HEMPCRETE NOISE BARRIER WALL FOR HIGHWAY NOISE INSULATION

Research & Construction

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Bachelor's thesis

Construction Engineering

Visamäki/autumn 2016

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ABSTRACT

Hämeenlinna
Degree Programme in Construction Engineering
Environmental Technology

Author Prabesh KC **Year** 2016

Subject of Bachelor's thesis Hempcrete Noise Barrier Wall for Highway Noise Insulation

ABSTRACT

The purpose of this thesis was to study the possibility of Hempcrete or hemp-lime composite noise barrier walls in the highways and to construct the walls for the acoustic test according to the European Union Standards EN ISO 717-1 and ISO 10140-2 for air-borne sound insulation. The thesis was commissioned by the company Hemprefine Oy, and all the standard tests were performed in the HAMK-Ruukki Sheet Metal Centre in Hämeenlinna and the VTT Technical Research Centre of Finland Ltd in Espoo.

Three Hempcrete walls were constructed in the HAMK –Ruukki Sheet Metal center with different mixing proportions of hemp shives, lime and water. Wall 1 was cast with only small shives in the mix, wall 2 was cast with only large shives in the mix, and wall 3 was cast in a state of the art design after the careful study of the acoustic behavior across Hempcrete walls.

The acoustic measurements in one-third octave bands showed varying insulating responses among three different walls. Wall 1 and 2 produced unsatisfactory results with a Sound Reduction Index, R_w of less than 20 decibels and were unable to meet the acoustic standards. However, wall 3 constructed in a state of the art design performed much better with a R_w of 46 decibels. The results showed that a specific structure of Hempcrete wall can provide a Sound Reduction Index of the wall which meets the European and the Finnish standards. In addition, the water-proof, rot-proof and the moisture-proof properties of the Hempcrete noise barrier wall along with its capacity to store carbon dioxide in its molecular fabric, make it an environmentally sustainable construction solution in the future. To maintain confidentiality and copy rights of the successful invention of the thesis work commissioned by Hemprefine Oy, the design and casting methods of Hempcrete wall- 3 have not been described within this publication.

Keywords Hempcrete, noise barrier, insulation, Sound Reduction Index.

Pages 55 p. + appendices 5 p.

FOREWORD

This Bachelor´s thesis was written to investigate the possibility of using Hempcrete Noise barrier walls for the very first time in the highway noise insulation. Therefore, it will be incomplete without thanking the helpful hands that have shaped it into completion.

I would like to thank Mikko Neuvo, the Chief Executive Officer of Hemprefine Oy, for trusting in my ability to write this thesis as an engineering student. In essence, it was his idea to investigate the acoustic behavior of Hempcrete noise barrier walls in Finland. I sincerely thank him for providing me with the international working environment, design specifications, as well as the relevant educational materials related to the thesis. I must thank the Principal Lecturer Harri Mattila of HAMK for being available in the meetings and discussions with the company executives and the engineering team of experts in Hämeenlinna and in Forssa. His ideas, insights and solutions have played a very important role in this project.

A great thanks goes to Noora Norokytö, the Project Manager of Turku University of Applied Sciences, for personally guiding me during the construction process. She has provided this thesis with numerous suggestions without which the whole project would never be complete. I must thank Jussi Toivonen, the Lab Engineer of Sheet Metal Center for supervising all the construction work. I have learnt immensely from his long experience in construction. I thank my colleague Clarissa Pajukoski for providing her valuable time in the casting of Hempcrete, and Minh Tran for helping me throughout the construction phase.

I express my sincere thanks to my Thesis Supervisor Tomi Karppinen for his time and his complete helpfulness throughout this thesis and our Senior Lecturer of HAMK Markku Raimovaara for his advice, encouragement and educational materials. The Study Counsellors Kirsi Napola and Anu Virtanen of HAMK should be sincerely thanked for their total, and wholehearted care towards the students. They have helped each one of us to be better students.

Finally, a big thanks to this beautiful country Finland for so many wonderful memories! Kiitos Sinulle.

Prabesh KC
14.12.2016

CONTENTS

1 INTRODUCTION 1

2 HEMP 2

2.1 Historical Context 3
2.2 Hemp in Finland 4
2.3 Soil Requirements 4

3 HEMPCRETE: HEMP-LIME MIX 5

3.1 Low-Carbon Construction 5
3.2 Constituents 6
3.2.1 Shives 7
3.2.2 Lime Binder 7
3.2.3 Water 9

4 BUILDING A WALL WITH HEMP 10

4.1 Building Methods 10
4.1.1 Tamping 10
4.1.2 Spraying 11
4.1.3 Blocks 12
4.2 Finishes 12

5 HEMPCRETE TEST WALLS CONSTRUCTION 13

5.1 Wall 1- Only Small Shives 15
5.2 Wall 2- Only Large Shives 17
5.3 Wall 3- State of the Art Design 18
5.4 Carbon Sequestration in Walls 1-3 20

6 HEMPCRETE PERFORMANCE 21

6.1 Compressive and Tensile Strength 23
6.2 Breathability 23
6.3 Thermal Insulation 23
6.4 Discussion on Increasing Mechanical Strength 23

7 DYNAMICS OF HEMPCRETE NOISE BARRIER WALL 25

7.1 Basics of Insertion Loss 26
7.2 Sound Measurement 29

8 EUROCODES OF NOISE BARRIER TESTS 31

8.1 EN 1793-1: Lab Test for Sound Absorption 32
8.2 EN 1793-2: Lab Test for Airborne Sound Insulation 32
8.3 EN 1793-4, EN 1793-5: In Situ Tests 33
8.4 EN 1794: Non Acoustic Performance 33
8.5 EN 14389: Durability 34

9 NOISE BARRIER WALL DESIGN 35

9.1 Basic Design by Eurocodes ... 35
9.2 Foundation Piles and Columns ... 37
9.3 Wind Load Calculations for Columns ... 40
9.4 Water-proof, Fire-proof, and Rot-proof design ... 42

10 ACOUSTIC TEST ... 43

10.1 Laboratory Procedure ... 43
10.2 Laboratory Measurements ... 45
10.3 Comparison with Other Materials ... 47

11 DISCUSSION ... 49

12 CONCLUSION ... 52

SOURCES ... 53

Appendix 1 Temperature and Humidity Data- Wall 1
Appendix 2 Temperature and Humidity Data- Wall 2
Appendix 3 Temperature and Humidity Data- Wall 3
Appendix 4 Hempcrete Wall Frame
Appendix 5 Use of Fans to Dry Walls

1 INTRODUCTION

This thesis is a research and construction project commissioned by Hemprefine Oy and assisted by HAMK-Ruukki Sheet Metal Centre to investigate, study and analyse the use of Hempcrete as noise barrier walls in the highways. The pressure has been increasing in our planet to meet the needs of sustainable and environment friendly construction. Finland has been one of the leading countries in the world in sustainable construction. Therefore, to serve this purpose, it is right time for Finland to use environmentally friendly composite building materials in the road-highway traffic too.

Hempcrete, a bio-composite mix of hemp shives and lime, is a building material with low embodied energy and also with a capacity to lock carbon dioxide in its fabric. More than that, the surprising properties such as acoustic insulation, fire resistance, breathability, regulation of humidity, and thermal efficiency have made it more advantageous than other building materials. It is important to mention that the advantages of Hempcrete are able to meet the demands of sustainable, healthy and energy-efficient construction. Designing and constructing with Hempcrete is a real demonstration of our commitment to saving the planet.

This thesis in a nutshell, is a research of the possibility of constructing Hempcrete noise barrier walls along the highways. It must be noted, however, that the thesis is not completely immune to any discrepancies for the very reason that Hempcrete has never been used as a noise barrier wall in the road and highway traffic before. Therefore, some of the tests had to be performed despite the unavailability of previous literature in this particular situation. The design considerations for the Hempcrete noise barrier wall are different from the conventional concrete or wood-timber walls, and thus, require different set of construction planning. In addition to it, the obvious challenges in this thesis were to mix Hempcrete in correct proportions in the mixer, so that the acoustic properties remained intact. For this reason, a sufficient planning had to be done in order to mix lime and water in a suitable manner and to read the wall section-moisture variations periodically.

All in all, it is definitely a great leap forward for Finland to begin to investigate the possibilities of Hempcrete in road-highway traffic as a noise reducing device. This thesis, thus, has tried its best to investigate the important aspects of Hempcrete from its constituent ingredients, history, construction practices, material properties to its very feasibility as a noise barrier wall along the highways.

2 HEMP

Hemp, also called hamppu in Finnish, is a fast growing plant that can grow from 1.5m to 4m, depending upon the climate of the location and its soil properties. The stem is thin and hollow, with a diameter of 4mm to 20mm. Also, there is a fibre of the hemp plant, contained inside the bark of the woody stem, which ranges from 1.2 m to 2.1m in length and is very strong as shown in figure 1. The quality depends upon the timing of the harvest. The inner woody stem is called shiv, or hurd, and it is being extensively used in animal bedding. (Sparrow & Stanwix 2014.)

Figure 1 A typical Hemp Plant ready for harvest (Source: Sparrow & Stanwix 2014)

A hemp stalk can be separated into fibres and shives. The fibres are located in the bark, and the shives are located at the core as pictured in figure 2. Hemp shives are the woody core parts of the hemp stalk, referring to their appearance and cellular structure which resembles to that of wood (Evrard 2003).

Figure 2 Fiber stripped off from the stalk (Source: www.hemparchitecture.com)

The hemp plant is retted for three to four weeks when the hemp is harvested. Retting is accomplished by letting the stalks lay in the field for several weeks and relying on the dew to conduct the process Thereby, the stalks can be baled, and the fiber can be stripped off in the processing factory. The woody core that is left behind, can be chopped further into pieces known as shives. Then the shives can be used as an aggregate for mixing with lime based binder which results in a lightweight Hempcrete with significant material properties that are both environmentally and economically sound. Figure 3 shows hemp shives manufactured and supplied by Hemprefine Oy in Forssa, Finland.

Figure 3 Hemp shives ready to be used as an aggregate (source: Hemprefine Oy)

2.1 Historical Context

Hemp has been cultivated in our planet since the ancient iron ages, and it is recorded in the historical documents that it was first cultivated in manure enrich soils of Asia. Traditionally, it has been used in textiles, sailing and paper production. Furthermore, the edible seeds had found their way into ancient Chinese medicine a long time ago. It is mentioned that hemp had reached Scandinavia from Asia during the time of the Vikings. However, recent discoveries are revealing that hemp cultivation began in Scandinavia a long time ago. The explanation for Hemp in the Encycolpaedia Britannica of 1856 shows that Hemp had become an economic commodity by the time.

“But it is not as a narcotic and excitant that the hemp plant is most useful to mankind; it is as an advancer rather than a retarder of civilization, that its utility is made most manifest. Its great value as a textile material, particularly for cordage and canvas, has made it eminently useful; and if we were to copy the figurative style of the Sanskrit writers, we might with justice call it the "accelerator of commerce," and the "spreader of wealth and intellect." for ages man has been dependent upon hempen cordage and hempen sails for enabling his ships to cross the seas; and in this respect still occupies a most important place in our commercial affairs.”

Even though Hemp found its way into the plains of America in the seventeenth century, it was made illegal by the Marijuana Bill which was passed in 1937. It is a fact that Hemp is a cannabis Sativa. However, the amount of THC (Tetrahydrocannabinol) is very minute as compared to marijuana. In general, the hemp cultivar produces less than 0.3 % THC but the content in marijuana can be up to 20 %. As a consequence of its connection with marijuana, the hemp cultivation became illegal in many western European countries as well after the 1950s.

After the 1990s, with the growing concern for environmental protection, Hemp production has found its way into the mainstream harvesting once again as a natural material. It is now cultivated legally in most of Europe, Asia, Canada and Australia. Initially, the cultivation grew rapidly in Europe. However, since 2000, the area of harvesting has remained static. (Karus 2005.)

2.2 Hemp in Finland

Hemp came to be known later in Europe than in Asia. The analysis of soil samples in the region of modern Switzerland, Austria and Germany suggests that the hemp cultivation could date back up to 800 BC. In case of Finland, however, there are very few records of information related to the history of hemp cultivation. The oldest site of hemp cultivation in Finland is known to be Ahvenanmaa, which is an island situated between Finland and Sweden. The strong evidence has come from the macro-fossil studies. According to this, hemp seeds have been found in habitation and burial complex near the castle of Kastelholma which could very well be dated to the Viking ages (800-1050 AD). (Laitinen n.d.)

Other new discoveries indicate that in the south-western Finland, hemp had been a commercial commodity traded as fiber since historic times (Laitinen n.d.). However, there have been new samples and discoveries which show that the hemp cultivation in Finland began much earlier, as close as 4000 BC (Laitinen n.d.). New evidences are emerging which will shine the light on the history of hemp cultivation in Finland.

Finnish hemp is retted in the winter, and it is harvested during the spring. The climate in spring is favorable to warm up the fiber.

2.3 Soil Requirements

Nutritious soil such as silty loams or clays are the most preferable soil layout for the optimal growth of hemp. Slightly alkaline soil with pH range of 6.5-7 provides a very favorable environment whereas sandy soil and peats are the most unfavorable types of soil. (ADAS 2005). Despite this, hemp is a low-activity crop because it requires no ongoing maintenance during its growth.

3 HEMPCRETE: HEMP-LIME MIX

In this thesis, Hempcrete, or Hamppubetoni in Finnish, refers to the building material that combines a lime based binder and hemp shives or fibres. In the early 1990s, hemp shives were used to make the concrete lighter. In terms of development, Hempcrete was first developed in France in the mid-1980s as an experiment to find replacement for medieval timber-frame buildings. In the post war Europe, the massive use of ordinary Portland cement in the repairing work in the construction activities prevented the breathability of the structures. This meant more moisture problems within the fabric, with incalculable damages to timber frames. Just then, new experiments were made. The hemp stem is very durable and has a very strong cellulose with an innate capacity to go from wet to dry and from dry to wet indefinitely without degradation. Therefore, it was ideal for mixing with lime mortar in constructing walls. This meant that Hempcrete was able to absorb and release moisture. (Sparrow & Stanwix 2014.)

The lime based cementitious binder used in Hempcrete is relatively weak in both compression and tension. Therefore, the wall made of hemp-lime mix has a certain amount of flexibility. On the other hand, if cement were to be used, the wall would resist movement due to the high tension (Woolley 2006).

Rich lime or Calcium Oxide is more appropriate for use in Hempcrete than cement due to the slow carbonation process of the lime. This is very compatible with the fast water uptake of the hemp shives. Along with this, the high pH of lime is beneficial to the structure because it acts as a protective shield against mould and bacteria. Woolley (2006) and Evrard (2003) claim that the following are the advantages of a Hempcrete structure:

- Good thermal insulation
- Good acoustical insulation
- Simplification and reduction in the number of layers and processes

The global energy crisis and environmental pollution related to the greenhouse gases have led to the rapid need of cost-effective and less carbon intensive products for construction. Thus, the lightweight Hempcrete can be an effective solution to these challenges.

3.1 Low-Carbon Construction

It has been scientifically and statistically shown that the construction activities account for about 50 % of the total CO_2 emissions worldwide. It is therefore, very important for builders, architects, and engineers to take into account this figure during any kind of project. Eco-construction has become a need of this century and it is important, more than ever, to find alternatives to constructions bases solely on concrete and chemicals.

Hempcrete has the advantage that it is a natural alternative for building materials. Nonetheless, it has a huge potential to stand out in the mainstream too. Hempcrete utilizes a renewable plant based resource which is carbon negative. Hemp plants absorb a certain amount of CO_2 during their growth. On the other hand, lime emits CO_2 during its manufacture. It is estimated that 110 kg of CO_2 is sequestered into one cubic meter of Hempcrete. The combination of lime based binder with the woody core of hemp plants becomes a matrix that captures a significant amount of carbon dioxide from the environment. The carbon is therefore locked inside the matrix.

When hemp grows, the natural biotic reactions occur whereby it takes in CO_2 and converts it to glucose, cellulose, hemi-cellulose and lignin.

Photosynthesis:

$$6H_2O + 6CO_2 \longrightarrow C_6H_{12}O_6 + 6O_2$$

Glucose to Cellulose

$$C_6H_{12}O_6 \longrightarrow C_6H_{10}O_5 + H_2O$$

In ratio

$6CO_2 : C_6H_{10}O_5 = 1.84 : 1$, which implies that 1 kg of hemp cellulose absorbs 1.84 kg CO_2.

After the molecular calculation, the summary of carbon sequestration or storage is presented in table 1.

Table 1 Hempcrete Carbon sequestration of 1m^3 wall (source: Woolley n.d.)

110 kg Hemp shiv	202 kg CO_2 absorbed
220 kg lime	94 kg CO_2 emitted
Hempcrete total carbon sequestration	108 kg CO_2

Therefore, the more Hempcrete is used in construction industry, the more carbon dioxide is stored. This is certainly a very powerful tool against the climate change by carbon emissions.

3.2 Constituents

Hempcrete is the mix of hemp shiv/ herds, fiber, and lime mixed in a desired proportion. Therefore, the elements of the bio-composite can give a range of characteristics to the final product. In the noise barrier wall tests for the purpose of this thesis, all the different elements of the bio-composite have been used. Small shives, large shives, and fiber have been introduced in three different specimens in different proportions. In general, the constituents of Hempcrete are shives, lime and water.

3.2.1 Shives

Since a long time, hemp shives have been used in the horse bedding, or as bio-fuel briquettes. Figure 4 shows the hemp shives produced by Hemprefine Oy in Forssa, Finland. The shiv is highly porous part of the plant, reason being that it is the location of the main transport for the cells. Therefore, it can act as a lightweight constituent in the Hempcrete, with low density and large volume of trapped air within its pores.

Figure 4 Hemp Shives supplied by the company Hemprefine Oy, Finland

When shiv binds with the binder such as lime, a matrix of voids and gaps are created in the Hempcrete adding to its porosity (Duffy et al. 2014).

3.2.2 Lime Binder

The use of binder in Hempcrete depends upon the desired characteristics of the final product. Usually, Hempcrete consists of a lime-based binder. The problem with cement is that its hydraulic nature combined with the high absorptive nature of shiv results in a poor and powdery material. Therefore, lime based binders have been found to be better in Hempcrete for the following reasons (Evrard & de Herde 2010)

- A hydrated lime sets and hardens through carbonation, and requires very less water
- The permeability of the lime improves the drying time of the entire wall and not just the surface
- The pH of lime is very high, which means that it can prevent mould growth in timber and shives
- The flexibility of lime prevents cracking in the wall
- The thermal conductivity of the hemp-lime wall is lower than that of hemp-cement.

There have been some occasions where cement has also been added to the mix. But, it is not advised to add cement because of the negative effects on the resulting product. The addition of small amount of cement can provide a quicker set, though at the risk of a loss of long term durability and loss of pore structure, mixes of this nature are prone to failure, particularly in extreme conditions (Holmes & Wingate 2003). Therefore, in case of Finland, addition of cement is not appropriate.

Tradical Hempcrete, a UK based manufacturer has non-hydraulic lime or air lime along with 15 % ordinary Portland cement, and 10 % unspecified pozzolans as additives (Bevan & Woolley 2008). There are, however, serious consequences if the mixing error happens in a big scale as pointed out by Bevan & Woolley. It is best to make differences between two different mixing proportions of binder of differing NHL, or, Natural Hydraulic Lime in table 2;

Table 2 Differences between NHL binders

Predominantly NHL (e.g.5)	*Insufficient NHL (e.g. 0 ,<1)*
Hemp can absorb too much water for the curing process	Setting takes a substantially longer time
This leads to dry hemp and dry powder	Risk of damage to the Hemp-lime mix during framework removal

It is also beneficial to take into account the pH of lime with temperature.

Temperature °C	pH
0	13.423
5	13.207
10	13.003
15	12.810
20	12.627
25	12.454
30	12.289
35	12.133
40	11.984
45	11.841
50	11.705
55	11.574
60	11.449

Figure 5 Temperature VS pH of lime (Source: lime.org)

Hence, there are other benefits as well for the use of lime in Hempcrete because of its alkalinity as demonstrated by figure 5. This particular property makes Hempcrete wall mould and termite- proof.

3.2.3 Water

Water is needed for the thorough mixing of all the constituents in the mixer. Due to the high porosity of the shiv, the water that is initially added in the mixer is quickly absorbed by the shives. To make sure that the binder is mixing properly, extra water has to be added. The moment lime has been mixed properly, the material is left with the moisture of about 70 % (Evrard & De Herde 2010). Therefore, special attention is needed for drying, and in the end, the dry moisture content should be about 5 % after evaporation. Enough water has to be added to get the slurry like mix.

There is, however, a need of a careful approach while adding water. There is a rush to add more and more water particularly if the mix looks dry and not workable during the mixing process. But a side-effect arises later in the product due to the high quantity of the water inside. As Duffy et.al (2014) point out this leads to the increased density of the wall as it compresses under its own weight. Along with this, the thermal performance of the wall is substantially lowered, and the drying or setting time is increased. It should be noted by the mixers on site that the hemp shives are properly mixed with lime inside the mixer before casting. If this does not happen, there cannot be enough adhesion between the casting element leading to poor results after the setting.

The solid mass is enough to hold together quickly, but it takes time to dry. Drying and curing time will vary according to the mix of the constituents, and also the climatic conditions or internal room temperature. Normally, this time frame is mentioned to be 4 weeks. (Woolley n.d.)

4 BUILDING A WALL WITH HEMP

Using renewable crops of agriculture as raw materials is one of the ambition of the UN conference on the environment in Rio de Janeiro in 1992. The way in which the built environment consumes natural resources means that it is one of the most significant contributors of the global and local environmental problems (Woolley 2006). Therefore, a huge change in the type of material used in building is required. For this reason, an agricultural crop such as Hempcrete can create a material with lower density, thus reducing the energy needed for transportation (Evrard 2003). Furthermore, lime requires less energy to produce than cement, with much lower carbon emissions, because it uses kilns at a lower temperature (Evrard 2003; Woolley 2006).

Hemp-lime concretes are environmentally friendly because they have a very low impact upon the environment, and have carbon negative properties. Evrard (2003) mentions that there is carbon dioxide storage in Hempcrete. One property of hemp is that as it grows, it takes up carbon dioxide from the atmosphere, and when it is used as a construction material, this carbon dioxide is stored inside the material during the lifespan of the structure. It is estimated that one square meter of Hempcrete wall stores 14-35 kg of Carbon dioxide over its life span of 100 years.

4.1 Building Methods

One thing to consider about the Hempcrete is that it requires a load bearing structure. Normally, timber frames are used. The methods of casting Hempcrete are tamping, spraying and blocks which will be discussed below.

4.1.1 Tamping

Tamping method uses temporarily attached boards, mostly plywood sheets, which create a mould. Then the mould is filled with Hempcrete. Normally, the mix is tamped with hands or a simple device such as a wooden stave. The main purpose of this is to avoid large air voids in the material so that the material has effective insulation properties. But the thing to remember is to have a balanced tamping pressure-neither too hard, nor too low, so as to avoid air voids in the material.

There has been a report from British Building Research Establishment (BRE 2002; BRE 2003) of two hemp houses constructed in Haverhill, UK using tamping. The result has been published which clearly mention that these hemp houses have qualities that are better than those of traditional constructions.

Figure 6 Tamped Hempcrete (Source: http://hempsteads.info)

Figure 6 shows the Hempcrete being tamped into the frame.

4.1.2 Spraying

The method of spraying is used when the project needs to save time. Plywood sheets, which are attached to one side of the load-bearing structure, are sprayed with Hempcrete mix evenly with the help of pipe pressure. The mix adheres to the plywood or the frame. This is beneficial in comparison to the human workers tamping manually using hands, which takes a lot of time than to simply spray as shown in figure 7.

Figure 7 Sprayed Hempcrete on Timber frame (Source: http://www.inmatteria.com)

4.1.3 Blocks

The method of blocks requires a load bearing timber framework. The blocks are placed on the framework, and necessary connections are made before the wall plate is installed. This method has seen popularity in France. The blocks are shown below in Figure 8.

Figure 8 Blocks of lime and Hemp (Source: http://www.hemparchitecture.com)

4.2 Finishes

The best suited finishes for a Hempcrete wall is such which is vapour permeable so that the breathability of the wall is not jeopardized in any-way. This also takes care of the fabric of the wall along with timber. Therefore, a two-coat lime plaster in the wall is appropriate, along with a lime render externally.

In addition to the lime render, there is a way to maintain the permeability of the wall nonetheless. This can be achieved by constructing timber clad-dings with ventilated air gaps.

5 HEMPCRETE TEST WALLS CONSTRUCTION

As per the measurement requirements and material supply from the commissioning company Hemprefine OY, three samples of Hempcrete wall were designed in the HAMK Sheet Metal Centre laboratory in Hämeenlinna, Finland for the purpose of testing using hemp shives, lime and water. The lime is more appropriate for use in Hempcrete than cement due to the slow carbonation process. This is very compatible with the fast water uptake of the hemp shives. In addition, the high pH of lime is beneficial to the structure because it acts as a protective shield against mould and bacteria. The different dimensions and different mixing proportions between hemp, lime and water in the mixing machine were calculated carefully before Hempcrete casting. A 300 litre mixing machine was used with the following classification in table 3:

Table 3 Class of the mixer used in the casting

KW	*Hz*	*V*	*A*	*r/m*	*cosØ*
3.0	50	330-420 Δ	6.8-6.2	1 41 5	0.81
3.0	50	660-720 Y	3.9-3.6	1 41 5	0.81
3.6	60	440-480 Δ	6.8-6.3	1 71 5	0.82

The initial measurements of the hemp shiv particles were performed for densities along with measurements for lime binder as presented in table 4.

Table 4 Constituents of the wall

Constituents	*Measured Density*
Small Shives	136 kg per m^3
Large Shives	132 kg per m^3
Slaked Lime, also known in Finnish as *Sammutettu Kalkki* or in Swedish as *Släckt Kalk*. $Ca(OH)_2$, pH 12.4, 74.09 g / mol	429.4 kg per m^3

After the exact measurements of the constituents, sufficient amount of hemp shives were first added to the mixing machine. Then, the right amount of lime was thoroughly added. Finally, the correct amount of water was poured as shown in figure 9 to achieve a final Hempcrete which could be casted into the wall frame open at one side as sown in figure 10.

It was observed that the ratio and proportion of mixing between hemp, lime and water varied significantly. Even though a common proportion of 19%: 31%: 50% by weight was used in theory for walls 1 and 2, in practice the amount of ingredients changed depending upon the capacity of the mixing machine.

Figure 9 Mixer filled with shives, lime and water in the Laboratory

One note of caution- the mixer can be overloaded if the hemp lime mix is filled to its full capacity. Therefore, a measurement is essential beforehand about the amount to be mixed in the mixing machine. After that, Hempcrete can be tamped carefully in the timber frame open at one side, manually as shown in the figure.

Figure 10 Hempcrete being casted in the test-site by manual tamping

One significant task was to dry the wall and speed up the process. In-order to understand the phenomenon of Relative Humidity and temperature inside the wall, sensors were installed in the wall depths. The installed sensors helped to record the surface temperature and relative humidity that were needed before the acoustic tests. The sensors were connected to a reading device that helped in recording the relative humidity and temperature of the certain cross section of the wall, taking in consideration the normal wall cross sections. The installing of sensors was carefully done to get the required depth and position.

5.1 Wall 1- Only Small Shives

A 2110 x 1240 x 170 mm wall frame was constructed in the Sheet Metal Laboratory for the purpose of casting Hempcrete. For the easiness, the wall was divided into two sections before the casting was done.

Type of shiv used: Only Baled shives (Small size)
Mixing Ratio of Hemp: Lime = 1:2 by weight (kg)

Table 5 Mixing proportions of hemp, lime and water in wall 1

Mixing	*Small Shives (litres)*	*Lime(litres)*	*Water (litres)*
1st	230	140	80
2nd	70	25	16
3rd	90	35	25
4th	90	37.5	30
Total	480	237.5	151

Table 5 shows that a significant amount of water is required in Hempcrete casting. The reason that the amount of water cannot be scientifically exact is that the person observing the mixture has to check the formation of Hempcrete inside the mixture periodically during the process. Therefore, sometimes more water has to be added, and sometimes more lime. The casting of wall 1 took roughly 5 hours. Since the capacity of mixer is limited, the mixing is done many times. It is advised to have a bigger capacity mixer to make the mixing easier and faster.

Figure 11 Wall - 1 after four days of casting in the HAMK SMC

After four days of casting, the walls were erected straight as shown in figure 11, and the frames were taken out from all the sides. Therefore, the front and the back of the wall were open for air movement, and fans were installed to fasten the drying time. In order to evaluate the drying time of the wall, it is best to check the inside of the wall for Relative Humidity (RH) and temperature. A 2-view sensor for RH and temperature was installed to measure the moisture scenario inside the wall. The graph in figure 12 shows the variations of RH and temperature over a span of a week in wall 1.

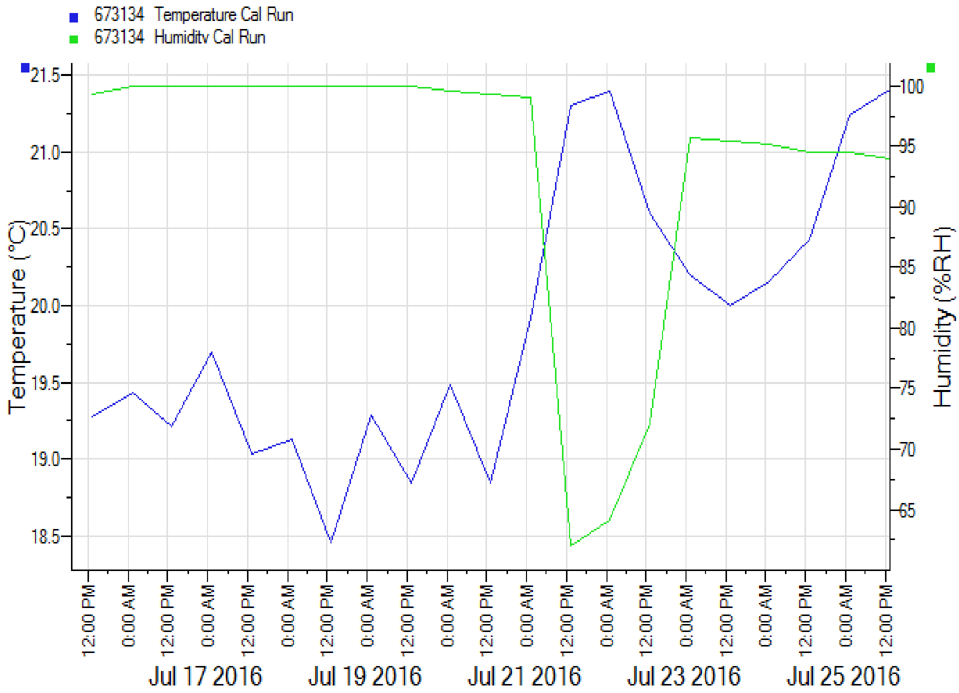


Figure 12 Relative Humidity and temperature inside wall 1

The measurement of RH and temperature is vital before the acoustic performance testing as required by the testing company. The RH-T graph in figure 12 shows the variations in rise and drop of the relative humidity and the temperature inside the wall from the test date of July 17 to July 25. The temperature roughly stayed between 18°C and 21°C. The RH was 96% in the beginning of the test and it dropped by a mere less margin to 94.5 % in the last day of the test. The sharp drop in the RH in July 21-July 23 is due to the addition of extra fans, one with hot air, which also increased the temperature in the same time period. This shows a challenge to dry the wall in normal room conditions.

5.2 Wall 2- Only Large Shives

A 2110 x 1240 x 200 mm Wall frame was constructed. For the easiness, the wall was divided into two sections.

Type of shiv used: Larger Hemp shives
Hemp: Lime: Water = 1:2:3 by weight (in Kg), approx.

Table 6 Mixing proportions of hemp, lime and water in wall 2

Mixing	*Large Shives (lit)*	*Lime (lit)*	*Water (lit)*
1st	140	95	60
2nd	170	115	70
3rd	140	95	60
4th	140	95	60
Total	590	400	250

As demonstrated in table 6, larger shives required more water in the mix, as compared to the mix with only small shives, along with the increment in the amount of lime.

Figure 13 Wall - 2 after four days of casting in the HAMK SMC

Test wall 2, shown above in figure 13, was erected straight after four days of casting. After a significant amount of time, sensors were attached to measure the changes in moisture content inside the wall. The following graph in figure 14 shows the RH-T variations inside the wall over a period of a week in a room temperature, with fans attached for some days, and then taken out.

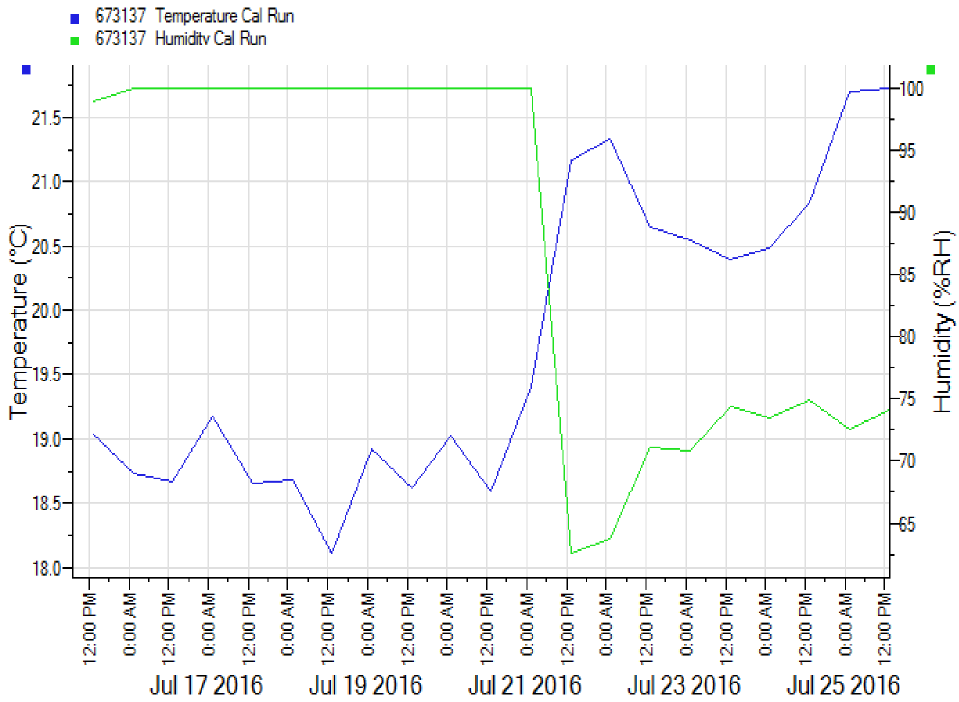


Figure 14 RH and Temperature inside Wall 2

The above graph shows that at the beginning of the test, the temperature and humidity inside the wall were 19 degrees and 96 % respectively. However, as the days go by, the humidity has lowered down. The final values show that Relative Humidity inside the wall was 74 % by the end of the week. The reason for this was the addition of extra strong fans in July 21. It explains that the drying time can be shortened by addition of fans.

5.3 Wall 3- State of the Art Design

Test wall 3 was the final element casted in the HAMK Sheet Metal laboratory which was drafted after the careful study in the field of Hempcrete and the acoustical dynamics of sound. A 2000 x 900 x 170 mm wall frame was first constructed which was divided into two sections which meant two moulds of 1000 x 900 x 170 mm each. The wall was carefully planned beforehand, and the latest information were utilised in sound transmission across the Hempcrete walls. To increase the acoustic insulation properties of the wall, the properties of lime and hemp shives in the mix were studied and analysed. For the protection of confidentiality, the design specifications of this wall are not explained in this section.

After successful casting, the wall samples 3 were erected after four days and allowed to dry in room temperature as shown below in figure 15.

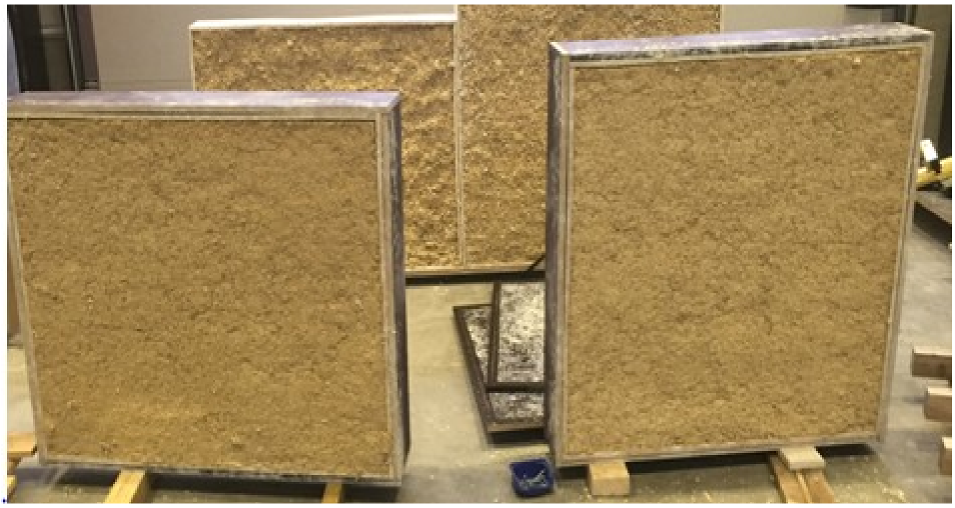


Figure 15 Walls - 3 after four days of casting in the HAMK SMC

Then, the walls were measured for their weight. One unit of the wall weighed 121.5 kg each with the frame. To measure the internal RH and temperature, a two-view sensor was inserted inside the wall after drilling a 100 mm hole.

The following graph in figure 16 shows the variations in RH and temperature inside the wall over a span of a week.

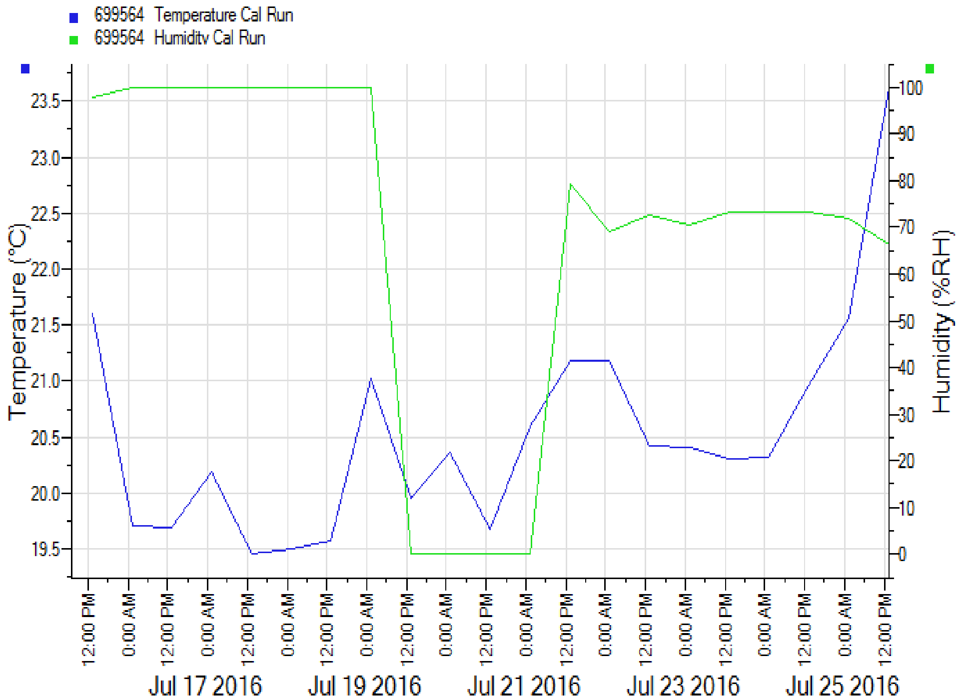


Figure 16 Relative Humidity and temperature inside Wall 3

Clearly, the strong drops in the RH from July 19 was due to the addition of the extra strong fans. However, even after the fans were shut down on July 22, the RH showed improvement by the end of the test. From more than 95% RH in the beginning of the test, RH dropped to 65% in a week, along with increment in internal temperature from 21.5°C to 23.5°C. It is to be noted that due to the presence of huge amount of water during the casting and mixing phase, a lot of water trapped inside the wall makes it harder for the composite wall to dry. Therefore, effective drying is required.

5.4 Carbon Sequestration in Walls 1-3

Scientific chemical calculations show, as performed in Chapter 3, that 1 kg hemp shives have locked 1.8 kg CO_2. In the same way, lime releases about 0.48 kg CO_2 per kg. The following tables 7, 8 and 9 show the amount of Carbon dioxide locked within the Hempcrete walls 1,2 and 3

Table 7 Amount of CO_2 Sequestered in Wall 1

Constituent	*Weight*	*Carbon Dioxide*
Lime	101.6 kg	48.76 kg released
Small Shives	65.2 kg	117.36 kg locked
Total Carbon dioxide Sequestration		*68.6 kg stored*

Table 8 Amount of CO_2 Sequestered in Wall 2

Constituent	*Weight*	*Carbon Dioxide*
Lime	171.6 kg	82.36 kg released
Large Shives	77.8 kg	140.04 kg locked
Total Carbon dioxide Sequestration		*57.68 kg stored*

Table 9 Amount of CO_2 Sequestered in Wall 3

Constituent	*Carbon Dioxide*
Wall 3	44 kg stored

The above tables show the amount of carbon dioxide stored in the three wall samples. As the walls vary in the amount of ingredients i.e. the lime and shives and dimension, they have different carbon sequestration. It is obviously noticeable that decreasing the amount of lime in the mix is a sure way of increasing the carbon sequestration. However, the amount of lime in the mix is pre-calculated as per the desired outcome of the wall. If a wall has very less lime in the mix, it might have problems in acoustic insulation. Therefore, a fixed proportion by weight or volume of shives, lime and water in the mix is required to produce Hempcrete walls for effective sound insulating properties. Furthermore, fibers can be mixed in the wall to increase the acoustic quality.

6 HEMPCRETE PERFORMANCE

The combination of hemp shives and a cementitious binder effectively creates a building material which can be very different than the conventional concrete. Therefore, it has different mechanical, thermal, acoustic and insulating properties compared to concrete. It has a lower density, a lower thermal conductivity and better acoustic insulation properties and is thus advantageous for the use in construction (Cerezo 2005; Evrard 2003; O´Dowd & Quinn 2005; Arnaud et al 2006).

The following table 10 shows the material properties of various building materials.

Table 10 Some material properties of lime-hemp wall mix and other building materials (Sources: Evrard 2003).

Material	*Young´s Modulus (MPa)*	*Compressive Strength (MPa)*	*Density (kg/m^3)*	*Thermal Conductivity (W/m.°C)*
Steel	210000	350-1000	7500-8500	52
Concrete	20000	12-80	2300	1.5
Cellular Concrete	1000-2500	5	420-1250	0.14-0.23
Brick	10000-25000	25-60	1300-1700	0.27-0.96
Wood	230-20000	4-34	350-900	0.12-0.3
Hempcrete	24	0.4	445	0.17

The more recent data from Lime Technology LTD for Tradical® Hempcrete® show the following material properties as shown in table 11:

Table 11 Hempcrete Properties Updated Data, 2014 (Source: Limecrete.co.uk)

Density	275kg/m^3
Flexural Strength	0.3-0.4 N/mm^2
Thermal Conductivity	λ=0.06W/m.K
Heat Capacity	1500-1700 J/kg
Mean Acoustic Absorption Coefficient	0.69 NRC
Air Permeability	0.75 gm/m^2/mm hg
Vapour Permeability	24.2 gm/m^2/mm hg
μ,Vapour Diffusion Resistance	4.84
Fire Rating	1hr BS EN 1365-1:1999
Carbon Capture	130kgCO_2/m^3
Air tightness	<2m^3/m^2.hr@50pa

There are many reasons why the research and tests performed on Hempcrete in many different countries have slightly different material values. All in all, the properties of the Hempcrete structure will vary depending upon the following variables:

- Individual properties of hemp shiv and fibres depending upon the location of their growth
- The exact mixing proportion of shiv, lime binder and water in the mix
- The method used in casting

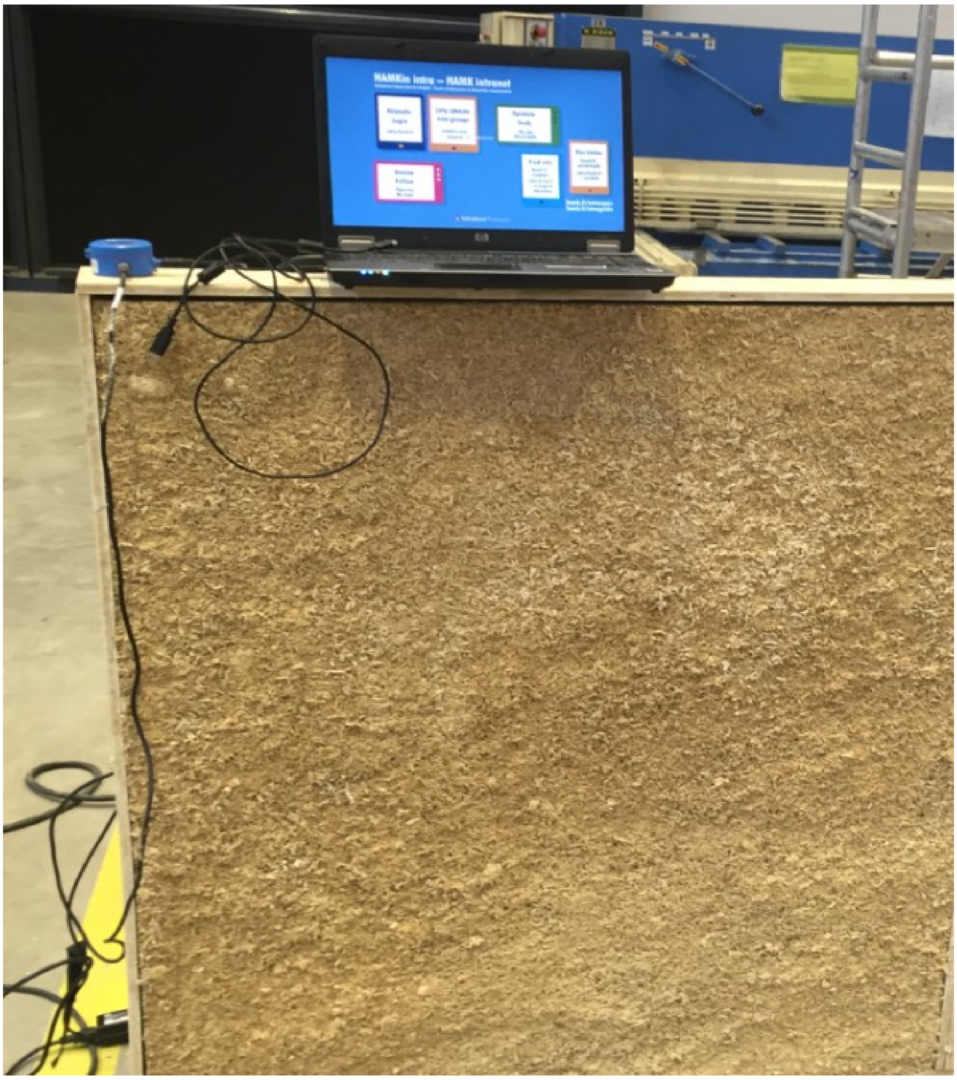


Figure 17 Test wall in the Laboratory with sensors

Figure 17 shows the wall specimen for tests in the laboratory.

6.1 Compressive and Tensile Strength

Since there are various methods of mixing hemp with lime and water, there can be variations in the results for compressive strength. This also comes with an engineering opportunity to manipulate the desired output of compressibility by changing the mixing ratios of hemp, lime and water or using variations of hemp shives and fibres. Furthermore, it also depends on the age of the material. The reported compressive strength of Hempcrete can vary from 0.02 to 1.22 MPa depending on the composition of the mixture (Arnaud & Cerezo 2001).

Because of the very low compressive strength of a Hempcrete wall, 0.4 MPa as compared to almost 80 MPa of a conventional concrete, it requires a load bearing frame to withstand its own weight. Therefore, a design for the framework is to be taken into consideration before casting Hempcrete. Another issue is the slow setting time for maximum compressibility. Arnaud & Cerezo (2001) mention that the hydrated lime takes up carbon dioxide while it sets, and the whole process of time is very lengthy. Therefore, the maximum compressive strength could show up after several months up to several decades.

Depending on the mixture, O´Dowd & Quinn (2005) have reported tensile strength from 0.12-0.23 MPa.

6.2 Breathability

Breathability refers to the ability of water in the gaseous vapour to move through a structure or medium, thus allowing water to pass through it. Lime, because of its open pore structure and vapour permeability, can be combined with the hemp shives which are micro porous themselves. Therefore, on account of the open pore structure of Hempcrete, it has an ability to store a significant amount of water moisture. The water remains until the capillary saturation is obtained, and then evaporation begins thus accelerating the drying time.

6.3 Thermal Insulation

Arnaud & Cerezo (2001) have successfully tested thermal conductivity of eight different mixtures and have found values ranging from 0.07 to 0.01 W/mK. Alongside this, Evrard (2003) reported a thermal conductivity of 0.17 W/mK for material placed in a room temperature, close to 24°C and relative humidity of 60-70 %.

6.4 Discussion on Increasing Mechanical Strength

Since the aim of construction differs from one project to another, so is the need of different type of material strengths. There are many ways in which the mechanical strength of Hempcrete can be achieved by modifying the composition of the matrix, e.g., by using different mixtures of the binding agents and by adding suitable pozzolans or additives. Mostly, these are silica flume and fly ash. Consequently, using undensified micro silica in combination with lime may improve the mechanical strength of Hempcrete. (De Bruijn 2008.)

Another method of increasing the mechanical strength has been reported by Karni & Karni (1995). In this method, Gypsum was used as a binder in combination with hemp. The compressive strength was reported to be 12.0 MPa. Therefore, the use of gypsum could also make hemp a potentially beneficial building material with a higher compressive strength.

Figure 18 Test of mechanical Strength in the laboratory

As shown in figure 18 above, it is indeed very difficult to increase the mechanical strength of the Hempcrete wall. However, the best way to make sure that the wall is strong enough is to carefully plan the mixing proportions of water, lime and hemp in the mixture, and add other binders such as silica or gypsum. This ensures that the resulting wall can withstand some structural pressure. It should be noted, however, that a Hempcrete wall must have a load bearing frame because it is not immune to stress and strain. There can be cracks, especially in the edges if the wall is allowed to dry without a support frame. Therefore, it is advised that at first, a suitable frame work is done. After this, it is easy to cast Hempcrete.

7 DYNAMICS OF HEMPCRETE NOISE BARRIER WALL

Noise originates massively in highways due to the motor engines, exhaust stack and road-tires friction. It is for this reason that the European roads are obliged to have a noise barrier if there is a community of people in the vicinity of the road-highway traffic network. The function of noise barriers is to block the noise coming from the highway or railroads, and prevent it from disturbing the surrounding communities. It is therefore, very important to place properly functioning noise barrier walls in between the highway and the community. In this thesis, the noise barrier wall has been designed and tested according to the needs of highway road traffic. Thus, the significant bulk of the thesis has been devoted to the testing for the road traffic noise and its mitigation. In order to get an idea of the noise level, it is best to make a scale of different noises from the threshold of hearing, to the threshold of ear pain as presented in figure 19 graphically.

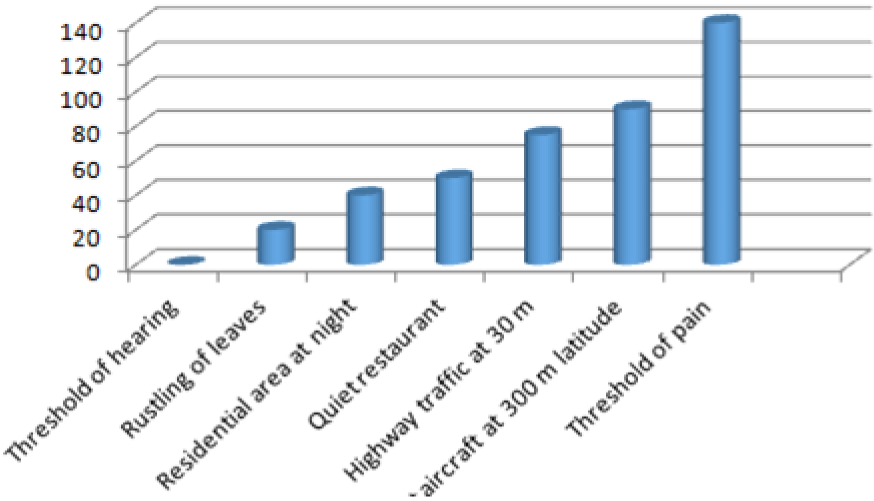


Figure 19 Decibel (dB) Graph: Different levels of noise (Sources: various online sources for numerical data)

The human anatomy of ear tells us that the human ear is capable of hearing a sound in the range of 20 Hz to 20000 Hz. But the sensitivity of human ear is not so efficient, so most of the transportation related noises such as the highway traffic are measured in A-weighted response network. So, A-weighting emphasizes on the sounds between 1000 Hz and 6300 Hz and its corresponding sound levels measured in decibels, dB, shown in figure 20.

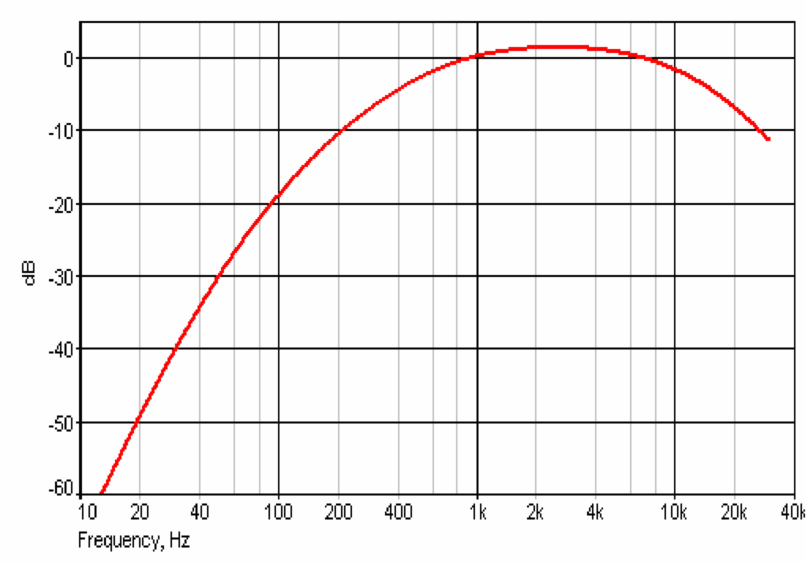


Figure 20 Frequency A-weighting (Source: http://sound.westhost.com)

A-weighting enables to measure the sound level pressure. Thus, the noise s that are not perceived by human ear, but have adverse health effects can be measured using A-weighting. It is a curve defined in the International standard IEC 61672:2003. Therefore, to calculate the Traffic or road-highway noise levels, this weighting is used.

7.1 Basics of Insertion Loss

Any barrier that just blocks the line of sight is capable of insertion loss of 5 dB, and with each additional height of 1 meter added to it, the loss increases by 1.5 dB respectively. The following figure 21 shows the insertion loss in Hempcrete wall when the line of sight is just blocked. For the easiness of our thesis calculations, the source and the receiver have been represented by a point, and not by line movement such as a moving traffic.

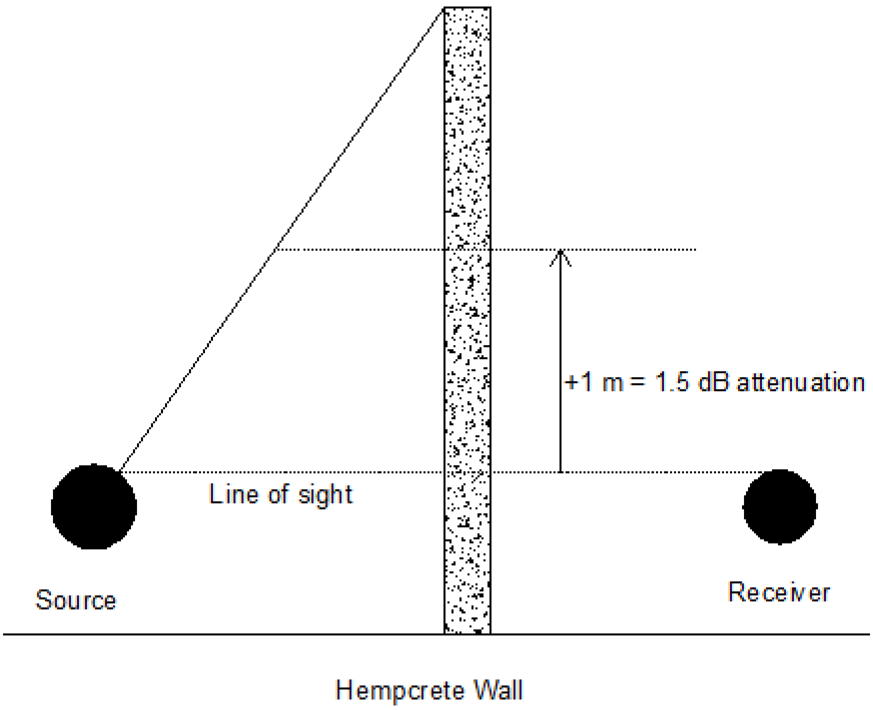


Figure 21 Attenuation of wall by Height

Mathematically, for this reason, the proposed Insertion Loss of Hempcrete wall is,

$$IL = 5dB + 20log\frac{\sqrt{2\pi N}}{tanh\sqrt{2\pi N}}\ dB$$

where,
N is the Fresnel number which is frequency dependent measure of the extra distance the sound should travel to reach the barrier,
To further describe the Fresnel number mathematically,

$$N = 2\frac{\delta}{\lambda}$$

where,
δ is the difference between the diffracted path and the direct path
λ is the wavelength of sound in the air.

This implied that Insertion Loss is directly proportional to the Fresnel number.

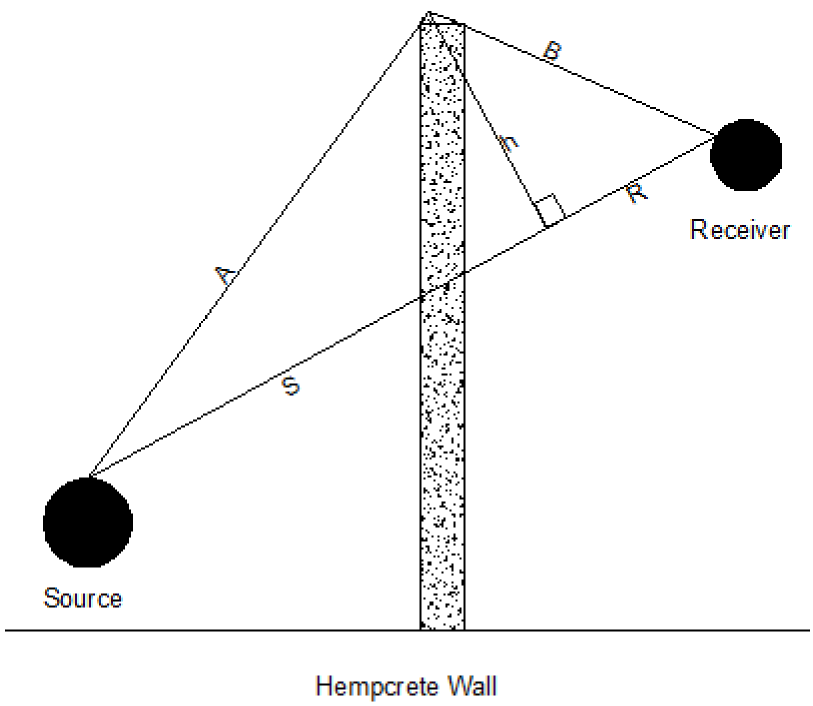


Figure 22 Calculation of Path Difference

The figure 22 implies that the path difference is,

$$\delta = A + B - (S + R)$$

Therefore, Fresnel number is directly proportional to the path difference. This impacts barrier attenuation.

From figures 21 and 22, it can be seen that when the barrier just breaks the line of sight between the source and the receiver, the value of Insertion Loss (when h=0) will be;

$$IL = 5dB + 20log \frac{\sqrt{2\pi N}}{tanh\sqrt{2\pi N}}\ dB$$

$$IL = 5dB + 0\ dB$$
$$= 5\ \text{dB}$$

Thus, a 5 dB attenuation in noise is obtained.

It is the minimum insertion loss obtained from a Hempcrete Wall. To calculate the actual maximum sound reduction, a sound measurement is performed in the laboratory according to the acoustic directives of air-borne sound test as per the ISO Standard.

7.2 Sound Measurement

As per the ISO standard, the determination of sound insulation is tested for the Sound Reduction Index, or R_w according to the ISO 717-1 Rating. This standard measurement requires a sound which is emitted into the one side of the wall. The final measurement is done after calculating the sound level difference between the two sides of the wall. Mathematically,

$$R_w = L_1 - L_2 + 10 \log \frac{S}{A} \, dB$$

Where,
L_1 is the logarithmic average of the source room measurements of sound
L_2 is the logarithmic average of the receiving room measurements
S is the area of the wall tested
A is the equivalent absorption area.

Furthermore, the equivalent absorption area is calculated by:

$$A = \frac{0.163\, V}{T} \; m^2$$

Where,
V is the receiving room volume
T is the reverberation time in the receiving room.

The test has to be performed according to the acoustic directives set by the European Standards Committee called as CEN. According to the ISO 140, the sound reduction is determined within the 50-5000 Hz and is expressed in decibels.

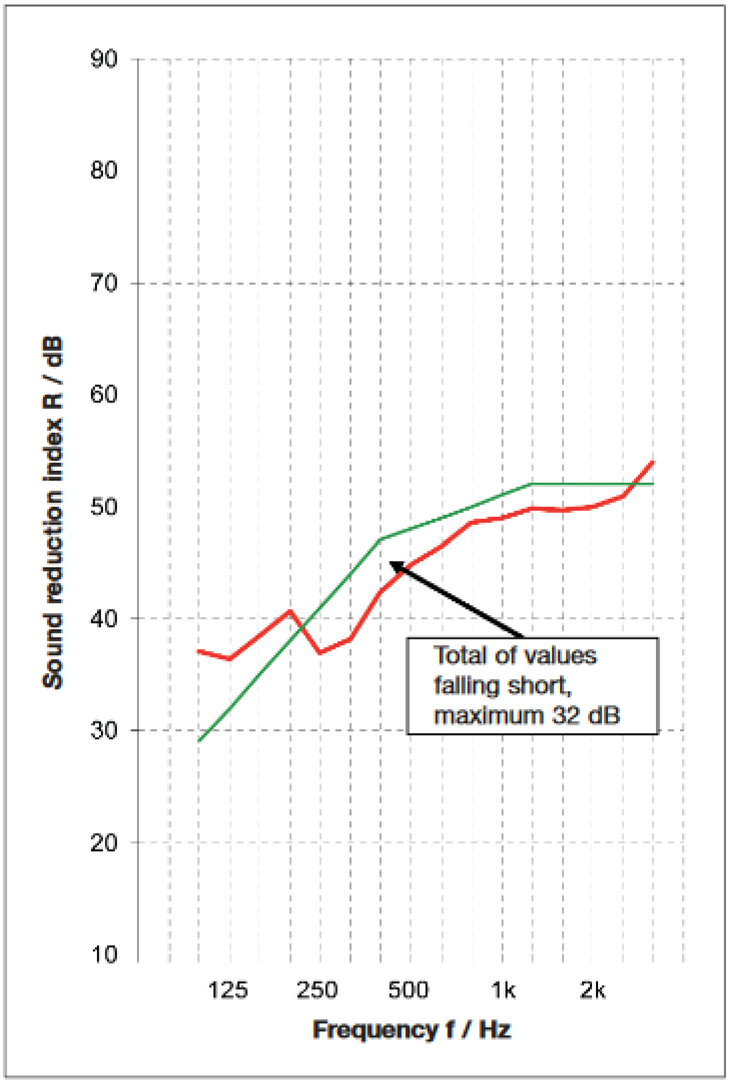


Figure 23 Sound Reduction Index Measurement (Source: www.hilti.dk)

For the measurement of Sound Reduction Index, a graph of frequency Vs Sound Reduction Index is plotted as shown in figure 23. The reference curve, shown in green line in the graph, is displaced vertically in such a way that a maximum of 32 decibels is resulted against the curve of the test specimen, shown in red. The result of the measurement, or the Sound Reduction Index R_w corresponds to the intersection of the 500 Hz line with the reference curve. The tests-related calculations of this graph are performed in the Acoustic Tests of this thesis.

8 EUROCODES OF NOISE BARRIER TESTS

It is very important for anyone involved in the designing of the noise barrier wall to have informed choices about the best practices of the designs. There are various specifications for noise barrier systems for transport noise in the European Union. In the past years, there has been a gradual emergence and updates of the Noise barrier guidelines in the EN standard. The barrier design has to meet from acoustic to highway safety criteria. The following are the EN design standards for a noise barrier wall. The following table 12 will help any manufacturer who intends to know the required standards in the European Union pertaining to noise reducing barriers, though not all of them mandatory to be tested. Normally, for National Road Networks within a country inside EU, EN-1793 Tests are advised.

Table 12 EN Standards and their description (Source: Parker 2006)

Standard	*Status*	*Briefing*
EN 1793-1	Published 2012, in revision	Sound absorption under diffuse sound condition
EN 1793-2	Published 2012, in revision	Sound insulation under diffuse sound condition
EN 1793-3	Published 1997	Road traffic A-weighted spectrum
EN 1793-4	Formal vote 2015	Diffraction index difference-additional devices
EN 1793-5	Formal vote 2015	Sound reflection under direct sound field conditions
EN 1793-6	Published 2012	Sound insulation under direct sound field conditions
EN 1794-1	Published 2012, in revision	Mechanical performance and stability requirements
EN 1794-2	Published 2011	General safety and environmental requirements
EN 1794-3	Enquiry 2015	Burning behavior of noise reducing devices
EN 14389-1	Published 2007, in revision	Long term performance -acoustical characteristics
EN 14389-2	Published 2004, in revision	Long term performance-Non acoustical performance
EN zzzz	Drafting 2015-16	Sustainability assessment
hEN 14388	Published 2005	Road traffic noise reducing devices-specifications

8.1 EN 1793-1: Lab Test for Sound Absorption

To measure the intrinsic acoustic capability of the barrier, product performance tests have to be performed with in-situ and ex-situ methods. EN 1793-1 deals with the traffic road noise reducing devices and their lab tests.
The tests performed in the nationally accredited laboratory require a sample panel up to 12 m^2 which is placed in a reverberation floor. The wall has to absorb noise, and it is measured within the frequency range of 100 HZ to 5KHZ. Using a single number rating, the absorption value is determined. This performance is the difference of pressure of level measured in Decibels, dB, and expressed as, DLα. The values are used to categorize the type of project, and how much effort is required in it. The following table 13 expresses the different categories and project features:

Table 13 Categorization of Absorption values and project features

Category	*Absorption DLα*	*Project*
A0	Not determined	Reserved for reflective barriers and absorption tests are not required
A1	<4	Highly impractical
A2	4-7	Composite barrier with absorptive section to be tested
A3	8-11	Most highway projects
A4	>11	Close corridors

8.2 EN 1793-2: Lab Test for Airborne Sound Insulation

This test, performed in a nationally recognized laboratory, needs a sample panel which is mounted in a window space between two reverberation room. The level of air-borne sound insulation is measured across the frequency range of 100 HZ to 5KHZ.
The single number rating is used to categorize the different performances of the barrier, expressed as DLR. It is the difference of A-weighted sound pressure levels. Table 14 shows the categorization of barriers:

Table 14 Air borne sound insulation categorization

Category	*DLR*	*Projects*
B0	Not determined	Barriers with gap, cannot be tested by EN 1793
B1	<15	Rarely considered
B2	15-24	Low barriers
B3	>24	Most highway projects

Therefore, it is advisable to have B3 categorization of the noise barrier wall, if it is used in a highway project. This requires DLR of at least 24 dB. Barrier with DLR lower than 20 dB, might be too thin to cope with low frequency noise. The robustness, and longevity of such noise barrier is not trustworthy. (Parker 2006.)

8.3 EN 1793-4, EN 1793-5: In Situ Tests

EN 1793-4 standard adds diffraction in its testing. The benefit is that the new devices could be added to the barrier to improve its performance. Also, with this standard, the acoustic behavior and capabilities of adding such elements are analyzed. A single number rating system is used to categorize the devices in terms of Diffraction Index Difference, ΔDI. The diffraction index difference is the difference between the results of the sound diffraction tests on the same reference wall, with and without the added device on top, in decibels. This standard is helpful to qualify products according to the design specifications before the installation on site.

To validate the internal lab tests, EN 1793-5 standard was developed and is still in its development. The reason being that EN 1793 cannot represent the installed operating conditions for a noise barrier perfectly. Now it has been widely used in Europe product sales literature for acoustic performance. The further benefit is that it could be used in projects which cannot be tested by EN 1793, such as noise barrier with gaps in them. The sample should be built at least 4m long and 4m high. (Parker 2006.)

8.4 EN 1794: Non Acoustic Performance

Even though noise reduction is the most important factor in the design of a noise barrier wall, there are certain mechanical and structural implications as well. Therefore, EN standards have been set to meet these guidelines. Some of the guidelines can only be country specific due to the variations in climate in the European Union with changing latitudes and longitudes. Essential practical tests for the noise barrier wall ensure that the wall is suitable to be installed in the highway. All in all, it requires the manufacturer to calculate or test the following:

- Wind load and static load
- Impact of stones
- Self-weight
- Safety in collision
- Dynamic load from snow clearance
- Resistance to fire
- Danger of falling debris
- Environmental protection
- Means of escape
- Light reflection
- Transparency

8.5 EN 14389: Durability

There are two European Standards pertaining to durability. EN 14389-1 gives specific details about the acoustic durability, whereby, a manufacturer of noise barrier has to specify the reduction in acoustic properties and capabilities after 5, 10, 15 and 20 years of exposure. On the other hand, EN 14389-2 outlines the non-acoustic guidelines. The non-acoustic guidelines are more difficult to follow, and in Germany, it has been regularly neglected even after 18 years of existence (Parker 2006).

Apart from structural functions, the noise barrier has to maintain performance throughout its working life. This often requires an in-depth study of chemical erosion, electric impacts, and ageing of the elements. The stages of the noise barrier working life, thus, could be divided into four stages (Clarbois & Garai 2015).

Stage 1- Design, consultancy and planning
Stage 2- Construction, manufacturing and contracting
Stage 3- Usage, maintenance and repair
Stage 4- Demolition and repair

9 NOISE BARRIER WALL DESIGN

There are a lot of considerations to take into account for the design of noise barrier wall constructed out of Hempcrete in Finland, because of the slightly extreme Finnish climatic conditions. The Eurocodes mention some requirements for the foundations of the noise wall, and it is worth to delve into the documents of Road Administration, Tiehallinto from Finnish Transport agency, published as Tien meluesteiden suunnittelu or Designing of road noise barriers.

9.1 Basic Design by Eurocodes

There are certain calculations that need to be made in the design of the noise barrier according to the Eurocodes. The following lists in table 15 are very important to calculate in the basic design of Hempcrete wall:

Table 15 The measurements for Hempcrete noise barrier wall

Measurements	*Hempcrete wall Project for this Thesis*
Height of the noise barrier	The noise barrier wall resembles the existing wall in dimensions. Hence, the height of 2100 mm is advisable in this case.
Horizontal wind load	The EN 1994-1-4 deals with these calculations. In Finland, 0.5 kN/m^2 can be taken as the wind load unless specified. To be on the safest side possible, 1 kN/m^2 has been taken in this thesis.
Horizontal dynamic load from snow clearance	The EN 1794-1:2003, Annex E
Vertical Load	Hempcrete wall, timber-load bearing support, column, base plate, connection bolts and piles
Soil Conditions	The soil type requires pile foundation.

Most of the initial calculations related to the geotechnical conditions of the site can be performed by a geotechnical engineer to evaluate the soil behaviour and give suggestions for the type of foundation. However, there are certain norms as mentioned in the EN 1994 and EN 1794 which outline the need to perform other calculations related to the wind load in a horizontal direction. This value differs from coast to coast in the European Union, and a value of 0.5 kN/m^2 is taken in the case of Finland. To make a very safe construction, 1 kN/m^2 has been taken in this thesis. The vertical load such as the load of the wall itself, along with the columns, base plates and joints and connections are calculated to perform the much needed calculations for the support-system of the foundation.

It is true that foundation design is not complete upon the completion of a construction drawing. The project specific foundation design requires the on-site study of the construction site, and calculations for soil behaviour. The bending moment and shear force can only be calculated after the careful design of the foundation. Figure 24 below shows the basic design of Hempcrete wall.

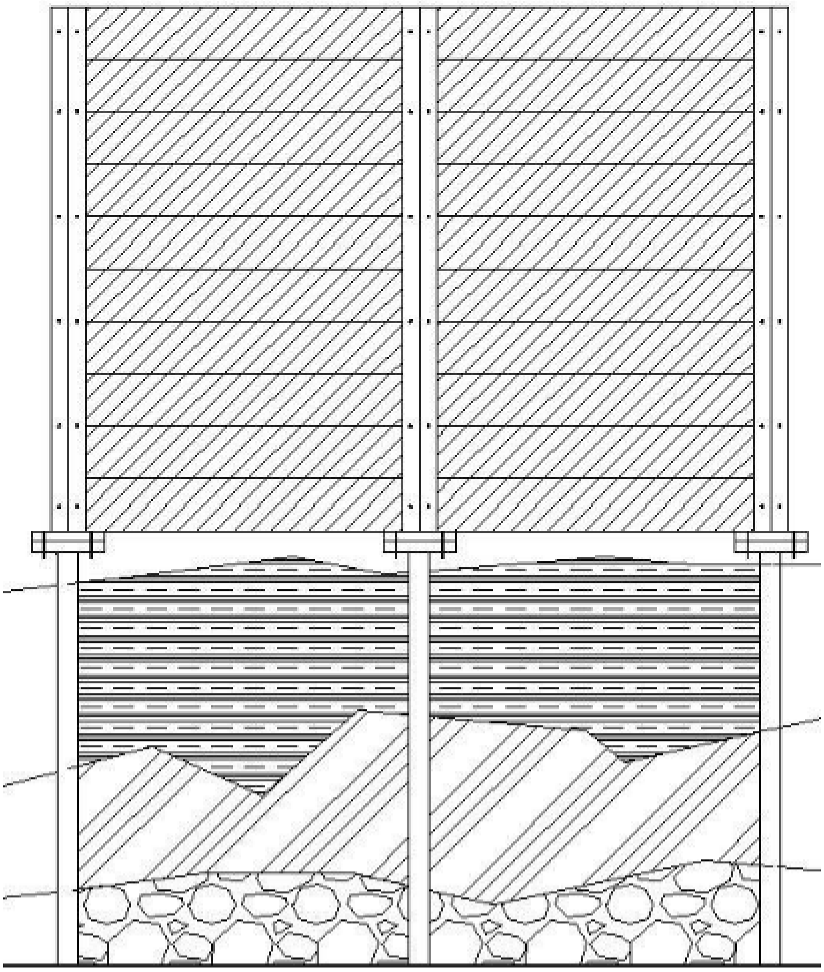


Figure 24 A basic design of the Hempcrete wall with steel columns and steel piles (Without moisture barrier for the ground)

The design of a wall thus, has to have a standard which can be compared to the EN codes and the codes used in Finland;

- EN 1971-1 Eurocode 7: Geotechnical design
- EN 1993-5 Eurocode 3: Design of steel structures- Part 5: Piling
- 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
- TIEH 2100062-09 Tien meluesteiden suunnittelu, luonnos 9.122009 (Designing of road noise barriers, draft for trial use 9.12.2009)

9.2 Foundation Piles and Columns

The Eurocodes specify the need to have a geotechnical survey before considering a pile foundation. Parameters of soil or backfill are determined according to the EN 1997. A good foundation requires a thorough study of the soil behavior of the construction site. If the soil conditions are not very firm, or if there is an elevation on the site, it is best to use foundation piles. For the sake of this thesis project, steel piles have been chosen for the reason that the test site of this thesis project has weak top-soil and roughly 30 degrees of elevation. In addition, the steel piles are robust, light to handle and can be drilled into the desired depth providing resistance to buckling or bending forces.

Finnish Piling Manual PO-2011 (RIL 254-1) gives instructions on the preliminary design of the piling foundations, and an effective and safe way of piling in Finland. The comprehensive set of instructions ensures that the piling does not affect the surrounding soil structure, and provides the most resistance from buckling. Rautaruukki (RR) steel piles, which have the CE ratings and comply with the Finnish piling manuals are the most widely used piles in Finland. As per the need of the project of a noise barrier wall, RR RD220 – RR RD400 steel piles of diameters from 220mm to 400mm are offered directly from Rautaruukki as shown in figure 25, along with the specified dimensions which are project-specific. Normally, the RR piles such as lesser than RR 220 are not used, because of problems associated with installations.

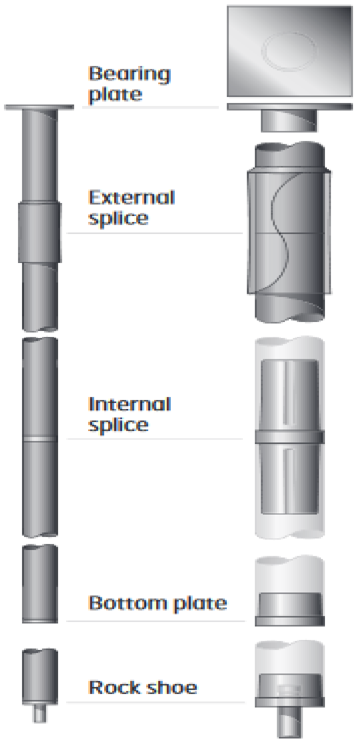


Figure 25 RR Piles from Rautaruukki (Source: www.ruukki.no)

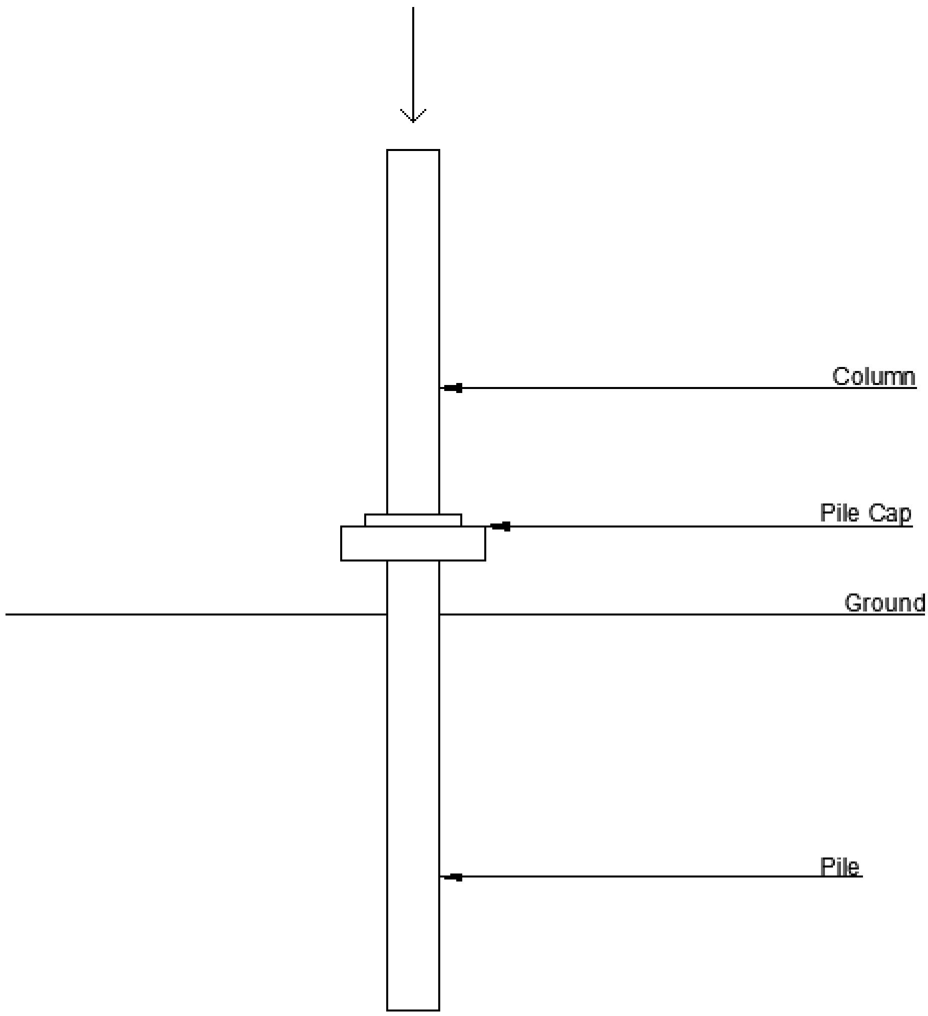


Figure 26   Pile Foundation and column for Hempcrete noise barrier wall

As shown in the figure 26, the function of the piles is to transfer the load from the superstructure into the more compact underground soil or rock. A single steel pipe pile can be inserted into the ground through drilling, driving or vibration.

In noise barriers, the steel piles can be chosen from the range of the cross-section required for the project.

In regard to piling of the steel into the foundation, it should be noted that since Finland is a Nordic country with a Nordic climate, rock shoes might be required for the piles.

After the piles have been set up as the foundation in the ground, the Hempcrete wall can be connected to the Steel column. Since Hempcrete in itself is non-load bearing, a load bearing timber frame provides sufficient bearing capacity for the wall. The typical timber wood that is moisture proof- known in Finnish as Kestopuu and Painekyllästetty puu (Pressure Integrated Wood) is the preferred choice as it provides protection in winter.

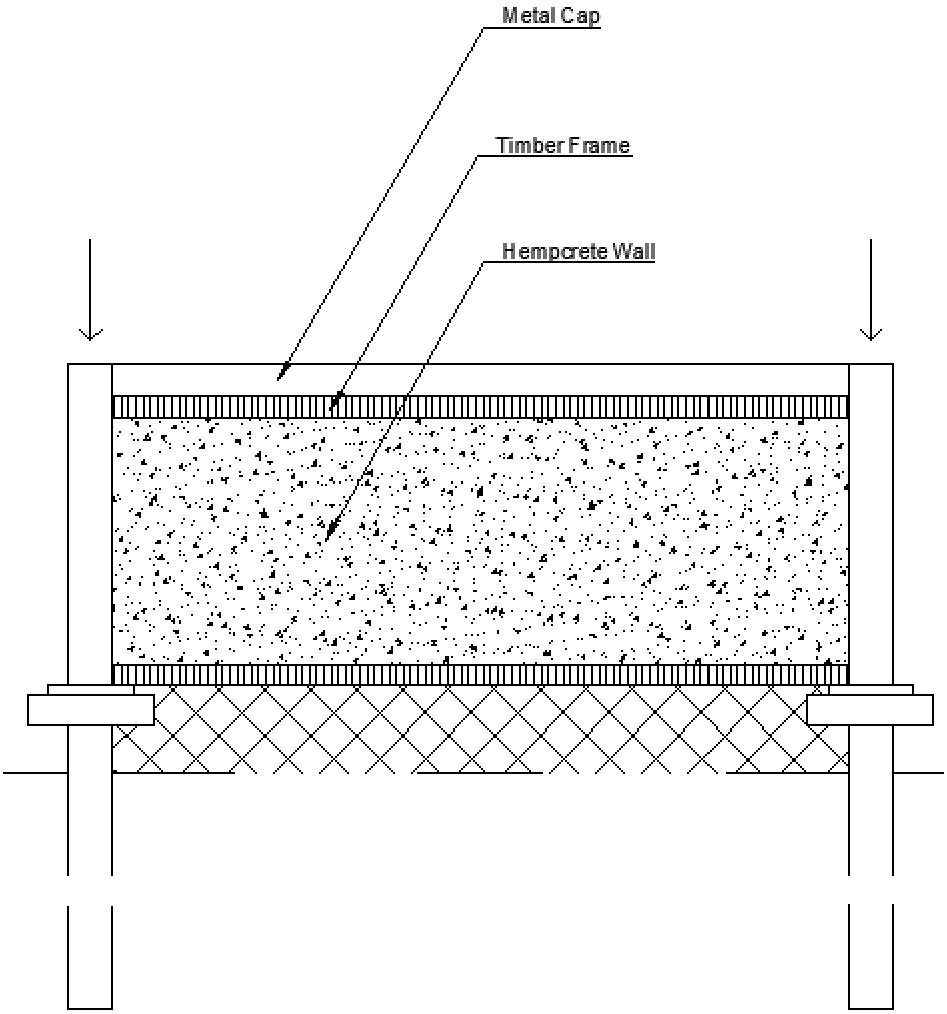


Figure 27 Hempcrete wall with pile foundation and steel column

In this way, a Hempcrete wall could be connected to the foundation piles and the steel column as shown in figure 27. The specific dimension of the piles is provided as per the requirement of the project and the economic costs. Rautaruukki provides RR piles and RR Columns which can be ordered as per the need.

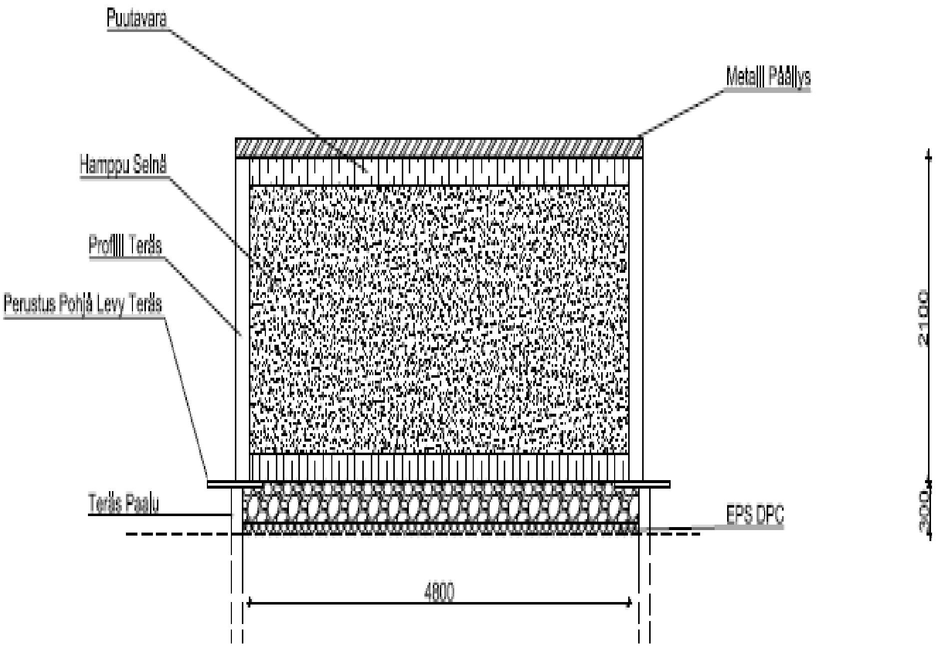


Figure 28 The front view of the wall after EPS Damp proofing for moisture protection from the ground

Finally, a basic design of Hempcrete wall only gives a preliminary forecast of the type of the wall that is possible to be installed in the highway. However, individual civil engineer and structural designer might bring unique solutions for columns and foundation models. The most common way of installing noise barrier in Finland is the use of steel piles, and columns connected to the base plate from the piles. The gap between the ground and the wall can be protected by a Damp Proof Course as shown in figure 28 and the use of gravel. However, as mentioned earlier, there are various ways of protecting the wall from ground moisture depending upon the type of project.

9.3 Wind Load Calculations for Columns

Deflection of column is given by,

$$e = \frac{qh^4}{8EI}$$

whereby,
e is the deflection in the upper end of the column;
q is the uniformly distributed load;
h is the height of the noise column;
EI is the bending stiffness of the column;

Hence, for the construction of a Hempcrete wall with steel piles foundation and steel columns as shown in figure 28, a calculation of column deflection can be performed with the given dimensions;

For a wall with distance between two steel columns of 4800 mm or 4.8 m and the height of 2100 mm or 2.1 m, and wind load considered 1 kN/m^2 and calculations made according to the EN 1991-1-4 General actions: Wind load;

$$e = \frac{qh^4}{8EI}$$

$$e = \frac{4.8\ x\ 1x\ 2.1^4}{8EI}$$

The design consideration for the column deflection is accounted by the Road Noise barrier standard for the Finnish system as presented in table 16.

Table 16 Road noise barriers (TIEH 2100062-09 standard), measurement of deflection:

Deflection of column	*Height of Noise barrier*
e<h/100	h<3m
e=30mm	h=3.0…4.5m
e<h/150	h>4.5m

Hence, we may decide to choose the steel profile as IPE 180; EI = 2772 kNm4

$$e = \frac{4.8\ x\ 1x\ 2.1^4}{8\ x\ 2772}$$

$$e = 4.2mm$$

On checking with the Finnish standard TIEH,
e < h/100 or e <21 mm, so this combination of column is valid technically for wind loads in Finland.

This structure of a steel column, technically, is able to sustain the wind load in the highways. The snow load is negligible because of the dimension of the wall. However, it is to be noted that this is just the basic design, and with careful illustrations from civil engineers and structural designers, a far better solution for load bearing columns and foundations can be designed. As for now, it can be mentioned that the possibility of the construction of Hempcrete noise barrier walls is very realistic depending upon the success of the certified acoustic test which will be discussed in chapter 10.

9.4 Water-proof, Fire-proof, and Rot-proof design

Between the latitude of 60-degree North and 70-degree North, Finland is a cold Nordic country with arctic conditions in the North, long winters and short summers. During winter, the country is covered with snow, and the temperature drops down to -10°C. The drop could be as low as -30°C. On the other spectrum, in summer, the temperature can rise to +20°C or more. The warmest temperature is July, with a mean temperature between +14°C and +18°C in most regions. This month, the daily maximum temperature can reach +30°C. January and February are the coldest months, with mean temperatures of -4°C in the South, and -15°C in the North. (Karjalainen 2009).

Finnish climate is affected by its position between the 60th and 70th parallels in the coastal zone of the Eurasian continental plate. Therefore, it shows both maritime and continental features depending on the direction of the air flow. The mean temperature is also higher, as much as 10°C in winter, than that of Greenlandic and Siberian latitudes. The temperature is raised by the Baltic sea, inland waters and the airflow from the Atlantic. (Finnish Meteorological Institute)

Hempcrete has the capacity to hold water in its capillaries because of its open pore structure. Therefore, it seems to manage moisture and rain effectively. Furthermore, it has been known to be water proof. Therefore, it is a fair assumption that Hempcrete wall can sustain easily in Finnish climatic conditions. However, timber frames are used to act as the load bearing structure of the Hempcrete. But since the sensitivity of the timber is very high to moisture, they can decay and even cause fungal growth on the surface. Therefore, it is essential to take into consideration the type of timber to be used. If typical Finnish timber called Kestopuu and Painekyllästetty puu is used for load bearing of Hempcrete, a magnificent water proof Hempcrete wall is obtained which is also rot-proof.

The addition of a small amount of cement can provide a quicker set, though at the risk of a loss of long term durability and loss of pore structure, mixes of this nature are prone to failure, particularly in extreme condition (Holmes & Wingate, 2003). Therefore, in case of Finland, the addition of cement is not appropriate.

In regards to piling of the steel into the foundation, it should be noted that since Finland is a Nordic country with cold Nordic climate, rock shoes might be required for the piles.

10 ACOUSTIC TEST

The European Committee for Standardization (CEN) has set a code of experimental ethics to effectively verify the capability of the noise barrier walls. Therefore, the experiment for acoustic properties were conducted in line with the outdoor installations in situ, such that the results were closer to the field reality. Therefore, the laboratory experiment is one significant chapter of noise barrier wall construction.

10.1 Laboratory Procedure

For the purpose of sound testing of Hempcrete walls, the calculation for sound reduction was accounted by the Weighted Sound Reduction Index, or R_W in decibels. Mathematically, an increase of R_W by 6 points means a decreased perceived loudness by a half. For the test, EN ISO 717-1 and ISO 10140-2 for sound insulation of walls were performed.

In order to calculate the quality of the wall, the wall was set up in the middle of two reverberation chambers so that the amount of sound that passes through it could be known.

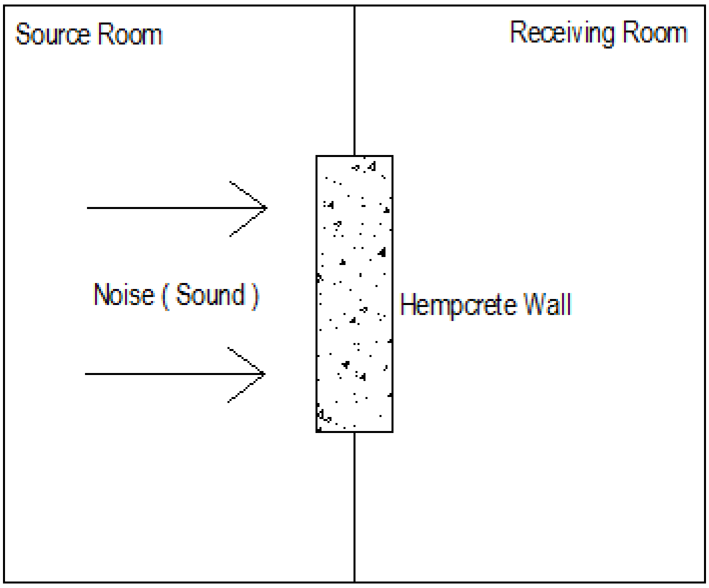


Figure 29 Arrangement of wall between two chambers for Acoustic tests

The figure 29 shows the laboratory set-up for the acoustic experiment. The basic principle is to measure the amount of sound blocked by the wall, in decibels. Therefore, a wide range of frequencies of sound are allowed to pass through the wall sample, and the index of sound reduction is calculated as per the behavior of the wall in a frequency Vs Sound reduction graph.

To perform the tests, the wall was mounted in a gap designed between the two chambers, and made sure that there were no holes or gaps in the edges. as in figure 30.

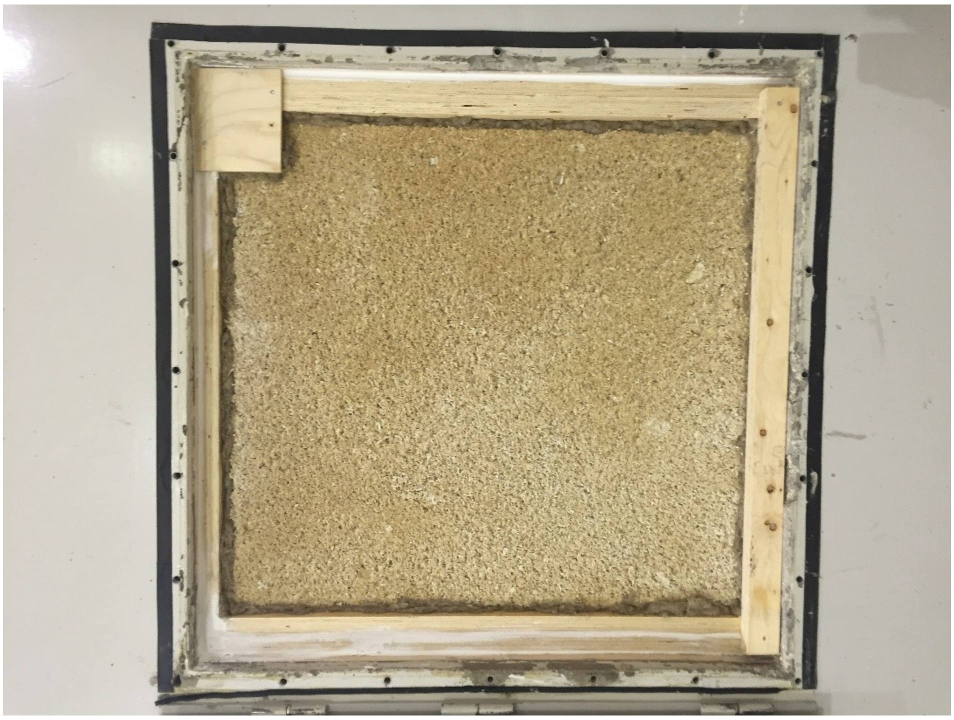


Figure 30 Set up of wall sample between reverberation chambers

After the wall setup, the two microphones in the opposite rooms were deployed to measure the accurate sound level difference due to the wall as shown in figure 31 below. The other instruments employed were sound level meter, acoustic calibrators, pre-amplifiers, and power-speakers and power amplifiers.

Figure 31 Highly sensitive Microphones to Measure Sound level in the laboratory

A power-speaker in the source room was placed in fixed positions, and back ground measurements were taken at each third octave frequency between 50 Hz and 5000 Hz.

The sound reduction was calculated according to the BS EN ISO 10140-2,

$$R_w = L_1 - L_2 + 10 \log \frac{S}{A}\, dB$$

Where,
L_1 is the logarithmic average of the source room measurements in sound
L_2 is the logarithmic average of the receiving room measurements
S is the area of the wall tested
A is the equivalent absorption area.

10.2 Laboratory Measurements

Before the test, the following measurements were taken into account:

Temperature of the laboratory	21.0 °C
Air Humidity	62 %
Source room volume	102 m^3
Receiving room volume	131 m^3

Then, the walls were calculated for their sound reduction. Table 17 shows the results of the lab measurement for wall made up of small shives

Table 17 Lab measurements obtained in one-third octave band for Small shives- wall

Frequency F (Hz)	R 1/3 octave(dB)
50	9.0
63	11.5
80	10.6
100	7.0
125	7.6
160	6.8
200	7.3
250	8.5
315	9.5
400	9.5
500	10.9
630	12.1
800	13.6
1000	15.8
1250	18.4
1600	21.2
2000	24.0

2500	27.1
3150 4000 5000	30.1 32.5 37.3

ISO-717-1 Rating of the wall was calculated to be:

$R_w (C_; C_{tr}) = 16(-1; -3)$ dB

Household transmission loss = 15 dB
Traffic transmission loss = 13 dB

Clearly, Sound reduction of less than 25 dB is not preferable for the noise barrier wall. Therefore, the wall made of small shives is unable to meet the European Standards. The tests for the wall made of larger shives was incompatible for the acoustic tests due to the weak mechanical strength. Table 18 shows the lab measurements for Hempcrete wall 3.

Table 18 Lab measurements obtained in one-third octave bands for Hempcrete wall 3-State of the art design

Frequency f (Hz)	R 1/3 octave (dB)
50 63 80	23.1 28.2 27.3
100 125 160	28.5 25.4 27.5
200 250 315	30.9 36.3 37.5
400 500 630	40.1 43.3 46.3
800 1000 1250	48.5 51.2 54.0
1600 2000 2500	56.9 58.9 60.5
3150 4000 5000	59.8 59.0 60.6

Therefore, the ISO 717-1 Rating for the Hempcrete wall 3-was calculated to be:

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

The sound reduction of High frequency noises, like household = 46-2= 44 dB
The sound reduction of low frequency noises, like traffic = 46-7 =39 dB

As can be seen from the results, the Hempcrete wall 3-state of the art design performed much better than other wall samples, and can be effectively implemented as a noise barrier wall along the highways.

10.3 Comparison with Other Materials

R_w is the weighted sound reduction index in decibels. So, this is helpful to calculate the air-borne sound insulating capacity of the building materials. The results of the experiments can be compared to other building materials so as to understand their qualities. Table 19 enlists the Sound Reduction Values for traditional noise insulators.

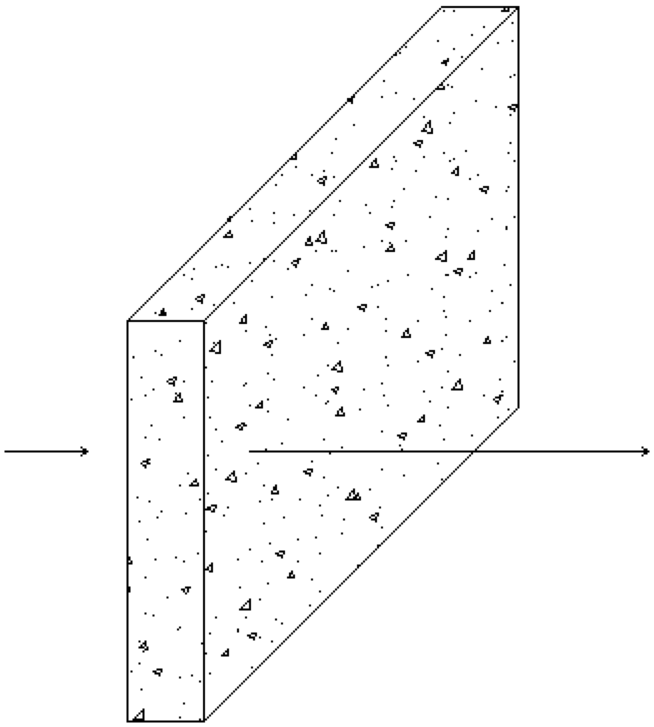
Table 19 Comparison of weighted sound reduction values (Source: Crocker 1998; http://www.environmentalpollution.in)

Material	Dimension Thickness (mm),	Kg/m^2	Sound Reduction R_w in Decibels
Hempcrete-State of the Art Design	*170*	*135*	*46*
Concrete Panel	125	300	48-54
Gypsum, without absorbent material in the cavity	200	170	46
Gypsum, Mineral wool in the cavity	150	100	48
Brickwork	113	220	35-40
Plywood	6	70	21
Wood Wool / Cement slabs	76	70	35

Hempcrete wall with the state of the art design seems to compete with many other building materials. This wall can be effectively used in the highway noise barriers compared to other building materials which create an environmental issue both during production and also after installation. The environmental benefits of the Hempcrete wall add to its transmission loss capacity of 46 dB, if designed in a specific way. Of course, as the acoustic tests have shown, the light-weight Hempcrete wall made up of small shives only, and large shives only, have performed very poorly in a noise barrier wall test. Therefore, the Hempcrete wall with the state of the art design is the best option for the sustainable, eco-friendly and effective noise reduction along the highways.

11 DISCUSSION

The Hempcrete noise barrier wall - State of the Art Design, proved to be very efficient in reducing the highway and traffic noise. After the Air-borne sound tests, the Sound Reduction Index of 46 dB was found.



$R_w = 46$ dB

Figure 32 Sound Reduction Index in Wall 3

The following graph in figure 33 shows the performance of the Hempcrete wall 3 based on the ISO 717-1 frequency rating for the acoustic test. The graph explains the quality of the wall along with the correction factors.

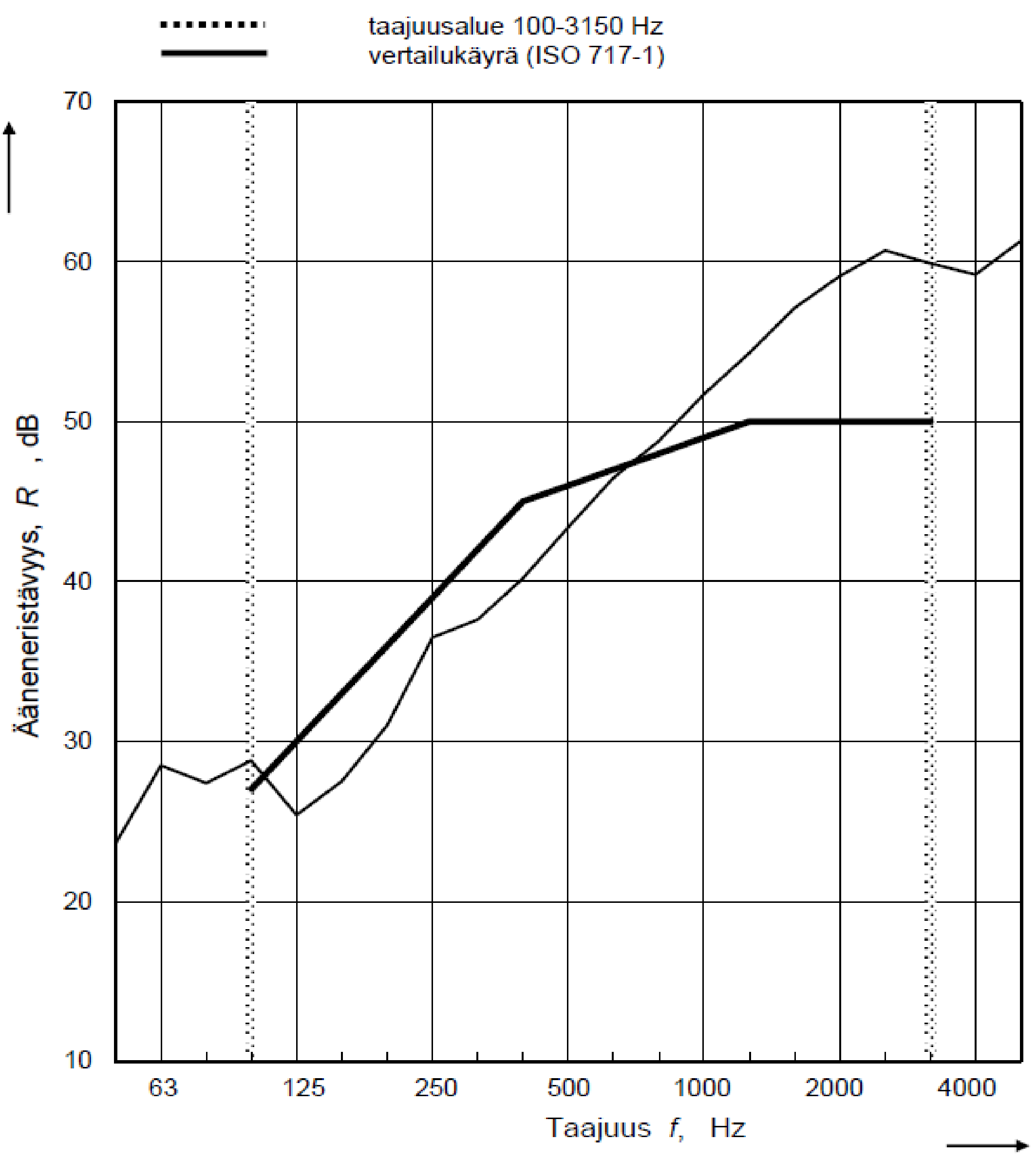


Figure 33 Frequency vs. Sound Reducing Index of the Hempcrete wall 3-state of the art design

From the graph 33, the following rating can be deducted:

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

The sound reduction Index is thus 46 dB, which implies that the wall has a capacity of reducing the incident sound by 46 decibels. The correction factors C and $C_{tr,}$ which are numerically negative, must be deducted from the noise reduction value to evaluate the household and traffic noise reduction respectively.

Therefore, the Hempcrete wall 3- state of the art noise reducing wall has the Noise reduction for Traffic of 39 decibels.

The Following table 20 simplifies the Correction factor of the noise for C, and C_{tr} for the wide range of frequencies in Wall 3- State of the art design:

Table 20 Correction factors of the Hempcrete wall-3 for different frequency ranges.

C	C value	C_{tr}	C_{tr} value
$C_{50-3150}$	-2 dB	$C_{tr\ 50-3150}$	-8 dB
$C_{50-5000}$	-1 dB	$C_{tr\ 50-5000}$	-8 dB
$C_{100-5000}$	-1 dB	$C_{tr100-5000}$	-7 dB

In Finland, for the dwelling houses, the Sound reduction index of the wall should be at least 55 decibels. Therefore, Hempcrete wall- state of the art design with 170 mm thickness is clearly not suitable for indoor sound insulation. However, there is an engineering opportunity to meet the requirements for the dwelling houses also if the thickness of the Hempcrete wall could be increased in order to achieve the Sound Reduction Value higher than 55 decibels. Since the scope of this thesis is highway noise insulation, more tests were performed only for the air-borne noise in the road-highway traffic scenario.

In the case of the highway noise, the Sound Reduction Index of greater than 24 decibels are considered for most projects. The distance of the highway from the population density, elevation of the road, and height of the wall are some of the parameters that need to be considered according to the individual projects. All in all, it can be fairly mentioned at this point that the Hempcrete noise barrier wall of 46 decibels noise insulation developed in this thesis work is, in fact, able to provide effective noise insulation along the highway.

The results comply with the European Union standards, and the national Finnish standards. Therefore, it could be rightfully said that the thesis finally succeeded in its objectives.

12 CONCLUSION

After all the tests and research, it can be fairly mentioned that the Hempcrete noise barrier wall can serve as an effective sound insulator along the highway. This however, takes into account the careful planning and mixing of the shives and lime in a fixed proportion by weight or volume. The design requirements of the Hempcrete noise barrier wall are higher. As the tests have carefully shown, wall 1 and 2, which were designed with only small shives, or only large shives in the mix, were unable to meet the acoustic standards set by the European Union. On the other hand, the State of the Art Design of Hempcrete wall developed in this thesis work produced a Sound Reduction Index of 46 decibels. This value of noise insulation is highly competent in reducing the highway noise as per the standards. If the sound reduction index, R_w of 46 decibels could be produced by the mean thickness of the wall of 170 mm, it can easily be deduced that the increment of the thickness of the Hempcrete noise barrier wall proportionally increases the sound reduction potential. This implies that the R_w value for the Hempcrete wall could be increased further more depending upon the acoustic and economical construction requirements.

Along with the acoustic protection, it is important now, more than any other time in our planet´s history, to reduce the impact of our construction upon the environment. The tests have demonstrated the low embodied energy of Hempcrete and its capacity to lock carbon dioxide in its molecular fabric. Mathematically, a cubic meter of Hempcrete wall could sequester up to 108 kg of carbon dioxide. This carbon negative property of Hempcrete could be properly utilised to mitigate the greenhouse gas emissions as well. In addition to it, a Hempcrete noise barrier wall is fire resistant along with a peculiar hygroscopic properties of moisture buffering. This breathability allows the wall to absorb or give off water depending upon the changes in humidity levels in the atmosphere. As a consequence, most of the moisture-related construction failures can be avoided. The mix of hemp and lime creates an alkaline surface that is termite and mould resistant. So there can hardly be any other building material other than Hempcrete that can provide both sustainable and environmental benefits in construction.

In conclusion, Hempcrete wall can provide an effective highway noise insulation as well as immense environmental benefits. It is high time for the construction industry to realise the importance of Hempcrete in construction. Today, in the second decade of the 21st century, designing and constructing with Hempcrete can be a new way forward from the traditional building materials that significantly affect the environment. After the success of this Hempcrete noise barrier test, Finland can rightfully claim its position among the leading countries in the search for sustainable construction methods.

SOURCES

ADAS. 2005. UK Flax and Hemp production: The impact of changes in support measures on the competitiveness and future potential of UK fibre production and industrial use. Accessed on 02.04.2016 https://www.votehemp.com/PDF/flaxhemp-report.pdf

Arnaud, L. & Cerezo, V. 2001. Physical Qualification of Construction Materials Based on Hemp. Report. É cole Nationale des Travaux Publics de l'É tat, Département Genie Civil et Bâtiment, Vaulx-en-Velin.

Bevan, R. & Woolley, T. 2008. Hemp Lime Construction: A Guide to Building with Hemp Lime Composites. IHS Bre Press. Accessed on 09. 10.2016. https://www.brebookshop.com/samples/321427.pdf

Bevan, R. & Woolley, T. 2009. Constructing A Low Energy House from Hempcrete and Other Natural Materials. Proceedings of the 11th International Conference on Non-Conventional Materials and Technologies. Accessed 01.05.2016. www.researchgate.net

BRE. 2002. Final Report on the Construction of the Hemp Houses at Haverhill, Suffolk. Building Research Establishment.

BRE. 2003. Client Report: Thermographic Inspection of the Masonry and Hemp Houses -Haverhill Suffolk. Building Research Establishment.

Cerezo, V. 2005. Mechanical, Thermal and Acoustical Properties of a Material Based on Vegetable Particles. Publications of the National Institute of Applied Sciences, Saint Valérien, France

Clairbois, J. & Garai, M. 2015. The European Standards for roads and railways noise barriers: state of the art. Accessed on 12.06.2016. http://www.conforg.fr/euronoise2015/proceedings/data/articles/000607.pdf

Crocker, M. 1998. Handbook of Acoustics. Wiley Interscience Publication.

De Bruijn, P. 2008. Hemp Concretes: Mechanical Properties using both Shives and Fibres. Swedish University of Agricultural Sciences. Faculty of Landscape Planning, Horticulture and Agricultural Sciences. Licentiate thesis.

Duffy, E., Lawrence, M. & Walker, P. 2014. Hemp-Lime: Highlighting room for improvement. Publications of University of Bath, UK.

Evrard, A. 2003. Hemp Concretes: A Synthesis of Physical Properties. Report. Construire en Chanvre, Saint Vale rien

Evrard, A. & and De Herde, A. 2010. Hygrothermal performance of lime-hemp wall assemblies, Journal of building physics.

Finnish Meteorological Institute. Accessed on 06.07.2016. http://en.ilmatieteenlaitos.fi/

Garai, M & Guidorzi, P. 2009. European methodology for testing the airborne sound insulation characteristics of noise barriers in situ: Experimental verification and comparison with laboratory data. Accessed on 13. 07.2016.
www.researchgate.net

Holmes, S. & Wingate, M. 2003. Building with Lime: A Practical Introduction. ITDG Publishing.

Karjalainen, S. 2009. Thermal comfort and use of thermostats in Finnish homes and offices. Building and Environment 44(2009): 1237-1245. Amsterdam: Elsevier

Karni, J. & Karni, E. 1995. Gypsum in construction: origin and properties. Kluwer Academic Publishers.

Karus, M. 2005. European hemp industry 2001 till 2004: Cultivation, raw materials, products and trends. Accessed 03.04.2016.
http://news.bio-based.eu/media/news-images/20050309-09/05-02%20EU-EIHA%20e.pdf

Laitinen, E. n.d. History of Hemp in Finland. Accessed 02.06.2016
http://www.druglibrary.org/olsen/hemp/iha/iha03115.html

O´Dowd, J. & Quinn, D. 2005. An Investigation of Hemp and Lime as a Building Material. Accessed 04.05.2016
http://djq.me/files/2005_May_JOD_DQ.pdf

Parker, G. 2006. Effective noise barrier design and specification.
Accessed on 12.06.2016.
http://www.acoustics.org.nz/journal/pdfs/Parker,_G_NZA2013.pdf

Rhydwen, R. Building with Hemp and Lime. n.d. Accessed 03.06.2016. https://www.votehemp.com/PDF/building_with_hemp_and_lime.pdf

Sparrow, A. & Stanwix, W. 2014. The Hempcrete Book: Designing and building with hemp-lime. Publishing UIT Cambridge Ltd

Woolley, T. 2006. Natural Building: A Guide to Materials and Techniques. The Crowood Press Ltd

Woolley, T. n.d. Zero Carbon Building Methods: The Case of Hempcrete Projects. Accessed on 03. 06. 2016 http://ebooks.narotama.ac.id/files/Smart%20Building%20in%20a%20Changing%20Climate/Chapter%206%20%20Zero%20Carbon%20Building%20Methods;%20The%20Case%20of%20Hempcrete%20Projects.pdf

Appendix 1

TEMPERATURE AND HUMIDITY DATA- WALL 1

1		1	2
2	S/N	673134	673134
3	Type	TV-4505	TV-4505
4	Description	Cal Run	Cal Run
5	Property	Temperature	Humidity
6	Logging Started	15.07.2016 13:11:46	15.07.2016 13:11:46
7	Logging Ended	25.07.2016 13:11:00	25.07.2016 13:11:00
8	Logging Duration	863953,60 s	863953,60 s
9	Offload Operator	minh1500	minh1500
10	Trigger Start	FALSE	FALSE
11	Start Delay	0,00 s	0,00 s
12	Interval	43200,00 s	43200,00 s
13	Stop Mode	When full	When full
14	Run Id	3845 j0v9 z77g	3845 j0v9 z77g
15	Last Calibrated	24.1.2013	24.1.2013
16	Calibration Agency	Manufacturer	Manufacturer
17	Offload Time	25.07.2016 14:32:04	25.07.2016 14:32:04
18	Number of Readings	21	21
19	Stop Reason	Still Logging	Still Logging
20	Logging Mode	Minutes Mode	Minutes Mode
21	Statistics Start Time	15.07.2016 07:11:00	15.07.2016 07:11:00
22	Statistics End Time	25.07.2016 13:11:00	25.07.2016 13:11:00
23	Minimum Reading	18,5 °C	62,0 %RH
24	Maximum Reading	21,4 °C	100,0 %RH
25	Average Reading	19,9 °C	93,4 %RH
26	Mean Kinetic Temperature	19,9 °C	

Appendix 2

TEMPERATURE AND HUMIDITY DATA- WALL 2

1		1	2
2	S/N	699560	699560
3	Type	TV-4505	TV-4505
4	Description	Cal Run	Cal Run
5	Property	Temperature	Humidity
6	Logging Started	15.07.2016 13:13:26	15.07.2016 13:13:26
7	Logging Ended	25.07.2016 13:13:00	25.07.2016 13:13:00
8	Logging Duration	863974,30 s	863974,30 s
9	Offload Operator	minh1500	minh1500
10	Trigger Start	FALSE	FALSE
11	Start Delay	0,00 s	0,00 s
12	Interval	43200,00 s	43200,00 s
13	Stop Mode	When full	When full
14	Run Id	11t9 y07h 8wat	11t9 y07h 8wat
15	Last Calibrated	30.10.2013	30.10.2013
16	Calibration Agency	Manufacturer	Manufacturer
17	Offload Time	25.07.2016 14:24:43	25.07.2016 14:24:43
18	Number of Readings	21	21
19	Stop Reason	Still Logging	Still Logging
20	Logging Mode	Minutes Mode	Minutes Mode
21	Statistics Start Time	15.07.2016 07:13:00	15.07.2016 07:13:00
22	Statistics End Time	25.07.2016 13:13:00	25.07.2016 13:13:00
23	Minimum Reading	18,6 °C	59,9 %RH
24	Maximum Reading	21,9 °C	100,0 %RH
25	Average Reading	20,1 °C	86,5 %RH
26	Mean Kinetic Temperature	20,2 °C	

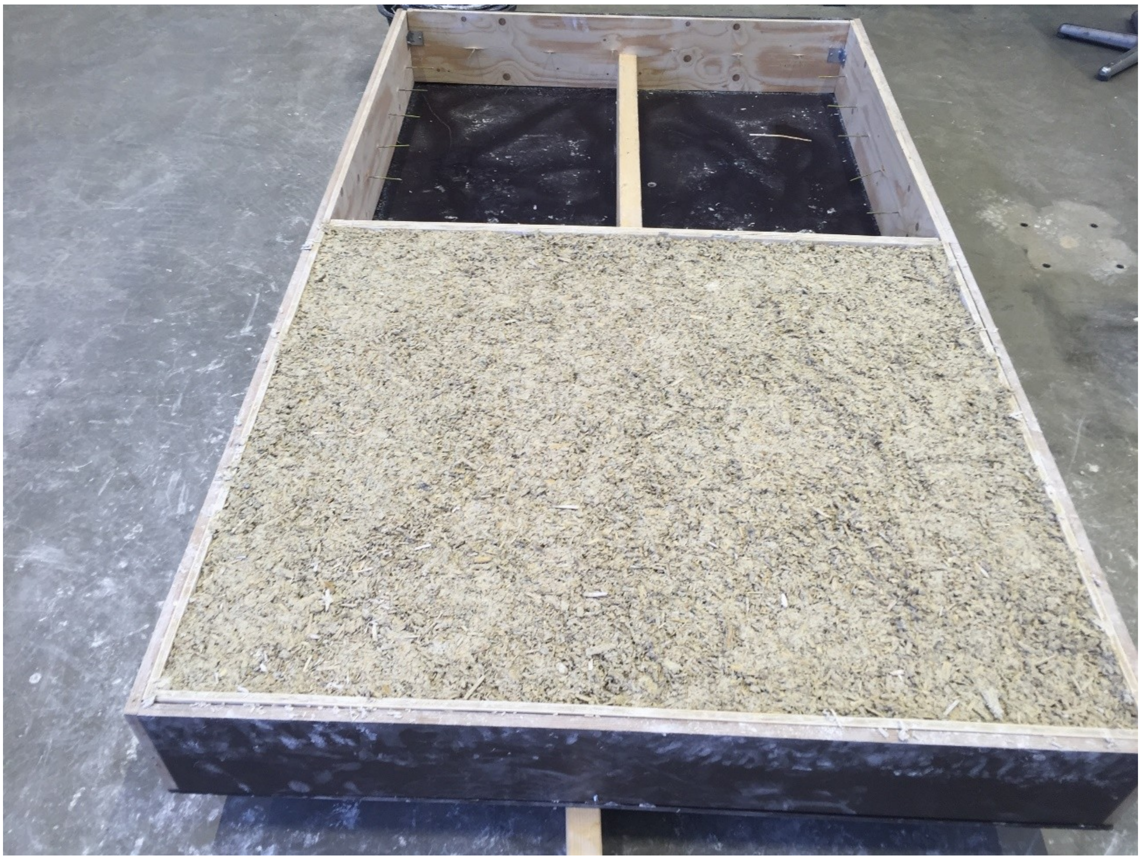
Appendix 3

TEMPERATURE AND HUMIDITY DATA- WALL 3

1		1	2
2	S/N	673137	673137
3	Type	TV-4505	TV-4505
4	Description	Cal Run	Cal Run
5	Property	Temperature	Humidity
6	Logging Started	15.07.2016 13:17:01	15.07.2016 13:17:01
7	Logging Ended	25.07.2016 13:17:00	25.07.2016 13:17:00
8	Logging Duration	863999,00 s	863999,00 s
9	Offload Operator	minh1500	minh1500
10	Trigger Start	FALSE	FALSE
11	Start Delay	0,00 s	0,00 s
12	Interval	43200,00 s	43200,00 s
13	Stop Mode	When full	When full
14	Run Id	5wap fspm i0jw	5wap fspm i0jw
15	Last Calibrated	24.1.2013	24.1.2013
16	Calibration Agency	Manufacturer	Manufacturer
17	Offload Time	25.07.2016 14:27:20	25.07.2016 14:27:20
18	Number of Readings	21	21
19	Stop Reason	Still Logging	Still Logging
20	Logging Mode	Minutes Mode	Minutes Mode
21	Statistics Start Time	15.07.2016 07:17:00	15.07.2016 07:17:00
22	Statistics End Time	25.07.2016 13:17:00	25.07.2016 13:17:00
23	Minimum Reading	18,1 °C	62,6 %RH
24	Maximum Reading	21,7 °C	100,0 %RH
25	Average Reading	19,8 °C	87,2 %RH
26	Mean Kinetic Temperature	19,8 °C	

Appendix 4

HEMPCRETE WALL-FRAME



Appendix 5

USE OF FANS TO DRY WALLS