required for hydration and carbonation of the hempcrete mixture (Walker R. , 2014). Such properties and composition make hemp hurds good material to use with binders as a building constituent.

Hemp shives must be correctly prepared before application and their usage in the mixture. Firstly, hemp plants must be retted for several weeks. Retting is the process of decomposition and degradation of pectineous substances that bind together bast fibers. This process happens by the action of microorganisms in soil and on the stems, and it is needed to facilitate and simplify the separation of fibers from the woody core of the plant. Then these separated woody straws are broken and chopped in smaller pieces, which are called shives (see Figure 13), and then used as an ingredient in aggregate for Hempcrete.



Figure 13. Hemp shives

#### 4.1.2 Legislation concerning hemp growth

Hemp refers to a variety of the *Cannabis sativa* plant species and is capable of containing of THC or, in other words, amount of psychoactive substance delta-9-tetrahydrocannabinol. That is why this plant is often legally controlled by the government under the national drug laws.

By reference to the European Monitoring Centre of Drugs and Drug Addicted (European Monitoring Centre for Drugs and Drug Addiction, 2018), cultivation and supply of cannabis plant for fiber is legal, but only for certified hemp varieties which THC content does not exceed 0.2% (EU Regulation 1307/2013). Therefore, special procedures for the determination and verification of tetrahydrocannabinol content in the

hemp has been established. On that basis, if the rules of hemp cultivation are satisfying and meeting the strict rules, conditions and tests, then growing of this plant cannot be prohibited in any Member State. Almost the same legislation conditions and rules are subjected to the imports of hemp, the main point of that is this THC limit is respected and observed.

## 4.2 Binder

The type of binder is very important. It is chosen according to certain properties and characteristics of final Hempcrete product.

Hempcrete is often made with the lime-based binders. Lime is material which has been used as a binder for plaster and mortars for many years. It is produced by burning limestone, chalk or marble at about 900°C. There are two principal kinds of lime: pure lime and hydraulic lime.

Pure lime is also called non-hydraulic or “slaked lime”. It primarily consists of calcium hydroxide ( $\text{Ca}(\text{OH})_2$ ), and is usually produced as putty. This type of lime sets very slowly through contact with atmospheric  $\text{CO}_2$  and moisture but has many applications in building processes.

Hydraulic lime, known as water lime, is made from lime that contains fine clay materials and can set under the exposure of water (Harrison, 2017). Plasters or mortars, which are made from hydraulic lime, has a faster setting time than non-hydraulic limes, and are often used for exterior coatings.

Lime has several environmental issues:

- It has a moderately high embodied body energy
- it is a finite resource
- due to its production and mining operations, lime is characterized by large emissions of  $\text{CO}_2$

(Rhydwen, 2015)

In some cases, cement can also be used as a binder agent in Hempcrete mixture. Cement may be the easier substance to work and use comparing to lime, and it requires less time and less labor intensity to prepare and produce mixture.

However, due to several issues, such kind of binder is ineffective. The main problem is that hydraulic nature of cement is incompatible with absorptive nature of hemp shives that results in poor material quality (KC, 2016). But cement can be added and used with hemp-lime mix, in order to speed up the hardening process and reduce the curing time (Arrigoni, ym., 2017).



Nevertheless, to use lime as a mortar or binder has many advantages:

- High porosity, high water vapor permeability
- Low thermal conductivity
- Long lasting material
- Recyclable
- Prevention of mold growth and making it undesirable to animals due to high pH value

Type, amount and a quality of lime can greatly affect the properties of Hempcrete. Strength and durability as well as setting time of the mixture are highly dependent on these variables. That's why it is important to know application area of Hempcrete, to choose correct proportions of lime binder in the mixture.

### 4.3 Water

Water plays an important role during the setting and curing processes of Hempcrete. Water must be added gradually during the mixing process. The amount of added water can lead to undesired consistency of Hempcrete mixture and can affect and impact all properties of final product.

Enormous and ample quantity of water ratio in the mixture will lead to increased setting and drying time of the whole Hempcrete object. Also, due to overabundance of water, structure will gain extra weight, which can lead to many problems such as a loss of the load-carrying capacity, or self-buckling, for example. That's why this process must be carefully and closely controlled.

### 4.4 Building Methods

Hempcrete can be cast in several different ways which have their own advantages and disadvantages. Mainly, Hempcrete is tamped, sprayed or cast by blocks. The casting method of this material is chosen according to a project or a type of Hempcrete application.

Furthermore, as it was mentioned before, Hempcrete is a non-load bearing material, which means that it must have a supporting structure such as frame (for example). Without such structure, it is extremely difficult for Hempcrete to resist and withstand the loads applied by either nature or by the structure itself.

#### 4.4.1 Blocks

Manufacturing and use of pre-cast Hempcrete blocks have increased during the past few years. Firstly, Hempcrete mixture is normally casted into special foams or moulds at the production factory and left to dry for

several months. When blocks are ready for use, they are transported on a construction site, and installed into supporting load-bearing frame. Figure 14 shows an example of Hempcrete blocks.



Figure 14. Hempcrete blocks (UK Hempcrete, 2017)

#### 4.4.2 Spraying

This method is widely used and has several significant advantages. It is used on-site with the use of a special hemp spray machine. Before casting the Hempcrete, a load-bearing frame must be constructed. Then plywood sheet is attached to that structure from one side. After constructing such formwork, Hempcrete can be sprayed. During this process the mixture is fulfilling the frame, layering and sticking to the plywood wall, forming the Hempcrete, which is then left to dry for some time (Figure 15).

Such application of Hempcrete greatly reduces construction times and saves humans resources (spend less time people's energy on mixing and constructing Hempcrete structures).



Figure 15. Spraying of Hempcrete mixture

#### 4.4.3 Tamping or hand casting

Tamping is a classical and the simplest way to cast Hempcrete. Wooden formwork must be constructed, according to a desired dimension of a Hempcrete block. Then the mixture is made and carefully tamped there by hands.

This method allows to reach the best and most effective properties of Hempcrete. By hand casting of the material, it is possible to equispace the material (evenly distribute the material in the formwork), in order to avoid large air voids and increase the performance of the final product.

#### 4.5 Hempcrete and carbon dioxide

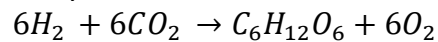
With the already existing and upcoming environmental problems, identification, developing and use of eco-friendly and sustainable materials and technologies, became extremely important objective during the last decades. Sustainable products are those which provide environmental, economic and social benefits without any detrimental and negative effect on the environment and public health during its whole lifecycle.

Hempcrete has a great potential in usage in various structures in the nearest future because it is an environmentally friendly and sustainable material.

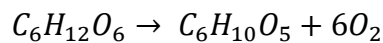
Firstly, industrial hemp is the ideal carbon sink. During its growth, due to the photosynthesis, hemp plants use energy from light to absorb and convert water and CO<sub>2</sub> into glucose, cellulose, hemi-cellulose and lignin, and then retaining carbon and releasing oxygen.

Carbon Sequestration of Hemp plant  
(simplified)

Photosynthesis:



Glucose to Cellulose:



(Hempcrete, 2013)

This process of capturing and storing of carbon dioxide is called carbon sequestration. According to Rhydwen (2015) for every ton of grown hemp approximately 500kg of carbon, or around 1800kg of carbon dioxide are sequestered. Hemp is an unpretentious plant (i.e. it can grow almost in all parts of the world and is a low-activity crop), it has a better ability for a rapid growth than most of the plants. Thus, this conduces to one of the fastest processes of absorbing carbon dioxide (Vosper, 2011).

Due to this ability of hemp, it is possible to say, that Hempcrete acts as a storage of CO<sub>2</sub>. With the higher amount of hemp shives in the mixture, it is possible to store a bigger amount of carbon dioxide in Hempcrete structure. But nevertheless, there is one environmental issue connected with Hempcrete – it is lime. The amount of CO<sub>2</sub> emissions during the limestone excavations, manufacturing of lime must be taken into account, as well as subsequent negative effects after these processes, such as the loss of vegetation, effects on air quality, potential contamination of ground water sources etc. (Pajukoski, 2017). That's why the amount of used binder in Hempcrete mixture is important (from the environmental point of view). On the one hand, a lower lime-to-hemp ratio can assure and guarantee a benefit to a Hempcrete element sustainability (Arrigoni, ym., 2017). While on the other hand, the reduction of lime binder can lead to great changes in properties and capabilities of the material, and which can negatively affect on the expectations from the final result.

Nevertheless, such chemical reaction as carbonation occurs after the casting and mixing of all constituents of Hempcrete. In this process, two mechanisms are playing a crucial role:

1. Absorption (diffusion) of carbon dioxide (CO<sub>2</sub>) in the porous structure of the material.

2. Chemical reaction between absorbed (diffused) carbon dioxide ( $\text{CO}_2$ ) and lime or calcium hydroxide ( $\text{Ca}(\text{OH})_2$ )

(Balen, 2005)

In other words, hydrated lime enters the reaction with water and air, lets the whole structure harden and dry. This reaction happens during the whole lifecycle of a Hempcrete element.

Overall, Hempcrete can be thought as a carbon sink. Due to the absorption of  $\text{CO}_2$  during the growth of hemp, and carbon capturing during drying process, this material has a negative carbon footprint. One cubic meter of Hempcrete can sequester from 117kg of carbon dioxide, depending on the binder embodied energy and re-carbonation ability of lime (Rhydwen, 2015).

With such great abilities, Hempcrete should be much more closely considered a sustainable material, which must and can be used in various “green” and eco-friendly structures.

## 5 PERFORMANCE OF HEMPCRETE

Hempcrete, as a building material, has unique characteristics and properties. Therefore, it is possible to use it in various fields of construction as Hempcrete can be acoustic, thermal insulation, or even good structural material.

The performance of Hempcrete varies and depends upon quality and proportions of constituents, which are added in the mixture. Thus, different ratios of hemp, lime and water mix are intended for unique target usage.

One of the main discrepancies between mixes is the ratio of binder and water usage. This proportion will have great effect on balance between structural strength and insulation properties. Thus, for example to make walls stronger, the amount of binder must be increased (Ahlberg, Georges, & Norlem, 2014)).

In the following sections, the main properties of Hempcrete are listed. It is important to know and remember that performance of each object, made from material can differ and vary, and totally depend on the quality of ingredients, designers and manufacturers of Hempcrete.

## 5.1 Acoustic properties

Hempcrete has specific sound properties and is a good sound absorbent material due to its dense and porous structure. Sound absorption is an ability to take in sound energy when sound waves are emitted.

Hemp-to-binder ratio plays an extremely important role in the quality and amount of sound reduction of Hempcrete. As it was tested by Prabesh KC, in his work (KC, 2016) the best performance of sound reduction was achieved with the Hempcrete block, in which different kind of hemp shives were mixed. Proceeding from this condition, it is possible to say that with mixing of several different hemp particles in one Hempcrete structure will significantly increase the sound absorptive ability of the material. Philippe Gle also came to this conclusion. In his report (Gle;Arnaud;& I Gourdon, 2011), he assumed and came to a decision that sound absorption in Hempcrete is intermediate between the excellent absorption of hemp shiv, and the sound reflection ability of the binder. According to this, type and ratio of the binder must be correctly investigated and decided before the manufacturing of Hempcrete structure, as it can reflect on the sound properties of the materials

As it was achieved and calculated by Prabesh KC (2016) in his sound tests of Hempcrete:

- The transmission loss of the Hempcrete wall=46dB
- The sound reduction of High frequency noises, like household=44dB
- The sound reduction of low frequency noises, like traffic=39 dB

Table 1. Comparison of approximate transmission loss values for different materials (U.S Department of Transportation Federal Highway Administration, 2000)

Material	Dimension Thickness (mm)	Weight kg/m <sup>2</sup>	Transmission Loss (db(A))
Hempcrete	170	135	46
Concrete block light weight	200	151	34
Dense Concrete	200	151	34
Light Concrete	150	244	39
Steel	1.27	10	25

Wood, Fir	50	32.7	24
Plexiglass	6	7.3	22

As it is shown in Table 1, it is possible to compare it to other materials, which are used in noise barrier walls. Overall, with such sound properties, Hempcrete can be used and implemented as a new material in noise barriers.

Furthermore, in theory, to achieve even a greater and much more significant number in noise reduction index a specific design of Hempcrete element is needed. It is possible to do that by adding several uniform layers of hemp fibers in the wall structure. This will increase the sound absorptive abilities and will not result in or decrease the mechanical properties of the material. But nevertheless, more detailed investigations and researches are needed.

## 5.2 Compressive and Tensile Strength

One of the most essential characteristics of any material are compressive and tensile strengths. Hempcrete is a non-load bearing material, which means it has low compressive and low tensile strength comparing to concrete, for example.

Compressive strength of any Hempcrete structure may vary. This is connected with several different factors and issues. Many researches have been done in this field, and according to Tarun Jami (2018) the compressive strength of Hempcrete can range from 0.2 to 6.94 MPa or can be even higher. This refers to several different factors and issues. Mostly, it is related to mixing ratios and mixing methods of the constituents.

The compressive strength of Hempcrete is a function of hemp shive particles, quality and chemical composition of binder content, as well as drying conditions, mixing and application method of the mix (Gregor, 2014). This means that with the change of one of these parameters or methods, will lead to an alteration of the strength of the material. The mechanical properties of Hempcrete can be enhanced with the addition of hemp fibers, and increased binder agent ratio in the mix (according to the binder content, the higher the content in the mixture is the closer the mechanical behavior of hemp concrete to the mechanical behavior of the pure binder (Gregor, 2014)).

Furthermore, the density of constituents and compaction of the material play its role. Compaction during the casting or mixing phase makes the mixture more consistent, massive and dense as the compactness increases. As researches showed that Hempcrete structures, which were fabricated and manufactured without any compaction, tended to have lower Young's modulus and dimensional stability than compacted ones (Jami, Karade, & Singh, 2018).

Another important special ability of Hempcrete is that compressive strength hinge on the age of the material, as it increases over time due to the process, which happens during the drying phase of the material. That is why, the material can reach its maximum compressive strength in several months or even years.

Nevertheless, with the possible increasing of compressive strength, other characteristics such as acoustic, thermal or other properties, which depend on the ratio of constituents, will be affected, too. For that very reason, it is important to find a balance in a mixture ratio of constituents and choose the most relevant for the application.

As basically, Hempcrete has a low compressive strength, most of the hemp structures need a load-bearing frame, which will carry all the loads on itself. Hereby it gives an opportunity to use acoustic and thermal characteristics of the material to its full extent. Therefore, it is not so important to try to increase and reach a maximum compressive strength of the material as the load-bearing frame will take all actions on itself.

### **5.3 Other Non-acoustic performance**

#### **5.3.1 Weather sustainability**

The climate in Finland is mostly influenced by the location of the country. Finland is located between the latitude of 60 and 70-degrees North and has short summers and long winters. Finnish climate is usually called intermediate climate, which combines characteristics of continental and marine climate. The weather in the country relies on weather disturbances and prevailing wind directions, as Finland is located in the wind zone where polar and tropical air masses meet together. That is why weather types can vary rapidly, especially in winter season.

Winter is the longest season, which lasts about 100 days and usually begins in mid-October in Lapland and during November in the rest of Finland. The average temperature during winter time usually remains below 0°C and can drop down to -30°C. Summer usually begins in the late May in southern Finland and lasts until mid-September. During that period, mean daily



temperature is always above 10°C and reach up to 30°C (Finnish meteorological institute).

As it is known, Hempcrete has a porous structure, which means it has an ability to store and hold water. According to some researches, Hempcrete can manage moisture related issues and problems effectively, but due to the ability of hemp to absorb high capacities of water and porosity of the whole structure, Hempcrete becomes a very sensitive material to the capillary actions. Following the tests and research made by Yoann Castel (2017) this ability of Hempcrete can deteriorate and change the characteristics of the material. High water content in the material can lead to the bulking of the aggregate with subsequent alterations of volume and decrease of compressive resistance of Hempcrete, due to the changes of the binder matrix. Firstly, in order to protect the material from extreme humidity and to avoid such quality degradation, it is extremely important to watch over conditions, in which and where Hempcrete is cast and constructed. Secondly, a hydrophobic product can be added during the manufacturing of Hempcrete, to limit the absorption of water by hemp (Yoann, Sofiane, & Mohammed, 2017).

Based on the above, it is assumed that such hydrophobic products and additives as water retainers facilitate sustainability and durability augmentation, especially in winter conditions. Freezing conditions usually exert influence on lime: pozzolan concretes such as Hempcrete. This strong impact is generally expressed in a reduction of compression strength. According to R. Walker "The freeze: thaw resistance of hemp concrete is a function of the hydraulicity of the binder", which means that Hempcrete, which contains the most hydraulic binder, will benefit from decreased water absorption and demonstrate better performance in freezing conditions due to a limited available water which can cause a freeze: thaw damage (Walker R. P., 2014).

Furthermore, Hempcrete is totally resistant to a salt exposure, sodium chloride and biological deterioration due to a microbial attack. This was tested and also proven by Walker, Pavia and Mitchell (2014). These facts allow to come to a conclusion that it is possible to use Hempcrete in realities of the Finnish weather conditions, but with the exception that the mixture of the material must be developed and must contain water retainers, in order to sustain periods of weather changes.

### 5.3.2 Fire resistance

There is a very limited data on fireproof tests from Hempcrete structures; however, suppliers and manufacturers claim that Hempcrete is a fire-resistant material. Several researches and fire tests were conducted by BRE Group in UK, in which 3m x 3m non-rendered Tradical® Hemcrete® wall in accordance with BS EN 1365-1:1999. The wall was subjected to the fire exposure, and it resisted it for 73 minutes (Sparrow & Stanwix, 2014).

Another test was conducted by Centre Techniques du Bois et de l'Ameublement in France. Blocks, manufactured by Isochanver, were classified as M1, improving to M0 class. According to French classification, these classes refer to 'non-flammable materials' (Daly, Ronchetti, & Woolley, 2009).

Even though there is very limited information available about fire proof properties of hempcrete, this material has positive fire resistance properties, which must be studied more deeply.

### 5.3.3 Reuse of Hempcrete

One of the most important features of Hempcrete is an ability to reuse it. Due to its physical capabilities and properties of constituent materials, Hempcrete can be remixed and reused in any other mixture. As Hempcrete is very easy to break, old structures can be demolished or dismantled, and after these steps the old cast Hempcrete can be remixed and added to a new aggregate.

## 6 PROTOTYPE DESIGN OF HEMPCRETE NOISE BARRIER WALL

Nowadays people are becoming more and more concerned about environmental problems, and therefore the implementation of innovative ideas related to a sustainable and energy efficient solutions in various sectors and fields is crucial. This trend also took place in a highway construction sphere, and at the moment any road structure must be designed in a way to meet requirements towards sustainability. As it was described before, one of the biggest issues in the road sphere – is excessive noise and noise pollution. Structures, which are supposed to mitigate and solve this problem, are also expected to be made with the use of environmentally friendly materials. But nevertheless, today the majority of noise barriers are still made from either concrete or plastics, hereby they usually have a negative impact on the environment.

Therefore, Hempcrete noise barrier can be a great solution, which meets all the demands of a modern noise wall structure. This material has unique acoustical properties, and a very low impact upon the environment. As this material and the whole structure of such highway noise wall are innovations in the road construction field, there are many important things which must be considered. In this section of the thesis, concept, prototype design and theoretical advantages and disadvantages of Hempcrete noise barrier wall are presented and described.

## 6.1 Structure description

A noise barrier wall made from Hempcrete can greatly fit in and contribute into sustainable road construction development. The main purpose of the use of Hempcrete as the main material for a highway noise barrier is to bring up the innovation of green, environmentally friendly and energy efficient structure into the sphere of road engineering. The main advantage of a Hempcrete noise barrier is that this kind of wall has a very low impact upon the environment due to the unique feature of the material to sequester carbon dioxide. Acoustical properties of the Hempcrete are also impressive, as tests, which were performed by KC Prabesh in his thesis (KC, 2016), showed Sound Reduction Index of 46dB. This result testifies that Hempcrete noise barrier wall can be and must be an effective device for mitigation of noise.

In this part of the thesis, a prototype of a Hempcrete noise wall is presented. As stated before, Hempcrete is a non-load bearing material, which means that it needs some special supportive frame. The design of the wall was chosen following several principles of Hempcrete structures. But nevertheless, the design of specific details, such as the foundation and dimensions of the barrier, must be chosen on the basis of the construction site of the barrier and the aims for which barrier is going to be used (because the thickness of Hempcrete is variable; with increased thickness greater sound reduction can be achieved; thus, the cost of the wall will be increased as well). In the Figure below, the 3d model of the prototype of Hempcrete noise barrier is presented.

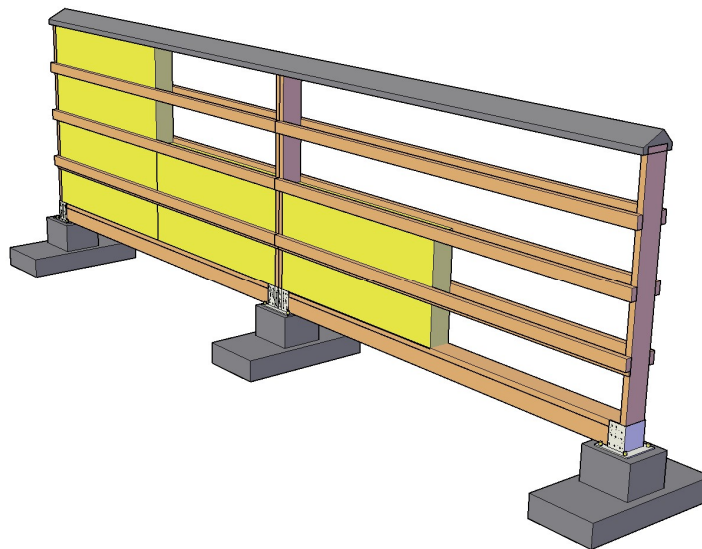


Figure 16. 3D prototype of Hempcrete noise barrier

In this model, the wall is showed in section view, in order to provide a better understanding of the structure. As it is possible to understand from the picture, yellow colored blocks represent Hempcrete blocks. The purpose of such design will be described in the next subsection. As for

structural design of the wall, it was made and calculated according to the European standards, which are going to be listed below.

- EN 1971-1 Eurocode 7: Geotechnical design
- EN 1991-1-1 Eurocode 1: Actions on structures – Part 1-1: General actions- Densities, self-weight and imposed loads
- EN 1991-1-4 Eurocode 1: Actions on structures – Part 1-4: General Actions – Wind actions
- EN 14388: Road traffic noise reducing devices. Specifications
- Set of EN 1793: Road traffic noise reducing devices. Test methods for determining the acoustic performance
- Set of EN 1794-1: Road traffic noise reducing devices. Non-acoustic performance.
- Set of EN 14389: Procedures for assessing long term performance
- TIEH 210062-09: Tien melusteiden suunnittelu, luonnos 9.12.2009 (Designing of road noise barriers, draft for trial use 9.12.2009)

## 6.2 Hempcrete Noise barrier wall design

Hempcrete noise barrier is absolutely a new kind of highway noise mitigation device, which has no analogues yet. The main desired aim was to design a cost efficient, easy maintainable environmentally friendly noise barrier wall, which can be used in various climatic conditions. Figure 17 contains a 3D drawing of Hempcrete noise barrier wall.

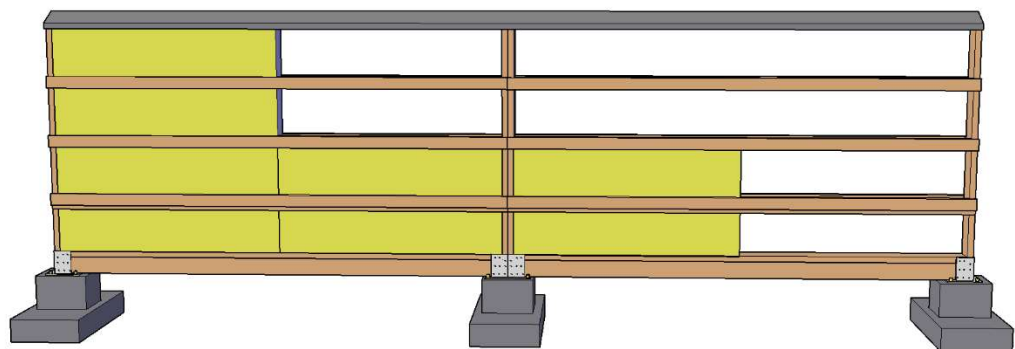


Figure 17. 3D drawing of Hempcrete Noise barrier wall. Front view.

Hempcrete noise barrier wall is divided into frames or modules, which make it possible to create as long noise barrier walls as needed. Each module is 4 meters 10 cm long, the height of the barrier is 2 meters 20 cm, the width of this barrier is 20 cm (later in this subsection, the selection of dimensions will be explained, as they were chosen according to several structural principles, and properties of the main material – Hempcrete).

Dimensions and 2D drawing of Hempcrete noise barrier wall is presented in Figure 18.

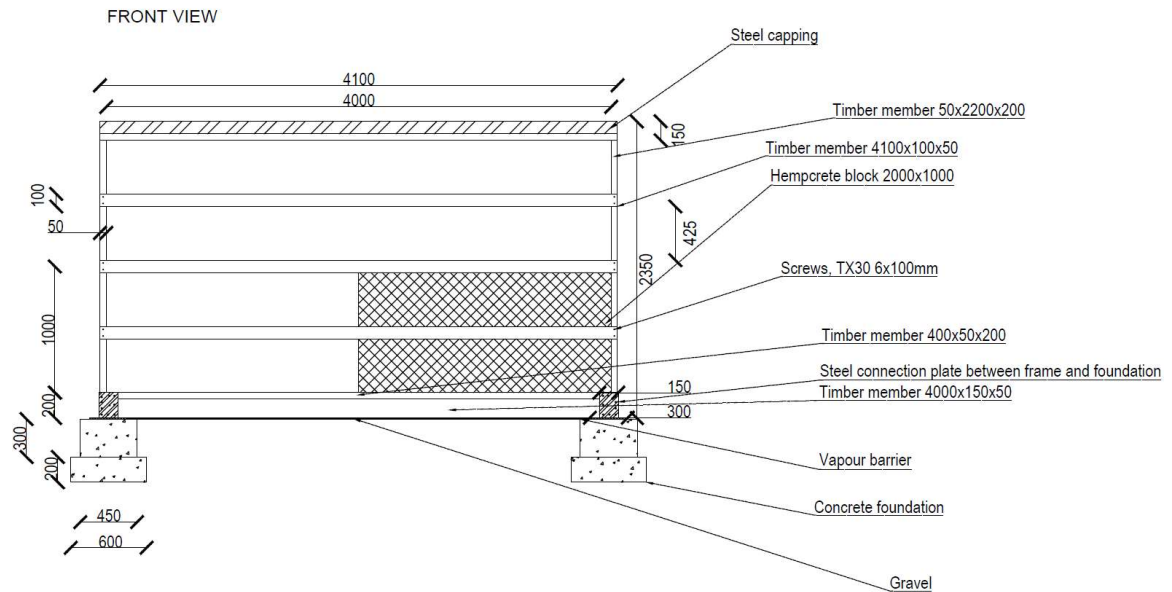


Figure 18. 2D drawing of Hempcrete noise barrier wall. Front view.

### 6.2.1 Hempcrete

Hempcrete blocks, which are used in this prototype of the noise barrier wall, are made and prepared almost according to the Hempcrete element of the wall element 3 by Prabesh KC (2016).

The main parameter, which plays a role in terms of acoustic properties – is thickness. This means that sound will be less absorbed by a Hempcrete block with smaller thickness. In a nutshell, in this prototype, a Hempcrete block represents a sandwich type of structure and consists of three different layers of hemp shives and fiber: small shives, 60mm (first layer); hemp fiber, 50mm (middle layer); large shives, 60mm (third layer). Such combination and distribution of the material contribute and ensure the quality of acoustic and mechanical properties. Based on the results of the studies and tests (KC, 2016), the sound reduction of such element is:

$$R_w = (C; C_{tr}) = 46 \text{ (-2; -7) dB}$$

Where,

The sound reduction of High frequency noises equals  $46 - 2 = 44 \text{ dB}$ ;

The sound reduction of Low frequency noises equals  $46 - 7 = 39 \text{ dB}$ ;

According to these results, it was decided that the thickness of 170mm Hempcrete block can be successfully used in a noise barrier. But for the best performance, for easier manufacturing of Hempcrete and further construction of the wall, the thickness should be increased up to 200mm.

Further on, Hempcrete blocks are desired to be 2000mm long and 1000mm height due to several reasons. Firstly, using such dimensions of Hempcrete will simplify the selection of other details for the barrier (supportive frame). Thus, it will make it easier to build the whole structure of noise barrier wall. Secondly, Hempcrete blocks with bigger proportions are much harder to manufacture, their compressive strength will be relatively lower, and the stability of the structure will be decreased.

In view of the foregoing, the most preferred dimensions for the Hempcrete block is 2000mm x 1000mm x 200mm. In the section “Construction of a noise barrier wall”, manufacturing of prefabricated Hempcrete blocks is presented and described in order to optimize and develop the prototype of a noise barrier.

#### 6.2.2 Supportive frame

As Hempcrete is a non-load bearing material, it is a must to design such supportive frame which will meet several criteria:

- Material compatibility with Hempcrete
- Load bearing capacity
- Sustainability and longevity
- Environmental impact
- Weather resistance

The given parameters are needed to be carefully considered as a supportive frame is the main component of a Hempcrete noise barrier wall, which has to act as a base for Hempcrete, sustain and resist all applied forces on it. For the given project, timber was chosen as a material for supportive frame. This decision is based on the following key factors.

Timber is a very common material, used in many kinds of structures, especially noise barriers. Comparing to other materials, it has very high structural performance and efficiency and a high compressive strength. Furthermore, timber is very adoptable, long-lasting durable material, and as it is much lighter by volume than both steel and concrete, it is much easy to work with and use it in different kind of projects.

One of the main advantages why timber is used as a main material for the supportive frame is that it works well and is totally compatible with Hempcrete. Wood has a porous structure and ability to absorb sounds. Such combination of absorbent material will increase the acoustic

performance of the noise barrier wall. Another significant and important factor of material compatibilities are thermal bridges. As it is known, thermal bridges between different materials can cause substantial damage, which can lead to a fatal consequence. Even though thermal bridges are also created between Hempcrete or hemp-lime composites and timber, the created effects are relatively small (Przemysław Brzyski, 2019) and does not affect or damnify the structure. While, at the same time, the use of steel with Hempcrete can be loss-prone, as thermal bridges, which are formed, cause heavy losses to the whole performance of the structure. As thermal bridges conduct the reduction of temperature between the materials, which create a risk of condensation and mould growth. It can be stated that condensation in Hempcrete can play a crucial role due to the properties and capability of the material to absorb water. Due to the oversaturation and reabsorption of water, Hempcrete blocks can be just damaged from within; thus, decrease in performance of the whole noise barrier wall will appear.

In the design of prototype Hempcrete noise barrier wall, pine sawn timber of class C24 is used as a material for a supportive frame. It is affordable material which has suitable structural properties for different types of wood structures. Pine is naturally sustainable and durable material, primarily consisting of cellulose, hemicellulose, and lignin in a matrix that gives resistance to a microbial attack. But nevertheless, due to special aspects and features of the Finnish climate, to increase the life period of any timber structure, wood should be impregnated. Impregnation of wood gives necessary characteristics, increasing strength, water, moisture and microbial resistance and reduces cracking. Pine wood is the best suited for impregnation due to the cell walls structure design which allows the impregnation to penetrate deeper. There are various types of timber preservation, and therefore special classification for pressure treated wood which is based on the European standards was made by the Nordic Wood Preservation Council (NTR). Based on that, in this project timber of Class A impregnation must be used. As this class is intended to pine wood structures, which will be in contact with earth, concrete, and ground or freshwater; and used for safety-promoting structures such as load-bearing structures, piers, fence posts, bridges etc. For more concrete and accurate information the following sets of European standards concerning wood durability should be checked: SFS-EN 351 (Durability of wood and wood-based products. Preservative-treated solid woods).

Coming down to a conclusion of this section, a timber supportive frame for a Hempcrete noise barrier consists of several different members of different measurements. Front and side views are presented both in 2d and 3d in Figure 19, 20, 21 and 22.

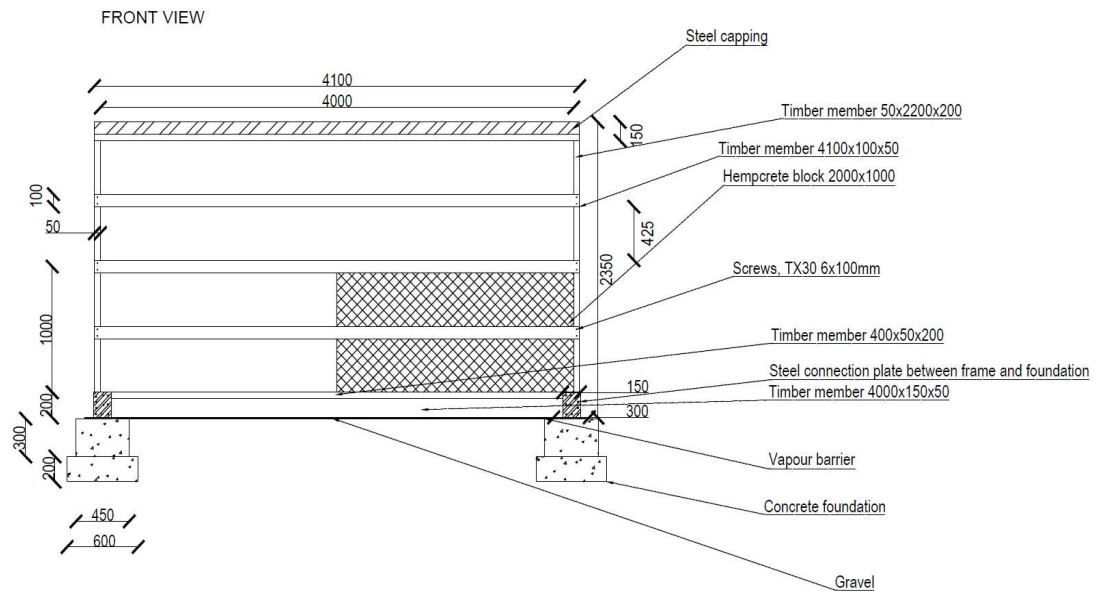


Figure 19. 2D drawing of Hempcrete noise barrier wall. Front view.

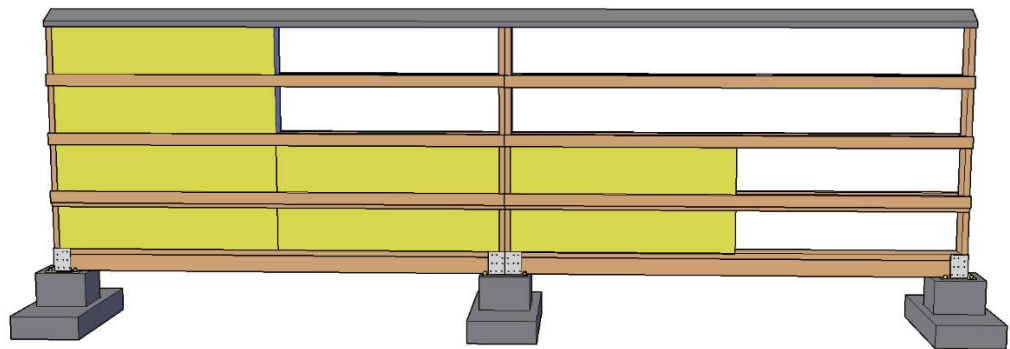


Figure 20. 3D drawing of Hempcrete noise barrier. Front view.



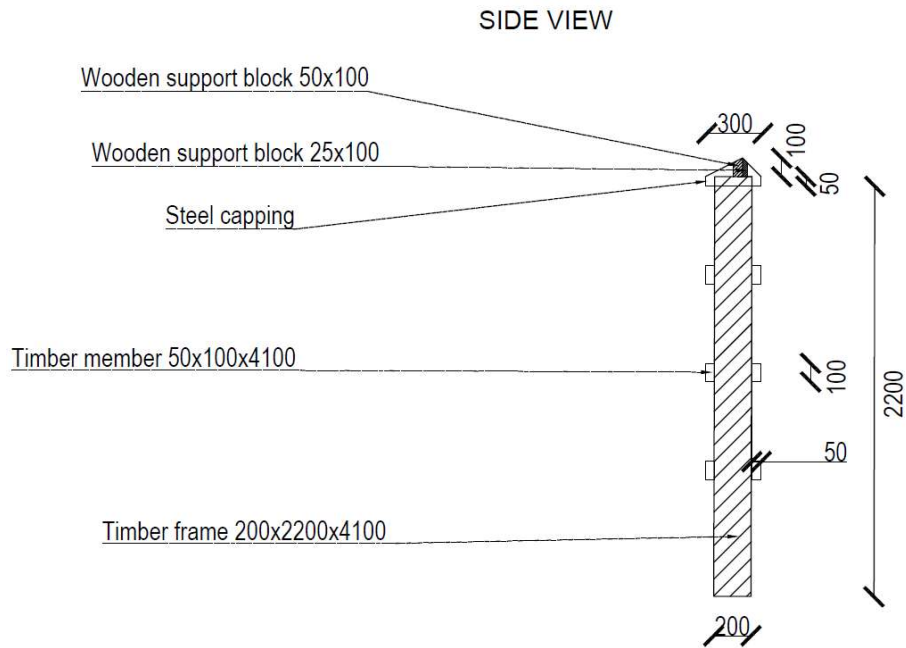


Figure 21. 2D drawing of Hempcrete noise barrier. Side view.

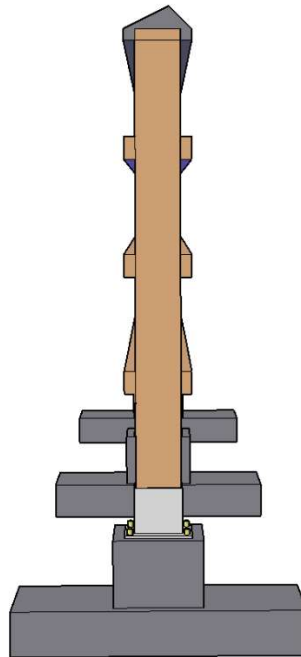


Figure 22. 3D drawing of Hempcrete noise barrier wall. Side view.

Such simple design, combination of materials, and use of timber as the main material for a frame will guarantee great sustainable, efficient and long-lasting performance. In addition, such structure will complete and fulfil one of the most important requirements set on a noise barrier walls – visual design. With proposed design of timber supportive frame, Hempcrete noise barrier will perfectly fit and integrate into the landscapes of Finnish roads and highways.

### 6.2.3 Foundation

The foundation of a noise barrier must provide stability. Thus, it must be carefully designed and planned. Nowadays due to the enormous amount of technologies used, there are a various types of foundations. However, most common types of foundation are slab and piling foundations. The final decision about its design must be made proceeding from the geotechnical survey, which is performed according to the Eurocodes and during the planning phase of the barrier. Soil behavior, its properties and parameters of backfill are determined firstly following the EN 1997 standard. Other factors such as possible ground movements, anticipated future excavation activities, ground water levels, extent of frost penetration, ground stability etc., must be taken into the account Briefly speaking, pile foundation is used in a weak soil, so its main function is to distribute loads from a structure into the rock or more firm underground soil. This kind of foundation can be successfully implemented in the project of Hempcrete noise barrier wall.

However, in this case a concrete slab foundation was chosen. This type of foundation is used in soils where drilling is impossible and places with frequent engineering works. A concrete foundation provides necessary sustainability and long-lasting performance to a Hempcrete noise barrier. In Figures 23 and 24 below, the prototype of foundation is presented:

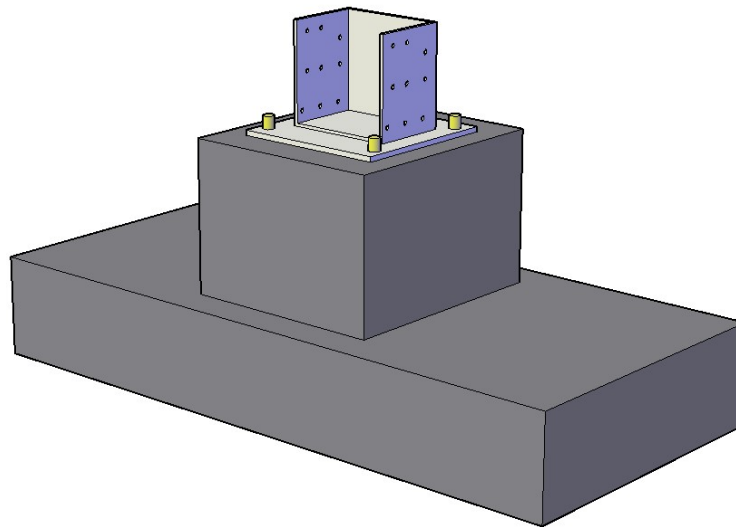


Figure 23. 3D drawing of foundation for Hempcrete noise barrier. Basic view.

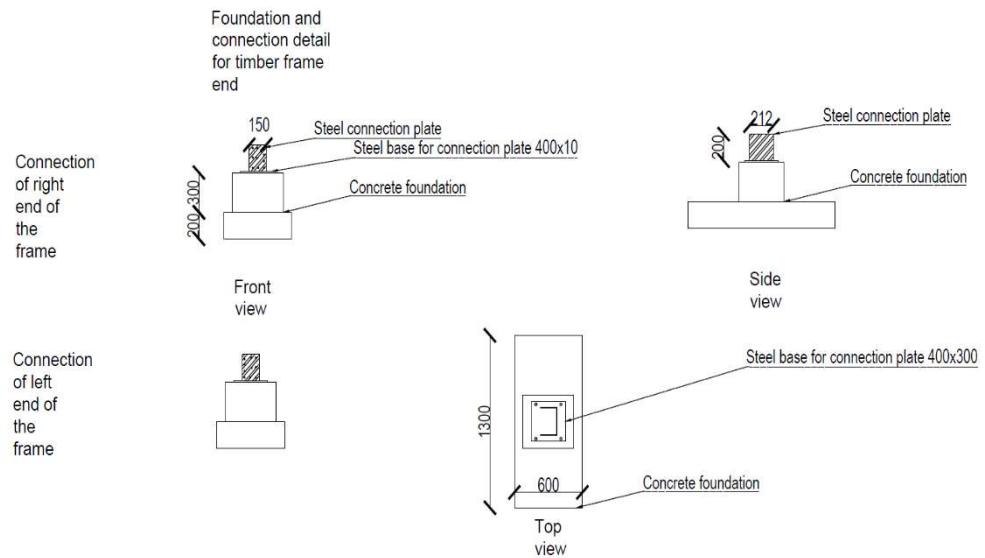


Figure 24. 2D drawing of foundation for Hempcrete noise barrier.

Precise drawings of foundation details and their connections with timber frame are presented in the Appendix 2.

Such T-Shaped concrete foundation will support whole Hempcrete noise barrier wall and take loads from the timber frame, in order to withstand lateral wind loads. Footings are placed below the frost line of the ground and afterwards connected with a timber frame with special connecting details. In this project concrete C30/37 – XF4 is used (research on the types of concrete foundations was done showing that most of the time this class of concrete is used in similar designs of noise barriers). But with the upcoming environmental trends, recycled aggregate can be used in a concrete foundation in order to decrease the environmental impact. The recycling of building components became a significant issue during the past years and there is a big opportunity to recycle concrete from demolished structures. The use of recycled aggregates is a serious step towards sustainability, which will contribute to the economy and saving of energy and raw material resources. In the technical report “Use of recycled concrete aggregate in high-strength concrete” written by M.C Limbachiya (2000), tests showed that the use of recycled concrete aggregate or RCA up to 30% had no effect on the strength and quality of the material.

To sum up, concrete foundation is chosen for the current design of Hempcrete noise barrier. In order to develop the structure, decrease the environmental impact and make it unique environmentally sustainable object, the foundation of the structure can be made with the use of RCA (recycled concrete aggregate) which has its advantages and disadvantages. As in this thesis, only a prototype of Hempcrete noise barrier wall is presented, the final design of foundation must be made only according to the installation site of the barrier. Additional information about the use

and properties of recycled aggregate concrete can be read in publications listed in References (R. V Silva, 2014), (Sakai, 2017), (Mukesh Limbachiya, 2000).

### 6.3 Calculations

Non-acoustic performance of noise barrier walls must be designed in according to the following European standards:

- EN 1794 -1 Road traffic noise reducing devices. Non-acoustic performance. Part 1: Mechanical performance and stability requirements
- EN 1991-1-4 Eurocode 1: Actions on structures. Part 1-4: general actions. Wind actions
- EN 1971-1 Eurocode 7: Geotechnical design
- EN 1991-1-1 Eurocode 1: Actions on structures – Part 1-1: General actions- Densities, self-weight and imposed loads

#### 6.3.1 Dead load

The dimensions and measurements of used materials are presented in Table 2.

Table 2. measurements of materials

	Length, l, m	Width, a, mm	Thickness, b, mm
Timber member 1	2,25	200	50
Timber member 2	4	200	50
Timber member 3	4,1	100	50
Timber member 4	4	150	50
Hempcrete block	2	1000	200

Density of pine:  $\rho_p = 420 \text{ kg/m}^3$

Density of Hempcrete block:  $\rho_h = 275 \text{ kg/m}^3$

Weight of timber members

$$W_t = (m_1 + m_2 + m_3 + m_4) \cdot g$$

Whereby,

$W_t$  is total weight of timber member of frame;

$m$  is the total mass of each timber member;

$g$  is the acceleration of gravity, equals to  $9,8 \text{ m/s}^2$ ;

Consequently, to find a weight a total weight of timber frame, a weight of each timber member must be found firstly. Hereby, with the use of abovementioned table of measurements of materials, calculating:

Timber member 1 :  $m_1 = l_1 * a_1 * b_1 * \rho_p * 2 = 18,9 \text{ kg}$

Timber member 2 :  $m_2 = l_2 * a_2 * b_2 * \rho_p * 2 = 33,6 \text{ kg}$

Timber member 3 :  $m_3 = l_3 * a_3 * b_3 * \rho_p * 6 = 51,66 \text{ kg}$

Timber member 4 :  $m_4 = l_4 * a_4 * b_4 * \rho_p * 2 = 25,2 \text{ kg}$

Total weight of timber frame:  $W_t = 1,269 \text{ kN}$

### **Weight of Hempcrete blocks**

With the same principle, calculating the weight of Hempcrete blocks:

Weight of Hempcrete blocks:  $W_h = (l_h * a_h * b_h * \rho_h * 4) * g = 440 \text{ kg}$

Weight of whole structure:

$W_s = W_t + W_h = 5,86 \text{ kN}$

## **6.3.2 Wind loads**

Wind loads of a Hempcrete noise barrier shall be calculated in accordance with EN 1991-1-4 (Eurocode 1: Actions on structures. Part 1-4: general actions. Wind actions) with following basic values:

Season factor  $c_s = 1$

Directional factor  $c_d = 1$

Fundamental value of the wind velocity in Finland  $v_{b,0} = 21 \text{ m/sec}$

Wind velocity  $v_b = 21 \text{ m/sec}$

### **Mean wind velocity**

Mean wind velocity depends on terrain roughness, orography and on the basic wind velocity factors, and must be found from the following expression:

$$v_m = c_r * c_0 * v_{b,0}$$

Where,

$c_r$  is the roughness terrain factor;

$c_0$  is the orography factor, equals to 1;

### **Terrain roughness:**

This factor accounts for the inconstancy of the mean wind velocity at the site of the structure due to the height above the ground, or the ground roughness of the terrain upwind of the structure in the wind direction considered. In order to determine this value, it is a must to check terrain categories and terrain parameters, which can be found in the EN 1991-1-4 instructions. For this kind of project, terrain category III is taken, which stands for the area with regular cover of vegetation or buildings or with isolated obstacles with separations of 20 obstacle heights; in other words, such as villages, suburban terrain or permanent forest.

For terrain category III, the following values must be applied:

$Z_0 = 0,3$  is the roughness length

$Z_{min} = 5$  is the minimum height

$Z_e = 2$  is the maximum height

From following values, Terrain factor must be calculated:

$$k_r = 0,19 * (Z_0/0,05)^{0,07} = 0,215$$

In order to find terrain roughness:

$$c_r = k_r * \ln(Z_e/Z_0) = 0,408$$

Proceeding further, all the needed values are determined and mean wind velocity equals:

$$v_m = c_r * c_0 * v_{b,0} = 8,581 \text{ m/sec}$$

### **Turbulence intensity**

This factor is defined:

$$I_v = k_1 / c_0 * \ln(Z_e/Z_0) = 0,527$$

Whereby,

$k_1$  is the turbulence factor, which equals 1 according to the National Annex

$c_0$  is the orography factor

$z_0$  is the roughness length

### **Peak velocity pressure**

The peak velocity pressure involves mean and short-term fluctuations of velocity, and must be calculated by following formula:

$$q_p = (1 + 7 * I_v) * 0,5 * \rho * v_m^2 = 215,83 \text{ Pa}$$

Where,

$\rho$  is air density, equals to 1,25 kg/m<sup>3</sup>

$I_v$  is the turbulence intensity

$v_m$  mean wind velocity

### Wind forces

The wind forces for the noise barrier may be calculated by using the following expressions:

$$A_{ref} = h \cdot l = 9,225 \text{ m}^2$$

whereby,

$A_{ref}$  is the reference area of the structural element

$h$  is the height of the Hempcrete noise barrier wall, equals to 2,25m

$l$  is the length of the wall, equals to 4,1 m

$$F_w = c_s \cdot c_d \cdot c_f \cdot q_p \cdot A_{ref} = 1,991 \text{ kN}$$

Where,

$c_s$  is the season factor;

$c_d$  is the directional factor;

$c_f$  is the safety factor, equals 1

$q_p$  is the peak velocity pressure

$A_{ref}$  is the reference area of the structural element

### 6.3.3 Basic calculations for foundation

As it was previously mentioned the design of foundation for the noise barrier always depends on the site and soil properties of construction. That is why following calculations are just an example and must be done by a professional engineer with all necessary information concerning the geotechnical works.

#### Critical parameters of foundation

Width of foundation  $B_f = 0,6 \text{ m}$

Length of foundation  $L_f = 0,6 \text{ m}$

Depth of foundation  $D_f = 0,5 \text{ m}$

#### Soil parameters

Soil type: Silt

Bulk weight of soil:  $\gamma_1 = 16 \text{ kN/m}^3$  ;  $\gamma_2 = 6 \text{ kN/m}^3$

Factor of safety (FOS) : 1, 25

Friction angle:  $\phi_{\text{characteristic}} = 28^\circ$

Design value of friction angle:  $\phi_{\text{design}} = 23^\circ$

### Calculation of factors

Bearing capacity factor :  $N_D = 8,7$

Bearing capacity factor :  $N_B = 2(N_D - 1) * \tan 23^\circ = 6,573$

Shape factor

$S_D = 1 + (B_f / L_f) * \sin 23^\circ = 1,391$

$S_B = 1 - 0,3 * (D_f / L_f) = 0,75$

Force factors

Horizontal force  $H_d = 2 \text{ kN}$

Vertical force  $V_d = 6 \text{ kN}$

$i_d = (1 - 0,7 * (H_d / V_d))^3 = 0,451$

$i_B = (1 - H_d / V_d)^3 = 0,296$

### Bearing capacity

$\sigma_{\text{allowed}} = \gamma_1 * N_D * D_f * S_D * i_d + 0,5 * \gamma_2 * N_B * B_f * S_f * i_B = 46,233 \text{ kN/m}^2$

Force allowed:  $5,86 \text{ kN}$

In other words, it means that those measurements of width, depth and length of foundation footings are critical, and they will handle only 5,86kN per one footing. It is a must to design such footings, so that the wall will be stable under the influence of potential bigger forces. Because of that, the width of foundation should be increased.

### Final width

Wind force  $F_w = 1,991 \text{ kN}$

Vertical force  $V_d = 6 \text{ kN}$

Force applied on the area  $a = 1,125 \text{ m}$

Moment  $M_w = F_w * a = 2,24 \text{ m*kN}$

Factor  $e_f = M_w / V_d = 0,373$

$B_{\text{final}} = B_f + 2 * e_f = 1,347 \text{ or } 1,3 \text{ m}$

All the above mentioned calculations can also be found in the end of this document in the Appendix 3.

## 6.4 Construction

The construction of Hempcrete noise barrier wall can be realized in several different ways, which basically depends on the casting types of Hempcrete blocks and the site of future placement of the wall. The main advantages of the presented prototype of the noise barrier are its simplicity in



structure and its modularity. This term will be explained clearly in the following text.

Hempcrete noise barrier mainly consists of three parts: four Hempcrete blocks, timber frame and foundation. Thus, in general, the construction of a Hempcrete noise barrier can be divided into several stages:

- Fabrication of Hempcrete blocks
- Examination of site and formation of geotechnical notes for the design of foundation for the noise barrier wall
- Prefabrication or preparation of the material for timber frame
- Construction of the foundation
- Assembling of the wall

The most difficult and, probably, the most time-consuming part of construction of the wall is the part of casting Hempcrete. Previously, at the beginning of this thesis, various types of Hempcrete casting were presented. On their basis, it is possible to arrive to a conclusion that they must be somehow improved and developed, in order to simplify the process of assembling the structure and making the whole process of construction of the wall more efficient. As the research was made, the best option for casting Hempcrete is the prefabrication of blocks with their further transporting to the construction site.

#### 6.4.1 Production of Hempcrete blocks

Hempcrete blocks allow several extremely effective and useful options, which are not available during other casting methods. First of all, the production of blocks can be unlimited in terms of time and material quantities. For example, the spraying or hand casting of Hempcrete is not possible without readymade a supportive frame. Even if those methods are applied, Hempcrete must dry at least three months, which means the wall must be under the protection almost all the time, so it does not receive any damage due to various circumstances. Furthermore, casting blocks on special facilities can be totally controlled; consequently, the quality of the Hempcrete will be much better. However, there are some problems. It is quite complicated to cast a block of a size which perfectly matches the frame. Another problem is that several blocks should be cast which are not connected to each other. Nevertheless, a solution for these problems was found specifically for this project and discussed below.

For this project of Hempcrete noise barrier special kind of Hempcrete blocks and their manufacturing process was developed. The main point is to make a simple prefabrication process of Hempcrete blocks, which can be connected with each other. In Figure 25 below, a 3D model of such block is presented.

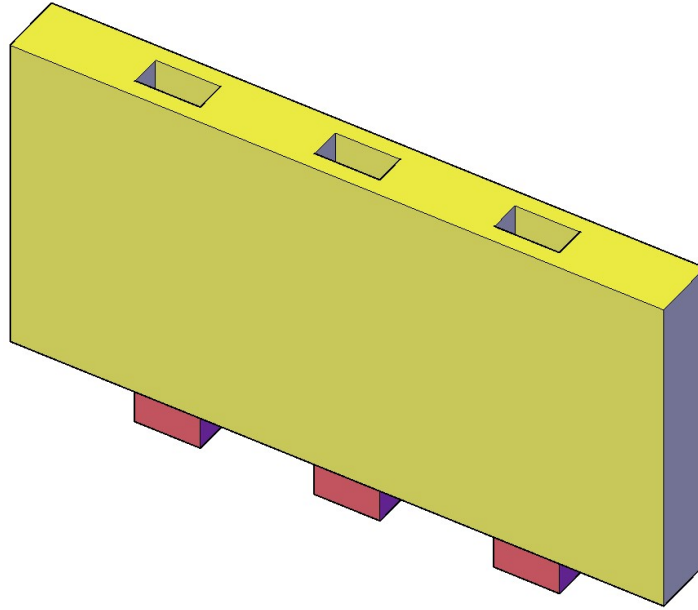


Figure 25. A modified Hempcrete block. Basic view.

The presented design somehow reminds and is based on the same principle as Lego blocks. Timber member connectors are integrated into the structure of Hempcrete. The improvements reside in the fact that with such a design blocks can be easily connected and disconnected, which simplify the assembling of the blocks into the supportive frame. Furthermore, it will add more stability to the structure, and partly remove some responsibilities and load distribution from the timber frame. Below, 2D sketch drawings of this type of block are presented in Figure 26, 27 and 28.

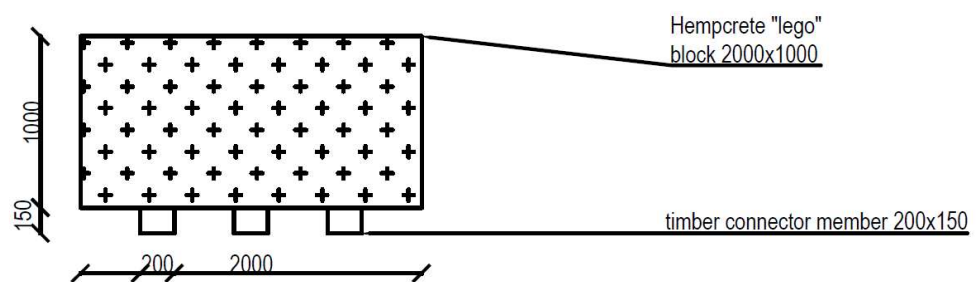


Figure 26. Hempcrete block. Horizontal view.

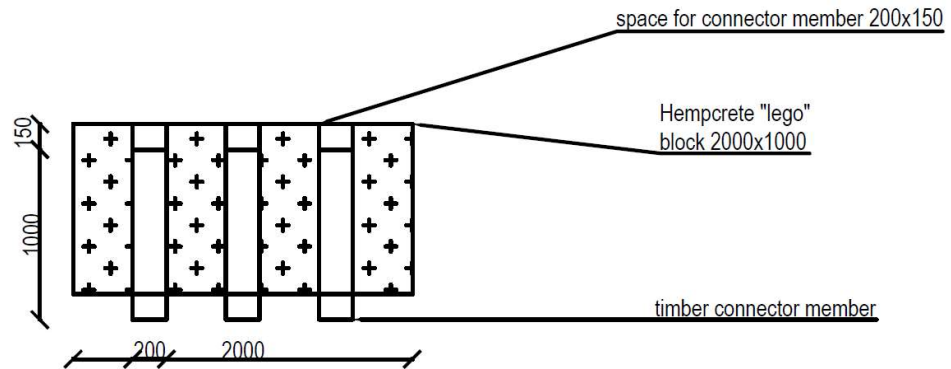


Figure 27. Hempcrete block in horizontal section.

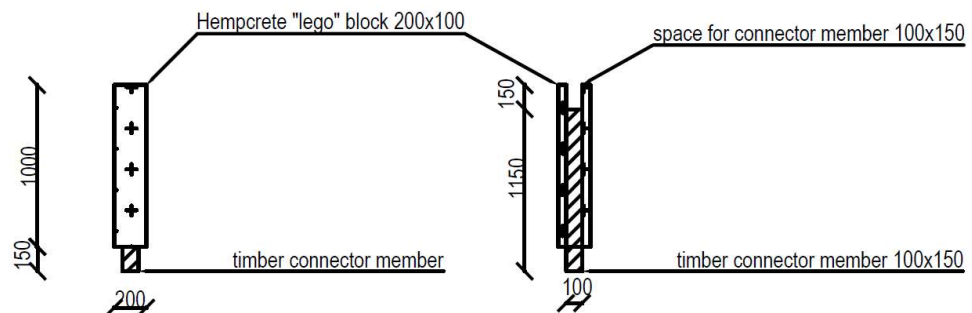


Figure 28. Side view and side section of Hempcrete block

Hempcrete modular or “Lego” block can be manufactured with the use of special mould, made for the project of Hempcrete noise barrier wall. The mould is made from timber and can be easily set up.

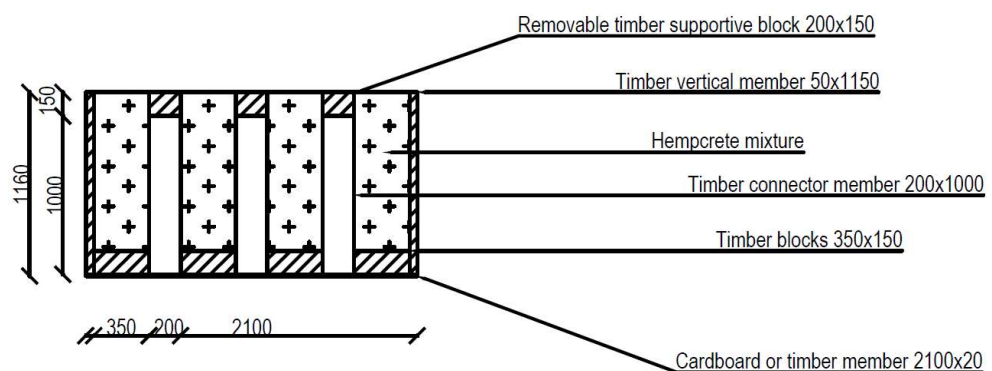


Figure 29. Timber mould with casted Hempcrete

In Figure 29, 2D sketch drawing of the section view of Hempcrete timber mould without cast mixture is presented. The dimensions for each of such moulds depend on the measurements of the needed Hempcrete blocks. The given prototype of mould consists of two vertical timber members, cardboard or plywood, four supportive blocks, three removable timber

supportive blocks, and lateral side cover members. Firstly, supportive blocks are connected to a bottom base (plywood); vertical timber members are mounted, and after lateral covers are installed. For the next step, before casting Hempcrete, it is important to cover every member of the mould with a special polyethylene paper cover, in order to prevent and avoid the adhesion of the material to timber. Further on, future reinforcements (timber connector members) of a block are placed. On the top of those members, removable timber supportive blocks are attached (these blocks are then removed after drying of Hempcrete, and space connecting space is then created). In Figure 30, Vertical section of timber mould with casted Hempcrete is presented.

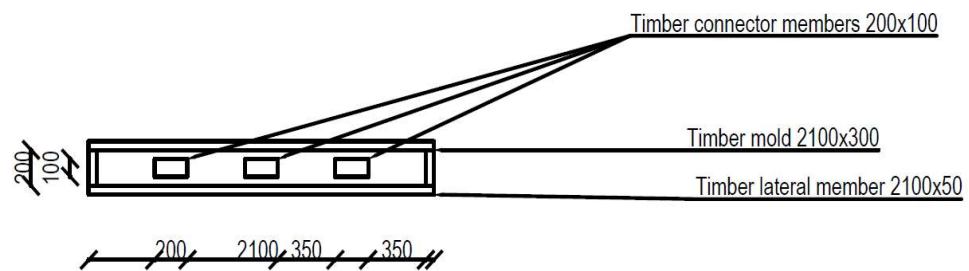


Figure 30. Vertical section of mould with casted Hempcrete

In Figures 31 and 32, 3D drawings of mould are presented for better understanding of the idea.

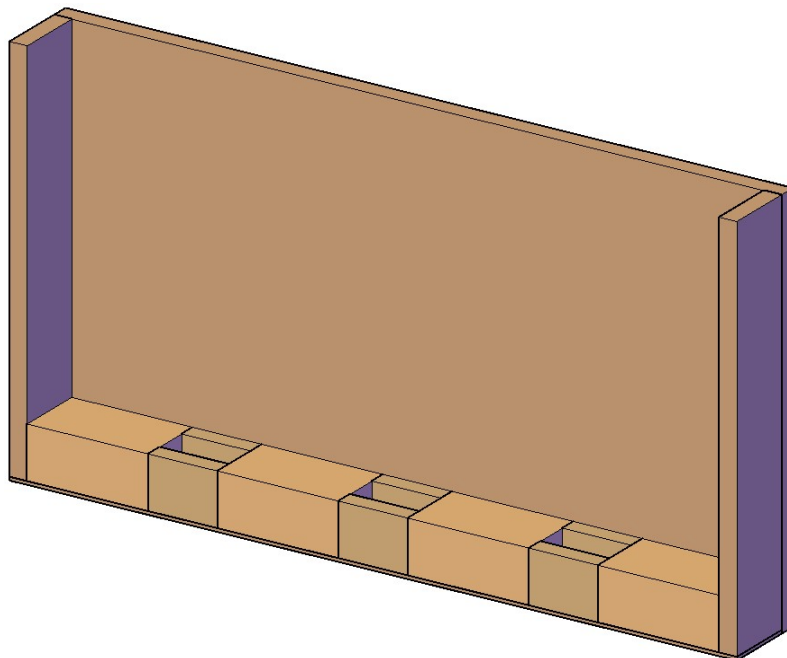


Figure 31. Section view of mould without Hempcrete mix

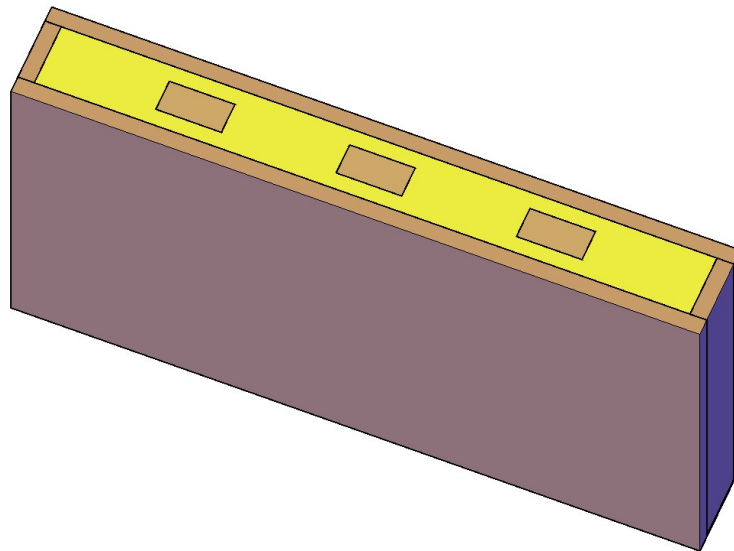


Figure 32. Basic view of the mould with casted Hempcrete

More 2D and 3D drawings of a mould for Hempcrete are presented in the end of this thesis in Appendices 4 and 5.

A top cover for the mould should be installed right after the casting of Hempcrete. Then the material has to dry out to reach its final firm consistence. To speed up and accelerate this process, lateral timber covers must be removed several days after casting. Approximately after three months of drying out, Hempcrete can be used. It is carefully extracted from the frame either by dismantling the whole mould, or by removing only top and vertical timber members. After all, details which we used in mould can be reused many times.

#### 6.4.2 Installation and maintenance of the barrier

During the manufacturing of Hempcrete blocks, the construction site must be prepared: geotechnical surveys, calculations and installation of foundation have to be done, as well as assembling of timber frame without top and roof members. When those objectives are completed, Hempcrete blocks can be transported to the site. This step must be carefully controlled, in order not to cause any damage to the material. Afterwards, Hempcrete blocks are inserted on the lower level of the frame from its top hatchway. Then other row of blocks is installed and connected to the lower ones. Once done with the preceding steps, upper timber member and roofing can be mounted and fixed.

Due to such modular design where the structure consists of several easy installing elements, maintenance or repairing works of the barrier can be done without much difficulty. It means that any timber member can be

replaced. Also, Hempcrete blocks can be removed and replaced by new ones, or special Hempcrete mixture can be prepared and cast straight onto the damaged block.

#### 6.4.3 Additional attributes

In order to implement and fit the structure into the surrounding locations and environment, additional attributes such as Virginia creeper can be used. It is a deciduous plant with a woody stem, and this plant is also known as Victoria creeper. It is a climbing plant which can grow fast on solid and smooth surfaces, using adhesive pads in the tips of its tendrils. Virginia creeper is usually cultivated as an ornamental plant, because of its attractive foliage and its ability to climb and cover different kind of structures. During summer time, its leaves have green colors, while in the autumn they are turning into red and yellow.

This plant grows all over the world. Mostly, it prefers moist soils, but also it grows well in a wide variety of soils. Five-leaved ivy often grows in open spaces and likes sun, and also tolerates shade, but it will climb up trees, poles, and other structures to reach the sunlight. This vine is salt tolerant and needs low maintenance. That is why Virginia creeper grows in most climatic conditions.

Due to the above mentioned characteristics, Virginia creeper can be used on a Hempcrete noise barrier. This plant will give a new appearance and add more pleasant visual impact. Moreover, Virginia creeper will not damage a structure of the wall anyhow, because of its small adhesive pads, which just stick and do not penetrate the material or structure. Figure 33 contains a picture of Virginia creeper.



Figure 33. Virginia creeper on a noise barrier in Finland

## 7 DISCUSSION

A prototype of Hempcrete noise barrier is a relatively new innovative idea, which has not been implemented yet in real life. The whole concept of the structure was to develop an environmentally friendly and energy efficient loadbearing system around Hempcrete blocks. As the performance and efficiency of reducing the traffic noise by this material is great (that was proven in the thesis written by KC Prabesh (2016) ). But nevertheless, in order to compile a complete description of the material and whole structure (noise barrier) itself, it is a must to make a comparison with already existing and widely used material or technology in noise barrier walls construction. Such comparison will show all advantages and disadvantages of the presented design, as well as its applicability.

Hempcrete is always compared to concrete, as those materials are not only similar in many usages, but also in some characteristics and properties. Shortly, concrete is one of the most durable and versatile materials which has many types of applications and various installation techniques, especially in noise barrier construction. Depending on the project, concrete noise barriers can be either reflective, or absorptive. Furthermore, this material has a high structural strength and resistance and, of course, concrete is able to withstand extreme temperatures,

moisture, intense sunlight. Those characteristics emphasize the ability of the material to sustain in any climate conditions and possibility to be used in multiple fields of application (U.S Department of Transportation Federal Highway Administration, 2000). A concrete noise barrier can be seen below in Figure 34.



Figure 34. Concrete noise barrier (U.S Department of Transportation Federal Highway Administration, 2000)

In this thesis, a comparison of Hempcrete and concrete was performed only by considering those parameters and material characteristics that are important and influence the effectiveness of a noise barrier wall. In other words, the following parameters i.e. sound properties, environmental impact and sustainability should be firstly compared, as they mostly influence the selection of the material for the barrier. Moreover, structural strength and flexibility, information availability and application techniques also play a significant role in comparison and in decision-making process of the material.

As it was mentioned before, Hempcrete has an incredible potential as a sound reducing material, as it is a great sound absorber, and in right mixture the proportion and preparation of the material, it is possible to achieve a noise reduction index 39 decibels (KC, 2016) and greater (depending on the additives, hempcrete mixture and layers inside Hempcrete). The main advantage of absorptive noise walls is that they act as a "sound sponge", "soaking" (absorbing) the sound in all frequency ranges. The peak frequencies of traffic noise are in the range between 500-1500 Hz, and the most difficult task is to prevent reverberations of low frequency sounds. Most of the absorptive materials tend to mitigate and deflect sound in range between 100-300 Hz (HONG KONG EPD, 2003 ). That is why the use of absorptive material, especially Hempcrete, is an efficient solution for the reduction of traffic noise.

Most concrete noise walls still refer to the reflective type. Therefore, several significant problems can emerge (this effect is mentioned under the chapter Noise barrier walls/ types of noise barriers). This problem may



seriously influence the efficiency of the barrier, as well as on the opinion of the community about the wall (as this aspect plays an important role during the selection of the material).

Another significant comparative parameter is the environmental impact of the materials. Hempcrete is an environmentally friendly, non-toxic renewable and easy recyclable material. It has a unique ability to sequester and store carbon dioxide in its structure due to the capabilities of its constituents (as it was described in the previous parts of this thesis). Moreover, on the basis of several studies, it is possible to consolidate that Hempcrete has a carbon negative footprint (Bedliva & Isaacs, 2014) (Jami & Kumar, 2017). The assessment of the environmental impact of traditional concrete is extremely complex and depends on various circumstances, because the main component of the material is cement. According to the research by Johanna Lenhe and Felix Preston (2018), cement manufacturing industry is a source of 8% of the world's CO<sub>2</sub> emissions, and is one of the most polluting industries in the world due to the several aspects. Firstly, in order to produce cement, it is needed to generate the energy to heat the raw ingredients over 1000 C°. For this process fossil fuels, which emit CO<sub>2</sub>, are mostly used. Secondly, emissions are also produced during the production of the main component of cement, clinker "as carbonates (largely limestone CaCO<sub>3</sub>) are decomposed into oxides (largely lime, CaO) and CO<sub>2</sub> by the addition of heat" (Andrew, 2018). Furthermore, cement generates dust during its production and is also a source of Sulphur oxides (SO<sub>x</sub>) and Nitrogen oxides (NO<sub>x</sub>), which have consequent hazardous impact on human health, vegetation development, animal life etc. (Shukla, Nagpure, Kumar, Sunisha, & Preeti, 2008).

Nevertheless, Hempcrete has several disadvantages. The most important ones are the weather durability and moisture resistant abilities of the material. Hempcrete is made from the mix of three main constituents: hemp fibers, lime and water. Due to the ability of water absorption and reactions, which happen during the curing, setting and drying processes, it is possible to get appropriate and needful material. But even when Hempcrete is completely cured and implemented in a project, water absorption still happens. In other words, there is a probability that Hempcrete structure may over absorb water under the influences of weather conditions. High amount of water usually causes serious deteriorations to the material, even if special water retainers and hydrophobic additives are used in Hempcrete. This represents the most detrimental threat during the weather fluctuations, especially in autumn/winter, winter/spring periods. During those periods, serious freeze – thaw damage can be caused to the porous structure of Hempcrete, because of water's ability to expand as it freezes. Those freeze and thaw processes cause serious deteriorations and degradation of material process and quality of the whole noise barrier wall hereby directly affecting the service durability of the structure. On the contrary, traditional

concrete is considered one of the most durable material, with the ability to withstand severe temperatures and extreme weather conditions. Concrete products are used in any climate conditions, as many studies have been done in order to improve the resistance of the material to high humidity and rain, freezing and thaw, chemicals and other destructive factors. The availability of information about the use of concrete, its properties and characteristics, is the biggest advantage of the material over the others like Hempcrete.

Therefore, in order to use a full potential of Hempcrete, it is extremely important to conduct deep research tests on various characteristics of the material, especially concentrating on studies related to material durability and the factors of material degradation. These parameters of the material are described differently by various researches and are most underexplored. As new proved information is available, more actual types, areas and potency of application and use of Hempcrete will become clearer and more comprehensible. That will contribute to the increased use of Hempcrete as the main material for a noise barrier.

## 8 CONCLUSION

The concept of Hempcrete noise barrier has a great potential to be used as an effective traffic noise reducing device. The presented prototype of the barrier was designed in a way to comply with the European Union standards and to meet the needed requirements for a noise barrier walls. The prototype of Hempcrete noise wall is resource efficient, environmentally friendly and sustainable structure with unique sound absorptive properties and its ability to sequester and store carbon dioxide. Hereby, the concept and the main idea of the barrier was to construct a “protective” load-bearing frame for the Hempcrete blocks. In order to use a Hempcrete as a sound insulator and leverage it effectively as an absorber of traffic noise, blocks are left uncovered (otherwise acoustic characteristics of the barrier will be significantly decreased). Moreover, the presented design of the wall provides the most cost-efficient and time-saving solution for the construction and maintenance of such Hempcrete structure.

As a part of this thesis, the research and assessment of the structure and of the main wall material (Hempcrete) was made, in order to evaluate the possibility of construction of Hempcrete noise barrier. With the reference to the foregoing studies and material presented in this thesis, it is fair to assume that the implementation of this project in the targeted area (Finland) may be difficult, challenging and, most probably, inefficient, due to weather conditions and climate pattern of the country. As there is a big chance that high amount of absorbed water by a Hempcrete can cause the deteriorations and damage the inner structure of the barrier and have a

significant impact on acoustic characteristics. Therefore, it is highly recommended to conduct freeze-thaw and weather durability tests for the Hempcrete under the conditions of the Finnish climate, in order to gain more precise knowledge, and consequently, develop the mixture of the material with the addition of special water retainers. The implementation of Hempcrete noise barrier is most suitable for use in countries with a dry climate. In such “perfect” conditions, the lifespan of Hempcrete can be more than 50 years (Léonard & Groslambert, 2017), as well as utilization efficiency will be increased (i.e. there will be much fewer problems with the degradation of the material and thus less expenditure for barrier maintenance, and possibility of extracting the maximum efficiency of the acoustic characteristics of the material).

In conclusion, the realization of this project and further introduction of Hempcrete noise barriers into the highway engineering and road construction can be innovative and interesting in terms of replacement of traditional building materials by sustainable alternative ones. For this reason, it is important to pursue more fundamental studies related to the characteristics of Hempcrete. As this material can greatly contribute to the controlling and reduction of effects of noise pollution, and the development of the sustainable road construction

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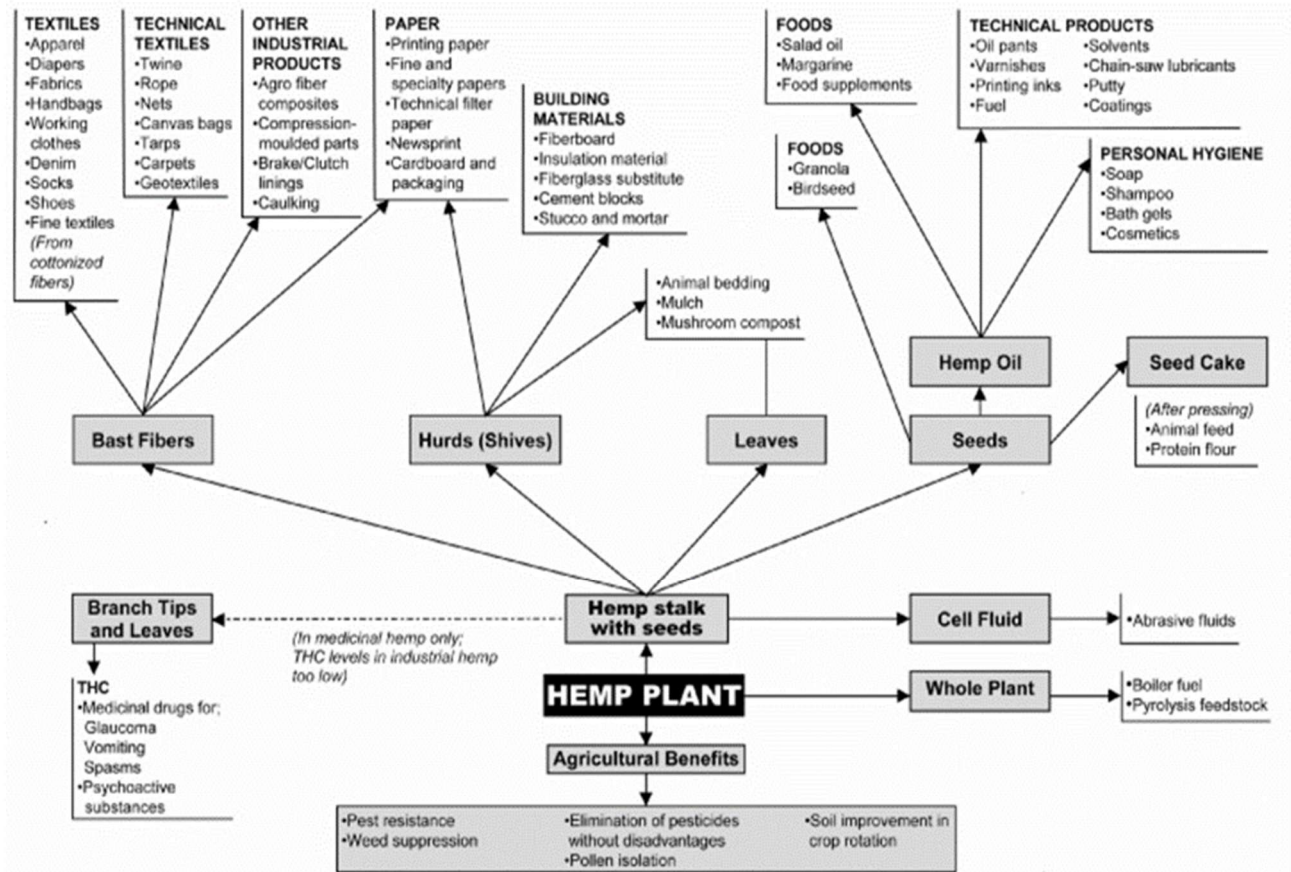
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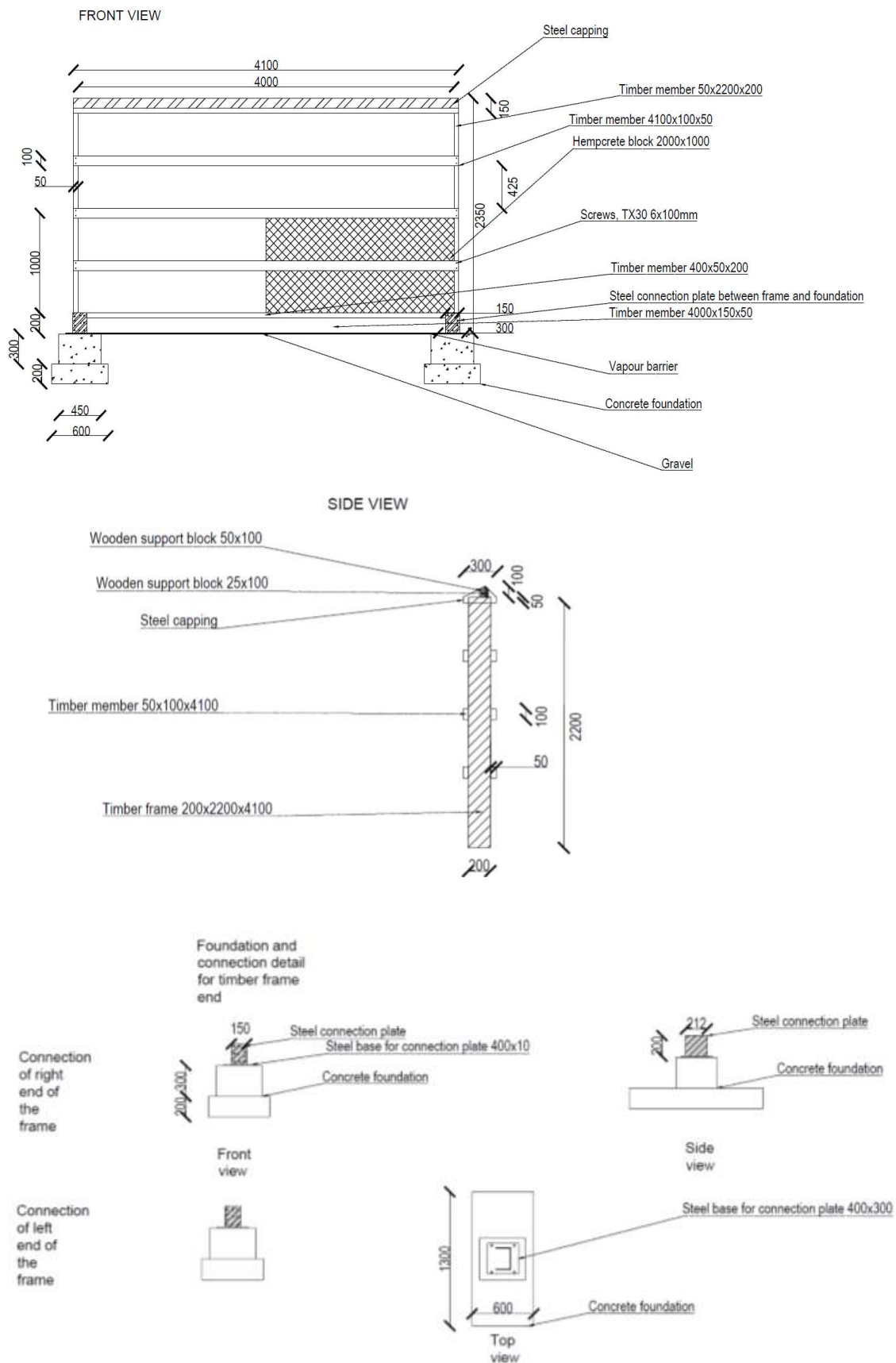
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## USE OF INDUSTRIAL HEMP (Johnson, 2018)





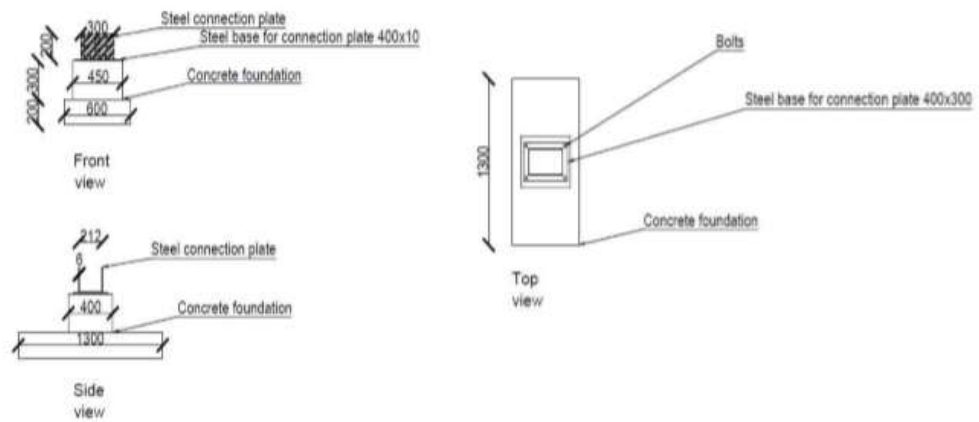
## HEMPCRETE NOISE BARRIER WALL DRAWINGS



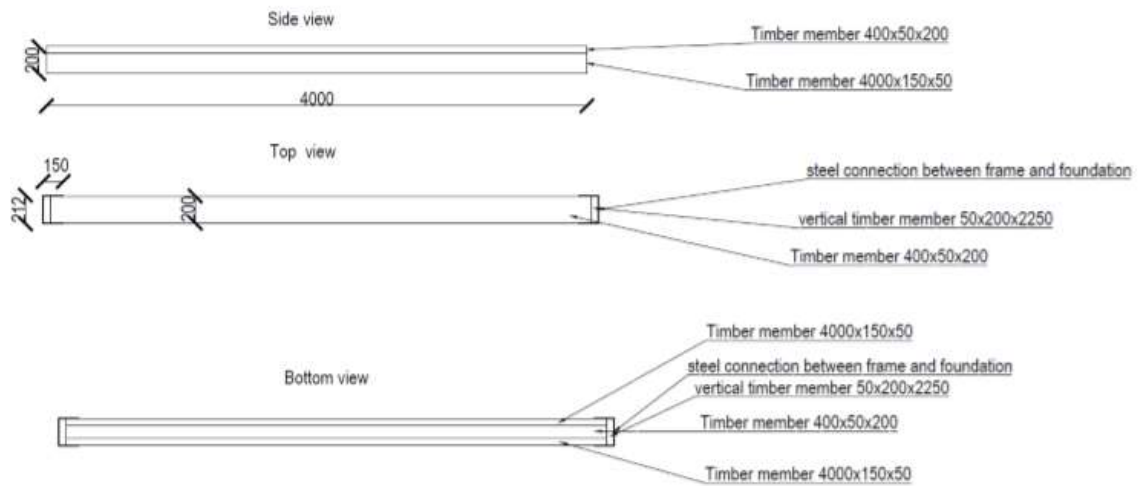
## Appendix 2(2)

Middle  
connection  
between  
frames

Foundation and connection  
detail for timber frames



Bottom timber members connections



## Appendix 2 (3)

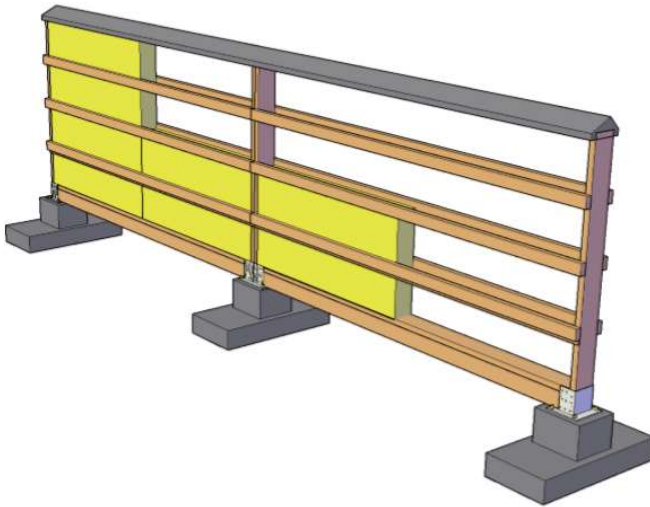


Figure 1. Basic view of Hempcrete noise barrier wall

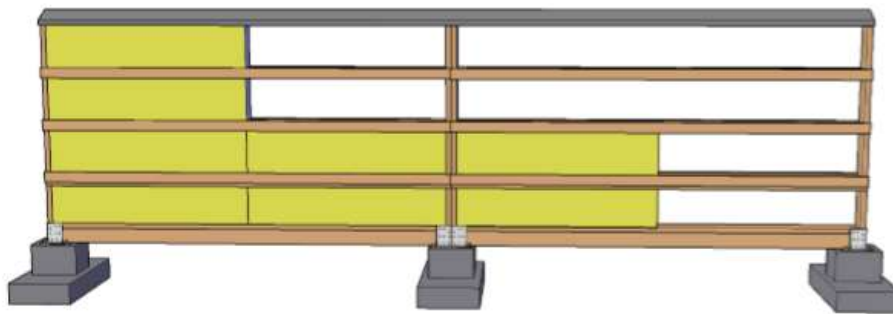


Figure 2. Front view of Hempcrete noise barrier wall

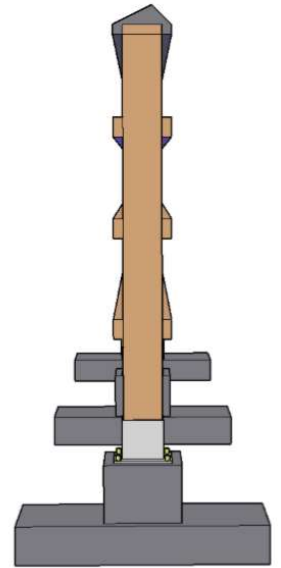


Figure 3. Side view of Hempcrete noise barrier wall

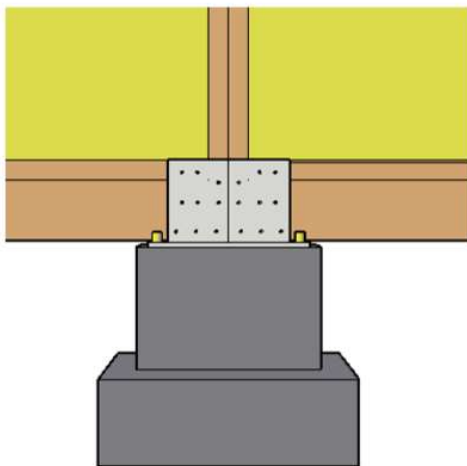


Figure 5. Connection of foundation and two timber frames

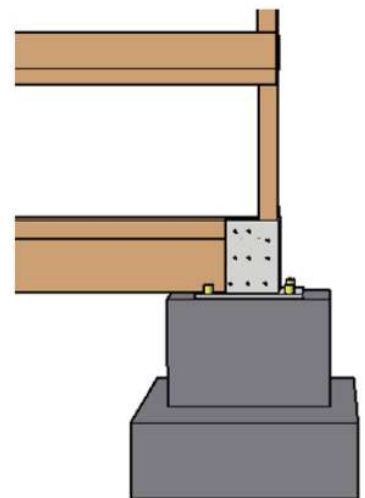


Figure 4. Connection of foundation and timber frame

## Appendix 2 (4)

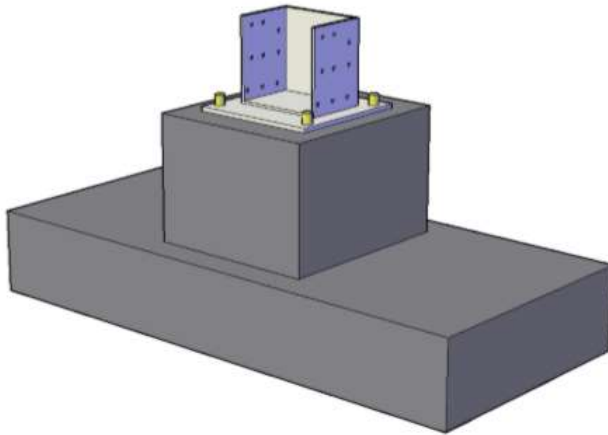


Figure 6. Basic view of foundation

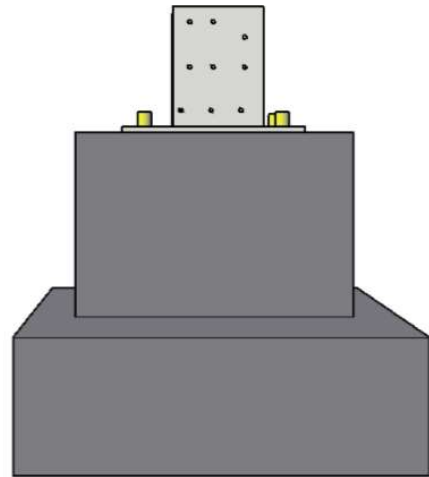


Figure 7. Front view of foundation

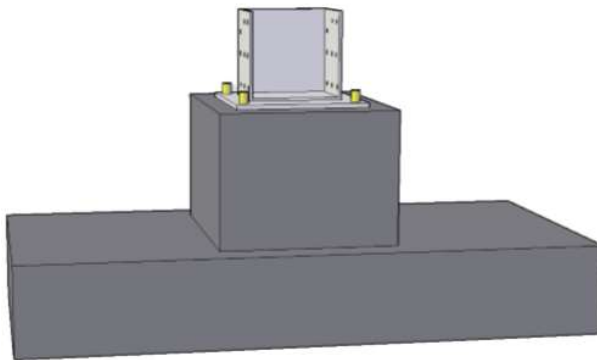


Figure 8. Side view of foundation

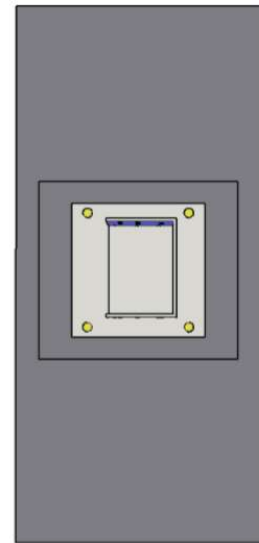


Figure 9. Top view of foundation

## Appendix 2 (5)

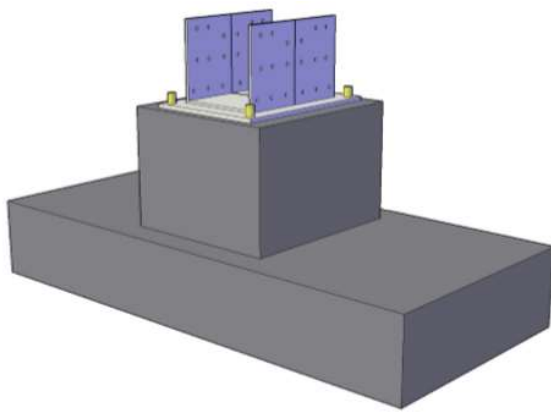


Figure 10. Basic view of middle foundation connection

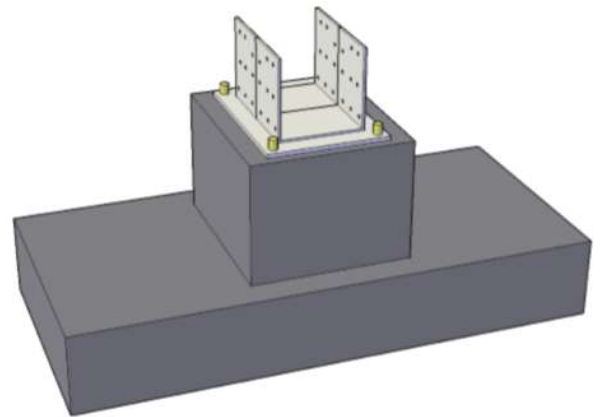


Figure 11. Front view of foundation connection

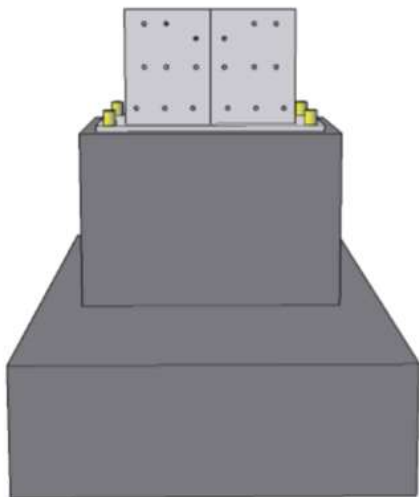


Figure 12. Side view of middle foundation connection

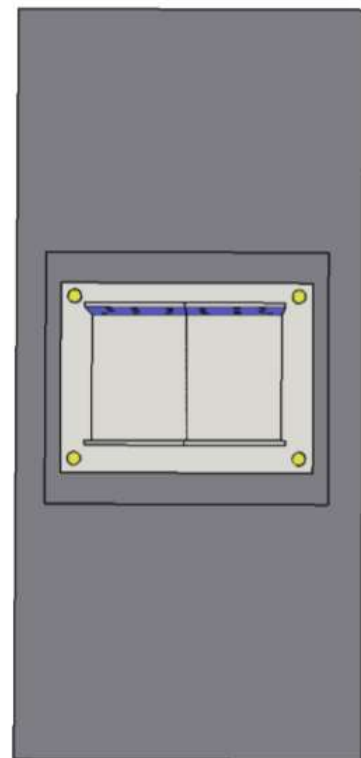


Figure 13. Top view of middle foundation connection

## HEMCRETE NOISE BARRIER WALL. CALCULATION OF LOADS

**Dead Load**

a – width

b – thickness

**Structure self weight**

timber member 1	$l_1 := 2.25\text{m}$	$a_1 := 200\text{mm}$	$b_1 := 50\text{mm}$
timber member 2	$l_2 := 4\text{m}$	$a_2 := 200\text{mm}$	$b_2 := 50\text{mm}$
timber member 3	$l_3 := 4.1\text{m}$	$a_3 := 100\text{mm}$	$b_3 := 50\text{mm}$
timber member 4	$l_4 := 4\text{m}$	$a_4 := 150\text{mm}$	$b_4 := 50\text{mm}$

density of pine  $\rho_p := 420 \frac{\text{kg}}{\text{m}^3}$

hemcrete block  $l_h := 2\text{m}$   $h_h := 1\text{m}$   $b_h := 200\text{mm}$

density of hemcrete  $\rho_h := 275 \frac{\text{kg}}{\text{m}^3}$

**Weight of timber members**

$$m_1 := l_1 \cdot a_1 \cdot b_1 \cdot \rho_p \cdot 2 = 18.9 \text{ kg} \quad m_2 := l_2 \cdot a_2 \cdot b_2 \cdot \rho_p \cdot 2 = 33.6 \text{ kg}$$

$$m_3 := l_3 \cdot a_3 \cdot b_3 \cdot \rho_p \cdot 6 = 51.66 \text{ kg} \quad m_4 := l_4 \cdot a_4 \cdot b_4 \cdot \rho_p \cdot 2 = 25.2 \text{ kg}$$

$$W_t := (m_1 + m_2 + m_3 + m_4) \cdot g = 1.269 \text{ kN}$$

**Weight of hemcrete blocks**

$$m_h := l_h \cdot h_h \cdot b_h \cdot \rho_h \cdot 4 = 440 \text{ kg}$$

**Weight of whole structure**

$$W_s := W_t + W_h = 5.584 \text{ kN}$$

**Wind load page SFS-EN 1991-1-4****Basic Values**

Season factor  $c_s := 1$

Directional factor  $c_d := 1$

Fundamental value  
of the wind velocity  
in Finland  $v_{b.0} := 21 \cdot \frac{\text{m}}{\text{sec}}$

Wind velocity  $v_b := v_{b.0} \cdot c_s \cdot c_d = 21 \frac{\text{m}}{\text{s}}$

**Terrain roughness**

Terrain category III  $Z_0 := 0.3$   $Z_{\min} := 5$   $Z_e := 2$

Terrain factor  $k_T := 0.19 \cdot \left( \frac{Z_0}{0.05} \right)^{0.07} = 0.215$

Terrain roughness  $c_T := k_T \cdot \ln \left( \frac{Z_e}{Z_0} \right)$

**Turbulence intensity**

Turbulence factor  $k_1 := 1$  Terrain orography factor  $c_0 := 1$

Turbulence intensity  $I_v := \frac{k_1}{c_0 \cdot \ln \left( \frac{Z_e}{Z_0} \right)} = 0.527$

**Mean wind velocity**

$v_m := c_T \cdot c_0 \cdot v_{b.0} = 8.581 \frac{\text{m}}{\text{s}}$

**Peak velocity pressure**

Air density  $\rho := 1.25 \cdot \frac{\text{kg}}{\text{m}^3}$

$$q_p := \left(1 + 7 \cdot I_v\right) \cdot \frac{1}{2} \cdot \rho \cdot v_m^2 = 215.83 \text{ Pa}$$

**Basic velocity pressure**

$$\frac{1}{2} \cdot \rho \cdot v_b^2 = 275.625 \text{ Pa}$$

**Wind pressure on surfaces****Wind forces**

Safety factor  $c_f := 1$

wall height  $h := 2.25 \text{ m}$  wall length  $l := 4.1 \text{ m}$

$$A_{\text{ref}} := h \cdot l = 9.225 \text{ m}^2$$

$$F_w := c_s \cdot c_d \cdot c_f \cdot q_p \cdot A_{\text{ref}} = 1.991 \text{ kN}$$

**Design of foundation****Critical parameters of foundation**

Width of foundation  $B_f := 0.6 \text{ m}$

Lenght of foundation  $L_f := 0.6 \text{ m}$

Depth of foundation  $D_f := 0.5 \text{ m}$

**Soil parameters**

Soil type: Silt Bulk weight  $\gamma_1 := 16 \frac{\text{kN}}{\text{m}^3}$  Friction angle  $\varphi_{\text{characteristic}} := 28^\circ$

FOS := 1.25  $\gamma_2 := 6 \frac{\text{kN}}{\text{m}^3}$

Design value of friction angle  $\varphi_D := 23^\circ$



**Calculation of factors**

$$N_D := 8.7$$

$$N_B := 2(N_D - 1) \cdot \tan(23^\circ) = 6.537$$

**Shape factors**

$$S_D := 1 + \frac{B_f}{L_f} \cdot \sin(23^\circ) = 1.391 \quad S_B := 1 - 0.3 \frac{D_f}{L_f} = 0.75$$

**Force factors**

$$\text{Horizontal force} \quad H_d := 2 \text{ kN}$$

$$\text{Vertical force} \quad V_d := 6 \text{ kN}$$

$$i_d := \left(1 - 0.7 \cdot \frac{H_d}{V_d}\right)^3 = 0.451 \quad i_B := \left(1 - \frac{H_d}{V_d}\right)^3 = 0.296$$

**Bearing capacity**

$$\sigma_{\text{allowed}} := \gamma_1 \cdot N_D \cdot D_f \cdot S_D \cdot i_d + \frac{1}{2} \cdot \gamma_2 \cdot N_B \cdot B_f \cdot S_B \cdot i_B = 46.233 \cdot \frac{\text{kN}}{\text{m}^2}$$

$$\text{FORCE ALLOWED} \quad 5.86 \text{ kN}$$

It means that those parameters of width, depth and length of footings are critical. And will handle only 5.86 kN/footing. It is a must to design such footings, so the wall will be stable even under the influence of bigger forces. That is why width of foundation should be increased.

**Final width of foundation**

$$\text{Wind force} \quad F_w = 1.991 \text{ kN} \quad a := 1.125 \text{ m}$$

$$\text{Vertical force} \quad V_d = 6 \text{ kN}$$

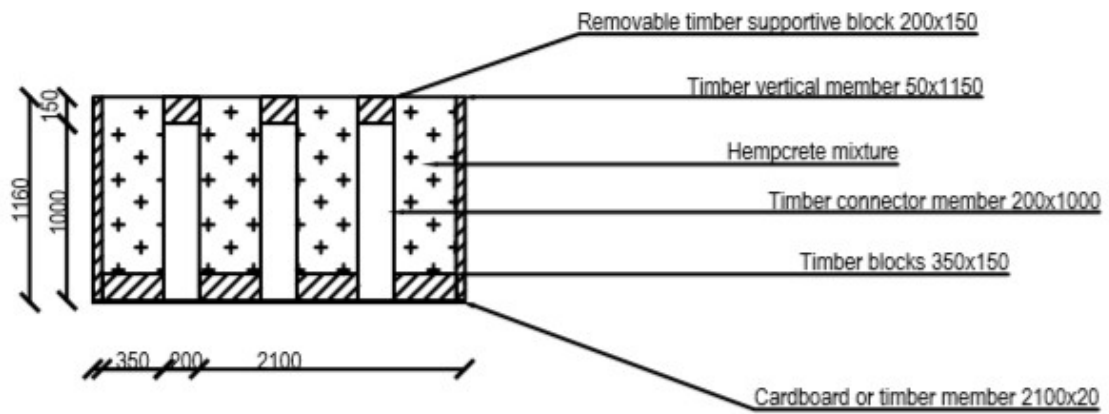
$$\text{Moment} \quad M_w := F_w \cdot a = 2.24 \text{ m} \cdot \text{kN}$$

$$\text{Factor} \quad e_f := \frac{M_w}{V_d} = 0.373 \text{ m}$$

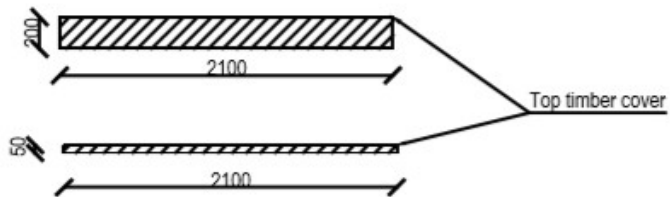
$$\text{Final width} \quad B_{\text{final}} := B_f + 2 \cdot e_f = 1.347 \text{ m} \quad \text{or} \quad 1.3 \text{ m}$$

## HEMPCRETE MOLD 2D DRAWINGS

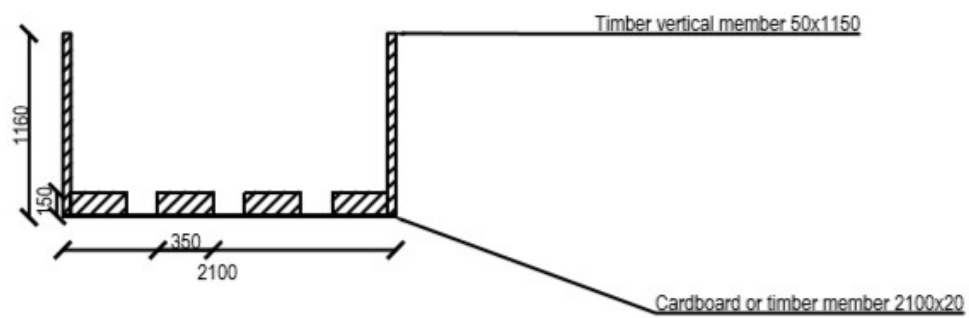
Horizontal section with hempcrete mixture



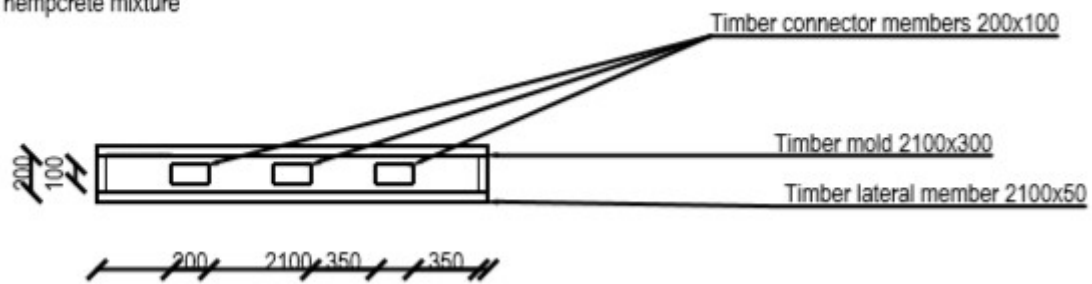
Top cover for the mold



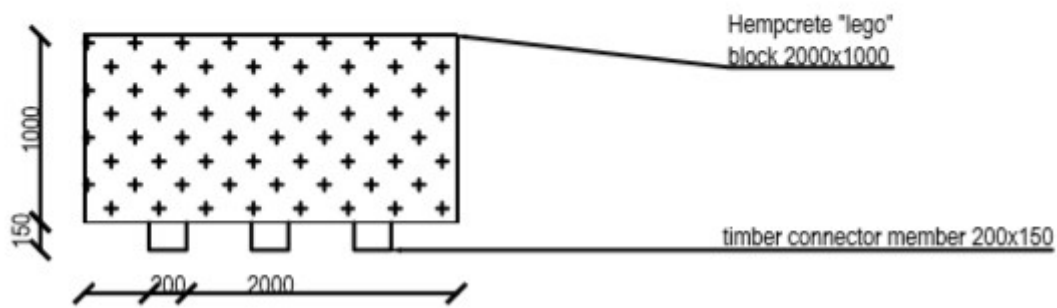
Horizontal section



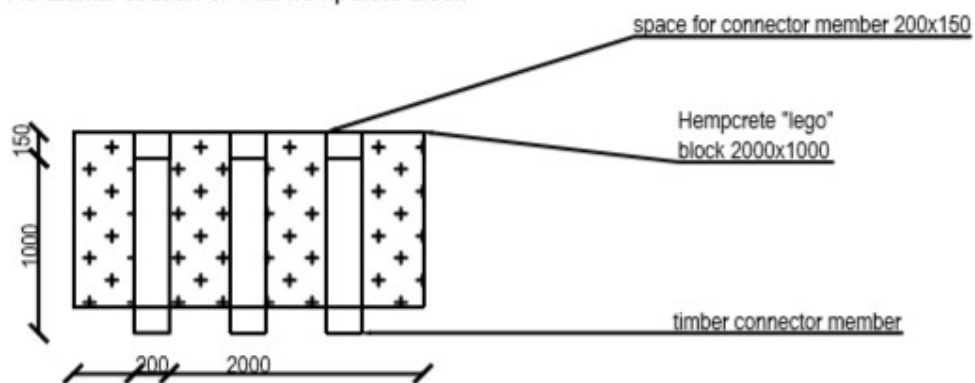
## Appendix 4 (2)

Vertical section with  
hemcrete mixture

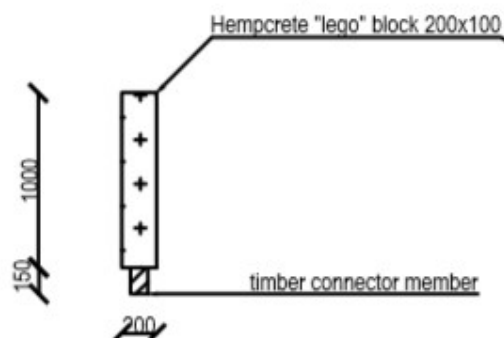
Horizontal view of final hemcrete block



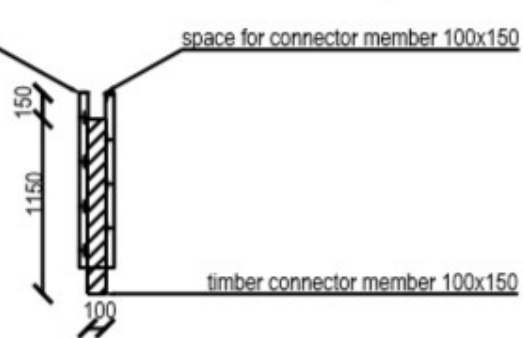
Horizontal section of final hemcrete block



Side view of final hemcrete block



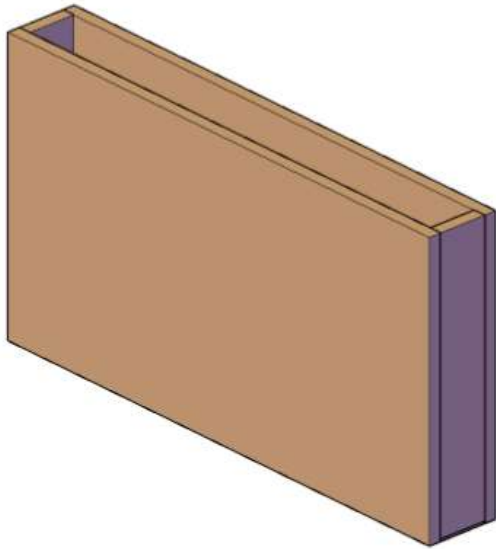
Side section view of final hemcrete block



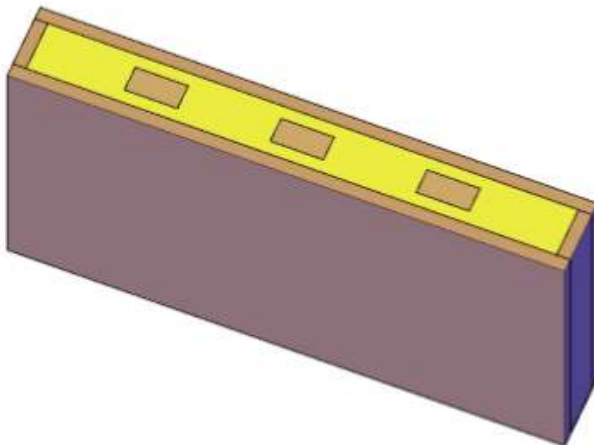
## Appendix 5 (1)

## HEMPCRETE MOLD 3D DRAWINGS

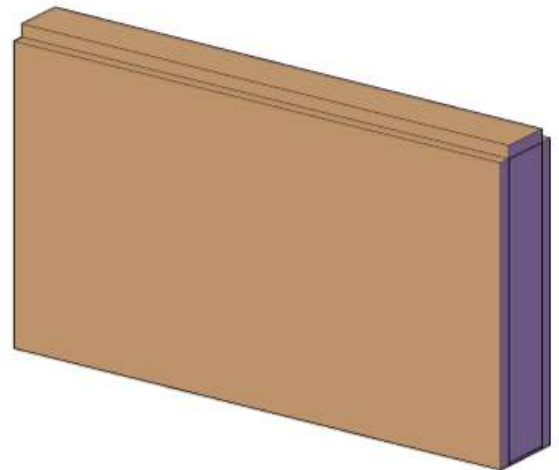
Basic view of the mold.



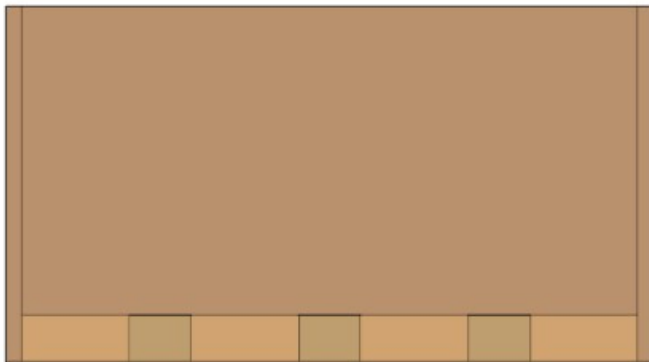
Basic views of the mold with the Hempcrete mixture.



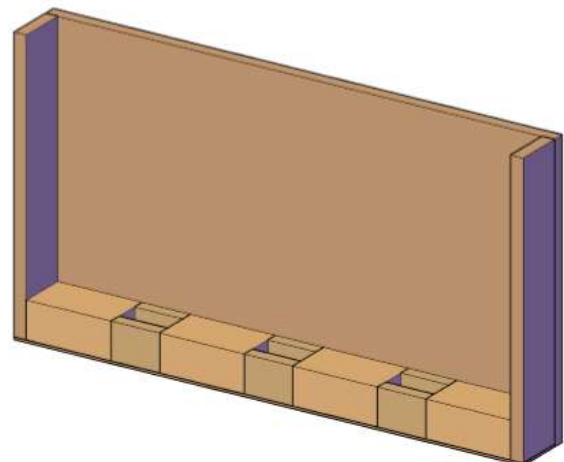
Basic view of the mold with top cover.



Front section view of the mold without hempcrete.

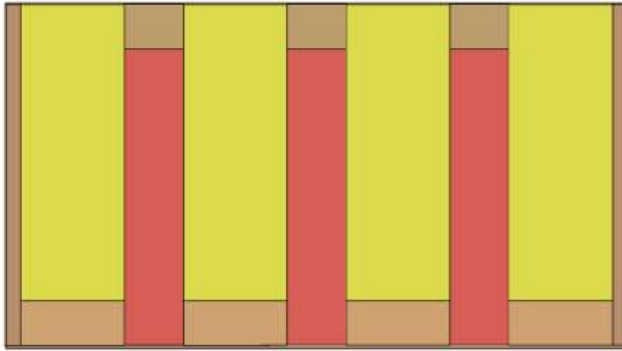


Section view of the mold without hempcrete.

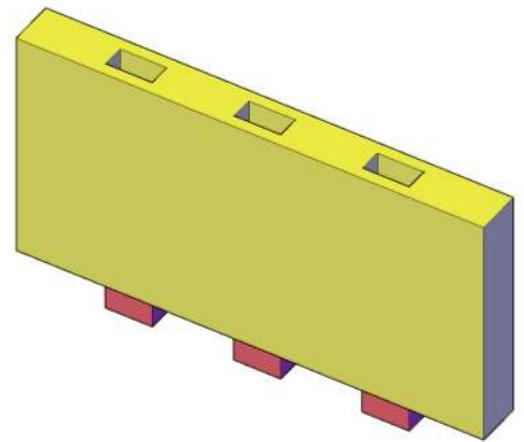


## Appendix 5 (2)

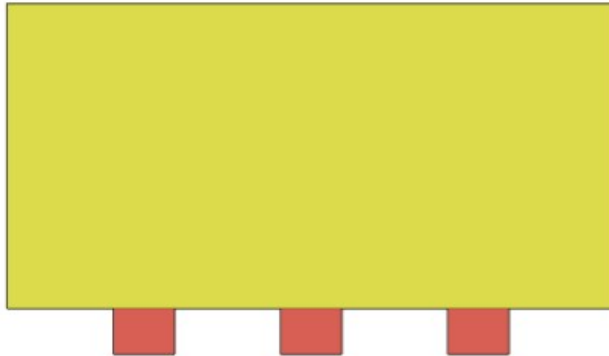
Front section view of the mold with Hempcrete mixture and timber connectors.



Hempcrete block basic view.



Hempcrete block side view.



Hempcrete block side view.

