MSc Thesis

The effectiveness of hempcrete in the reduction of the environmental and financial costs of residences

(A case study in the Netherlands)

Alexandra Vontetsianou

January 2023

The effectiveness of hempcrete in the reduction of environmental and financial costs of residences

A case study in the Netherlands

Dissertation

to obtain the Master of Science Degree at the Delft University of Technology, to be defended publicly on 30th of January 2023

by

Alexandra Vontetsianou
s.n. 5373239

School of Civil Engineering and Geo-sciences
Master Track: Building Engineering
Specialisation: Building Physics and Technology

Committee Members:

Dr. ir. M. Ottelé,	Chair	TU Delft, CiTG, Materials & Environment
Prof. dr. H.M. Jonkers,	Member	TU Delft, CiTG, Materials & Environment
Dr. ir. M.J. Tenpierik,	Member	TU Delft, ABE, Building Physics
Dr. ir. B. Hasselaar,	Member	DGMR Sustainability & Health

Keywords: hempcrete, hemp concrete, hempcrete blocks, hygrothermal properties, biobased materials, biobased design, environmental footprint, sustainability

Cover image retrieved from the internet

Contents

Preface

The current master thesis has been performed in order to obtain my MSc degree in Civil Engineering at Delft University of Technology. It has been the final step in this memorable two-year educational journey which contributed to my professional and personal growth. It is a result of collaboration between Delft University of Technology and DGMR. The topic had aroused by my interest in bio-based building materials and the potential that they can provide for a more sustainable future. An aspect, which despite its importance is frequently overlooked.

At this point, I would like to sincerely thank all the people who supported me during my thesis, without whom its completion would not have been possible.

A massive thank you goes to my family. To my parents, who always believed in me and consistently supported me and my choices. To my sisters, Stephania and Ioanna, who motivate me to become a better person and somehow always know how to cheer me up. I would also like to express my gratitude to my friends, the new ones and the old ones, who became my family in the Netherlands or did not let the distance set us apart. Among others a special thank you to Evi, Elena and Ioanna.

A sincere thank you goes to all the members of my thesis committee, for their support during my thesis. To Dr. ir. M.J. Tenpierik, for his thoughtful advises on my research and his great assistance on providing additional technical support for the needs of the hygrothermal simulations. To Dr. ir. M. Ottelé and to Prof. dr. H.M. Jonkers, for their constructive criticism and guidance. To Dr. ir. B. Hasselaar, my supervisor in DGMR, for giving me the opportunity to perform my thesis in an amazing working environment and whose enthusiasm on the topic motivated me to strive for more.

Furthermore, I would like to thank all the people that participated in the interviews which are part of the current research. Their contribution was a valuable input which highly influenced the course of research and allowed the collection of knowledge on hempcrete as it has been experienced in practice.

Last but not least, a special thank you goes to the people of DGMR, who were always willing to respond and provide suggestions derived from experience.

Alexandra Vontetsianou
Delft, January 2023

Summary

The aim of the current graduation project is the investigation of the potential of using hempcrete for the construction of residences in the Netherlands. The research focuses on the prefabricated block form of the material and investigates different aspects that can play a major role and eventually affect the choice for the selection of the material in building applications. Such aspects are: the regulation and performance proofing requirements which are associated with the application of an unstandardised material, the application methods, the strengths and limitations related to the nature of material, the current industry barriers, its hygrothermal, energy and environmental performances according to the Dutch building regulation in comparison to popular industrialised materials in the Netherlands and the related costs. The compared industrilised options were two: the Aerated Autoclaved Blocks, which account for an industrialised option with equivalent properties as these of the hempcrete blocks, and the option of Sand-lime bricks in combination with Fiberglass insulation, which is currently a widely used construction option in the Netherlands. Dynamic hygrothermal simulations were performed in WUFI software, whereas available EPDs were used for the investigation of the environmental impacts of the materials under scrutiny in a life cycle analysis. Available literature, interviews with parties characterised by different roles and high experience regarding the use of biobased materials in the building industry were also used as a means for the completion of the current graduation project.

Apart from the available literature, the research methods followed in the current graduation project were influenced by the results of the performed interviews, which indicated aspects that could be further explored. The results of the research show that in terms of performances, the material is able to satisfy the requirements of the modern Dutch building regulation and therefore the later does not account for the reason behind the limited propagation of the material in the Dutch building industry. Nevertheless, the current Dutch regulation is currently a barrier that discourages the international material supply and disregards important properties of hempcrete as its moisture buffering capacity and specific heat capacity which can can play an important role. The Sand lime brick option has been proved more competitive in comparison to the Autoclaved Aerated option, as hempcrete outperformed its industrialised version AAC in the vast majority of the analyses performed in the current study. Hempcrete shows a better moisture buffering capacity and environmental footprint. The hygrothermal performances of hempcrete blocks were also proved beneficial in the condensation analyses, where even hempcrete walls with lower thermal resistance still reached the same performances as the better thermally designed SL walls. Hempcrete design of the residence exhibited slightly lower energy performances, which can be attributed to the lower volumetric heat capacity of the material.

Abbreviations

AAC : Autoclaved Aerated Concrete
AAC_{Rd} : Autoclaved Aerated Concrete - ($R_T = 5m^2K/W$)
ADP: Abiotic Depletion Potential
AP: Acidification Potential
D1: Detail 1
D2: Detail 2
D3: Detail 3
DoP : Declaration of Performances
EAD: European Assessment Document
EEA: European Economic Area
EOTA: European Organisation for Technical Assessment
EP: Eutrophication Potential
EPD: Environmental Product Declaration
ETA: European Technical Assessment
EU: European Union
FG: Fiberglass insulation board
GHG: Green House Gas
GWP: Global Warming Potential
H1: Hempcrete 1
H2: Hempcrete 2
H3: Hempcrete 3
H4: Hempcrete 4
$H3_{Rd}$: Hempcrete 3 optimised - ($R_T = 5m^2K/W$)
LCA: Life Cycle Assessment
LUC: Land Use Change
NECP: National Energy and Climate Plan
NDC: Nationally Determined Contributions
NMD: National Milieu Database (aka National environmental database)
MPG: Milieuprestatie Gebouwen (aka Environmental performance of Buildings)
ODP: Ozone Depletion Potential
RH: Relative Humidity
S1: Section 1
S2: Section 2
S3: Section 3
S4: Section 4
SL: Sand-lime bricks
UF: Unit Factor
WDP: Water Depletion Potential

Proposal

0.1. PROBLEM STATEMENT

The building industry represents one of the highest primary energy consuming sectors with a significant contribution to greenhouse gas emissions, material depletion and waste.

The severe environmental consequences of the building industry have been acknowledged and global measures have been taken towards their limitation. Norms, regulations and standards set high requirements for energy efficient buildings with respect to the environment and the users. Biobased materials are gradually gaining space into the building industry as an efficient and more sustainable alternative to conventional building materials. Hempcrete is a natural, healthy, and sustainable material with high performances in main aspects that define indoor comfort and sustainability. It distinguishes itself from other biobased materials due to its negative environmental footprint. However, even though the existing research on the material reveals some special properties that can be proven beneficial for the alleviation of the modern environmental problems, hempcrete has not yet established its place into the Dutch building industry. The lack of its standardisation results to uncertainty about its application, effectiveness and associated risks and creates restraints that hinder the propagation of its use in the Netherlands. These restraints may be associated with the developers, the suppliers, the government or even the capabilities of the material.

The current graduation study will deal with the lack of produced and distributed knowledge regarding the application of hempcrete in Dutch building projects which is currently responsible for the reluctance of interested parties to increase its use in the Netherlands. The study has been performed in collaboration with DGMR and investigates the level of advantageousness – in sustainability and financial terms - of using hempcrete in residences in the Netherlands. For this purpose, the effectiveness of the material in the reduction of environmental and financial costs when both its qualities and restraints are considered is assessed in a case study. Hempcrete's use is approached in a multidimensional way as different aspects like the application requirements, the energy performances, the indoor comfort regulation levels, financials (benefits and losses e.g. net surface, price) and sustainability will be investigated by means of simulations and interviews.

0.2. RESEARCH OBJECTIVES

The introduction of new building products in the market is a complex procedure. The material performances have to be sufficient to compensate for the difficulties and risks that are associated with the new product's use in order to attract interested parties willing to explore its capabilities. Common issues like a lack of standards and regulations, a need for additional research and a lack of certified suppliers can create hesitancy and hinder its establishment in the market when the potential profits are not competent to those of a traditional material. Appealing profits can gradually attract investors and increase motivation towards research and governmental interference, which are essential for the establishment of the new product.

According to the aforementioned the objectives of the current research have been set and are presented below:

Principal objective:

- *The principal objective of the current study is to assess the level of advantageousness in terms of sustainability and finance of the use of hempcrete in residences in the Netherlands in comparison to frequently selected conventional and industrialised design options when both the material related qualities and restraints are considered.*

Secondary objectives:

- *Define the required properties of hempcrete for a safe and adequate application.*
- *Map the current difficulties and issues faced in the Netherlands when hempcrete is used in the construction of residences.*
- *Assess the performances of hempcrete in comparison to conventional design options in the aspects of indoor comfort and energy efficiency in residences in the Netherlands.*
- *Assess the performances in environmental and financial terms.*

0.3. RESEARCH QUESTION

The objective of the current study can be summarised in simple terms in the question: Is it advantageous to build with Hempcrete in the Netherlands under the existing restraints? However, this question is too broad and needs to be narrowed down to a more specific research scope. Thus, the following research question has been composed:

- *How effective is hempcrete at reducing environmental and financial costs while establishing indoor comfort in residences in the Netherlands in comparison to the design options of using aerated concrete blocks or sand-lime bricks?*

After defining the main research question the problem was deconstructed to four self-contained sub-problems which are summarized in the following sub-questions:

1. What are the properties and the related parameters that need to be examined to guarantee that hempcrete blocks are safely* and adequately** applied with regard to their intended use in a selected case study?
2. What are the current restraints in hempcrete's use in the Netherlands and how can they affect the decision of using hempcrete in building constructions?
3. How does the hempcrete block design perform in the analyses relevant to the required building aspects in comparison to the AAC design option and the sand-lime option?
4. What impact does choosing a hempcrete block design instead of the two predefined conventional Dutch masonry design options have on the environmental and financial costs?

Where:

* *The term safely refers to the minimisation of the possibility for degradation or health threatening situations (e.g. fire safety, air quality) to occur.*

** *The term adequately refers to the exploitation of the material's beneficial properties and the abatement of its weaknesses as efficiently as possible.*

0.4. RESEARCH METHODOLOGY

After consideration, the most appropriate method to address each of the aforementioned problems was defined.

Firstly, the properties that should be addressed to guarantee a sufficient performance of the product for its use are defined by studying the literature. The intended use for the hempcrete blocks is defined in the case study (façade and internal partitioning) and then the essential requirements associated with the selected intended use are determined (e.g. thermal insulation, thermal mass, acoustic insulation, resistance to high moisture levels etc.). The parameters that are associated with each of the requirements (e.g. thermal insulation: thermal conductivity (λ)) are identified by the standards and DoPs of some selected industrialised materials with similar applications and properties.

A range for the values of parameters which are associated with the main properties of hempcrete (Section 3.3. The main properties of Hempcrete) are specified according to the available studies and regulation. Hempcrete is not standardised in the Netherlands, so governmental specifications regarding its material properties or performances do not exist yet. The required level of performances and thus the values for the related properties are defined by the existing Dutch regulations depending on the location of hempcrete's application in the case study.

The current restraints that hinder the propagation of hempcrete's use in the Netherlands are specified by two different means. A study on the current Dutch building regulations and the available literature demonstrates the governmental and practical issues that hempcrete projects face in the Netherlands. Furthermore, interviews with parties with experience on hempcrete applications have been performed to provide additional information as experienced in practice. The persons selected for the interviewing are professionals with different roles.

According to the outcome of the aforementioned, some critical detailed sections and the type of analyses that need to be performed were defined. These analyses were a degradation risk assessment analysis, a building energy performance analysis, and a Life cycle Analysis. The same analyses were performed for the conventional and industrialised wall designs. The materials of the conventional and industrialised wall designs were selected with the aim to provide a fair comparison and enough stimulation for the promotion of hempcrete's use. For this purpose, a residence with an adequate scale to allow the performance of the different simulations was selected. The residence is located in the Netherlands and has already been constructed. Indoor conditions have been monitored and features as the energy consumption are known. The aforementioned allow assess the simulation results in comparison to the reality.

The outcomes regarding the option of applying hempcrete instead of the other two conventional construction materials in the case study have been collected and are presented in the final chapter in combination with the respective sub-questions. These outcomes include the results of the analyses as well as some applicational aspects that were identified during the design of the detached residence and are mainly related to the different structural system (Timber structural frame vs loadbearing masonry). The possible effects of these outcomes on the financial benefits and costs of the residence, are also elaborated.

0.5. DISCUSSION ON ALTERNATIVE RESEARCH MEANS

The research means

Other methods could also have been suitable for the purpose of this study. Some alternatives and the reasons why they will not eventually be part of the study are elaborated in this section.

Constructions of building mock-up sections could also allow performances (such as hygrothermal, acoustical, related, moisture related performances etc) to be tested in real time conditions. However after studying the literature it was understood that sufficient similar research had been already performed towards defining such performances. Besides, suppliers of the material already exist in the market and as a result some essential for the material properties have already been tested and defined. In addition the expected time needed for a graduation project of 40 ects is approximately nine months. This period was considered insufficient for the mock-ups to be adequately designed, constructed and tested in order to finally provide complete results.

On the other hand, simulations could be a time efficient alternative to acquire sufficient information on aspects as condensation and mould growth risks, dynamic moisture regulation and dynamic thermal conductivity alterations due to it while additionally allowing a comparison of the aforementioned properties and their results (e.g. enhancement of thermal comfort, influence on the energy consumption) between hempcrete and the substitute material.

Furthermore, making use of questionnaires instead of interviews was also considered initially as questionnaires could allow input from more parties to be implemented into the study. However, it was decided that interviews could correspond better to the purpose of the study. With interviews parties have more time to express themselves and elaborate on their thoughts especially when open questions are included too. The interviewer can interfere, explain or request for further information when needed. In this way, additional unexpected input can arise for the study. A significant part of the study was to identify applicational and practical aspects that can be associated with the use of hempcrete in practice in actual Dutch building projects. Since my experience on the Dutch building industry is only limited I decided that preparing questionnaires where interviewees would be asked to answer defined questions may could lead to unintended omittances or inexpediencies due to my lack of in practice experience. Interviewing on the other hand could provide further enlightenment to the study.

The sofware

Indoor comfort and energy consumption simulation

Hempcrete as a porous material is able to dampen indoor humidity variations through the exchange of moisture (Moisture Buffer effect) and provide high indoor comfort levels due to its special hygroscopic properties. Its porous nature determines its sorption and capillary behaviour and thus effects significantly the moisture balance equation in a room. A negligence of such an influence may lead to an incorrect prediction of the direct and indirect energy demand due to the relation between the latent heat effects, the comfort condition modifications, the heat transport parameter and the moisture content. Thus, an accurate modelling of the coupled transient heat and the moisture equations should be part of this study [1].

After research, two different possible simulation methods were found:

- Use of the COMSOL Multiphysics software and the introduction of results to Design Builder
- Use of the WUFI software

According to studies [1], COMSOL and WUFI can be used to create a transient air heat and moisture model capable of providing an accurate simulation of the moisture exchange between a lime hemp concrete blocks and the surrounding air.

Regarding the first simulation method, the detailed properties of the hempcrete sections can be defined in COMSOL and then they can be introduced in Design builder for a building energy performance and indoor comfort analysis.

On the other hand, WUFI is another standard tool for the assessment of hygrothermal performances in one-dimensional and two-dimensional cross sections. Importing the results in WUFI Plus allows to dynamic hygric and the thermal simulations both in room and building component scales [2].

Studies that compare the COMSOL model results to the results of an actual experiment and the results of a WUFI Pro simulation have been performed [1]. The results of such comparison proved that there is an agreement between the simulations performed between the two different types of software. The simulated models predicted accurately the moisture exchanges, with COMSOL to exhibit slightly more accurate predictions. Nevertheless, temperature variations between the surface of the specimen and the modelling results indicate an overestimation of the latent heat effect amplitude in both software computations.

According to the findings of the aforementioned studies [1], both software methods are considered acceptable for the purposes of the current graduation study. WUFI simulation is expected to be more direct than the COMSOL Multiphysics simulation since the energy and comfort performances of the building can be predicted directly by making use of WUFI . Consequently, WUFI was selected for the purpose of the study.

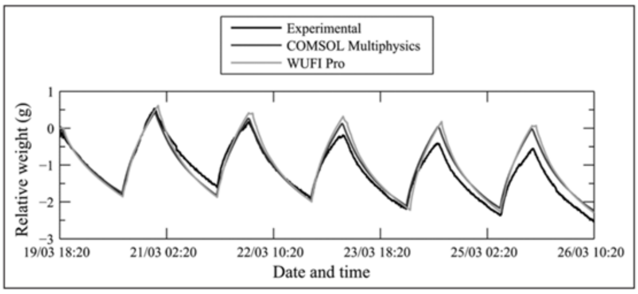


Figure 1: The relative weight of the specimen as simulated and measured during the experiment [2].

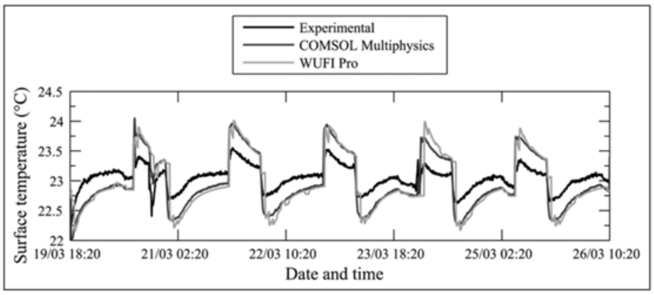


Figure 2: The temperature on the surface of the specimen as simulated and measured during the experiment [2].

0.6. THE INTERVIEWS

The performed interviews had the form of semi-structured interviews. This type of interview was selected because it is beneficial when examining uncharted territory with unknown issues. Semi-structured interviews include probing and open-ended questions which aim to gather information and potentially reveal unforeseen aspects. The process of preparing, setting up, conducting and analysing this type of interviews can be time consuming and thus allows only a limited number of participants [3]. For this reason consideration is required regarding the selection of the potential respondents. For the purpose of this study, respondents with different roles and experience in hempcrete applications had been approached with the goal to acquire a wider image on the current situation. Hence, the respondents were selected to be:

- Chadi Maalouf - Associate Professor at the French University of Reims Champagne-Ardenne with high experience in hempcrete and other biobased materials.
- ISOHemp - Hempcrete supplier with trading activities in the Netherlands and other countries.
- Ralf van Tongeren - Specialised architect in biobased design and Secretariat of the Dutch hempcrete association.
- Frank Lambregts -The building physics project leader of the currently largest scale hempcrete project in the Netherlands.
- Jean Franzen - Biobased materials and sustainability advisor in DGMR

The interview guides were prepared to include the overview of planned discussion topics and the relevant questions in a logical order. Each interview included different questions with regard to the role of each interviewee. Effort was made to condense the issues that needed to be addressed to no more than ten open-ended questions per interview in order to sufficiently guide the procedure and collect information without bombarding participants with questions. Notes have been made in advance with the information that was aimed to be gathered by each question so that intervening could be done more easily and efficiently. The aim of the questions was to collect knowledge from the experience of the interviewee but also to spot possible omittances which could have lacked from the literature review. The latter led in some case to acquire information that already have been found in existing literature. The interview guides were sent to the respondents beforehand to allow some preparation before the interview.

The interview guides for each interviewee are presented in the Annexes (Figure: A.1, Figure: A.2, Figure: A.3, Figure: A.4). The text which can be found in brackets and italics under each of the main open-ended questions was not included in the interview guides which were sent to the interviewees. It includes the additional questions or clarifications that could be addressed in case they were not mentioned in the answers.

Bibliography Proposal

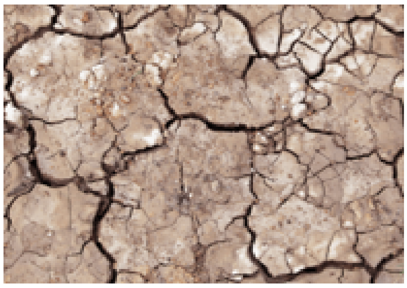
[1] S. Dubois, A. Evrard, and F. Lebeau, “Modeling the hygrothermal behavior of biobased construction materials,” *Journal of building physics*, vol. 38, no. 3, pp. 191–213, 2014.

[2] WUFI, *Wufi product overview*, https://wufi.de/en/software/product-overview/, Accessed: 2022-07-07.

[3] W. Adams, “Conducting semi-structured interviews,” in Aug. 2015. DOI: 10.1002/9781119171386.ch19.

1

State of Affairs



1

1.1. BIOBASED MATERIALS

Historical Review

THE term of industrialisation refers to different periods in history. Each industrialisation period is defined by a particular innovative invention that had the power to change the process of production drastically. The first industrial revolution started in the 18th century and flourished in the 19th century. It was aroused by the invention of steam engines capable of allowing mechanised production. At the end of the 19th century the invention of electrical power engines initiated mass production and lead to the outbreak of the second industrial revolution, followed by the third industrial revolution in the middle of the 20th century when digital information technology became the norm for the automated production [1].

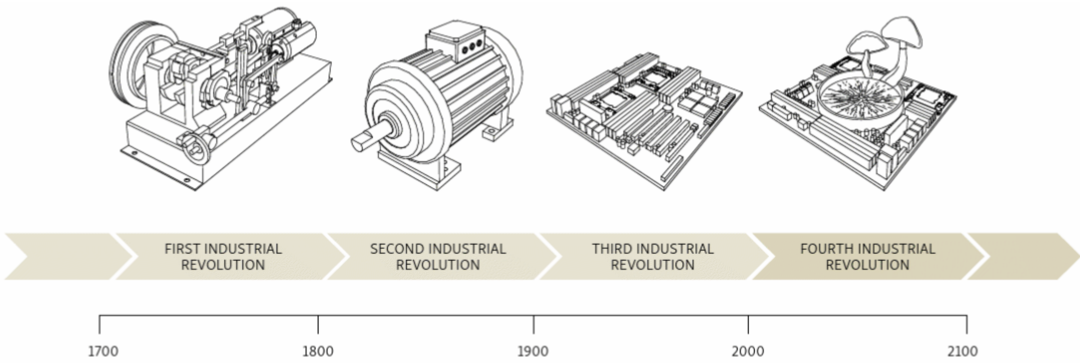


Figure 1.1: The industrial revolution timeline [1].

Industrial revolution created a need for standardisation. Mass production was only possible if adequate machines were able to be maintained, replaced or duplicated when required. Before the outbreak of the industrial revolution, machinery components used to be duplicated following a dialectical system method. According to this method, the new component used to be remodelled in response to an existing component by making sure that both elements suit each other. Components could only be produced linearly one after another in reference to their adjacent element, which resulted in a slow procedure unable to keep pace with the new reality that mass production had created [1].

The concept of modularity gradually developed. This technical system was an absolute system based on normative measurements independent of any physical references. Components were produced according to technical drawings which described precisely the required dimensions. This production principle entered the market at the end of 19th century and allowed a more parallel production. The difficulty of sharing the technical documentation and producing by hand components that precisely correspond to the defined dimensions, however limited its use. The introduction of machines capable producing normative components facilitated and accelerated the production [1].

Before industrialisation, natural and biodegradable materials had been used as building materials since centuries. Countless examples of such constructions have been created and constitute the fundamental aspects in the traditional architecture of different civilisations. Earth constructions made by adobe which were dated around 8000 to 6000 BC have been discovered in Turkestan [2]. The oldest rammed earth buildings were constructed at Catahyouk in Turkey around 10,000 years ago [3]. Rammed earth was also used initially for the construction of the 4000-year-old Great Wall of China, while the covering of the Wall with stones and bricks only occurred later [2]. Cob houses found at the Tiébéle village and decorated with tribal motives have been developed to an architectural landmark of Burkina Faso. Multistorey cob buildings dated from 9th to 13th century have been constructed in the city of Shibam in Yemen and belong to the UNESCO's World Heritage List since 1982 [4],[5]. Cultivated building materials had also been used for ages. According to the German architect Frei Otto, the history of building with bamboo probably begins with the history of Man's development and it is most likely that it has not yet come to an end. This statement, which was made in 1985, correctly predicted the current revival of the interest in Bamboo's potential as a building material [6]. Wood has been omnipresent in traditional architecture, with Japanese, Chinese and Central European traditional buildings representing some of the most characteristic examples. Hempcrete has been detected in the abutments of Merovingians bridges in France dating back to the 6th century AD [7] and straw bales have been firstly used in buildings with the form of blocks in the 1870s.

The sudden increase of the world's population created the need for a rapid construction of shelters. The industrial revolution and the new technological possibilities allowed the invention and fast production of new materials with astonishing structural performances that outperformed natural materials and thus marginalised them. The already gained knowledge on biodegradable materials was forgotten while the aroused interest in the new invented materials created prosperous conditions for exploratory research. The properties of those materials were mapped in detail and developed gradually in parallel to building standards in order to meet the required needs which got stricter over time. Eventually conventional industrialised materials evolved significantly while natural and biobased materials remained frozen in time [6].

Biobased materials in modern times

The 21st century is characterised by an environmental crisis. The scientific society, motivated by the dire need for a change, has seen potential in biobased materials. Scientists put in test progressively innovative applications driven by the will to substitute conventional industrialised materials. Numerous examples can be found in literature. The rapidly flourishing knowledge in timber and the modern technology had made the construction of the 85m tall Mjøstårnet timber building possible. Progress towards the determination of hempcrete's required properties for building applications have been observed in different countries . Mycelium composites produced by biding high efficiency natural insulators as hemp fibres and straws with mycelial growth have been proven to exhibit excellent thermal performances competent to those of glass wool and XPS [8]. Composites made of starch and sugar beet pulps have been assessed as an lightweight and eco-friendly insulative alternative and have been found to exhibit a remarkably low thermal conductivity (0.070 W/m) [9]. Researchers at the USA's Rensselaer Polytechnic Institute currently work on the development of hemp fiber-reinforced thermoplastic rebars, with the ambition to replace with a sustainable and durable alternative the conventional steel rebars and their substitute fibre reinforced polymer (GFRP) rebars in corrosive environments [10]. Bio-polymers have proven to manifest remarkable potential as cementing agents and insulators and composites made of corn starch, sand and water can reach an unconfined strength of 20MPa [1]. However since the sustainability of agricultural generated biopolymers can be debatable, due to the amount of land, nutrients and fertilizer that it requires, scientists have been searching for alternatives in agricultural residues. Spent coffee grounds incorporated with natural wax display phase change properties and can be useful for building applications in terms of thermal performances [11].The suitability of Poly lactic acid - a thermoplastic biopolymer that can be produced by food waste [12]- to replace a percentage of aggregates in concrete mixtures [13] or to form efficient insulating foams [14] has been assessed in recent studies.

Modern Architecture has also been influenced by this trend. Neri Oxman, a tenured professor at the Massachusetts Institute of Technology and the founder of the Mediated Matter Group, innovates at Material Ecology, the field where Biology interconnects with Technology for the creation of ecological and sustainable designs [15]. Zaha Hadid Architects (ZHA) design of the first entirely wooden stadium Gateway to Stroud has been approved [16]. Francis Kéré , architect and Chair of Architectural Design and Participation professorship at the Technische Universität München, known for his intelligent use of local materials to connect and respond to the natural climate [Pritzker Price Website] and his devotion to sustainable designs and sensitive approaches, has received the Pritzker Price of 2022 [17]. MVRDV one of the biggest Dutch Architecture firms in the Netherlands, has used timber for significant large scale projects as the PUJIANG PEAKS, a building of 95000 m^2 surface with timber structure and façade [18].

The environmental impact of buildings and the benefits of biobased materials

The life of a building is composed by the five stages (Figure 1.2). According to studies, the highest environmental impact appears during the building's use phase as a result of its operational energy and maintenance costs. The main emissions produced during this stage are those caused by the fossil fuel combustion for the heating, cooling and the generated electricity for the building's operation. Depending on the location and the building's characteristics, the energy consumption in the use phase can even surpass 80% of the total energy use [19]. Figure 1.3 depicts a breakdown of the energy consumption of the residential sector in the Netherlands according to a study performed by Eurostat in 2019. The required energy for space heating reaches 61.8% and thus accounts for the highest proportion of the total energy consumption in buildings. Considerable amounts of energy are observed in the categories of lighting and appliances and water heating, with a percentage of 18.3% an 17.4% respectively [20].

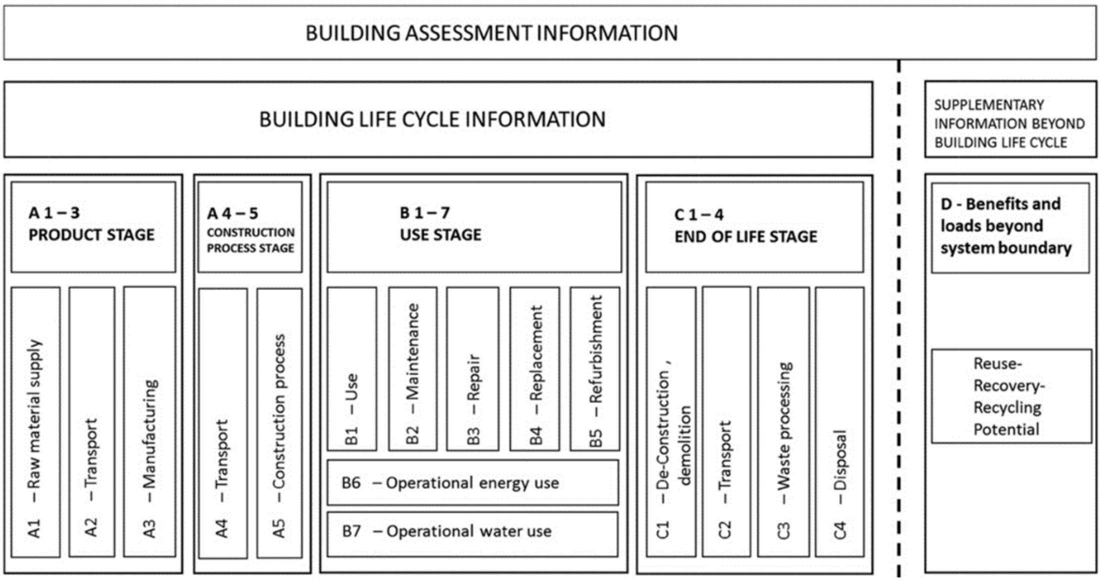


Figure 1.2: The different stages in life cycle assessment according to EN 15978 and EN 15804 [21] .

Share of final energy consumption in the residential sector by type of end-use, 2019
(%)

	Space heating	Space cooling	Water heating	Cooking	Lighting and appliances	Other end uses
EU	**63.6**	**0.4**	**14.8**	**6.1**	**14.1**	**1.0**
Belgium	73.2	0.1	11.9	1.7	12.8	0.4
Bulgaria	52.1	0.5	18.2	8.6	20.7	0.0
Czechia	68.9	0.1	16.7	6.1	6.6	1.6
Denmark	59.7	0.0	22.6	1.7	15.4	0.6
Germany	66.8	0.2	16.7	6.3	9.1	0.9
Estonia	71.4	0.0	11.7	5.1	11.7	0.0
Ireland	60.6	0.0	19.8	2.2	16.5	0.9
Greece	56.3	4.9	13.3	6.2	19.2	0.0
Spain	42.4	1.0	17.8	7.4	31.3	0.0
France	65.3	0.3	11.3	5.5	17.6	0.0
Croatia	67.1	2.0	10.4	7.0	13.6	0.0
Italy	66.3	0.8	12.0	6.5	12.9	1.4
Cyprus	37.4	10.5	22.1	7.7	20.5	1.7
Latvia	65.8	0.0	18.6	6.9	8.0	0.6
Lithuania	70.2	0.0	8.6	6.7	14.5	0.0
Luxembourg	82.2	0.2	7.8	2.4	7.4	0.0
Hungary	70.7	0.2	13.1	5.0	10.9	0.0
Malta	18.3	11.4	26.5	14.1	29.0	0.8
Netherlands	61.8	0.2	17.4	2.2	18.3	0.1
Austria	69.6	0.0	14.2	2.7	10.4	3.1
Poland	63.2	0.0	17.3	8.9	10.6	0.0
Portugal	27.4	0.6	17.6	36.0	18.3	0.0
Romania	62.3	0.3	13.7	10.1	13.7	0.0
Slovenia	62.5	0.8	16.8	4.2	15.8	0.0
Slovakia	72.8	0.1	12.6	4.3	10.2	0.0
Finland	66.1	0.2	15.3	1.0	12.0	5.5
Sweden	55.2	0.0	14.2	1.6	19.8	9.2
Norway	66.2	0.1	13.0	1.6	18.3	0.8
United Kingdom	62.2	0.0	17.6	2.8	17.4	0.0
North Macedonia	:	:	:	:	:	:
Albania	32.7	7.7	20.2	27.2	12.2	0.0
Serbia	61.2	0.5	13.9	7.3	17.1	0.0
Bosnia and Herzegovina	72.3	0.6	9.9	5.1	12.1	0.0
Kosovo*	69.2	3.7	7.0	7.7	10.1	2.3
Moldova	68.6	0.1	10.1	12.5	8.7	0.0
Ukraine	52.9	0.6	14.1	16.6	15.8	0.0

(*)This designation is without prejudice to positions on status, and is in line with UNSCR 1244 and the ICJ Opinion on the Kosovo declaration of independence.

Source: Eurostat (online data code: nrg_d_hhq)

eurostat

Figure 1.3: Share of final energy consumption in the residential sector by type of end use,2019 [20].

The selection of materials can highly influence the energy performance of a building during its use phase. In addition, its environmental impact is closely associated with the products' recycling or re-use potential and the embodied energy that occurs during their manufacturing. The structural components of a building have been estimated to account for the highest proportions of the embodied energy which is partially caused by the large quantities used. As a result, an optimised structure and an adequate construction method with an aim to decrease the amount of structural material could significantly influence the environmental impact of a construction. Studies have proven that the selection of a precast concrete floors instead of in-situ case can decrease the environmental impact of a construction since due to the larger spans that precast beams can withstand, less columns and footings are required [19].

The environmental impact of a construction can also be defined by its levels of embodied carbon. In general natural materials account for lower values of embodied carbon. Timber emissions have been estimated to usually vary from 0.30 to 0.40 kg CO2/kg. On the other hand, steel accounts for the highest with an average of 2.53–2.71 kg CO2/kg. Consequently, reinforced concrete's embodied carbon is almost doubled in comparison to that of common concrete with a range of 0.19-0.24 kg CO2/kg and 0.10 to 0.16 kg CO2/kg respectively. Common bricks have similar embodied carbon values that vary from 0.14–0.23 kg CO2/kg [22]. Insulating materials account for remarkably high values with stone wool, glass wool, EPS and XPS to range between 2.77-5.85 kg CO2/kg, 1.62-8.63 kg CO2/kg, 3.25-6.25 kg CO2/kg and 5.21-13.22 kg CO2/kg respectively [23].

The gradually increased adaptation of biobased materials into the building industry can alleviate some modern environmental issues as the global warming and the depletion of resources. However, biobased materials have more to offer than just their low embodied carbon levels. Bio-philic design has been proven to enhance the well-being of users. The thermal, hygroscopic and acoustic properties that biobased materials incorporate allow high levels of indoor comfort to be reachable, while the feeling of connection with the nature that they create can significantly reduce the levels of physical and psychological stress [24],[25].

Provisions for a sustainable implementation of biobased building materials

Industrialised materials fall short of biobased materials in terms of sustainability and environmental preservation and conceivably will flounder to cope with the environmental goals of future standards. Nevertheless, considerable research needs to be done towards biodegradable materials to bridge the gap created by their multi-annual marginalisation. A guarantee that they are able to satisfy the modern standards' requirements and are liable to mass production is essential for their re-introduction in the building industry [1].

An excessive production to cover the building industry needs without precaution or proper analysis can often lead to undesirable results. Hyper cultivation of coniferous plantations during the 20th century in Great Britain had caused a sever acidification of soils and a serious loss of biodiversity. Besides, in a highly populated world, soils degraded or highly occupied at the expense of food production is not the optimum approach. Nevertheless, when a balance is achieved, the production of cultivated materials has some additional hidden benefits [1]. With sustainable management, forests can maintain their biodiversity and productivity since the operations are structured to be profitable without being unfavourable to the ecosystem or society [26]. Such a management promotes the conservation of soils, the protection of watersheds, the increase of carbon sequestration and the development of recreation and tourism [1]. Locals can enjoy the environmental and financial long term benefits and get the motivation to sustain the forest resources. Thus, urbanization can be alleviated.

1.2. Building Legislation

Current State Of Affairs

The building industry represents one of the highest primary energy consuming sectors with a significant contribution to greenhouse gas emissions, material depletion and waste. According to studies, the sector accounts for 35% of the global energy consumption, 40%-50% of the global amount of greenhouse gas emissions, and 40% of the global economy's material use [27], [28]. Its sharp growth has been proven harmful for the environment. Ozone depletion, global warming, destruction of the natural environment and loss of biodiversity are only some of its detrimental results.

The severe environmental consequences of the building industry have been acknowledged and global measures have been taken towards their limitation. The European Union's efforts to mitigate the environmental impact of human activities are epitomised with its participation in the Paris agreement. With the Paris Agreement, intermediate milestones have been set to ensure a gradual reduction of the greenhouse gas emissions adequate to limit the global temperature increase in the 21st century to a maximum of 2 degrees Celsius with an additional ambition for a further reduction to a maximum of 1.5 degrees [29]. For this purpose, commitments and guidelines had been defined for all the parties in order to guarantee their collaborative work towards the mutual goal of the emissions' reduction for an ultimate net-zero emissions world.

The Paris Agreement was negotiated by 296 parties and was accepted by consensus at the UN Climate Change Conference (COP21) which took place in Paris on the 2nd December 2015. It went into force on the 4th November 2016 and today includes 193 parties [30]. In the period between 2015-2017, the parties defined and submitted their nationally determined contributions (NDCs), namely their initial action plans and commitments for their contribution to the reduction of the global warming. In 2020-2021, the NDCs had been revised and more strict measures have been implemented to strengthen each party's climate plan. According to the agreement until 2030 the countries must have reduced their emissions by at least 45% compared to the 2010 levels. By 2050, the transition to net-zero emissions word must have been completed [29], [31].

The Netherlands has set its national targets for the reduction of the national greenhouse gas emissions. The Dutch government aims to a greenhouse gas decrease of 49% by 2030, and a 95% decrease by 2050 compared to the 1990 levels. The policy and measures that need to be followed for the achievement of these climate goals are presented in the Climate Plan, the National Energy and Climate Plan (NECP) and the National Climate Agreement. The Netherlands, as every member state of the European Union submitted an Integrated National Energy and Climate Plan (NECP) to the European Commission by the end of 2019. The Climate Agreement, which accounted for a significant part of the aforementioned, contains the arrangements between the highest greenhouse gas producing sectors, namely the sectors of electricity, industry, built environment, traffic and transport, and agriculture for the achievement of the national climate goals [32]. The agreement is based on the principle that the transition towards the minimization of the greenhouse gas emissions should be feasible and affordable for everyone [33],[34],[32].

The revision of old directives (as standards, regulations and norms) and the development of new ones has been the main means to realise the aforementioned environmental goals. For the building industry, those directives set the required guidelines for the establishment of energy efficient constructions with high levels of sustainability.

Standardisation of building products in the European Union

Construction products should provably contribute to the establishment of safe and healthy indoor conditions. For the design and fair trade of such products, the EU has stipulated the Harmonised European Standards under the provisions of European Construction Products Regulation. Manufacturers must draw up a declaration of performance and affix a CE marking for every construction product when there is the wish to comply with a Harmonised European Standard.

For the Declaration of Performances (DoP), the manufacturer needs to define the intended use (e.g. indoor or outdoor) of the material according to the ones stated in the relevant Harmonised Product Standard and indicate the essential features and properties related to the intended use according again to the relevant standard. The Declaration of Performances should at least include one declared performance and in the case that the European Commission or a Member State has set a requirement linked to a special characteristic, the related performance to that essential characteristic should under all circumstances be defined by the manufacturer. The CE marking signifies that the product had acquired all the legal requirements regarding safety, health and environmental protection manners and can be sold throughout the European Economic Area (EEA).

However, sometimes specific products may not be covered by a harmonised standard. In this case, manufacturers can request for a European Technical Assessment, according to which the declaration of performances will be drawn up and the CE marking will be arranged. The European Technical Assessment (ETA) is issued by a certified technical assessment body according to the directives of the European Organisation for Technical Assessment (EOTA). The final document (European Assessment Document, EAD) accounts for a harmonized technical specification, which contains the essential information for the product's technical assessment. It provides information on the intended use and the relevant performances of a product and includes a general description of the product, the list pf the essential characteristics of the product as agreed by the manufacturer and the EOTA, the methods to assess the relevant to the essential characteristics performances and the principles of the factory production control [35].

Nevertheless, the DoP, ETA and CE marking only indicate the essential properties for a product's intended use and not whether the product is suitable for a specific application. The latter arises from the national building regulations of EU Member States [36],[37].

The environmental product declarations (EPDs)

Another type of declaration that gradually becomes essential for the trading of a product are the Environmental Product Declarations (EPDs). EPDs are a reliable and verifiable means to define the environmental performance of construction products and services. EPDs in EU are composed according to the EN15804 standard which is based on the Life Cycle Assessment method (LCA). They account for an objective tool to compare the environmental impact of materials or products and respectively optimise the building's design. They are not yet mandatory in the European Union, nevertheless,some countries as the Netherlands, Belgium, Sweden and Norway have already established their compulsory use with their building regulations. In addition, EPDs are commonly used in green building schemes and modern certification standards as WELL, LEED, BREEAM, which are accreditation means to guarantee the high sustainability levels in buildings [38].

The importance of standardisation for a safe application of unstandardised products

In order to draw a safe and fair conclusion on whether a building product is suitable for a specific application, designers should focus on two main aspects. Firstly, designers must be able to conclude that all the essential for the intended use properties have been properly tested and declared by the manufacturer in the DoP. That allows an identification of the product's capabilities and limitations and provides security to the developers about the credibility of the declared information. For an unstandardized building product, as already stated before, manufactures have to request for an ETA according to which the DoP is issued and the CE marking is arranged.

In addition, after ensuring that the properties of the material are properly certified, designers must check whether the material can serve its purposes and perform sufficiently as part of a building system. For standardised materials, EU has issued material related harmonised standards, where all the required methodology to assess their performances is in detail described. For the case of unstandardised materials, designers must decide on their own which aspects of the product should be assessed and according to which factors the results can be accepted or not. To some extend national building provisions can be used for this purpose as the Building Decree (Bouwbesluit 2012) in the Netherlands. In this way, the impact of the material on the performances (e.g. environmental, energy, indoor comfort) of the building can be used as a factor to assess its suitability after performing the related analyses. However, in order to acquire accurate results, engineers must be able to understand how the material is expected to perform on a smaller scale e.g. a building element or part of a building element and if its application has be done correctly, so namely in a way that allows the delivery of the expected performances. Due to the lack of official material related guidelines, assessing the performance and application of an unstandardised material in small scales heavily relies on the personal knowledge and experience of the involved engineers.

1

1.3. THE BUILDING LEGISLATION IN THE NETHERLANDS

Bouwbesluit 2012 – The Dutch Building Decree

Bouwbesluit 2012 contains regulations regarding the construction, renovation, use and demolition of structures as well as the required constructions activities. It applies to both existing and new structures with residential and non-residential uses and sets the minimum required levels. It includes technical building regulations on the point of view of safety, health, usability, energy efficiency and environmental performances as well as regulations related to installations, uses and construction and demolition activities.

The history of building regulations in the Netherlands begins during the 20th century when the great urbanisation waves caused by industrialisation and the outburst of several epidemics created unhealthy living conditions in the urban centres. The first attempt for the creation of building regulations in the Netherlands, is reflected in the Housing Act of 1901, which stipulated the requirement for the establishment of regulations by every municipality regarding the construction, renovation or the expansion of residences. These regulations formed the building code of that time and accounted for the directions that builders should comply.

The dire urge for massive reconstruction after the Second World War, quickly bared the inappropriateness of that building code. The differences in the regulations created by the different municipalities impeded the construction of standardised residences in multiple locations in the Netherlands, since usually the design required several modifications in order to comply each time with the respective local regulation. Several governmental acts over the years attempted to eliminate this issue and direct towards a standardization of the building regulations. The proposal for a national building decree firstly appeared in the 80s and came into effect in 1992 with the completion of the first Building Decree phase. The Building Decree 2012 (Bouwbesluit 2012) accounts for its current modern form [39].

BENG (Bijna Energieneutrale Gebouwen) – The energy performance regulation

In addition to the Dutch Building Decree, all new buildings in the Netherlands should comply with the Bijna Energieneutrale Gebouwen (BENG) regulation. This regulation sets the requirements for the design of buildings with reduced energy consumption levels and almost energy neutral performances. The results are assessed according to the NTA 8800:2022 standard. The energy performance assessment is based on three fundamental requirements, which are:

BENG 1 → According to which the maximum energy demand in kWh per m^2 of usable area per year ($kWh/m^2.yr$) is determined. For the assessment of a building according to the BENG 1 requirements the total demand for the cooling and heating of the building is calculated. The performance of the building in this requirement can be improved with an optimisation on the building envelop which can be achieved by adequately selecting a glass to wall ratio on the façade, a sufficient insulation thickness, a limitation of thermal bridges, a sealing upgrade etc. The calculation is based on an neutral ventilation system and the requirement can be met either with renewable or fossil energy.

BENG 2 → According to which the maximum primary fossil foil energy consumption in kWh per m2 ($kWh/m^2.yr$) is determined.

In the case of BENG2 the total fossil energy consumption is calculated based on the sum of primary energy consumption for heating, cooling, hot water and ventilation. For no residential buildings the primary energy consumption for lighting and humidification is additionally considered. In comparison to the energy requirement (BENG 1), the fossil energy consumption calculation also includes the system losses, the efficiency of generators and the primary energy factors of the national energy mix. The amount of energy generated by renewable resources, can be deducted from the total primary consumption.

BENG 3 → According to which the minimum share of renewable energy in percentage (%) is determined. The share of renewable energy is calculated by dividing the amount of renewable energy with the sum of both total primary fossil and renewable energy. In some cases, the BENG 3 requirement may not be possible to be met due to location related circumstances. In this case and under special circumstances that are described in the relevant guideline, residential buildings may deviate from the requirement [40],[41].

The LCA analysis

Among others, Bouwbesluit 2012 sets the requirement for the determination of the buildings' environmental performance, which is done according to the Life cycle assessment (LCA) method.

LCA is a widely used technique according to which the environmental aspects of a product can be evaluated. It gives an insight regarding the contribution of each of the life cycle stages to the overall environmental load and enables a prioritisation of improvements and comparisons between different products. A complete LCA (Cradle-to-Grave) includes all the stages of a product's life, starting from the raw material extraction to the product's dispose after its use. Two additional variations of LCA can be distinguished, namely the Cradle-to-Gate and the Cradle-to-Cradle. Cradle-to-Gate is a partial LCA, where the use phase and the disposal phase of a product are omitted and only the stages from manufacture to the factory gate are taken into consideration. On the other hand, the Cradle-to-Cradle assessment represents a modification of the traditional Cradle-to-Grave assessment, where at the end of its life the product is recycled. LCA quantifies objectively the energy and material usage that are observed during each of the product's stages by translating them into the resulting environmental emission equivalents. It considers five stages: the premanufacturing, the manufacturing operation, the product's delivery, the use phase of the product and the end-life management (disposal, recycling, re-use) [42]. The method is a globally accepted environmental assessment tool and represents the base for the creation of EPDs and environmental project reports.

In building scale, the relevant guidelines and analysis boundaries which are defined by the European Union EN 15978 standard are used. EN 15878 has been created in accordance with the EN 15804 standard, which describes the methodology for the calculation and composition of EPDs. EN 15804, had been revised and accepted by the European Committee in 2019. The new version (EN 15804+A2) made the declarations of modules A1-A3, C1-C4 and D compulsory and defined that a Cradle-to-Gate analysis is possible only under special conditions. It introduced more complex and detailed calculation methods for the determination of the end-life benefits and loads (Annex D) and increased the number of the environmental categories to 13 core and 6 additional categories (Table 1.1) [43],[44]. EN 15978 and EN15804 versions are related to each other. The version of EN 15978 which is currently in force (EN 15978:2011) accounts for the environmental assessment of building with EPDs created according to the old standard EN 15804+A1. The newest standard EN 15978:2021 which is related to EN 15804+A1 and the newest m is currently published into its draft form. The Netherlands as other EU countries is currently into a transitory stage. The national environmental database is updated with new EPDs.

For the environmental analysis of buildings in the Netherlands, the Dutch Determination Method Environmental Performance Construction (Bepalingsmethode Milieu - prestatie Bouwwerken) has been developed in accordance to the EN15804+A2 standard. For the calculation, the National environmental Database (NMD) which includes data on the environmental profiles and quantities of building products, defined according to the NMD requirements and procedures is used. The total amount of emission equivalents is calculated for each of the life stages of the building. The results in each of the environmental impact categories are then multiplied by a specified weighting factor and converted to monetary values (€). The weighted sum is then converted to a single score environmental performance indicator by dividing by the gross floor area in m^2 and the building's lifespan in years [45].

Impact Category	Indicator	Unit
Climate change – total	GWP - total	kg CO2-eq.
Climate change – fossil	GWP - fossil	kg CO2-eq.
Climate change – biogenic	GWP - biogenic	kg CO2-eq.
Climate change – land use and change to land use	GWP - luluc	kg CO2-eq.
Ozone layer depletion	ODP	kg CFC11-eq.
Acidification	AP	mol H+-eq.
Freshwater eutrophication	EP freshwater	kg PO4-eq
Seawater eutrophication	EP-seawater	kg N-eq.
Land eutrophication	EP-land	mol N-eq.
Photochemical ozone formation	POCP	kg NMVOC-eq.
Depletion of abiotic raw materials, minerals, and metals	ADP-minerals & metals	kg Sb-eq.
Depletion of abiotic raw materials - Fossil fuels	ADP-fossil	MJ, net cal. val.
Water use	WDP	m3 world eq. deprived
Fine particulate emissions	Illness due to PM	Illness incidence
Ionizing radiation	Human exposure	kBq U235-eq.
Ecotoxicity (freshwater)	CTU ecosystem	CTUe
Human toxicity, carcinogenic	CTU human	CTUh
Human toxicity, non-carcinogenic	CTU human	CTUh
Land-use related impact/soil quality	Soil quality index	Dimensionless

Table 1.1: Environmental impact categories in accordance with the Determination Method.

Bibliography Chapter 1

[1] D. E. Hebel and F. Heisel, "Cultivated building materials," in *Cultivated Building Materials*, Birkhäuser, 2017.

[2] G. Minke, *Building with earth: Design and technology of a sustainable architecture*, 2012.

[3] D. Ciancio and C. Beckett, *Rammed earth construction: cutting-edge research on traditional and modern rammed earth.* CRC Press, 2015.

[4] U. W. H. Convention, *Old walled city of shibam*, Accessed: 2022-05-11. [Online]. Available: %5Curl%7Bhttps://whc.unesco.org/en/list/192/%7D.

[5] U. W. H. Convention, *Yemen's old city of sana'a and old walled city of shibam added to list of world heritage in danger*, Accessed: 2022-05-11. [Online]. Available: %5Curl%7Bhttps://whc.unesco.org/en/news/1310%7D.

[6] E. Ganotopoulou, "Biodegradable materials: A research and design handbook; enhancing the use of biodegradable materials on building's envelopes in the netherlands.," 2014.

[7] E. G. Özdamar, "Hemp as a potential material in architecture: Is it possible in turkey?" *ICONARP International Journal of Architecture and Planning*, vol. 9, no. 1, pp. 131–154, 2021.

[8] M. Jones, A. Mautner, S. Luenco, A. Bismarck, and S. John, "Engineered mycelium composite construction materials from fungal biorefineries: A critical review," *Materials & Design*, vol. 187, p. 108 397, 2020.

[9] H. Karpaky, C. Maalouf, C. Bliard, A. Gacoin, M. Lachi, and G. Polidori, "Mechanical and thermal characterization of a beet pulp-starch composite for building applications," in *E3S web of conferences*, EDP Sciences, vol. 85, 2019, p. 08 005.

[10] S. A. Rima, *Hemp rebar could offer low-cost non-corroding alternative to steel*, https://www.dezeen.com/2022/03/15/hemp-rebar-low-cost-low-carbon-alternative-steel-design/, Accessed: 2022-05-11, Mar. 2022.

[11] J. Yoo, S. J. Chang, S. Wi, and S. Kim, "Spent coffee grounds as supporting materials to produce bio-composite pcm with natural waxes," *Chemosphere*, vol. 235, pp. 626–635, 2019.

[12] Y. Hu, W. A. Daoud, B. Fei, L. Chen, T. H. Kwan, and C. S. K. Lin, "Efficient zno aqueous nanoparticle catalysed lactide synthesis for poly (lactic acid) fibre production from food waste," *Journal of cleaner production*, vol. 165, pp. 157–167, 2017.

[13] A. Patil, N. R. Banapurmath, E. P. Sumukh, V. M. Chitawadagi, and P. P. Revankar, "Investigation of poly lactic acid as a sustainable alternative material for generic applications of construction replacing manufactured sand and river sand," KLE Technological University, Hubli, India., 2020.

[14] K. Oluwabunmi, N. A. D'Souza, W. Zhao, T.-Y. Choi, and T. Theyson, "Compostable, fully biobased foams using pla and micro cellulose for zero energy buildings," *Scientific Reports*, vol. 10, no. 1, pp. 1–20, 2020. [Online]. Available: Nature%20Publishing%20Group.

[15] O. Neri, *About neri oxman*, https://oxman.com/#about-neri-oxman, Accessed: 2022-05-11.

[16] I. Block, *Zaha hadid architects wins approval for world's first all-timber stadium*, https://www.dezeen.com/2019/12/27/worlds-first-timber-stadium-zaha-hadid-architects/, Accessed: 2022-05-11, Dec. 2019.

[17] T. P. A. Prize, *Diébédo francis kéré bibliography*, https://www.pritzkerprize.com/laureates/diebedo-francis-kere, Accessed: 2022-05-11.

[18] MVRDV, *Pujiang peak*, https://www.mvrdv.com/projects/819/pujiang-peaks, Accessed: 2022-05-11.

[19] A. F. Abd Rashid and S. Yusoff, "A review of life cycle assessment method for building industry," *Renewable and Sustainable Energy Reviews*, vol. 45, pp. 244–248, 2015.

[20] Eurostat, *Share of final energy consumption in the residential sector by type of end-use, 2019*, https://ec.europa.eu/eurostat/statistics-explained/index.php?title=File:Share_of_final_energy_consumption_in_the_residential_sector_by_type_of_end-use,_2019_(%25)_T3.png, Accessed: 2022-05-11.

[21] A. Hafner and S. Rüter, "Method for assessing the national implications of environmental impacts from timber buildings-an exemplary study for residential buildings in germany," *Wood and fiber science: journal of the Society of Wood Science and Technology*, vol. 50, pp. 139–154, Aug. 2018. DOI: 10.22382/wfs-2018-047.

[22] L. F. Cabeza, L. Boquera, M. Chàfer, and D. Vérez, "Embodied energy and embodied carbon of structural building materials: Worldwide progress and barriers through literature map analysis," *Energy and Buildings*, vol. 231, p. 110 612, 2021.

[23] G. Grazieschi, F. Asdrubali, and G. Thomas, "Embodied energy and carbon of building insulating materials: A critical review," *Cleaner Environmental Systems*, vol. 2, p. 100 032, 2021.

[24] S. Bardage, "Performance of buildings," in *Performance of Bio-based Building Materials*, Elsevier, 2017, pp. 335–383.

[25] M. Yadav and M. Agarwal, "Biobased building materials for sustainable future: An overview," *Materials Today: Proceedings*, vol. 43, pp. 2895–2902, 2021.

[26] F. G. Wolfgang, *Cie4110 timber structures and wood technology, tu delft lecture notes*, https://brightspace.tudelft.nl/d2l/le/content/399202/Home, Accessed: 2022-05-11.

[27] M. Asif, T. Muneer, and R. Kelley, "Life cycle assessment: A case study of a dwelling home in scotland," *Building and environment*, vol. 42, no. 3, pp. 1391–1394, 2007.

[28] I. Hamilton and O. Ralpf, "Executive summary of the 2020 global status report for buildings and construction," *Global Alliance for Buildings and Construction*, 2020.

[29] E. Commission, *Climate action paris agreement*, https://ec.europa.eu/clima/eu-action/international-action-climate-change/climate-negotiations/paris-agreement_en, Accessed: 2022-05-18.

[30] U. Nations, *Climate action the paris agreement*, https://www.un.org/en/climatechange/paris-agreement, Accessed: 2022-05-18.

[31] U. Nations, *Climate action | for a livable climate:net-zero commitments must be backed by credible action*, https://www.un.org/en/climatechange/net-zero-coalition, Accessed: 2022-05-18.

[32] G. of the Netherlands, *Climate policy*, https://www.government.nl/topics/climate-change/climate-policy, Accessed: 2022-05-18.

[33] Klimaatakkoord, *Letter to the house of representatives, accompanying the proposal for a national climate agreement*, https://www.klimaatakkoord.nl/documenten/kamerstukken/2019/06/28/letter-house-of-representatives, Accessed: 2022-05-18.

[34] Klimaatakkoord, *National climate agreement - the netherlands*, https://www.klimaatakkoord.nl/documenten/publicaties/2019/06/28/national-climate-agreement-the-netherlands, Accessed: 2022-05-18.

[35] E. Commission, *Internal market, industry, entrepreneurship and smes | european assessment documents and european technical assessments*, https://ec.europa.eu/growth/sectors/construction/construction-products-regulation-cpr/european-assessment-documents-and-european-technical-assessments_en, Accessed: 2022-05-25.

[36] K. V. K. N. Bouwkeramiek, *Brochure product specification masonry brick according to nen-en 771-1*, https://www.knb-keramiek.nl/publicaties/knb-publicaties/brochure-productspecificatie-metselbaksteen-volgens-nen-en-771-1/, Accessed: 2022-05-25.

[37] E. Commission, *Internal market, industry, entrepreneurship and smes | harmonised standards*, https://ec.europa.eu/growth/sectors/construction/construction-products-regulation-cpr/harmonised-standards_en, Accessed: 2022-05-25.

[38] E. T. I. E. SYSTEM, *Internal market, industry, entrepreneurship and smes | harmonised standards*, https://www.environdec.com/all-about-epds/epd-applications, Accessed: 2022-05-25.

[39] M. van Overveld, P. van der Graaf, S. Eggink-Eilander, and M. Berghuis, *Praktijkboek bouwbesluit 2012*, https://www.rijksoverheid.nl/documenten/richtlijnen/2011/10/05/praktijkboek-bouwbesluit-2012, Accessed: 2022-05-25, 2011.

[40] M. van Binnenlandse Zaken en Koninkrijksrelaties, *Energieprestatie indicatoren - beng*, https://www.rvo.nl/onderwerpen/beng/indicatoren, Accessed: 2022-05-25.

[41] R. Netherlands Enterprise Agency, *Building regulations*, https://business.gov.nl/regulation/building-regulations/, Accessed: 2022-05-25.

[42] I. V. Muralikrishna and V. Manickam, "Chapter five - life cycle assessment," in *Environmental Management*, I. V. Muralikrishna and V. Manickam, Eds., Butterworth-Heinemann, 2017, pp. 57–75, ISBN: 978-0-12-811989-1. DOI: https://doi.org/10.1016/B978-0-12-811989-1.00005-1. [Online]. Available: https://www.sciencedirect.com/science/article/pii/B9780128119891000051.

[43] Z. Quist, *The revised epd standard 'en15804 +a2': What's going to change?* https://ecochain.com/knowledge/en15804-consequences/, Accessed: 2022-05-25, Jan. 2021.

[44] A. Gaasbeek, *What the revised en 15804 epd standard means for you*, https://pre-sustainability.com/articles/what-the-revised-en15804-epd-standard-means-for-you/, Accessed: 2022-05-25, Jul. 2019.

[45] N. E. D. FOUNDATION, *Guide to environmental performance calculations*, https://milieudatabase.nl/wp-content/uploads/2020/09/Guide_to_environmental_performance_calculations_July_2020.pdf, Accessed: 2022-05-25, Jul. 2020.

2

HEMPCRETE

2.1. HEMPCRETE

2.1.1. WHAT IS HEMPCRETE?

HEmpcrete is a bio- aggregate- based material, produced by the wet mixing of the chopped woody core of hemp plant with a lime binder. The use of hemp in constructions is not a new concept. Archaeologists have detected hemp shrives used in a French bridge dated back to the 6th century AD [1]. However, the material in its modern form firstly appeared in France around the 80s, when people were searching for effective alternatives to replace degraded wattle and daub sections in the timber frames of medieval buildings. The use of ordinary Portland cement mortars to those sections was proven to cause the retention of moisture which resulted the deterioration of timber frames [2].

Hemp is the English term for the cannabis plant. The term (hænep in old English) is cognate to the Proto-Germanic word hanapiz, which is believed to have its origin to the Scythian word kanabis. Its scientific name is Cannabis Sativa [3]. The hemp plant belongs to the family Cannabaceae, genus Cannabis. In comparison to other plant species, hemp has found its place in numerous applications due to its remarkable fibre strength, length and absorbency, its premium oil quality, and its favourable acoustic and thermal properties. It is primary used in the sectors of construction and insulation, paper and textile and food and nutrition, whereas cosmetics and automotive sector represent its growing markets [4]. Hemp is often mistaken to the cannabis plants used to produce marijuana or hashish. Even though hemp contains the tetrahydrocannabinol (THC) compound too, which is known to provoke psychoactive effects in humans, the cultivated hemp variety of cannabis entails remarkably lower amounts of THC in comparison to the varieties cultivated for the production of marijuana or hashish [5].

Lime is produced from calcium carbonate ($CaCO_3$), a substance which can be detected in quarried limestones, coral rocks, chalk or shells. For the production of lime, limestone is heated into a pre-heater with counter current combustion process. Flue gases flowing in the opposite direction dry and heat the limestone [6]. The preheated material is introduced into a rotary kiln, where the temperature of the material is homogenised. The rotation and inclination of the kiln forces the material towards the outlet of the kiln, where a gas burner is situated. The created heat is absorbed by the limestone by means of convection and radiation and when the calcination temperature is reached the material starts to decompose. During the calcination, carbon di-oxide (CO_2) is released and quicklime (CaO) is collected [7], [2]. The residual content of CO_2 depends on customer application but usually ranges between 0.1-0.2 mass percent. According to the mass balance, at full calcination 44% of the feed is released as CO_2. The lime production is characterised by two different types of emissions, the combustion emissions which are associated with the carbon-based fuel combustion and the process emissions which are associated with the amount of CO_2 emitted by the raw material during production. The latter account for the 60-75% of the total CO_2 emissions [6].

For its application in building, quicklime is mixed with water (slaking) and calcium hydroxide is produced (Ca(OH)2). The material reacts with the carbon dioxide found in the air and hardens by the process of carbonation and is converted to calcium carbonate (CaCO3). As a result, the whole process of the limestone treatment is known as the lime cycle [7], [2]. According to studies, a hempcrete box of 1m^3 consisting of Hemp Shives and 90% Hydrated lime has a carbon sequestration potential of 470.29 kg of CO_2, while reaching 307.26 kg of CO_2 sequestration in a 28 days growth period [8].

Hempcrete's setting is done in two phases. During the initial setting phase, hempcrete needs to be supported by form-work until strength reaches to a sufficient level to carry its self-weight. The second phase of setting starts when the form-work is removed and lasts for weeks. During this phase, the excess water is dried out and hempcrete continues to harden until reaching its final strength. The nature and the characteristics of the binder can significantly influence the process of setting and the properties of the product's end result. Depending on the nature of the application, the desired properties of the end results may differ. Choosing the adequate binder and the appropriate proportions of ingredients is essential to achieve the desired properties. However, in general, in order to be effective all hempcrete binders should allow to hempcrete to reach sufficient strength levels to carry its self-weight after the initial set, to retain enough permeability to let the excess water draining and to achieve sufficient long term structural strength [2].

2.2. HEMPCRETE'S APPLICATION IN MODERN BUILDINGS

2.2.1. FLOORS, CEILINGS AND ROOFS

Hempcrete can be used in floors in the form of insulating, vapour permeable slabs. However, it cannot stand alone as an insulating material since it requires a significant thickness in order to be efficient. In most of the cases, it is combined with other vapour permeable materials and breathable types of insulation. In this manner, floors with additional thermal mass which can act as heat stores can be created and thermal bridges can be minimised when hempcrete walls are properly connected to the hempcrete flooring layer.

Hempcrete for floors requires higher amounts of binder than usual hempcrete walls in order to achieve higher structural strength and carry higher loads. As a result, the insulative performances of hempcrete floors are lower than those of typical hempcrete walls. On ground floors, the hempcrete layer is cast on top of an insulating, free draining sub layer which replaces the need of using a plastic damp proof membrane. The sub layer should not allow any water capillary movement within its particles and the hempcrete slab should be above the ground level in order to avoid common problems which are associated with organic materials and ground conditions. Coated expanded clay aggregate or recycled glass foam aggregate are frequently used as the most sustainable sub-base options. Since the floor consists in its total by insulative materials, its total thickness is lower than that of typical concrete floors. The floor thickness is defined by the needed U value. The hempcrete layer is designed to be as thin as possible (80 mm – 150 mm) in order to be structurally stable and the sub -base thickness is calculated to compensate for the required thermal resistance (120 mm – 180 mm) [2].

2

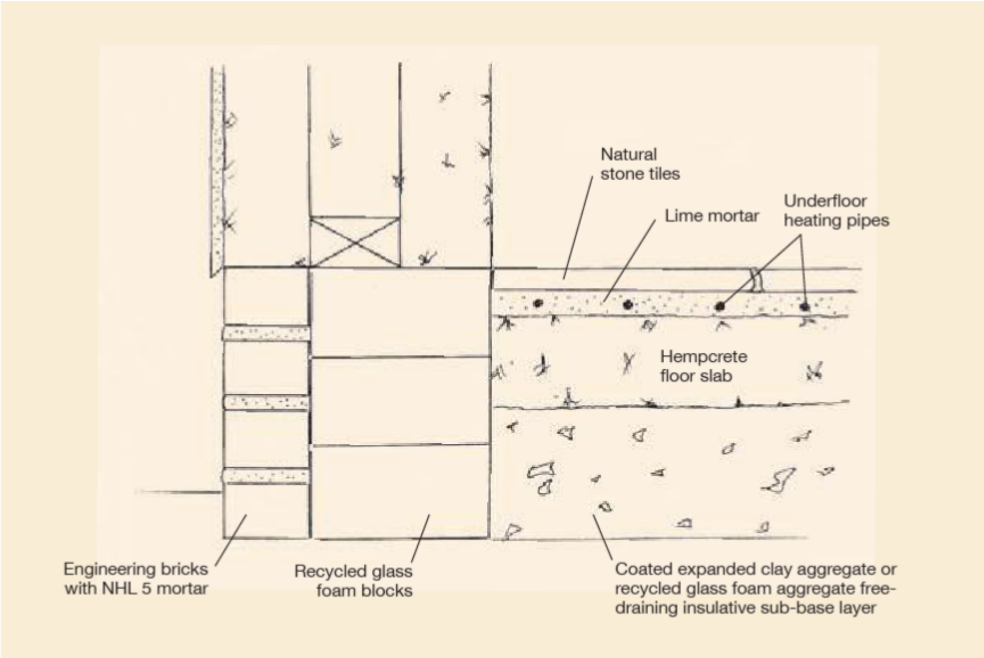


Figure 2.1: Hempcrete construction - Ground floor [2]

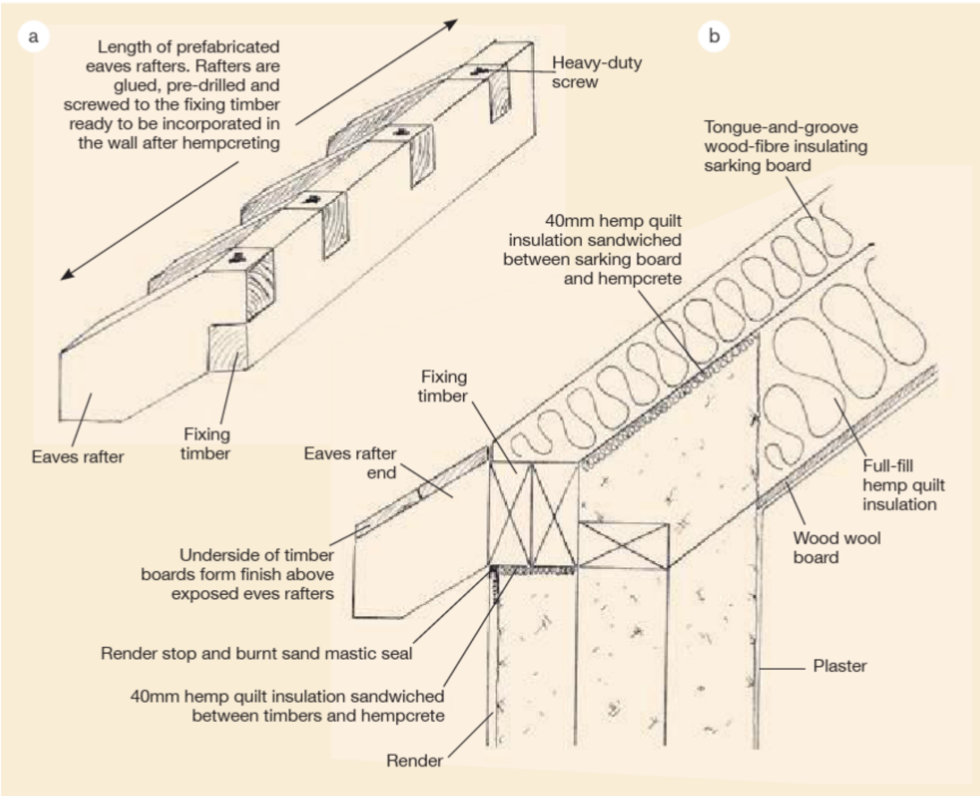


Figure 2.2: Hempcrete construction - Roof [2]

Hempcrete is rarely used in internal floors due to its extra expense, unless the higher acoustic and thermal properties that it can provide are needed between the different building levels. In this case, timber battens are fixed perpendicularly to the underside of rafters or joins and provide the required structure and reinforcement for the hempcrete ceiling. In roofs (inclined or flat), hempcrete is also cast between rafters. Since roofs require higher insulative performances, hempcrete insulation of different consistency (very low density mix) can be cast straight on fresh cast hempcrete ceiling. As an alternative, in the case that no hempcrete ceiling is wanted to be used, the hempcrete insulation can be cast on permanent shuttering of breathable carrier boards as wood wool boards [2].

2.2.2. WALLS

Cast in situ hempcrete is created on site and then cast into temporary or permanent shuttering and formwork. Simple stud-work of softwood is created to structurally support the building and hempcrete is cast in between the studs. The breathable nature of hempcrete allows the use of untreated timber. There are two ways to place the cast in situ material, either by hand placing or spray applying with fully mechanised delivery. The spray applied mixture has hemp shives of a finer grade than the hand placed one. The cast in situ hempcrete is characterised by higher insulative performances and lower mechanical strength than the prefabricated hempcrete block. In addition, the cast in situ method is more cost effective. However, due to the nature of the production and application of the in situ hempcrete, the final performances of the end product are difficult to be predicted. The process of production and application as well as the drying conditions on the site create uncertainty as they can influence the properties of the produced hempcrete significantly [2].

(a) Blocks (b) Sprayed (c) Cast in situ

Figure 2.3: Different forms of hempcrete. (The images were retrieved online)

Prefabricated hempcrete blocks provide considerable advantages in larger scale projects. Since hempcrete blocks are produced in monitored environments with standardised methods the properties of the end product can be predicted. In addition, the drying of the hempcrete is completed off-site and thus the required time of the on-site constructions is significantly reduced. Hempcrete blocks are connected to each other by using a thin mortar made of hydraulic lime and sand in between or around a structural timber frame. In order avoid any damage of the blocks caused during their manufacture, storage or transportation, the blocks should be characterised by a sufficient structural integrity. To achieve that, higher density hempcrete mixes with increased proportions of binders are produced in the expense of the insulation performances and the sustainability of the material. Attempts to create structural hempcrete blocks have been made, however it has been proven that the amount of the additional binder required for the higher mechanical strength results in lower insulation performances. Thus, this type of hempcrete blocks are impractical for exterior walls [2].

For the construction of walls made of hempcrete blocks a thin mortar made of hydraulic lime and sand is used. The thickness of the mortal joint should be thin enough to minimize thermal bridging but also thick enough to guarantee the integrity of the wall. In general, hempcrete blocks alone are enough to satisfy the requirements of the modern standards, however when this is not the case, a combination with other means of insulation is possible. Combining hempcrete blocks with in situ hempcrete can be an efficient and sustainable solution.

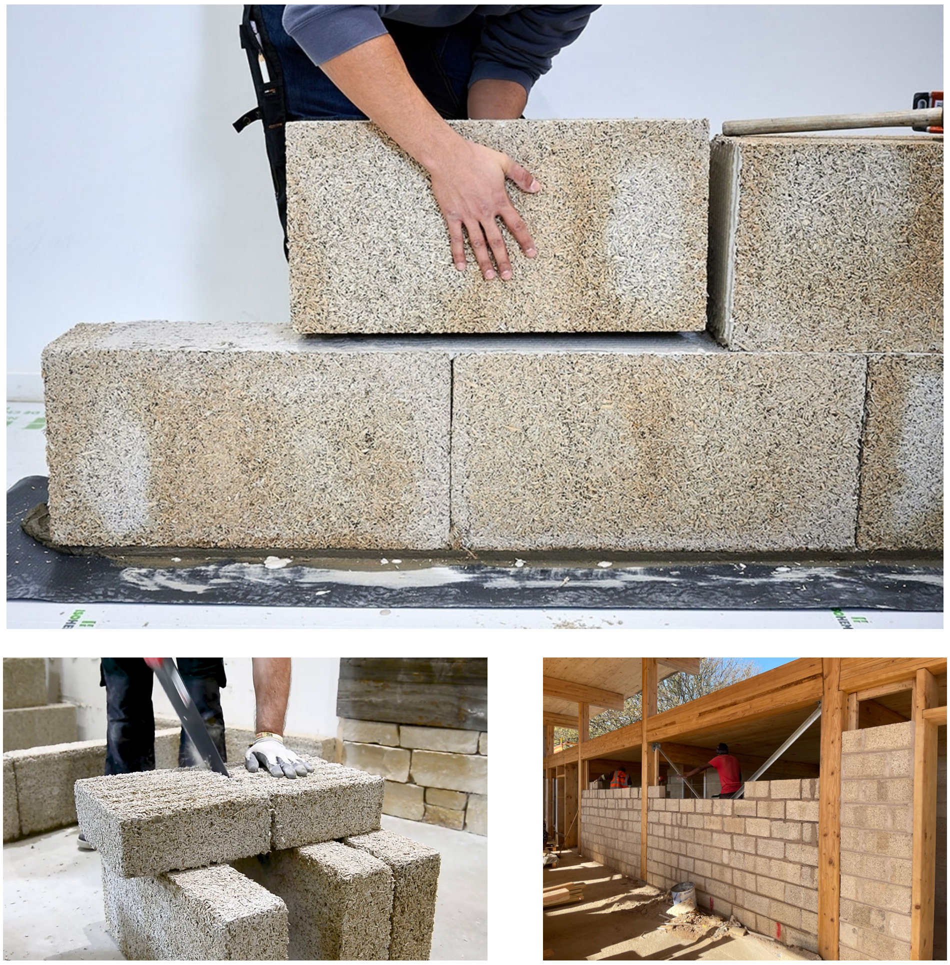


Figure 2.4: Hempcrete blocks - Application. (The images were retrieved online)

In comparison to cast in situ hempcrete that requires several weeks of drying and can be affected considerably by the climate conditions, the plastering and rendering of walls made of hempcrete blocks can start once the wall construction is complete. Hempcrete blocks are not susceptible to aspects as temperature, exposure, humidity and effective drying and that accelerates and facilitates the construction process.

Breathability is a quality of hempcrete that needs to be sustained. For this reason, all hempcrete renderings should be vapour permeable. The choices include breathable plasters and render finishes or external cladding with vented air gaps. The applied plasters should be at least as vapour permeable as the applied hempcrete. However, preferably the plasters should be characterised by a higher permeability. Usually two coat lime finishing plasters are selected for application due to cost efficiency, nevertheless, clay plasters can also be used in internal applications for aesthetic and moisture regulating reasons. Additional mechanic strength can be introduced to clay and lime plasters by incorporating hemp shiv, fines, chopped straw or commercial meshes. Clay plasters in comparison to lime plasters have the advantage of higher moisture buffering capacities, higher thermal mass and lower carbon footprints. They can contribute better to the health of the hempcrete wall, since they can absorb higher amounts of moisture excess from the walls and release it to the atmosphere. On the other hand, lime plasters are remarkably durable and thus suitable for external applications. They gain strength over time due to the carbonisation of lime and are able to reseal small cracks on the surface (especially air-limes and feebly hydraulic limes). Plastering with lime requires at least 5°C, but ideally should be done in temperatures between 8 °C and 22 °C. In some cases, applying plaster on the external walls may not be an optimum solution. In plastered facades with limited sunlight as north facades, drying after rain may not be possible and thus accumulated moisture may burden the hempcrete walls. In such a case cladding with a vented air gap between the cladding and the face of the hempcrete is a more appropriate solution. Measures to prevent moisture ingress into hempcrete from the cladding fixing should be taken and the airtightness of the wall should be ensured. Design measures should also be applied to minimise water accumulation due to precipitation. During construction, it is also important to cover the upper side of uncompleted hempcrete walls temporarily to protect them from rain water intrusion.

As hempcrete is not loadbearing, a structural frame around it for the support of windows, doors and cupboards is required. A typical framework for windows is made of two horizontal and two vertical timber elements in a box form attached to timber studs. A lintel, transfers the loads from above the window to the studs. Sealing beads are required for air-tightness and water tightness reasons. There are several choices that can be applied as stainless steel, PVC, glass-fibre or hardwood beads. Hardwood beads can be fixed after rendering with burnt sand mastic to seal the joint between the render and the frame.

For rooms with extensive moisture as kitchens and bathrooms the moisture regulative properties of hempcrete could be proven beneficial. For this purpose, non-porous materials as tiles and waterproof paints should avoided. Tiles could be used in places where the water accumulation possibility is high since repetitive contact with stagnant water can lead to the degradation of hempcrete. For the same reasons, shower walls should not be made of hempcrete. Using renderings with high moisture regulation capacities as clay plasters to enhance the breathability of the walls is recommenced in rooms with high moisture contents.

Hempcrete is a highly alkaline material and thus attention must be paid to the materials which which is in contact, as they can be corroded. Metals as steel can be highly affected when they are not properly galvanised. Structural fixings made out of steel should no be used within hempcrete. Secondary hanging materials as screws, straps and joist hangers should be made of stainless steel, be galvanised treated or pre-painted with anti-corrosion coatings [2].

2

2.3. THE MAIN PROPERTIES OF HEMPCRETE

2.3.1. COMPRESSIVE STRENGTH

The compressive strength of a material is characterised by its ability to withstand compressive loads without failing or changing its shape. Since hempcrete is made by hemp, which is a natural product, its performance in compression may slightly vary. In comparison to concrete, hempcrete has remarkably lower compressive strength and cannot be used as a load bearing material on its own. The limited compressive strength of the material can be attributed to a variety of factors as: the arrangement of the shives, the high flexibility of the aggregate, the nature of the binder and the high porosity of the end product.

The compression strength of hempcrete can be affected by numerous factors as the type of the binder, the shiv/binder ration (S/B), the water/binder ratio (W/B), the curing and moulding conditions and the production method. Studies have assessed how the different curing conditions (30%,75% and 90%), the binder content and the particle size affect the setting and hardening of the material as well as some critical mechanical properties as the compressive strength and the modulus of elasticity [9]. According to these studies the Young modulus of hempcrete with intermediate performances (compressive strength between 0.19 MPa and 1.18 MPa) can range between 7-160 MPa. An overview of how different parameters and conditions affected the compression strength can be seen in Table 2.1 [10]. Despite the different hempcrete mixture compositions, the compression strength as measured in the different studies remained under 1 MPa for both moulded or sprayed mixtures . Due to carbonisation hempcrete increases its compressive strength with time. At outdoor conditions, the compressive strength of hempcrete reached 0.43 MPa and 1.01 MPa after one and ten months of curing respectively. The compressive strength of samples with the same properties only reached 0.73 MPa after a 10 month indoor curing [11].

In the overviewing Table 2.2 [12], the vast majority of studies' results again display hempcrete samples with compressive strengths lower than 1 MPa. Some exceptions appear at the studies of Tronet et al. (2016) [13], where commercial pre-formulated lime-based binders were used and the compressive strength of the samples reached 4.74 MPa, and those of Sassoni et al. (2014), where patented MgO based binder with water-soluble vegetable protein resulted to a maximum compressive strength of 3.04 MPa [14]. The studies of Kioy, 2005 also indicated hempcretes with increased densities and higher compressive performances that reached 1.98 MPa, however the composition of the mixture was not found [12].

The performance of hempcrete in compression can be improved by increasing the binder proportions and increasing the density of the mixture with compaction. Furthermore, studies [15] have shown that replacing an amount of lime with clay results to the creation of hydraulic compounds that can also affect positively the compressive strength. According to (Murphy et al., 2010), samples with lower hemp content are characterized by higher compressive strengths but more brittle failures [16]. The effect of time and hemp proportions in hempcrete made of commercial binders (TH) and hydrated calcic lime binders (CL90) can be seen in Figure 2.5. Adding cement to the mixture results in higher levels of compressive strength (Murphy et al., 2010) [16],[12].

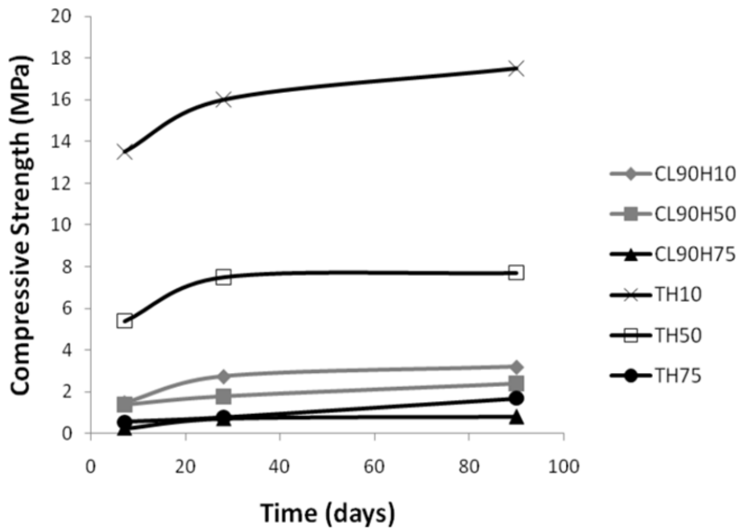


Figure 2.5: The effect of time and hemp proportions on the compressive strength development of hemp composites made of commercial binders (TH) and hydrated calcic lime binders (CL) [16].
Where: CL90H10 – 10% hemp; CL90H50 – 50% hemp; CL90H75 – 75% hemp with 90% calcic lime binder and TH10 – 10% hemp; TH50 – 50% hemp; TH75 – 75% hemp with Tradical binder

Studies	Binder Type	S/B	W/B	Curing	Moulding Spraying	Mechanical Results
Arnaud, and Gourlay, 2012	NHL2, NHL3.5, NHL3.5 Z	0.5	1.16 1.50 1.60	28d 20 C° 30% RH 50% RH 75% RH 98% RH	16x16x32 cm^3 mould	The Young's modulus of the samples produced with NHL 3.5 binder cured in 50% RH was obtained with the maximum 9 MPa and the maximum compressive strength 0.18 MPa. As RH value increased, compressive strength decreased significantly. In samples produced with NHL 3.5Z binder cured 50% RH, compressive strength up to 0.31 MPa was provided and Young's modulus was measured at 36 MPa. Compressive strength in samples produced with NHL 2 ranges from 0.10 MPa to 0.22 MPa and Young's modulus ranges from 5MPa to 24 MPa.
Chabannes et al., 2015	50% NHL3.5 50% hydrated calcic lime	0.5	1.5	10 months 20°C and 50% RH Outdoor	11x22 cm^3 mould	The compressive strength of the samples cured in 10 months at 20 ° C and 50% RH was obtained 0.73 MPa.For 1 month curing at outdoor, the compressive strength was obtained 0.43 MPa and 10 months curing at outdoor the compressive strength was obtained 1.01 MPa. Outdoor curing improved the carbonation process, which enabled samples to reach a compressive strength of 1.01 ± 0.08 MPa after 10 months. This was attributed to favourable %RH conditions for CO_2 diffusion and dissolution.
Elfordy et al., 2008	70% hydrated lime, 15% hydraulic lime 15% pozzolana	0.47	1.47	undisclosed	Spray	Densities of samples with compressive strength of 0.180 MPa to 0.8 MPa were obtained from 291 kgm-3 to 551 kgm-3. Density and thermal conductivity of the samples 0.179 Wm-1K-1 for 417 kgm-3, 0.421 Wm-1K-1 for 475 kgm-3, 0.542 Wm-1K-1 for 496 kgm-3 and 0.485 Wm-1K-1 for 551 kgm-3 was measured. Increasing mortar density provides both thermal conductivity and mechanical properties.

Table 2.1: Influence of different parameters and conditions on the compression strength of moulded and sprayed hempcrete [10]

Study	Composition	Density	Compressive Strength (MPa)
Arnaud and Gourlay , (2012)	NHL3.5	460	0.180
	NHL3.5Z	480	0.310
	NHL2.5	480	0.100-0.220
	Commercial pre-formulated lime based binder	460-500	0.300-0.340
Kioy, (2005)	NA	610	1.880
	NA	830	1.980
Cerezo, (2005)	NA	356	0.300
	NA	391	0.350
	NA	504	0.700
Tronet et al., (2016)	Commercial pre-formulated lime based binder	(-)	1.360
		(-)	1.630
		(-)	2.130
		(-)	4.740
		(-)	3.950
Sutton et al., (2011)	Commercial pre-formulated lime based binder	270-330	0.100-0.200
Sassoni et al,. (2014)	Patented MgO based binder withwater-soluble vegetable protein (Canti,2013)	330	1.150
		640	3.040
Sinka et al., (2014)	60% Dolomitic Lime +40% Metakaolin	540	0.266
		397	0.154
	Pure Dolomitic Lime	461	0.181
		367	0.136
		345	0.125
Sassu et al., (2016)	NHL3.5	643	0.414
	85% NHL3.5 + 15% Portland Cement	753	0.357
	Portalnd Cement	638	0.622

Table 2.2: Influence of different parameters and conditions on the density and compression strength of hempcrete (Jami et al., 2019) [12].

2

2.3.2. FLEXURAL STRENGTH

The flexural strength of a material describes its ability to withstand bending stresses. Hempcrete samples with commercial binder (TH) have been found to reach higher levels of flexural strength in comparison to those made by hydrated lime (CL90). Murphy et al. (2010) performed experiments regarding the influence of time and hemp proportions on the development of flexural strength of hempcrete (Figure 2.6). In general commercial binder samples were detected to reach their early flexural strength considerably faster than the hydrated lime samples. Low hemp content samples increased their flexural strength remarkably fast while composites with higher hemp concentrations were characterised by lower load carrying capacity and a more ductile failure. The stiffness of the end product is affected predominantly by the type of binders. Commercial binder composites showed increased Young's modulus values with increased binder contents. They showed no increase in elasticity in time and in general their flexural strength decreases over time [12].

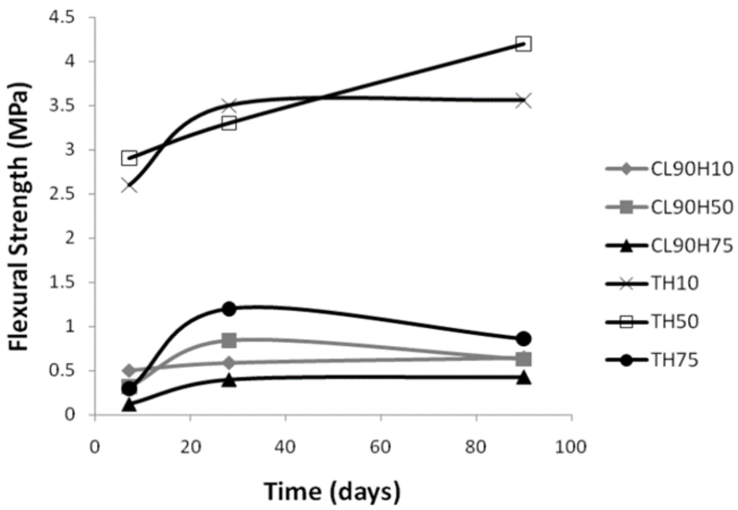


Figure 2.6: The effect of time and hemp proportions on the flexural strength development of hemp composites made of commercial binders (TH) and hydrated calcic lime binders (CL) [16].
Where: CL90H10 – 10% hemp; CL90H50 – 50% hemp; CL90H75 – 75% hemp with 90% calcic lime binder and TH10 – 10% hemp; TH50 – 50% hemp; TH75 – 75% hemp with Tradical binder

2.3.3. SHEAR STRENGTH

According to studies, the particle size distribution of the hemp shives is beneficial for the shear strength of hempcrete since it can provide a better compaction. The variation of their shapes, their rigidity and the characteristics of their surface increase the friction angle. In addition, hempcrete is characterized by a significant ductility. According to experiments [17], hempcrete samples which were tested in triaxial compression for the evaluation of their shear strength, did not eventually reach the critical state within the strain limits due to their high level of ductility. It was observed that the ductility increased with the rise of the confining pressure and the samples showed a considerable evolution towards a deviatoric behaviour. The strain capacity at failure developed from 6% to 19%, with unconfined and confined compression conditions respectively. The majority of the samples showed localised bulging and crushing at their lower parts. This was associated with the non-uniform pore distribution, the high compressibility of the hemp shives and the densification which occurred at the lower parts of the specimens. The aforementioned resulted in a large strain capacity with a localised lateral expansion. A small number of samples showed a more brittle failure mode of localised shear banding. Different Young modulus values were detected for the different failure modes, with higher modulus values appearing in specimens with shear banding failures and particularly lower values in those with bulging failures. Specimens with a combination of banding and bulging (the vast majority of the specimens) failure, were characterised by intermediate values of Young modulus. The peak friction angle of the specimens was measured at 46o and the cohesion strength -which was proposed by the authors to account for the safe shear strength for design purposes - at 0.36 MPa.

2.3.4. DYNAMIC RESISTANCE

The flexibility of the hemp shives in combination with the rigidity that the binder creates, result in a product which has the ability to sustain high deformations under stress without fracturing or failing even in conditions when the full mechanical strength of the binder is surpassed. The absence of brittle phase in shear response, can provide energy dissipation by deformation in lateral loading as earthquakes [18]. Its resistance to crack under deformation in combination with the additional racking strength that provides to the load bearing timber frame, make hempcrete constructions significant resistant to lateral and seismic loading [2].

2.3.5. FIRE SAFETY

The density and nature of the incombustible lime-based binder which encloses the hemp aggregates results in a difficult to burn product. In reality in the case of walls made of hempcrete blocks, it has been observed that the lime mortar at the joints accounts for the most vulnerable part of the construction while the hempcrete blocks show sufficient levels of fire resistance [2]. Several studies have been performed to assess the behaviour of hempcrete in the case of fire. Two characteristic tests and their results are presented below.

<u>Test 1</u>

Hempcrete composites were subjected to a flame test for 10 minutes while they were placed at a 10 cm distance from the source. The area closed to the flame deteriorated and became prone to crumbling, however, specimens showed no ignition or tendency to spread the fire. Incorporating hydrated lime in hempcrete mixtures had been observed to enhance the fire resistance of the composites [19].

<u>Test 2</u>

Samples were prepared and tested according to the European standard EN 13823:2010: "Reaction to fire test for building products". The reaction test lasted for 1600 seconds. The conditions in the chamber were first normalised with additional burner for 300 seconds and then the main burner was turned on. A visual observation revealed a small ignition of the shives at the surface of the hempcrete. However, this initial ignition finished fast and only the main torch continued to burn with an open flame until the end of the test. Some small parts of the samples failed and broke down towards the end of the test. Nevertheless, after the end of the test the material did not continue burning and spraying water all over was enough to cool the sample down. After the test, the tested sample was classified as class C s1, d0, where s1 is the highest class for the smoke evaluation and indicates almost zero generation of smoke and d0, which is also the highest class in the relevant assessment, indicates no generation of flaming droplets. Class C is used to describe the surface reaction to the fire and indicates some material burning at the surface, nevertheless it is considered as satisfactory. The FIGRA graph obtained by the test demonstrated that class B is possible to be assigned to the material only by slightly improving the its reaction to fire. The generated curve slightly surpasses the B Class limit of 120 W/s at the beginning of the experiment, which means that the surface ignited only at first and the burning stopped afterwards. The parts that ignited were proven to be some lighter parts of the material, which were not properly cured. Those parts occurred due to imperfections in the curing projects and could be easily avoided by using an improved technology or adding more binder to the mixture. Thus, the achievement of class B is indeed considered possible [20].

2.3.6. THERMAL BEHAVIOUR

In situ monitoring and laboratory experimental studies have revealed hempcrete's favourable thermal properties. Depending on the mixture, the thermal conductivity (λ) of hempcrete can range between 0.06-0.18 W/(mK) for dry densities between 200 and 800 kg/m^3 [12].

Hempcrete combines both micro and macro pore scales. Micro pores found within the hemp hurd and macro pores found within the hempcrete interconnect with each other. According to studies, the porosity of hempcrete can range between 71.1% and 84.3% by volume. The level of porosity can affect the thermal properties of the hempcrete product as the conductivity is closely related to the density of a material and increases with a quasi-linear relation. Cerezo, has defined the relation between the density and conductivity of hempcrete through the equation $\lambda = 0.0002 \times \rho + 0.0194$ [21]. Other studies [12], have found that an increase of 50 kg/m^3 in the density of the material can result to a rise of 0.005 W/mK in the thermal conductivity of the material. Exceptional thermal conductivity values that range between 0.07-0.09 W/mK have been reported by Sutton et al., 2011. In additions, hempcrete's thermal conductivity increases with an increase in the relative humidity levels[12].

Apart for its ability to store heat, the hygrothermal properties of hempcrete have an influence also on the material's thermal conductivity. Water is considered as a significant heat conductor in comparison to dry air, which is reflected on the difference between their thermal conductivity values (λ_{water}=0.6 W/(mK) and λ_{air}=0.026 W/(mK) respectively). Studies have shown that the thermal conductivity of hempcrete can increase even by 30% in humid environments, as the capillary condensation of water into the pores of the material is unfavorable for the thermal insulating performances [22].

Even though light weight insulation is characterised by lower λ values, the U- values of hempcrete constructions approximate those of composite walls with light weight insulation since hempcrete accounts for the whole thickness of the walls. For 300mm hemp concrete walls, a range of 0.22-0.89 W/m^2K in the U- values of different hempcrete compositions has been observed [23]. The theoretical U-values of hempcrete are based on a static model calculation. However, dynamic monitoring of hempcrete constructions has proven that the thermal performance of hempcrete in real life is actually better [12]. In addition, combining hempcrete with a timber frame, can minimise cold bridges due to their similar thermal conductivity values [2].

Hempcrete displays some special properties due to the breathability, the voluminous moisture handling and the high heat capacity that it combines. Studies have shown that a relationship between the relative humidity and the thermal capacity of a hempcrete wall exists. In comparison to lightweight insulation, hempcrete has the capacity to store and conduct heat which changes depending on the relative humidity levels. In more detail, a specific heat capacity of around 1500 J/kgK in dry state and 2900 J/kgK at about 99% relative humidity has been detected in studies [12]. Moisture inside the material, can impede the rapid heat flow which is observed in sudden temperature fluctuations. The change on the phase of the moisture from water vapor to liquid water or conversely, results in an energy release or absorption respectively [2]. The internal moisture adds thermal mass to the material and the high thermal inertial allows the rapid warmth of the material with a conservation of heat despite the ambient temperature alterations [10].

However, the active thermal mass of hempcrete has been estimated to be relatively low compared to those of concrete and clay bricks. In more detail, the volumetric heat capa-city of concrete, clay bricks and hempcrete approximates 2000 $kJm^{-3}K^{-1}$, 1400 $kJm^{-3}K^{-1}$ and 512$kJm^{-3}K^{-1}$ respectively [24],[25]. Thus, researchers have been focused on impro-ving the thermal properties of hempcrete by incorporating phase changing materials in the mixture. According to studies, such an action can improve significantly the thermal performances resulting in a material with 35-85% increased specific heat capacity and reduced thermal conductivities [26].

The airtightness of hempcrete has also been defined by studies. In more details the air permeability of a test building made of hempcrete panels was measured according to the the test method A - finished state and with no temporary seals- of the BS EN 13829 standard. The results indicated that the value of n50, which represents the number of air changes per hour at 50 Pa accounted for 0.55 [27]. Commercial hempcrete (in poured or sprayed form) with airtightness values better than 2 also exists in the market [28].

2.3.7. Acoustics

Hempcrete incorporates to its acoustic performances both the advantages of its micro and macro-porosity. It is an efficient sound absorbent and sound insulating material [12]. It displays very good acoustic quality which can be modified adequately depending on the composition of the mixture. Altering the binder type, the particles' nature, distribution and size, the compaction or the amount of the binder in the mixture can significantly affect the product's acoustical properties [2]. However, the type of the binder has been proven to have a higher influence on the acoustic performances of hempcrete in comparison to the shiv distribution and the physical parameters of the porosity and density. Composites made of Lime-Pozzolana binders exhibit better absorption than composites with more hydraulic binders or binders which include Portland cement. Unrendered hempcrete walls have been proven to absorb 40-50% of the incident sound signal while noise reduction Coefficient (NRC) can differ significantly depending on the rendering and the binder characteristics. Unrendered, rendered and commercial hempcrete composites have displayed NRC values of 0.2, 0.4 and 0.69 respectively [12].

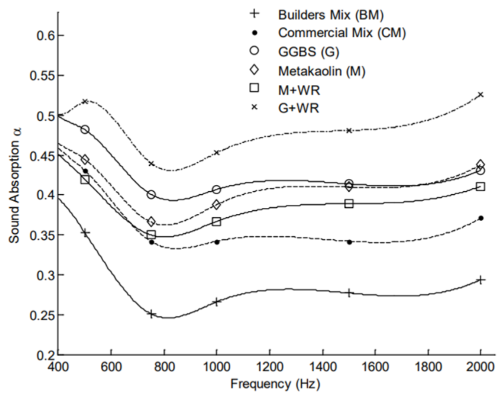
Binder	ρ (Kg/m^3)	α: 500 Hz	α: 1000 Hz	α: 2000 Hz
Builders mix (BM)	573	0.32	0.24	0.26
Commercial Mix (CM)	583	0.45	0.37	0.39
GGBS (G)	505	0.49	0.42	0.44
Metakaolin (M)	493	0.46	0.39	0.44
GGBS & water retainer (G+WR)	522	0.52	0.45	0.53
Metakaolin & water retainer (M+WR)	469	0.42	0.37	0.41

Table 2.3: Sound absorption coefficients at frequencies of 500 Hz, 1000 Hz and 2000 Hz of unrendered hemp lime concrete walls made of various binders [29].

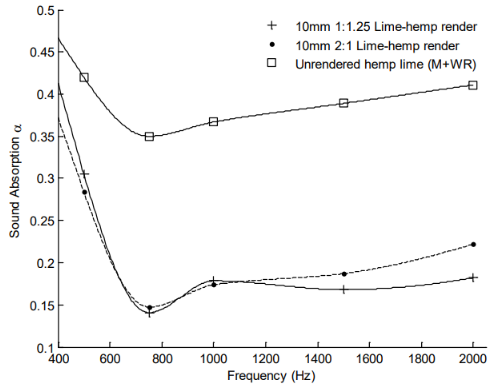
In more detail, Table 2.3 demonstrates the sound absorption coefficients for six unrendered hemp concretes made of different type of binders. The total results of the experiment are presented in Figure 2.7 [29]. The composite with the 10% Portland cement (Builders Mix) exhibited the lowest absorption coefficients in all the tested frequencies followed by the composite with the commercial hydraulic lime binder (CM). Lime pozzolan binders on the other hand displayed higher absorption coefficients, which can be explained by the lower density and higher open porosity that characterises the pozzolanic binders. All the composites under scrutiny, had high absorption coefficients at 500 Hz, 1000 Hz and 2000Hz, which decreased sharply around the frequency of 800 Hz. A mild fluctuation of the absorption coefficients was observed at the frequencies between 800 Hz and 2000Hz. Nevertheless, higher sound absorption values have been also detected in other studies. Such values account for $\alpha > 0.9$ (for frequencies: 100Hz ÷ 200Hz), $\alpha > 0.6$ (for frequencies: 400Hz ÷ 500Hz) and $\alpha > 0.6$ (for frequencies: 1000Hz ÷ 2000Hz) [30]. Hempcrete blocks with a sound absorption coefficient of α_w= 0.85, exist also in the market [31].

Binder	α: 500 Hz	α: 1000 Hz	α:2000 Hz
Unrendered Control Wall (M+WR)	0.42	0.37	0.41
Hemp-Lime Render 1.25:1 (10mm)	0.31	0.18	0.18
Hemp-Lime Render 1:2 (10mm)	0.28	0.17	0.22
Hemp-Lime Render 1.25:1 (20mm)	0.29	0.16	0.18
Hemp-Lime Render 1:2 (20mm)	0.28	0.15	0.19

Table 2.4: Sound absorption coefficients of rendered hemp lime concrete walls [29].



(a) Unrendered Hempcrete



(b) Rendered Hempcrete

Figure 2.7: Sound absorption coefficients of unrendered (left) and rendered (right) hemp lime concrete walls [29].

The influence of rendering can be seen in Table 2.4 and Figure 2.7. The absorption coefficients in walls with two different types of renders were assessed in comparison to an unrendered wall. In the total of the cases, the highest absorption was detected at the 400Hz. For the case of the rendered walls the absorption coefficient decreases sharply (more than 50%) in the range between 400 and 800 Hz. In fact, the absorption coefficients for the frequencies of 800 Hz and higher are considerably lower that those derived in the lower frequencies. For the case of the rendered wall, a notable decrease takes place between the range 400-800 Hz, too. The absorption coefficients of the rendered walls show a significant reduction in comparison to those of the unrendered wall especially in the highest frequencies. The rendering had caused the blocking of frequencies above f = $(\rho_{air} \times c_{air}) / (2\pi \times \rho_{material} \times d_{material})$. Thicker rendering caused an additional slight decrease on the absorption coefficients across the majority of the frequencies [29].

Hempcrete can also display good sound insulation performances. According to studies, a hempcrete wall with a 20 cm thickness can exhibit Sound reduction index values (Rw) of around 22-32 dB (unrendered) and 39-40 dB (rendered) [32]. Similar values can be found in commercial hempcrete blocks with the same thickness [33].

2.3.8. MOISTURE REGULATION

Hempcrete's high levels of permeability and hygroscopicity are associated with the high porosity of the aerogel structure of the shiv. When an adequate binder is selected (e.g. binders with high amounts of calcium lime) these properties can be further enhanced. Hempcrete exhibits high performances in indoor moisture regulation. In high indoor humidity concentrations, allows the condensation of the water vapour inside the material and thus the development of mold is avoided. On the contrary, in indoor air-dry conditions, hempcrete releases the moisture which is concentrated in the interior of the material back to the environment [2].

In more detail, hempcrete exhibits high water vapor permeability which approximates 2.3 x 10^{-11} kg/(Pa.m.s) and stays almost constant for low to medium levels of relative humidity. In addition, it can display an exceptional moisture buffer value (MBV) of 2g/m^2..%RH which reflects its ability to absorb and release moisture in repeatedly changing relative humidity conditions and thus regulate the ambient relative humidity [12].

Tests have been performed on walls made of precast hempcrete blocks to monitor the hygrothermal response of the material in different temperature and RH conditions for both coated and uncoated hempcrete walls. The binder of the precast blocks consisted of 72% CaO (in mass) and 28% of hydraulic binder (lime and pozzolan). Measurements were carried out on the wall's surface, within the wall and on the ambient air. According to the results, the uncoated wall has a short response to temperature and RH, which were influenced by the setpoints of the experiment. An homogeneous vapour diffusion was detected under a vapour pressure gradient and isothermal conditions. On the other hand, in the case of a constant vapour pressure with a reduction on the temperature, the variations of the ambient temperature increased remarkably (sorption/desorption phenomena and/or condensation/evaporation). For the case of the coated wall, the additional vapour resistance that is present to the assembly due to the coating, had led to a reduction in the vapour pressure through the wall and a delay in the vapour diffusion. Nevertheless, it did not stop the sorption desorption and/or evaporation–condensation phenomena [34].

2.3.9. DURABILITY

According to studies, hempcrete is in general a durable material that can endure the majority of factors which often cause the degradation of the usual building materials.

Hempcrete constructions are not prone to degradation caused by salt exposure, since the size of the pores is relatively large and hinders crystallisation [12]. The alkalinity of the lime creates an unfavourable environment for mould and insects and the absence of nutrients impedes the growth of microorganisms [12]. The high levels of permeability and hygroscopicity allow to hempcrete to undergo repeated absorption and desorption of moisture for an almost unlimited period of time. However, attention must be paid to the selection of external coverings, where moisture can be trapped and affect the durability of hempcrete [12], [2]. Furthermore, tests have shown that hempcrete's resistance to freeze thaw is closely related to the hydraulicity of the binder. Specimens which have been tested in near saturation conditions for a total of 10 freeze thaw cycles between -15 and 20 °C showed higher deterioration in lime binders, as they showed a greater decrease in compression strength and a higher weight loss than those detected in builder and commercial binders. Binders with greater hydraulicity show remarkable resistance to freeze thaw [35]. Cyclic wetting and drying cycles influence differently the durability of hempcrete depending on the type of the binder. Samples with calcic lime binders have been found to degrade and lose mass and compressive strength. On the other hand, cyclic wetting and drying was found to improve the compressive performances of hydraulic binder composites [12].

Due to the high levels of hempcrete's water permeability, the selection of appropriate coatings is of a major importance in order to avoid an entrapment of moisture inside the material that could lead to its degradation. Experiments have been performed to assess the behavior of hempcrete and the influence of different coatings in climate conditions. In more detail, the behavior of two walls made of prefabricated hempcrete blocks with two different coatings and exposed to outdoor conditions on the one side and controlled indoor conditions to the other were monitored for one year. The binder used for the blocks was a natural Prompt cement and for the interior coating of both walls under scrutiny a commercial lime-based binder was used. However regarding the exterior coating of the walls, a premixed lime and cement based industrialised coating with additive was applied, whereas for the second wall an on site lime and cement based hand-mixed coating was used. The walls were exposed to indoor climate conditions with a variation in temperature between 15 °C and 28 °C and in humidity emissions between 170 g/h and 200 g/h. They were installed on PASSYS test cells and were oriented towards the South. Sensors were placed inside the blocks and in a distance of 7.5 cm from the coating apart from monitoring the walls were also simulated in Wufi [36].

The indoor coatings were applied only a little after the wall was completed, in order to also asses their influence on the drying of the wall.The results of the experiment showed that the blocks without an indoor coating dried only a bit faster in comparison to those where indoor coating was applied, which demonstrates that applying coating on the interior side of a hempcrete block wall that have not been yet dried does not compromise the drying process when the coating is vapour permeable (Figure 2.9). The effects of indoor humidification on the the wall were also investigated. For this purpose an internal humidifier that emitted moisture loads of 6 h/day was implemented. The RH inside the room raised to more than 90% with a controlled temperature that remained constant at 25 °C. During the night the RH reduced to around 40% which caused a variation between 1500 Pa and 3000 Pa. The moisture under the interior coatings remained stable with oscillations between 1800 Pa and 2200 Pa. According to the aforementioned, it can be concluded that for the case of short term moisture loading even in high levels, moisture do not intrude deeply into the material (Figure 2.10).

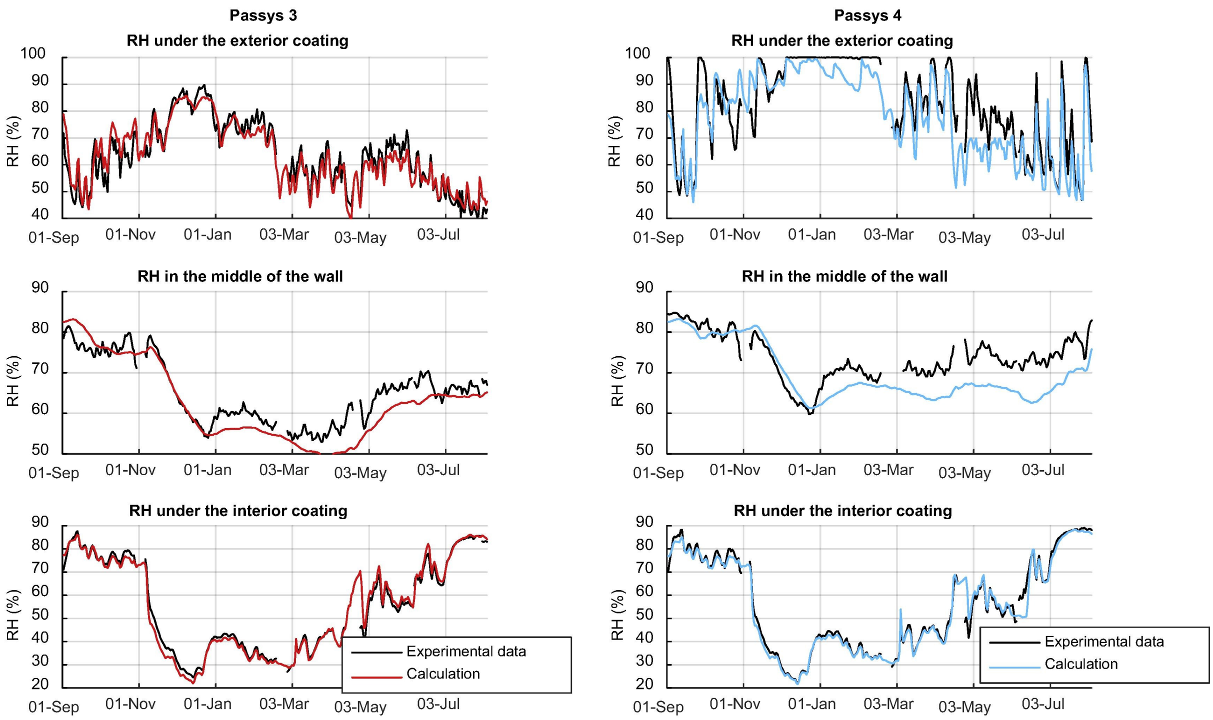


Figure 2.8: The measured and calculated RH in the walls with the industrialised coating (Left-Passys 3) and the on site prepared coating (Right - Passys 4) [36].

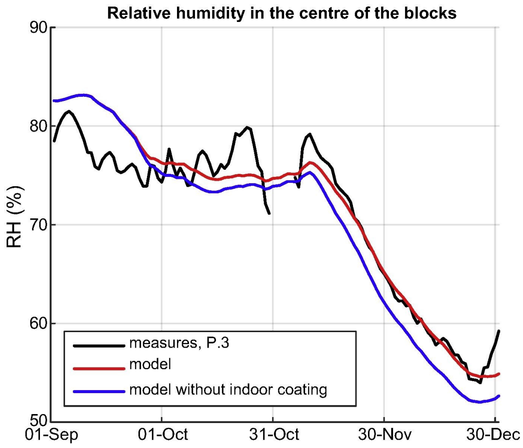


Figure 2.9: Drying of walls with interior and without interior coating [36].

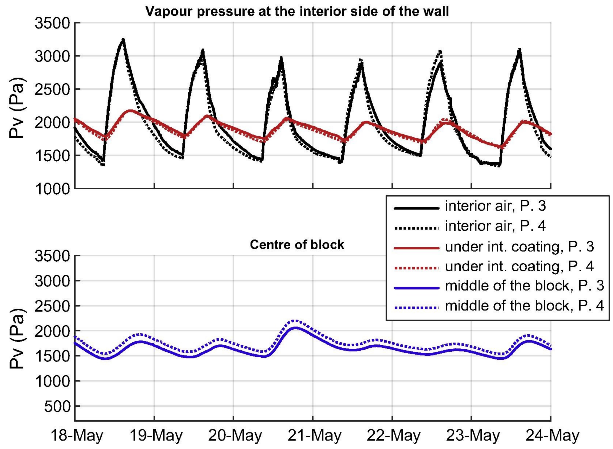


Figure 2.10: RH of indoor air and in the wall [36].

The influence of the exterior coatings was also investigated. The monitoring captured a major difference in the RH level under the the two different coatings after a big rain event. In the case of the hand-mixed on site coating (PASSYS 4), a sudden increase in RH under the coating surface was detected whereas for the case of the industrialised coating (PASSYS 3) no reaction was detected. According to the testing, the hand-mixted on site coating absorbed instantaneously high quantities of water whereas the industrialised one did not absorb any. In addition, the RH under the hand-mixed coating remained high for days and dried homogeneously. The variations of RH in the center of the blocks is small in a short term period for the case of both coatings, however the average RH in the center of the PASSYS 4 wall is higher that in the case of PASSYS 3. The difference between the RH at the center of the two walls slightly increased after the rain event (Figure 2.11).

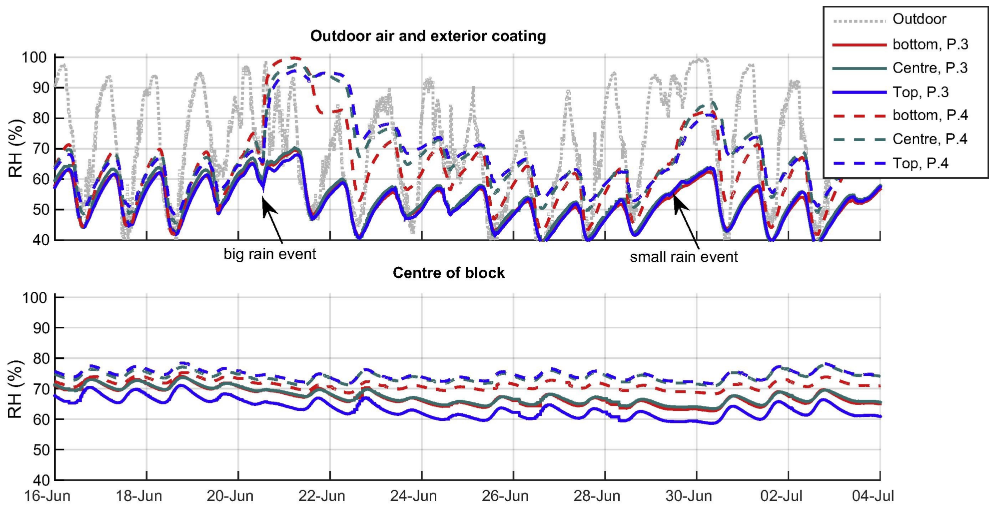


Figure 2.11: The RH levels under the two different coatings and in the center of the wall [36].

The long term impact of the coatings was also assessed during the same study. The RH humidity under the two coatings differed significantly as it can be seen in the upper graph of Figure 2.12(a). For the case of the industrialised coating (PASSYS 4) several peaks that even reached 100% RH had been detected under the coating especially during winter when the RH remained almost always at 100%. The latter had also an influence on the moisture detected inside the material. During the first months (until November) moisture levels at the center of the blocks for both walls had reached almost the same values, however during the winter period the difference in RH between the two walls increases and rises to around 20%. Furthermore, the moisture in the wall in long term conditions had also been influenced by the indoor humidity especially for the period between March and July, when the measurements at the center of the hempcrete follow the trend of indoor humidity (Figure 2.12).

Regarding the risk of mould growth both walls showed in general negligible risks (CFU/g <10^4). An exemption was detected at the surface under the hand-mixed coating were the CFU/g value surpassed 10^6 due to the high levels of RH that remained for an extended period [36].

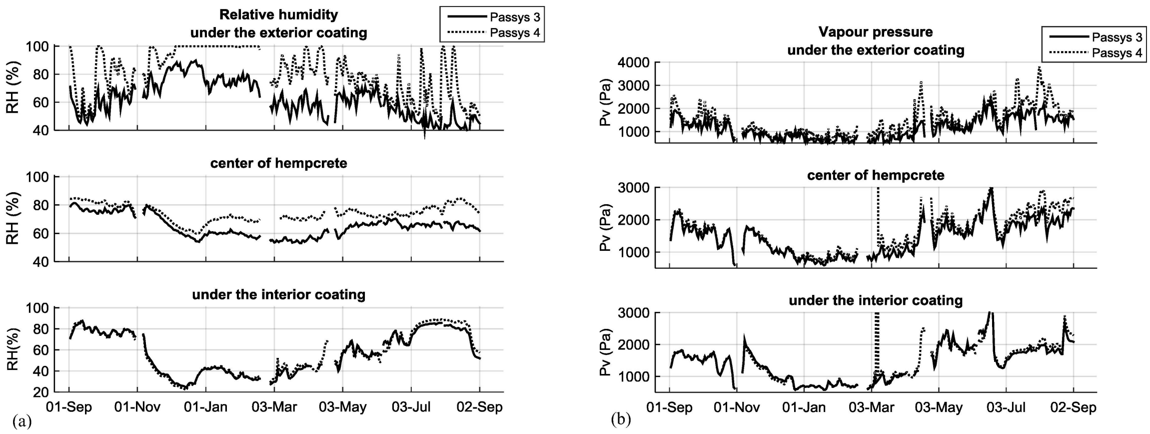


Figure 2.12: Relative humidity (a) and vapour pressure (b) at different depths in the wall; averaged values over 24 hours and at measurements at 3 different heights [36].

2.3.10. SUSTAINABILITY

Sustainable materials contribute to the creation of energy efficient constructions ensuring that no compromises are made at the expense of the environment, the society or the users. They account for environmentally friendly solutions, which have the capacity to create and sustain high levels of indoor comfort with the lowest or if possible zero energy consumption and fractional environmental or social implications. Nowadays, the level of sustainability that characterizes a material is defined by various parameters. Some of these parameters are the number of emissions that are created during the lifetime of the material and its embodied energy, the level of intervention in the nature and the landscape, the circularity re-usability and recyclability potential, the durability of the material, the type and use of resources and its efficiency in reducing energy consumption and create comfortable indoor environments.

Hempcrete is a bio-based carbon negative material (-0.15 kg CO_2/kg) [37]. The higher environmental impact is displayed during the production of the binder. Its primary material hemp absorbs significant amounts of CO_2 during its cultivation. According to studies, hemp has been found to sequester 1.84 kg of CO_2 per kg of dry hemp through photosynthesis during its growth. In addition, after its manufacture hempcrete continues to absorb

CO_2 from the atmosphere via carbonisation. The total amount of sequestered CO_2 have been estimated to compensate for the production of lime and even result to negative levels of embodied carbon.

In addition hempcrete is a durable and long-life material. Carbonisation happens in the operational phase of the material and results to the increase of its mechanical strength over time. As a result, the need for any substitution of the material is extremely rare. The recycling of hempcrete is possible, as it can be crushed and re-used in new hempcrete mixtures or insulation fillers , however such procedure is preferable to be avoided as it results in a down-cycling of the material [38]. Casted hempcrete blocks on the other hand can be re-used without any processing or additional treatment. Inter alia, due to its favourable hygrothermal properties, which were described in the relevant sections, hempcrete exhibits high levels of energy efficiency and indoor comfort.

Hemp is a fast-growing annual plant that can reach 4m in height. It grows in various temperatures and neutral to alkaline soils ($pH \geq 6.5$), it can be cultivated locally and thus transportation related costs and CO_2 emissions can be avoided. [2],[39]. Hemp's cultivation requires no pesticides or fungicides or any significant nutrients; thus the soil is not burdened with toxic and quality degrading substances [2]. Its deep roots break the soil in depth and contribute to its health, which makes it suitable for rotational cultivation [39]. Its fast growth and exceptional CO_2 sequestration, makes hemp more efficient in CO_2 absorption than agro-foresting [40], [41].

2.4. APPLICATIONS IN OTHER COUNTRIES

France

France has a great history of almost 30 years in Hempcrete constructions. The first hempcrete applications in French buildings appeared in the middle 80s. Tests on the material have been carried out since the 90s. Hempcrete related regulations already exists since 2012.

The Règles professionnelles d'exécution d'ouvrages en bétons et mortiers de chanvre are four professional regulation documents that describe the expected performance requirements of hempcrete mortars and concretes as well as the key points of using hempcrete in four types of applications (walls, coatings, roof insulation and floor insulation). The documents were developed by the French Association of Hempcrete (Association Construire en chanvre) and have been accepted in 2012 by the French Product Prevention Commission (Commission prévention produits -C2P-) of the Quality Agency (Agence qualité construction -AQC-). According to the regulation, the professionals that are responsible for the implementation of hempcrete in building constructions should be adequately trained and experienced with validated skills (validation des acquis de l'expérience -VAE-) [42],[43]. In addition to these documents, the French Hempcrete Association has released [44]:

1. The Hemp Aggregate for construction label (Label Granulat Chanvre Bâtiment) to guarantee the quality and the invariability of the hemp aggregate characteristics. [45]

2. The Laboratory assessment and Classification report related to the fire resistance of non- loadbearing hempcrete walls with wood frames.

3. A booklet with hempcrete construction details references (Carnets de Détails)

4. The verification of hempcrete environmental product declarations (EPDs : FDES in French) which are released in the INIES database.

5. A list with verified hemp and lime suppliers.

6. A list with approved laboratories for hemp concrete an mortars validation tests.

7. The informative booklet for hempcrete in France (Rapport sur la filière chanvre construction)

8. A list of architects, contractors, companies and professional trainers that are verified parties of the hempcrete Association.

All the aforementioned, have contributed to the spread and establishment of hempcrete's use in France.

The UK

A significant number of buildings already exist in the UK. The British Board of Agrément (BBA) has approved hempcrete products. Currently there are not any agreed industry standards in the UK so suppliers and manufacturers have set their own hempcrete standards [46], [2].

The USA

Hempcrete has not yet been standardised in the USA. There are not any hempcrete related certifications attributed by the International Code Council (ICC) or the American Society for Testing and Materials (ASTM) [46]. Thus, the realisation of permits for building constructions which incorporate hempcrete requires a case-by-case notice to the local building authorities. Industrial Hemp in the United States had been legalized recently. The Agricultural Act of 2018 has allowed the cultivation, processing and sale of hemp and facilitated contractors who previously had to import hempcrete [47].

The qualities of hempcrete have been acknowledged and the ASTM sub-committee currently works on the development of hempcrete standards. In 2020, interest parties have been invited to participate in the development of standards [48]. Since hempcrete is regarded as a non-load bearing material the committee has decided to focus on developing performance standards rather than material specifications. According to the sub-committee chair- , such an action facilitates the approval of hempcrete buildings and simultaneously allows a higher level of freedom to manufacturers. Hempcrete of variable materials, different binder consistencies and manufacturing methods will be accepted as long as the end product meets the performance requirements [47].

Canada

Companies with expertise in hempcrete projects have operated in Canada for more than ten years (e.g. Hempcrete Natural Building Ltg, DU CHANVRE).

2.5. THE SITUATION IN THE NETHERLANDS

The possible restraints

Even though hempcrete has some proven qualities, its use in the Dutch building industry remains limited. The number of Dutch constructions that integrate hempcrete barely exceeds 50 [49]. Some public Dutch projects have incorporated hempcrete in their design. One recent example accounts for the building that houses the municipality Voorst, which is currently under renovation. The building is planned to retain its concrete structure, however, its façade will be completely stripped and replaced by a new one made of hempcrete. This project is the first in the Netherlands to apply hempcrete on such a scale [50]. The Dutch Hempcrete association (Kalkhennepnederland) performs research on the material. It includes a number of companies and individuals with knowledge and interest in hempcrete projects. Interested parties can addressed the association for any hempcrete related question [49].

According to studies [4], [51], there are several possible factors that may hinder the market penetration of such a material. The factors may be related to the developers, the suppliers, the government and the capabilities of the material. Some examples are presented below:

Developers		
Hempcrete is a very convertible material. Its properties can differ significantly depending on the manufacturing conditions and the consistency of the mixture.	Research Time delay Increased risks	[52]
There is lack of guidelines to define the requirements that hempcrete products should meet in order to serve their role adequately.	Increased risks	[52]
No many buildings have been constructed so far. The interest parties cannot witness the hempcrete performances in practice.	Increased risks	[52]
Conventional materials meet the expectations of the developers. The developers don't feel the need to risk losing time on exploring a new material.	High performance substitute material	[51]
Biobased material are often regarded as expensive solutions.	Increased costs	[52]
Biobased material are often regarded as impermanent materials	Maintenance costs	[52]
Developers experience difficulties in finding certified suppliers of the material in a convenient distance.	Projects delays, Travel costs	
Tenders requirements	Less gaining opportunities	[52]
Type of contracts	Strict deadlines Absence of design freedom	[52]

Table 2.5: Possible restraints related to the Developers.

2

Suppliers		
Hempcrete is a very convertible material. Its properties can differ significantly depending on the manufacturing conditions and the consistency of the mixture.	Need of research Time delay Increased risks	
There is lack of guidelines to define the requirements that hempcrete products should meet in order to serve their role adequately.	Increased risks	[52]
Due to the psychoactive component THC that hemp contains, its cultivation is subjected to each country's regulation.	Restrictions in resources	

Table 2.6: Possible restraints related to the Suppliers.

Government		
Regulations with strict requirements	Increased risks	[51]
Types of required studies in order for a hempcrete construction to be accepted by the local authorities.	Increased studies, costs	[51]
Type of declarations required for hempcrete use	Increased bureaucracy	[51]
Lack of accreditation	More beneficial substitute material	[52]

Table 2.7: Possible governmental restraints.

Material	
Relatively low compressive strength	Application limitations
In-situ produced hempcrete require a significant amount of time for setting and drying.	Project delay
Hempcrete needs to have a particular thickness to be thermally effective.	Net surface decrease

Table 2.8: Possible restraints related to the nature of the material.

Bibliography Chapter 2

[1] H. Bedlivá and N. Isaacs, "Hempcrete–an environmentally friendly material?" In *Advanced Materials Research*, Trans Tech Publ, vol. 1041, 2014, pp. 83–86.

[2] W. Stanwix and A. Sparrow, *de la source The hempcrete book: designing and building with hemp-lime*. distributeur Green Books, 2017.

[3] WordSense|Dictionary, *Hænep (old english) origin history*, https://www.wordsense.eu/h%C3%A6nep/, Accessed: 2022-05-24.

[4] G. Crini, E. Lichtfouse, G. Chanet, and N. Morin-Crini, "Traditional and new applications of hemp," in *Sustainable Agriculture Reviews 42*, Springer, 2020, pp. 37–87.

[5] T. E. of Encyclopaedia Britannica, *Hemp*, https://www.britannica.com/plant/hemp, Accessed: 2022-05-18.

[6] M. Eriksson, B. Hökfors, and R. Backman, "Oxyfuel combustion in rotary kiln lime production," *Energy Science & Engineering*, vol. 2, no. 4, pp. 204–215, 2014.

[7] H. Shahin, S. Hassanpour, and A. Saboonchi, "Thermal energy analysis of a lime production process: Rotary kiln, preheater and cooler," *Energy Conversion and Management*, vol. 114, pp. 110–121, 2016.

[8] T. Jami and S. Kumar, "Assessment of carbon sequestration of hemp concrete," in *International Conference on Advances in Construction Materials and Systems*, RILEM Chennai, India, 2017, pp. 1–9.

[9] L. Arnaud and E. Gourlay, "Experimental study of parameters influencing mechanical properties of hemp concretes," *Construction and Building Materials*, vol. 28, no. 1, pp. 50–56, 2012, ISSN: 0950-0618. DOI: https://doi.org/10.1016/j.conbuildmat.2011.07.052. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0950061811004065.

[10] İ. Demir and C. Doğan, "Physical and mechanical properties of hempcrete," *The Open Waste Management Journal*, vol. 13, no. 1, 2020.

[11] M. Chabannes, E. Garcia-Diaz, L. Clerc, and J.-C. Bénézet, "Studying the hardening and mechanical performances of rice husk and hemp-based building materials cured under natural and accelerated carbonation," *Construction and Building Materials*, vol. 94, pp. 105–115, 2015.

[12] T. Jami, S. Karade, and L. Singh, "A review of the properties of hemp concrete for green building applications," *Journal of Cleaner Production*, vol. 239, p. 117 852, 2019.

[13] P. Tronet, T. Lecompte, V. Picandet, and C. Baley, "Study of lime hemp concrete (lhc)–mix design, casting process and mechanical behaviour," *Cement and Concrete Composites*, vol. 67, pp. 60–72, 2016.

[14] E. Sassoni, S. Manzi, A. Motori, M. Montecchi, and M. Canti, "Novel sustainable hemp-based composites for application in the building industry: Physical, thermal and mechanical characterization," *Energy and Buildings*, vol. 77, pp. 219–226, 2014.

[15] R. Haik, A. Meir, and A. Peled, "Low energy bio-aggregate-clay-lime concrete," *International Conference on Advances in Construction Materials and Systems*, pp. 657–664, 2017. [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85070585200&partnerID=40&md5=104044b949a2059c849f4051b1aad9a9.

[16] F. Murphy, S. Pavia, and R. Walker, "An assessment of the physical properties of lime-hemp concrete," *Proceeding of the bridge and concrete research in Ireland, Cork*, pp. 431–438, 2010.

[17] M. Chabannes, F. Becquart, E. Garcia-Diaz, N. Abriak, and L. Clerc, "Evaluation of shear strength parameters of bio-based concretes by means of triaxial compression," *Academic Journal of Civil Engineering*, vol. 35, no. 2, pp. 292–299, 2017.

[18] A. Youssef, T. Lecompte, V. Picandet, and N. Challamel, "Compressive and shearing behavior of lime and hemp concrete," *Academic Journal of Civil Engineering*, vol. 33, no. 2, pp. 405–411, 2015.

[19] S. Pochwała, D. Makiola, S. Anweiler, and M. Böhm, "The heat conductivity properties of hemp–lime composite material used in single-family buildings," *Materials*, vol. 13, no. 4, p. 1011, 2020.

[20] M. Sinka, L. Radina, G. Sahmenko, A. Korjakins, and D. Bajare, "Enhancement of lime-hemp concrete properties using different manufacturing technologies," *Academic Journal of Civil Engineering*, vol. 33, no. 2, pp. 301–308, 2015.

[21] U. Dhakal, U. Berardi, M. Gorgolewski, and R. Richman, "Hygrothermal performance of hempcrete for ontario (canada) buildings," *Journal of cleaner production*, vol. 142, pp. 3655–3664, 2017.

[22] S. Amziane and L. Arnaud, *Bio-aggregate-based building materials. applications to hemp concrete. iste ltd and wiley*, 2013.

[23] R. Walker and S. Pavia, "Moisture transfer and thermal properties of hemp–lime concretes," *Construction and Building Materials*, vol. 64, pp. 270–276, 2014.

[24] J. Ahlberg, E. Georges, and M. Norlén, "The potential of hemp buildings in different climates," *A comparison between a common passive house and the hempcrete building system, UPPSALA University, Sweden*, 2014.

[25] M. Charai, H. Sghiouri, A. Mezrhab, M. Karkri, and K. El Hammouti, "Comparative study of a clay before and after fired brick-making process," *Materials Today: Proceedings*, vol. 31, S103–S108, 2020.

[26] Y. Abdellatef and M. Kavgic, "Thermal, microstructural and numerical analysis of hempcrete-microencapsulated phase change material composites," *Applied Thermal Engineering*, vol. 178, p. 115 520, 2020.

[27] A. Shea, M. Lawrence, and P. Walker, "Hygrothermal performance of an experimental hemp–lime building," *Construction and Building Materials*, vol. 36, pp. 270–275, 2012, ISSN: 0950-0618. DOI: https://doi.org/10.1016/j.conbuildmat.2012.04.123. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0950061812003273.

[28] Tradical, *Tradical - building lime innovation*, https://www.tradical.com/pdf/Tradical_Information_Pack_small.pdf, Accessed: 2022-09-05.

[29] O. Kinnane, A. Reilly, J. Grimes, S. Pavia, and R. Walker, "Acoustic absorption of hemp-lime construction," *Construction and building materials*, vol. 122, pp. 674–682, 2016.

[30] F. Contrada, A. Kindinis, and A. Dony, "Hemp-lime in construction: Applications, comfort qualities and critical analysis," May 2015.

[31] UBAtc, *Atg technical approval for certification - isohemp*, Accessed: 2022-09-23. [Online]. Available: %5Curl%7Bhttps://api.butgb-ubatc.be/api/public/file/ATG3169E.pdf%7D.

[32] P. Glé, T. Blinet, and C. Guigou-Carter, "Acoustic performance prediction for building elements including biobased fibrous materials," Jun. 2018. [Online]. Available: https://www.researchgate.net/publication/325788893_Acoustic_performance_prediction_for_building_elements_including_biobased_fibrous_materials.

[33] Isohemp, *Hemp block isohemp*, Accessed: 2022-12-25. [Online]. Available: %5Curl%7Bhttps://www.isohemp.com/sites/default/files/fichiers/ish_technical_data_sheet_block20.pdf%7D.

[34] F. Collet and S. Pretot, "Experimental highlight of hygrothermal phenomena in hemp concrete wall," *Building and Environment*, vol. 82, pp. 459–466, 2014, ISSN: 0360-1323. DOI: https://doi.org/10.1016/j.buildenv.2014.09.018. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0360132314003102.

[35] R. Walker, S. Pavia, and R. Mitchell, "Mechanical properties and durability of hemp-lime concretes," *Construction and Building Materials*, vol. 61, pp. 340–348, 2014.

[36] A. Piot, T. Béjat, A. Jay, L. Bessette, E. Wurtz, and L. Barnes-Davin, "Study of a hempcrete wall exposed to outdoor climate: Effects of the coating," *Construction and Building Materials*, vol. 139, pp. 540–550, 2017, ISSN: 0950-0618. DOI: https://doi.org/10.1016/j.conbuildmat.2016.12.143. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0950061816320633.

[37] Y. Florentin, D. Pearlmutter, B. Givoni, and E. Gal, "A life-cycle energy and carbon analysis of hemp-lime bio-composite building materials," *Energy and Buildings*, vol. 156, pp. 293–305, 2017.

[38] A. Arrigoni, R. Pelosato, P. Melià, G. Ruggieri, S. Sabbadini, and G. Dotelli, "Life cycle assessment of natural building materials: The role of carbonation, mixture components and transport in the environmental impacts of hempcrete blocks," *Journal of Cleaner Production*, vol. 149, pp. 1051–1061, 2017.

[39] H. van der Vorst, M. Harmsen, and R. Borgers, *Handboek bouwen met kalkhennep*. SBRCUR, 2018, ISBN: 9789053676608. [Online]. Available: https://open.isso.nl/publicatie/handboek-bouwen-met-kalkhennep/2018?query=kalkhennep.

[40] C. Wilson, *The future for hemp*, https://ec.europa.eu/environment/forests/pdf/respondents-additional-inputs/European%20Industrial%20Hemp%20Association%20(EIHA).pdf, Accessed: 2022-05-18.

[41] C. Wilson, *The future for hemp*, http://eiha.org/media/2019/08/Catherine_Wilson-CannaWellness-EIHA_2019.pdf, Accessed: 2022-05-18.

[42] A. C. E. Chanvre, *Règles professionnelles d'éxécution - sebtp*. https://www.decitre.fr/livres/construire-en-chanvre-9782359170467.html, Accessed: 2022-05-18.

2

[43] I. DUFFAURE-GALLAIS, *Béton de chanvre : Des règles professionnelles validées par l'aqc*, https://www.lemoniteur.fr/article/beton-de-chanvre-des-regles-professionnelles-validees-par-l-aqc.1918909, Accessed: 2022-05-18, Jul. 2012.

[44] A. C. E. Chanvre, *Construire en chavre*, https://www.construire-en-chanvre.fr/bonnes-pratiques#rapport_chanvre_construction, Accessed: 2022-05-18.

[45] A. C. E. Chanvre, *Construire en chavre*, https://www.construire-en-chanvre.fr/missions, Accessed: 2022-05-18.

[46] Hempmonster, *Hempmonster building better hempcrete faq*, https://www.hempmonster.com/hempcrete-faq/, Accessed: 2022-05-18.

[47] K. HUNT, *Standardization news - green building with hempcrete - standards help further the use of a sustainable building material.* https://sn.astm.org/?q=features/green-building-hempcrete-ma20.html, Accessed: 2022-05-18, Apr. 2020.

[48] ASTM, *Standardization news - help needed developing hempcrete standards.* https://sn.astm.org/?q=update/help-needed-developing-hempcrete-standards-ma20.html, Accessed: 2022-05-18, Apr. 2020.

[49] K. Nederland, *Projecten in nederland*, https://kalkhennepnederland.nl/kalkhennepproject nl/, Accessed: 2022-05-18.

[50] D. T. Snoeken, *Huis van de gemeente voorst*, https://www.tweesnoekenarchitectuur.nl/projecten/huis-van-de-gemeente-voorst/, Accessed: 2022-05-18.

[51] L. :Probst, E. Monfardin, L. Frideres, and S. Moujahid, "Business innovation observatory smart living advanced building materials case study 18," Accessed: 2022-05-24, European Union, 2014.

[52] A. M. Jefimova and S. Tafertshofer, "Innovation adoption for eco materials in the construction industry in sweden: How three players can actively foster the adoption process-a case study on the material hempcrete with the company house of hemp," 2021.

3

THE RESEARCH

IN the following chapter each of the research sub-questions is addressed. The different means used are also elaborated below. The findings of the interviews are assigned to the sub-questions according to their relevance and are presented in the respective section each time.

3.1. SUB-QUESTION 1: THE DEFINITION OF THE REQUIRED PROPERTIES OF HEMPCRETE

3.1.1. RELATED FINDINGS AND CONCLUSIONS FROM THE INTERVIEWS

❖ The definition of the required properties of hempcrete for a safe and adequate application

In terms of physical performances, the moisture buffering capacity of hempcrete is the benefit that distinguishes it from other conventional building materials and as a result should be taken into account in building simulations. This aspect should be sustained during the design of the building and thus breathing constructions without vapour barriers are suitable for hempcrete applications. Mortars with low porosity as concrete mortars should be avoided, since they hinder the breathability of the walls and can lead to condensation problems. Its relatively low thermal conductivity as well as the acoustic performances are also beneficial for indoor comfort.

Hempcrete is not prone to biogenic degradation caused by microorganisms, insects or pests due to the presence of the lime, so in comparison to other biobased materials with other types of binders no additives are required for its protection. In addition, it is also resistant to fire even without stucco cover. However, water accumulation can lead to the failure of the material when it is not well designed. Accumulation of moisture can also lead to the decrease of hempcrete performances with time. However, there is not yet a clear scientific view regarding the exact effects that long-term moisture and water accumulation has on the performances of the material.

Even though hempcrete is a very convertible material whose properties can differ depending on the composition of the mixture, studies have already been performed and the effects of the different ingredients and their quantities have been explored with means of simulations and experiments. Taking into account studies that already existed in 2009 regarding hempcrete compositions with improved mechanical and physical properties, the university of Reims investigated the impact on the indoor comfort on a building level. During the last years, its research has been mainly focused on the enhancement of the environmental benefits of hempcrete, with the creation of composites with lower environmental impact. The results of existing studies were sufficient to lead to the definition of compositions adequate for building components with different mechanical and thermal requirements (e.g. wall, roof, floors) which are currently present in the French regulation. Aspects as the thickness of the wall and type of mortar to avoid condensation, the required thermal and mechanical performances, the types of ingredients and their amounts of percentages are part of such regulation. From 2020, the French hempcrete regulation includes also guidelines related to the environmental requirements of the material.

Regarding hand-made hempcrete, in which case the differences in the performances of the product can be higher and more frequent, experiments on defining the standard deviation of the end result are important. The prefabricated versions of hempcrete, as the case of hempcrete blocks which is the form of hempcrete under scrutiny in the current study, are gaining more space into the building industry as a more assured way to acquire an homogeneous product with precisely known properties. Risk are significantly decreased when prefabricated blocks are used in building construction. Issues that may be related to material with different local performances or hemp shivs that are not adequately covered by lime (e.g. biodegradation risk or fire safety risks) are not present in prefabricated blocks where the mixture of the components is monitored, protected and automatised.

Nevertheless, hemp is a natural product and thus it is not always easy to predict how it will react in pressing during the fabrication of the blocks. This adds some complexity to the production process and creates the need for a good quality control. ISOHemp's quality control includes four steps. The first step concerns the control of the mixture itself. The second control step takes place just after the pressing of the blocks. The blocks that fail to meet the requirements of that stage are crushed and re-introduced in the production process. The third control step takes place after the first drying of the blocks and the last one just before the blocks obtain their total strength.

Currently, hempcrete is mainly applied in houses and small scale residential buildings. ISOHemp has been involved in individual houses [1], [2] and renovation projects [3] in the Netherlands, while its bigger Dutch project so far was a four apartment building. Nevertheless, the hempcrete block company had some bigger projects in Belgium, such as multi-housing projects [4] and renovation projects [5],[6]. For the case of new projects, hempcrete blocks were mainly used for the construction of homogeneous facade walls whereas for renovation projects they were used as partition walls or inner insulation layers of the facade. ISOHemp customers do not frequently choose hempcrete blocks for the construction of separation walls in new buildings. According to the interviewee this is probably associated with the willingness of customers to invest more for the construction of the facade and less for the construction of interior walls.

However, besides its benefits, hempcrete is also characterised by some limitations. It has relatively low mechanical strength and hence it cannot be used as a load bearing material. A structural frame is always required, which in most of the cases is preferred to be made of timber in order to increase its environmental and social impact. It has a low thermal inertia, which can lead to over heating in the summer depending on the location of the building. As a result studies should be made beforehand, since solar shading may be needed in some cases.

3.1.2. The standardisation method for hempcrete's production

As can be summarised by the literature review and the interviews, hempcrete is a very convertible material with properties that can alter significantly depending on numerous parameters as: its form, binder type, additives, level of compaction, shive/binder ratio, water/binder ratio, casting conditions etc. Manufacturers can modify the composition of the mixture and the production procedure to acquire suitable properties for the end product's required performances. The latter may allow the optimisation of the product and thus enables various application options, nevertheless it simultaneously increases the complexity and confusion around its standardisation.

As different mixture compositions result in the enhancement of some specific properties to the detriment of others, a standardisation focused only on the material itself and the mixture specifications can be proven inappropriate for such a material as hempcrete. Pre-defining mixture recipes may lead to pre-established known performances, however those performances can cover adequately the requirements of only some limited applications. This is not an optimum solution and thus another approach needs to be followed.

Taken the aforementioned into consideration, it can be stated that for the case of hempcrete, a standardisation focused on the definition of performances according each time to the intended use is a more suitable approach. This kind of standardisation allows freedom to the producers and a case by case optimisation of the product according to the design ambitions, while it demonstrates which are the essential properties to be defined and their minimum acceptable operational values. A such performance based standardisation necessitates a clear definition of the intended use and the associated performance targets.

Nevertheless, existing literature provides information on the relation between the mixture composition and the performances of the produced hempcrete. In addition, factors that may decrease some of the targeted qualities of the material have also been in their vast majority identified. The incorporation of this knowledge in the standards can decrease frustration and help producers to avoid unnecessary research and costs. This can be done by including indications and guidelines regarding the ingredients and the ranges of their proportions that could lead to the intended performance.

3.1.3. THE APPLICATION AND THE INTENDED PERFORMANCES

Since no official EU performance specifications related to hempcrete have been issued yet, the assessment of the material's performances for building applications in the Netherlands relies on the personal knowledge and experience of the involved engineers and the building performance requirements set by the national building codes (Table A.1 *Annexes*). In the current section of the study, a logical strategy to accumulate and assess the application requirements will be developed. The strategy will aim to ensure that the expected designed performances will be accurately approximated in practice.

In the current case study, hempcrete blocks are used at wall systems on the façade and the partitioning of the internal spaces. Hence, it should be proven that the selected hempcrete products can be incorporated and result to an integral wall system that can serve the required performances. The first step of this procedure is to understand the purposes that each of the two different wall systems should serve. An overview of those purposes can be seen in Table 3.1.

The suitability of the material to serve the purposes for each intended application is measured by assessing the values of the parameters that characterise each purpose. Those parameters can be collected from the harmonised standards and DoPs of already standardised materials with the same intended use and purposes. Thus, it is logical to select some representative and commonly used product alternatives and investigate the parameters that are examined and included in their DoPs. The directness of this approach can however lead to unintended omittances and thus it is important to generalise a bit more. Consequently, apart from the DoPs of specific products that were taken into consideration later, some relatable harmonised standards were firstly studied. The general reference standard that was taken into consideration for this purpose is Eurocode 6, which accounts for the design of masonry walls. An overview table regarding the standards that have been selected as references and the relatable characteristics to the hempcrete blocks which were used as the selection factor can be seen in Table 3.2.

Intended use	Purpose
External facade	Non load bearing
	Thermal Insulation
	Fire resistance
	Fire reaction
	Acoustic Insulation
	Supporting of wall decoration/appliances
	Air-tightness
	Water tightness
	Resistance to insects and pests
	Resistance to micro-organisms
	Durability in temperature alterations
	Durability in high humidity conditions
Internal partitioning	Non load bearing
	Thermal mass
	Fire resistance
	Fire reaction
	Acoustic Insulation
	Acoustic Absorbance
	Supporting decoration/appliances
	Durability in high humidity conditions
	Resistance to micro-organisms

Table 3.1: Purposes of each wall system according to the Intended use.

Harmonised Standard	Common characteristic with the hempcrete blocks
NEN-EN-1-1:2006+A1:2013 Eurocode 6 - Masonry	Masonry wall
NEN-EN 12859 Gypsum blocks - Definitions, Requirements and Test Methods	Indoor, unprotected, non-load bearing block made of fire safe material
NEN-EN 771-4+A1 Specification for masonry units - Part 4: Autoclaved aerated concrete masonry units	Porous masonry
NEN-EN 771-2+A1 Specification for masonry units - Part 2: Calcium silicate masonry units	Lime as binder
EAD 040005-00-1201 Factory-made thermal and/or acoustic insulation products made of vegetable or animal fibres	Biobased prefabricated products for thermal and acoustic insulative applications

Table 3.2: Selected standards for referencing and the respective relatable to hempcrete blocks characteristics.

3.1.4. THE PROPERTIES AND THE RELATED PARAMETERS

In order to acquire a more comprehensive view of the properties and parameters that should be tested for a safe application of hempcrete, actual DoPs and certifications of building products were additionally checked. As already stated, hempcrete is not yet standardised and for this reason no DoP was available for the hempcrete blocks. However, the blocks have already acquired an ATG certification, where essential properties of the product have been tested and declared. Thus, exploring the properties that the certification body decided to include was considered important for this study. In addition, as it is described in detail in the following sections of the report, lightweight autoclaved aerated concretes display similar performances with hempcrete and thus can be used in the same applications. For this reason the properties that have been declared in the DoP of an autoclaved aerated concrete product had also been explored. According to the information collected by all the aforementioned documents the essential for hempcrete properties were defined (Table 3.3 and Table 3.4).

Intended use requirement	Performance	Related Parameter	Related Characteristic	Reference Standard **
Wall Integrity	Geometry	Dimensions	Biobased Insulation	EAD 040005-00-1201
Wall Integrity	Geometry	Tolerences	Biobased Insulation	EAD 040005-00-1201
Wall Integrity	Geometry	Plane parallelism of bed faces	Biobased Insulation	EAD 040005-00-1201
Wall Integrity	Geometry	Flatness after one sided wetting	Biobased Insulation	EAD 040005-00-1201
Wall Integrity	Dimensional stability	Percentage of dimensional changes under specified temperature and humidity ($\Delta\epsilon_l$ $\Delta\epsilon_b$, $\Delta\epsilon_d$)	Biobased Insulation	EAD 040005-00-1201
Wall Integrity	Deformation	Percentage of dimensional change in thickness under specified compressive load and temperature conditions ($\Delta\epsilon_d$)	Biobased Insulation	EAD 040005-00-1201
Wall Integrity	Compressive strength	σ_m	Biobased Insulation	EAD 040005-00-1201
Wall Integrity	Tensile strength perpendicular to faces	$\sigma_(mt)$	Biobased Insulation	EAD 040005-00-1201
Wall Integrity	Bending	$\sigma_(mb)$	Biobased Insulation	EAD 040005-00-1201
Wall Integrity	Behavior under point load	Point load at 5 mm deformation	Biobased Insulation	EAD 040005-00-1201
Wall Integrity	Mortar	Bond and Shear strength	Wall Block	NEN 1052
Wall Integrity	Hanging devices	Axial and Transversal resistance of anchored devices	Wall Block	ETAG 001

** Some requirements were present in multiple standards, however due to the biobased nature of the material EAD was mentioned in this table as the most characteristic standard.

Table 3.3: General properties for walls made of blocks.

Intended use requirement	Performance	Related Parameter	Related Characteristic	Reference Standard **
Acoustics	Specific Airflow Resistivity	R_s	Biobased Insulation	EAD 040005-00-1201
Acoustics	Weighted sound Absorption coefficient	α_w	Biobased Insulation	EAD 040005-00-1201
Acoustics	Direct airborne sound insulation	R_w	Biobased Insulation	EAD 040005-00-1201
Biological resistance	Evaluation of action of microorganisms (fungi, bacteria)	• Visual examination (growth percentage) • Changes in mass (Average percentage change) • Changes in other physical properties (Average percentage change)	Biobased Insulation	EAD 040005-00-1201
Durability in moist environments	Moisture movement	• Drying shrinkage coefficient • Moisture expansion coefficient • Total movement coefficient	Biobased Insulation	EAD 040005-00-1201
Fire Safety	Fire reaction	Fire reaction class	Biobased Insulation	EAD 040005-00-1201
Fire Safety	Fire resistance	Fire resistance class	Wall system that can be used for compartmentation	NEN-EN 12859
Hygrothermal Properties	Sorption/ desorption	• Sorption Curve at 23 ^{o}C • Desorption Curve at 23 ^{o}C • Relative Humidity and Moisture content(mass/mass, mass/volume, volume/volume) at 23 ^{o}C and 50% RH (RH in residences)	Porous material	NEN-EN 771-4+A1
Thermal Properties	Thermal Conductivity	λ_d, (23,50), 90/90	Biobased Insulation	EAD 040005-00-1201
Water Vapour Permeability	Water Vapour diffusion resistance	μ	Biobased Insulation	EAD 040005-00-1201
Water Absorption	Water Absorption coefficient	W_s	Biobased Insulation	EAD 040005-00-1201

** Some requirements were present in multiple standards, however due to the biobased nature of the material EAD was mentioned in this table as the most characteristic standard.

Table 3.4: Required properties for the intended use of the hempcrete blocks.

3.2. SUB-QUESTION 2: THE CURRENT RESTRAINTS

3.2.1. RELATED FINDINGS AND CONCLUSIONS FROM THE INTERVIEWS

- The mapping of the current difficulties and issues that can be faced in the Netherlands when hempcrete is used in the construction of residences.

Hempcrete is not yet standardised in Europe. The lack of such standardisation hinders the creation of an ETA which can be used as a reference for the composition of DoPs for hempcrete products and the acquisition of a CE trading mark. In order to cope with that absence of standards, the biggest producer of hempcrete blocks currently in Europe has used an ATG certification as an alternative. This type of certification takes into account current European standards according to the characteristics of hempcrete and defines its essential properties by making use of European standardised test methods. It is a step towards the standardisation of the material as it is based on the directions that an ETA for hempcrete products is expected to include once it is completed. However, the CE mark can be acquired only if an ETA exists. The latter creates some frustration to customers, which after some discussion can be overcome. In general, this absence of CE has not been a reason for ISOHemp blocks to not be accepted from contractors or customers for the scale of projects - individual houses and mainly apartment buildings - that the company works on. Besides, a CE mark is obligatory only if a relevant to the product norms exist. Nevertheless, such a lack is expected to be an issue if hempcrete blocks are considered to be applied in bigger projects such as industrialised or governmental buildings. For this reason, actions are taken within the industry to accelerate the process of acquiring standards for hempcrete.

This absence of standardisation restraints the propagation of hempcrete's use in the Netherlands only to an extent. Other actions are also required for a real incorporation of the material into the Dutch building market. Regulation may alleviate some risks, nevertheless the biased idea that biobased materials always lack of performances in terms of degradation and fire safety is currently a barrier. Indeed this is the case for hempcrete which is not sensitive to fire nor to degradation from biogenic factors as microorganisms, insects and pests due to the presence of lime but is regarded as so according to the interviewees. In addition, a current lack of environmental consciousness is also an important barrier, as better environmental performances sometimes fail to adequately compensate for any additional costs related to biobased materials. Providing knowledge and stimulation for their use by the development of an environmental regulation, which can reveal the difficulties of industrialised materials to cope with environmental requirements is a step towards the elimination of these barriers and the increase of hempcrete's use. This is indeed the case in France, where hempcrete is not yet systematically used in building constructions, even though relevant regulation already exists from 2012. However, the incorporation of the environmental performances of the material in the newest version of the regulation issued in 2020, is expected to encourage its use. In the Netherlands, environmental requirements already exist in the building Decree, however the presence of biobased materials is the NMD (National milieu database) is still limited. Regarding hempcrete blocks, at least one producer will be introduced in the database soon. That will enable the to include hempcrete blocks in the sustainability certifications of buildings as BREEAM.

Besides, according to the interviewees the existing literature and research provide already information about the characteristics of the material, its properties and the way according to which it should be applied in buildings. These studies can be used as references to cover the lack of standardisation. Furthermore, buildings outside the Netherlands which are made of hempcrete, already exist for some decades and indicate that hempcrete is a reliable material. Nevertheless, even though hempcrete has been applied in neighbouring countries of the Netherlands, which are characterised by similar climates, some differences with the Dutch climate still exist. In addition, there is still some research to be done on how water and moisture accumulation inside the material affects its long term performances. Although the existence of hempcrete buildings that have been constructed decades ago gives an insight on how the material performs in long terms, still there is not a complete scientific point of view regarding this aspect.

Hempcrete is more expensive than conventional building materials. The latter can influence significantly the choice of selecting it for building applications. The current lack of suppliers has an impact on the price of the product, which can be further increased due to additional transportation costs. The production of hemp in amounts able to cover the building industry demand is also essential in order to improve hempcrete's affordability and avoid risks related to possible delays of projects. According to literature, the Netherlands has a relatively modest scale of hemp production which accounts for 10% of the total production in the European Union and makes it the second country in Europe after France which in 2019 produced 70% of the total EU production [7]. Nevertheless, hemp is beneficial for other applications besides construction, thus only a proportion of that 10% can be used for hempcrete. In more detail, 1,877 ha of planted hemp were tracked in the Netherlands in 2019, of which 69% existed in Groningen and 19% in Drenthe [8]. As it can be easily understood by these numbers, the vast majority of hemp production takes place almost exclusively in the northeastern part of the country. This accumulation of hempcrete's raw material production doesn't only affects the costs but also the environmental impact of the material.

Hemp producers in the Netherlands are hesitant to increase the current hemp cultivation without a proven demand by the industry. Contractors on the other hand are hesitant to construct with hempcrete due to the absence of a constant flow supply. The latter vicious cycle could be solved if hempcrete could be supplied from producers from other countries, since motivation could be given to both the aforementioned parties. The current Dutch regulation however restricts the supply of building materials from other countries in the Netherlands. Building products are required to be tested according to the Dutch standards (NEN standards) in order to be admitted in the National Environmental Database (NMD) and be allowed to be used in big building projects, even though the products are already tested according to European standards. Additional testing costs and delays can demotivate producers to import the product in the Netherlands. Alternative methods of testing the material are allowed by the regulation if a contractor wants to use a material that is not tested according to the Dutch standards. However, these alternative testing methods can differ per case and may not guarantee the acquisition of a building permit.

However during the interview, the ambition to increase its distributors in the Netherlands has been expressed by ISOHemp. The current distributors of ISOHemp blocks in the Netherlands are mainly sellers specialised in ecological building materials, however increasing the availability of the blocks in traditional building material shops is currently a goal. As a means to achieve this goal, a collaboration between ISOHemp and BIA Beton [9], a Dutch concrete block production company with distributors around the Netherlands has started. To cope with the demand, ISOHemp opened in September 2021 its new factory (currently the biggest in Europe) and increased the hempcrete block production from one to five million per year.

During the past years, the environmental consciousness in the building industry has seen a rise and as a result the demand in biobased materials has been increased. However, the biobased construction in the Netherlands only account for a relatively small percentage (2%-5%). From this projects only a small percentage accounts for hempcrete constructions, which mainly refers to individual houses. According to an interviewee, the Netherlands still lacks behind in this aspect in comparison to the its neighbouring countries. Among others, the latter is also connected to the historical development of construction in the Netherlands. The high presence of clay in the rivers led to masonry driven construction methods which jostled biobased materials from the traditional architecture and construction mindset.

An advance order is frequently required for biobased materials in order to avoid projects' delays. The required time needed between the place of the order and the acquisition of the material can vary. ISOHemp has prepared stocks to make delivery within one week possible and in general the amount of the stocks is sufficient to cope with the current demand. Nevertheless, the production progress of hempcrete blocks takes 12 weeks in total, due to the time needed for the blocks to acquire their final strength, as a result it takes 14 weeks to prepare an order for a project in case of a stock shortage.

Contractors are hesitant to work with materials that they do not know sometimes even when the client insist on them, as a result the absence of trained hempcrete contractors can be a barrier to the propagation of hempcrete's use in the Netherlands. In addition, the absence of standardisation and CE marking is sometimes used as an argument to avoid working with an unfamiliar material. Studies performed in France showed that when hempcrete is applied externally some frustration about the correct way of application can arise to the constructors. This frustration may lead to the the creation of sensitive parts on the facade, which can be prone to rain infiltration. The current French hempcrete regulation which includes not only performance requirements but also acceptable composition mixtures, decreases the risks however following training lessons for how to apply hempcrete and getting a validation of participation is also requested with the aim to avoid such effects of inadequate application. Using hempcrete in the form of blocks can nevertheless decrease some risks. A certification of a prefabricated product can more easily be obtained. In addition, contractors are already familiarised with the process of constructing masonry walls. As a result, learning how to work with hempcrete blocks is not a demanding procedure. According to ISOHemp producers, it takes a half day lesson to provide information on the contractors on how to use hempcrete blocks adequately. According to another interviewee, positive reactions from contractors arose when the benefits of hempcrete are properly explained.

In order to sufficiently map the current barriers for hempcrete's use in the Netherlands, it is important to include the experience gained by the the renovation of the municipality building in Voorst, which is currently the largest hempcrete project in the Netherlands. For this project, handmade hempcrete was used for the construction of the facade. Hempcrete's high sustainability score was the reason behind architects' decision to use it on the building's facade. Its moisture buffering capacity was also considered as a plus but due to the use of the building (office building), it was concluded that it could not have an important impact on the indoor environment eventually. In more detail, the Dutch building regulations sets high ventilation requirements for office buildings and as a result indoor air temperature and RH are not expected to be influenced by the slow hygrothermal procedures of hempcrete. For the aforementioned reason, the dynamic hygrothermal performances of hempcrete were not included in the study. The building physics studies were based on the existing literature and the experience of the building physics engineer. During those studies, no particular difficulties related to the use of hempcrete were encountered and existing literature was sufficient to provide information. No simulations regarding the material and the indoor environment were required. The additional requirements related to hempcrete which were imposed by the local authorities were limited to the construction of a mock up, which could provide information on the properties, its correct casting process and the image of the hand made hempcrete which would constitute the facade. Part of the mock up was transported to the lab where measurements of its thermal performance on two different conditions, namely in completely dried state and laboratory conditions were taken. The laboratory conditions results were used for the calculation of the thermal performances of the facade. The material related issues were limited to some shrinking on the facade handmade hempcrete.

The client (namely the municipality), has played a crucial role for the selection of the material in this case. It prescribed high requirements for sustainability and was willing to financially invest more for their achievement. In addition, this ambition towards a high sustainability score was enough for the client in order to compensate for the fact that the material had not yet been used in such scale in the Netherlands. In more detail, the concept of hempcrete design is so new in the Netherlands that the material is not really considered or proposed as an option for the construction of walls and only the possibility of using hemp-lime plaster as a finish of the walls can however sometimes arise in discussions. For the building physics project leader, it was the first time to participate in a hempcrete project. However, environmental consciousness gradually increases in the Dutch market and clients think about biobased options.

It can be concluded from the aforementioned that the issues or additional requirements that appeared during the project were associated with the hand-made form of the material. The properties of prefabricated blocks are defined and monitored during production so no additional research for mock-ups is needed. In addition, the mechanical projection allows to produce an homogenised material with expected performances. For the aforementioned reasons, prefabricated forms of hempcrete gain space into the industry.

The fact that the Dutch regulation does not take into account the hygrothermal properties of the materials but only focuses on the definition of the thermal resistance of the facade (Rc) is not optimum as it fails to adequately reveal one of the greatest benefits of hempcrete and other biobased materials. Four out of five interviewees mentioned the absence of this aspect from current regulations and commented on the benefit that such implementation could have to the promotion of hempcrete's use. The current regulation for the determination of the energy and thermal performances of building in the Netherlands is only based on static calculation methods. It does not take into account aspects as the moisture buffering capacity and the specific heat capacity of the material which can however have an influence on the results. If thermal mass is taken into account in calculations buildings with thinner walls (than those defined by the Bouwbesluit according to the static calculation of thermal resistance) are able to meet the energy requirements of the BENG regulation in case of materials as hempcrete that incorporate such aspects. The latter can be beneficial in terms of environmental and financial costs.

Currently there is a high lobby towards the assessment of the environmental performances of industrialised materials as concrete and steel as a means to sustain their dominance into the market. Studies on circularity and re-use potential of these materials reveal gradually new knowledge which reinforces their position into the Dutch building industry. However, the same lobby does not apply to biobased materials such as hempcrete, which only account for a small proportion of the market, even though by nature biobased options can be more beneficial for the environment due to their capabilities of greenhouse gas absorption and environmentally safe end-life deposition. The new knowledge on the environmental performances of dominant industrialised materials allows the implementation of various industrialised products with lower environmental footprints (MKI -Milieu Kosten indicator) in the Dutch environmental database (Nationale Milieu Database). On the other hand, the biobased options in NMD remain limited while their environmental performances are not yet in depth explored to reveal their true potential. Nevertheless, the University of Wageningen currently works on the preparation of category 1 product cards for the National Environmental Database (NMD) for a whole range of biobased building materials, which will also appropriately include biogenic carbon storage and end-of-life scenarios. The project is planned to finish until the end of the summer of 2023 [10].

According to ISOHemp, clients' first questions on the hempcrete blocks focus on fire and water degradation risks. The price of the material is also an aspect that is frequently discussed as clients tend to think that biobased materials are expensive. Information on the thermal insulation value is also requested afterwards. Contractors find it difficult to make this transition from conventional to biobased material since they generally lack of knowledge on how to use biobased materials. As a result it is important for them to understand which is the optimum place for ISOHemp blocks and which of the conventional building materials can be effectively replaced by the blocks.

3.3. SUB-QUESTION 3: THE PERFORMANCES ASSESSMENT

3.3.1. RELATED FINDINGS AND CONCLUSIONS FROM THE INTERVIEWS

- *The assessment of the performances of hempcrete in comparison to conventional design options in the aspects of indoor comfort, energy efficiency and sustainability in residences in the Netherlands.*

Compared to regular building materials hempcrete has a low thermal conductivity that can vary from 0.065 to 0.14 W/(mK)depending on the composition of the mixture. Due to its porosity, it exhibits some interesting hygrothermal properties which make it an effective moisture buffering material capable of regulating indoor moisture and relative humidity, which is not the case for the majority of conventional materials. This aspect can enhance indoor comfort and limit energy consumption in buildings. Especially when hempcrete application is coupled with sensitive relative humidity ventilation the energy consumption of the building can be decreased even more. However, covering the thermal requirements of modern regulations may result to thick walls, which can decrease the net surface of the building. In order to decrease the required wall thickness additional insulation means may be needed. The scientific society currently aims to define such means.

Although hempcrete has a good thermal insulation capability, its thermal conductivity value is still higher than these of lightweight insulation products. In addition, as it has been already mentioned it can not be used for load bearing applications as other kinds of masonry materials. Improving these aspects can be quite beneficial for the promotion of hempcrete's use. As a result, increasing the mechanical and thermal insulating performances of the material were the main ambitions that led to the definition of mixtures used for the production of ISOHemp blocks. Currently the company's R&D team focuses on the development of loadbearing blocks and blocks with a λ value less than 0.065 W/(mK). To achieve such mixtures, the influence of higher amounts of lime and alternative fibres (e.g. flax fibres) is explored.

In addition, hempcrete has a significantly lower environmental impact in comparison to other conventional building materials. If the cultivation of hemp is done locally, extra benefits can arise, as the costs and environmental footprint related to transportation can be decreased and new occupational opportunities can be created. Regarding the mixture, the type and amount of binder can influence remarkably the environmental impact of hempcrete blocks. More sustainable mixture solutions do not include cement and only make use of lime, which has the ability to sequester CO_2 via carbonisation. Decreasing the amount of lime leads also to the decrease of this sequestration capacity. Thus, ISOHemp focused in other means to further lower the environmental impact of the material. Such means was the limitation of hydraulic lime into the mixture by replacing a proportion by hydrated lime, which is a more environmental friendly option. However, hydrated lime has lower strengths than hydraulic lime, so only a fraction of the later can be replaced. As an additional means, ISOHemp introduced the possibility to produce blocks by making use only of rainwater in its new factory. Wastewater from the production process is cleaned and used again. Furthermore, blocks that do not meet the requirements during the quality control are crashed and the material is reintroduced in the production process.

According to an interviewee, it is important to also consider the social and environmental benefits of hempcrete that are not part of any current regulation. Hempcrete also has advantages in terms of biodiversity and soil regulation. It has the ability to regenerate soils that have been heavily burdened by pesticides within 3 years. It does not require high amounts of water and does not need pesticides to grow, which account for the two most important current environmental challenges.

3.3.2. IMPORTANT FEATURES OF HEMPCRETE

According to the literature and the interview findings hempcrete's leading qualities are its moisture regulative capacity and its remarkably low environmental impact. These qualities should be enhanced or at least sustained when it is used in building applications. Literature and existing buildings with hempcrete walls in neighboring countries of the Netherlands indicate that hempcrete is a reliable material, beneficial for the indoor comfort and the energy efficiency of the buildings and thus create motivation for the increase of its use in the Netherlands. Nevertheless, there are still some differences between the Dutch climate and that of the neighboring countries, so it is important to assess the performances of hempcrete in the Dutch climate conditions.

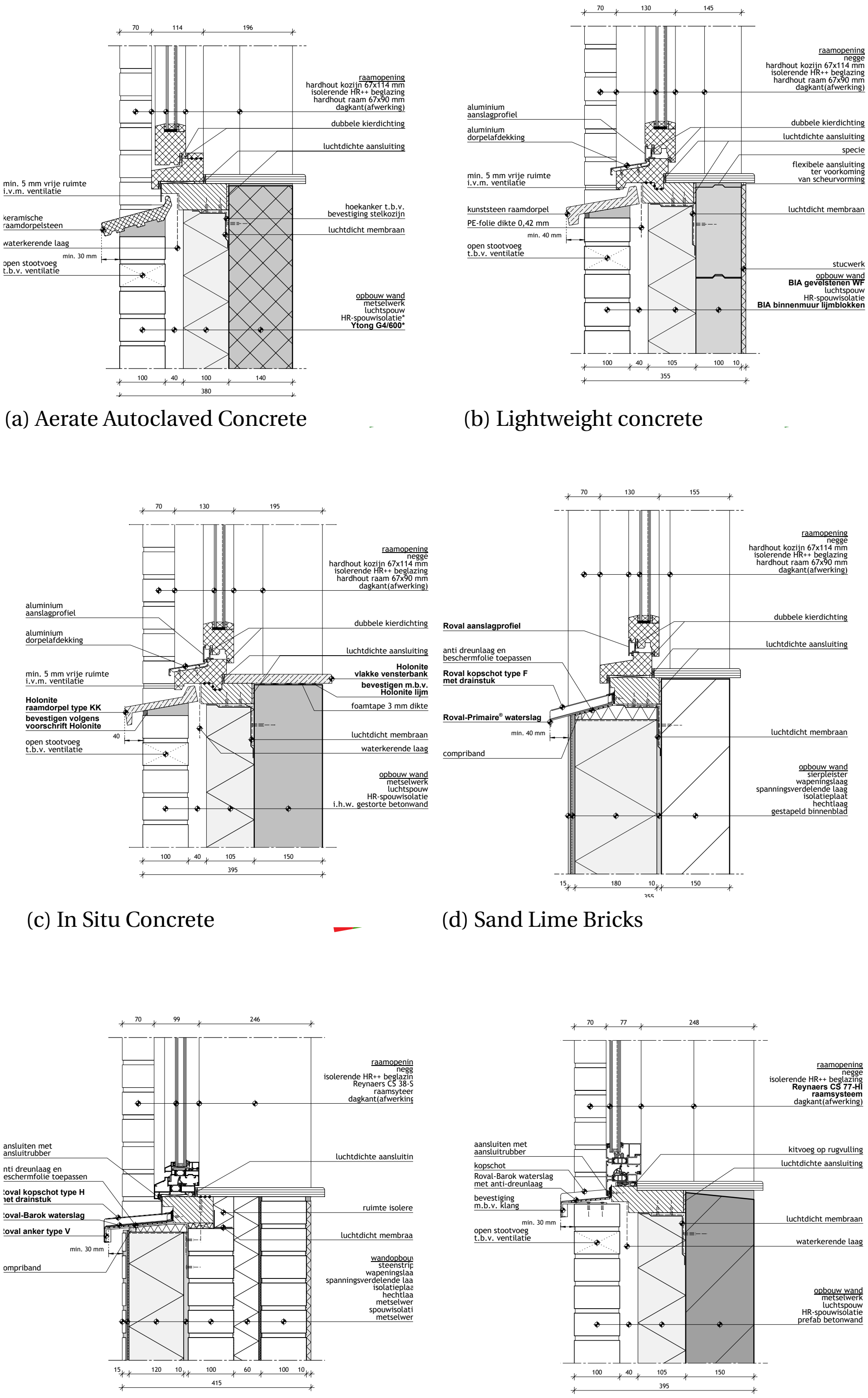
The biggest current restraints for hempcrete are the current regulation, the negative idea about biobased materials' durability and reliance regarding the aspects of fire safety, biogenic degradation and water/moisture accumulation and the increased initial costs. The current study will provide information and assess the barriers related to the material itself, so namely those of hempcrete's reliance, durability and costs.

The literature review, the interviews and the product certification of hempcrete blocks show that hempcrete is a fire safe material that can reach the reaction class B -si,d0 according to EN 13823.

3.3.3. THE SELECTION OF THE SUBSTITUTE MATERIAL

An efficient way to quantify the level of advantageousness or the deficiencies of a product is to compare its performances to those of a substitute one. The selection of a suitable substitute product is a complex procedure that requires consideration since an arbitrary selection may result to an unfair comparison and mistakenly drawn conclusions. In order to be comparable with each other the materials must exhibit similar characteristics, have defined boundaries and be compared according to the same factors .

One of the system boundaries was the place of application. Construction materials that have been taken into consideration for the selection are materials that are currently used in building applications in the Netherlands. For this purpose, frequent external wall detailing sections had been collected. An overview of those can be seen in Figure 3.1. Another important factor for the selection was to include materials that display some similar to hempcrete characteristics. Thus, it was decided to consider only materials that constitute masonry constructions, namely those that can be produced in the form of bricks or blocks. Then, the main design targets had been addressed, and some key aspects in which the substitute materials should be able to perform well were defined. Eventually the required key aspects have been determined to be:



(a) Aerate Autoclaved Concrete

(b) Lightweight concrete

(c) In Situ Concrete

(d) Sand Lime Bricks

(e) Clay Bricks

(f) Prefab Concrete

Figure 3.1: Common wall constructions in the Netherlands [11].

1. Sufficient Thermal Mass
2. High Acoustic Performances
3. Moisture regulation
4. Sustainability
5. Limited costs

After assessing the aforementioned aspects on the available construction materials the options for an appropriate selection were narrowed down to three materials and two designing options:

- **Option 1:** Autoclaved Aerated Concrete (*Cellenbeton* in Dutch)
- **Option 2:** Calcium Silicate Bricks (*a.k.a.* Sand lime bricks - *Kalkzandsteen* in Dutch)

The properties of low density autoclaved aerated concrete (AAC) blocks approximate remarkably those of hemp-crete. AAC blocks are known for their moisture regulative properties, good acoustical performances and high fire resistance. Low density AAC (400 kg/m3) have a compressive strength comparable to that of hempcrete, and thus just as hempcrete, are considered as a non load bearing infilling material. In addition, AAC blocks with the aforementioned densities display thermal conductivities commensurate to those of hempcrete. According to the aforementioned, hempcrete blocks can be considered as an equivalent alternative that can be used in the exact same applications as the already established AAC blocks. The latter can allow a direct and fair comparison between the two different materials. However, even though AAC blocks are regularly used in constructions in the Netherlands, the frequency of their application is significantly lower compared to that of the sand lime bricks.

When it comes to masonry constructions, sand lime bricks account for the most popular option in the Netherlands. Sand lime bricks display high mechanical strength and cost efficiency. They can be load-bearing and in this manner abolish the need of a structural frame. The latter is often a desirable aspect of which hempcrete lacks. In addition, sand lime bricks are fire resistant, acoustic insulating and moisture regulating. They can contribute to the establishment of indoor comfort due to the thermal mass that characterises them. However, the high thermal conductivity values that they exhibit make them inappropriate for thermal insulating applications. Thus, when sand lime bricks are used in exterior walls in the Netherlands, a thermal insulation is always required.

At first glance, selecting a material as AAC that exhibits analogous performances, limitations and application characteristics as hempcrete may seem as a more appropriate option to make a fair comparison. Besides, hempcrete is regarded as an infilling option only in non load-bearing applications. Hence, in cases where structural frames are preferred to be avoided it is not competent to sand lime bricks. The conclusions on the performances of hempcrete regarding important building aspects can be directly derived and understood when it is compared to AAC as they can be based in numerical results and will not be affected by more complex parameters derived from any requirements related to great application differences. Making such comparison is crucial to provide an insight on the advantages and disadvantages of using the biobased and unstandardised hempcrete instead of its equivalent industrialised and standardised alternative. However, the results of such study can be related to only a small proportion of the building constructions in the Netherlands. They cannot account for a great stimulus for the developers, as buildings made of sand lime bricks seem to currently be the biggest competitor of hempcrete. Nevertheless, a comparison of hempcrete constructions with sand lime cannot be as straight forward due to the considerable application differences. The different thermal and mechanical properties of the materials are expected to lead to constructions with advantages and disadvantages in different aspects. As a result, in that case the comparison between the options and their assessment will be considerably influenced by the case study requirements.

To conclude, both comparisons bring different features to the study. A hempcrete-AAC comparison is not highly influenced by the application and case study related requirements and provides more straight forward conclusions regarding hempcrete's performances. On the other hand, a hempcrete - Sand lime comparison, creates a stronger stimulus for the developers but can be highly influenced by the case study and design requirements. As a result, both comparisons will be part of the current graduation project.

3.3.4. THE PROPERTIES OF THE SUBSTITUTE MATERIALS

Aerated Autoclaved concrete

Aerated concrete is a relatively homogeneous material which is classified as a lightweight concrete. Depending on its density and strength can be a load bearing or non -load bearing material. It has a district cellular structure, consisting of disconnected air voids and and microscopic pores with entrapped air. Its properties are highly depended on its microstructure and composition. Aspects as the type of binder, the pore formation and curing can lead to significant variations in it proprieties. Depending on the method of curing, aerated concrete can be either autoclaved or non-autoclaved. Aerated autoclaved concrete consists of sand, cement, lime, fly-ash, gypsum, aluminium powder paste, water and an expansion agent [12],[13]. Its density can vary from 250-1800 kg/m^3 [14].The chemical response of the aluminium paste creates the remarkable porosity of the material. The production of AAC does not require any combustion and thus does not result to the pollution of air [14].

3

The decreased density and the fact that they do not contain any course aggregate results at the reduction of self weigh and dead loads which can lead to the reduction of structural elements. Studies have shown that this decrease in weight can reduce the value of production of structural materials up to 20% [15]. After production, the finished AAC product has an air content of 70% - 80% and a volume of up to 5 times of the volume of the raw materials used. That makes it a very resourceful efficient material [13],[15]. In addition, due to their low weight AAC blocks can accelerate and facilitate the construction process since buildings with AAC blocks require less formwork and propping in construction. Regarding its production, the use of fly ash reduces the need for cement intake and thus the green house gas emissions [15].

As in the case of conventional concrete, the porosity and the pore size distribution influence highly the strength, permeability, diffusivity, creep and shrinkage of the AAC products. Depending on the production method followed (foaming or gas method), the porosity of the end product can vary a lot. Reducing the density by the formation of macropores decreases the compressive strength of the AAC (Table 3.5) For high densities (1200 kg/m^3) the compressive strength of autoclaved aerated concrete can even reach to 14 MPa [16]. In general, the compressive strength has been found to increase linearly with density [12]. Density has a great influence on the thermal conductivity of the material too. In addition, as it is a porous material, the thermal conductivity of AAC is also highly dependent on water content and the changes due to the ambient conditions [17]. The water vapor permeability coefficient alters in relation to relative humidity. In more detail, studies have shown that the water vapor permeability coefficient for high relative humidity can account for more than five times the respective value in low relative humidity conditions [18]. Studies have focused on predicting and modeling the thermal conductivity of AAC in relation to porosity and moisture content (Figure 3.2). Some have proved that the thermal conductivity in dry state conditions can be six times less compared to that measured in increased moisture [18]. Ambient temperature can also influence the thermal conductivity of AAC, however this influence is quite lower compared to that of moisture content[18]. The material is characterised by a high moisture buffering capacity and according to studies exhibits a moisture buffering value (MBV) which approximates 1 g/m^2..%RH [19],[20].

Dry density (kg/m3)	Compressive strength (MPa)	Static modulus of elasticity (kN/mm^2)	Thermal conductivity (W/m°C)
400	1.3–2.8	0.18–1.17	0.07–0.11
500	2.0–4.4	1.24–1.84	0.08–0.13
600	2.8–6.3	1.76–2.64	0.11–0.17
700	3.9–8.5	2.42–3.58	0.13–0.21

Table 3.5: Properties of autoclaved aerated concretes [12].

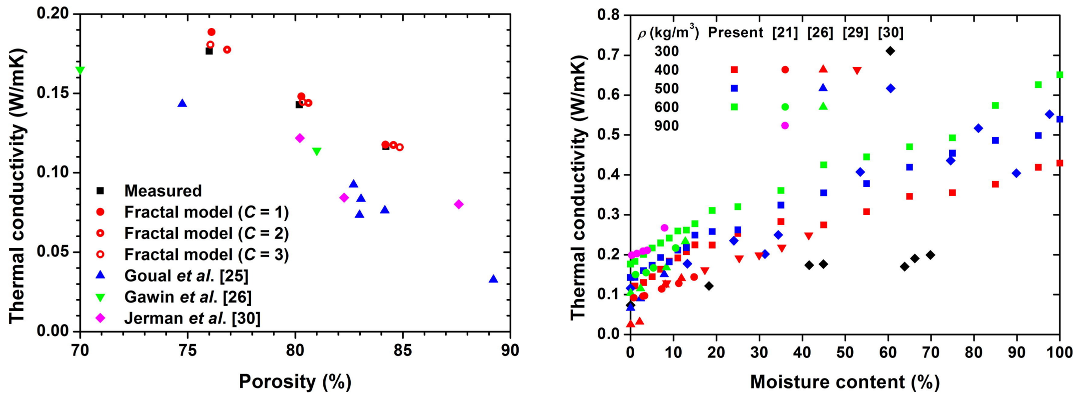


Figure 3.2: Thermal Conductivity of AAC in dry state (Left) and different moisture contents (Right) [17].

Drying shrinkage is an important aspect in aerated concretes. The high total porosity (40-80%) and specific surface of their pores (≈ 30 m^2/g) results in significant dry shrinkage. However, aerated concretes that incorporate lime, the drying shrinkage has been reported to be lower that in aerated concretes produced only with cement. Autoclaving can also reduce shrinkage. Autoclaved products have been found to exhibit reduced shrinkage values accounting for 25% or even 20% of those of the respective air-cured products[12]. Water absorption and capillarity are also important aspects for aerated concretes. In dry state, when the pores are empty, water vapour diffusion is the dominant moisture transport mechanism. On the contrary, in case of contact with water, capillary suction predominates [14]. According to material libraries of some widely used hygrothermal tools as Ubakus and Wufi software, its water vapour resistance factor can take values around the range of 8-10.

The sound absorption coefficient of AAC is in general low, however it can be enhanced with special treatment such as adding high alumina cement during manufacturing. The acoustical qualities of such porous materials as AAC can be affected by the air permeability and open porosity of the product. The incidence absorption coefficient of commercial samples with different densities made of the three most common types of AAC in relation to porosity and pores' interconnection is depicted in Table 3.6. As the density of the material increases, the coefficient of the air permeability decreases. The AACs with lowest densities display higher transmittance of sound and higher porosity, characterised by pores with thin walls and lower volumes of open pores [21].

Type of AAC	Gas cement concrete				Gas cement concrete with combine binder				Foam cement concrete			
Density (kg/m^3)	250	300	400	500	250	300	400	500	250	300	400	500
Total porosity (%)	91.5	89.4	85.9	82.3	91.1	89.3	85.7	82.1	91.5	89.4	85.9	82.3
Proportion of interconnected pores (%)	30.3	31.8	33.7	36.0	35.3	38.0	40.5	41.5	26.1	27.5	29.7	31.8
Ratio of connected pores volume to total pores volume (%)	33.1	35.6	39.2	43.7	38.8	42.6	47.3	50.6	28.5	30.8	34.6	38.6
Mean normal incidence absorption coefficient	0.35	0.28	0.25	0.15	0.36	0.31	0.27	0.21	0.24	0.22	0.15	0.12

Table 3.6: Acoustic and porosity related properties of autoclaved aerated concretes [21].

Changes in temperature and moisture content of porous materials provoke length and volume alterations that cause failures such as cracking of finishes and spalling after the completion of repetitive climate cycles. That is indeed the case also for AAC. AAC can be susceptible to freeze thaw in high saturation degrees, since then the material becomes brittle and cracks. For repetitive 50 repetitive cycles of 8 h freezing and thawing of 8 h at respectively 15 °C and 20 °C, commercial AAC samples with different compressive strengths(1.8-4 MPa) and bulk density (350-500 kg m^{-3}) showed different levels of degradation [18], [22].

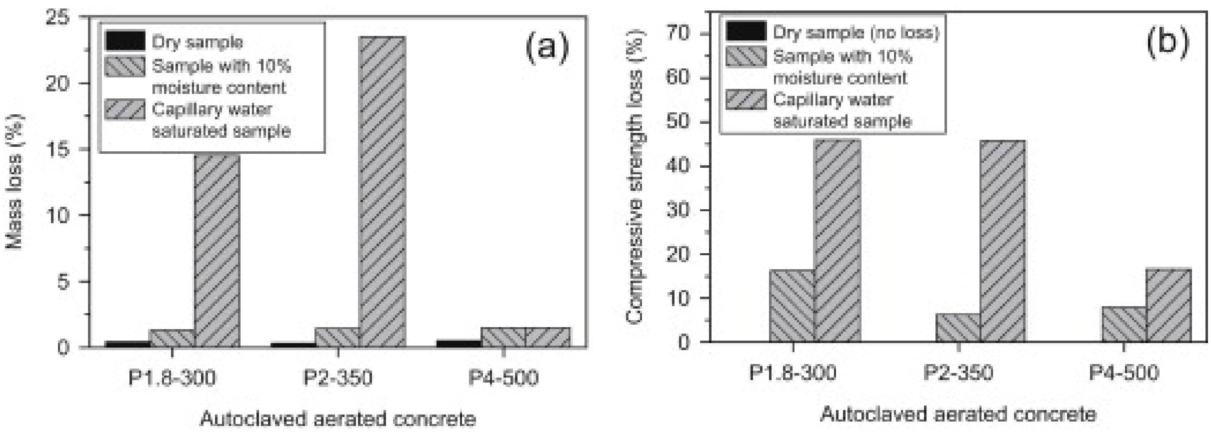


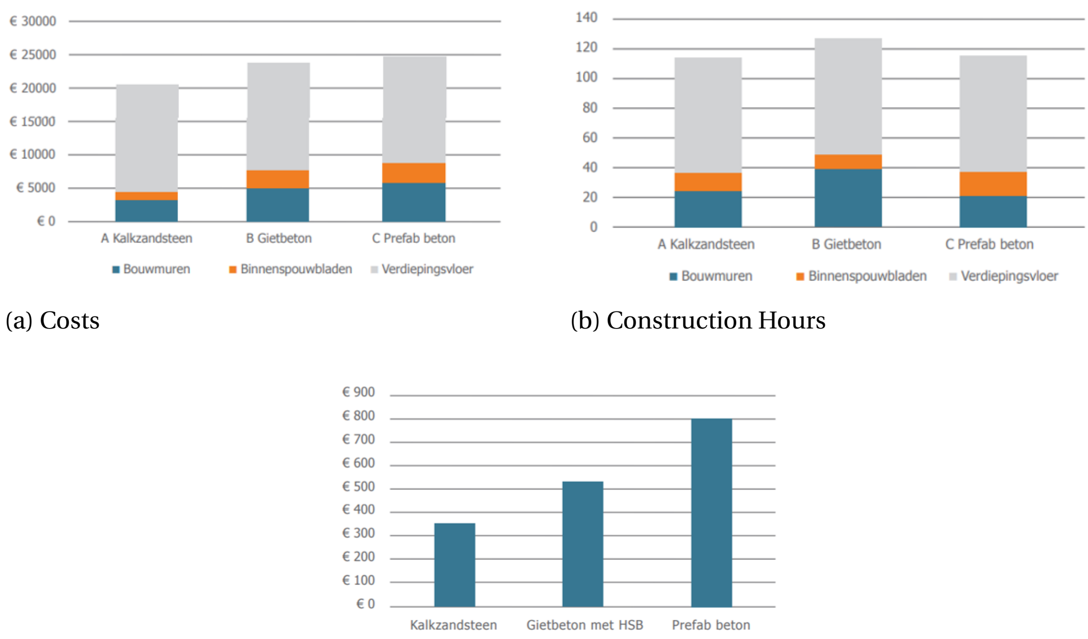
Figure 3.3: Degradation of AAC in 50 repetitive freeze thaw cycles [18]

Sand lime bricks

Calcium silicate bricks or sand lime bricks consist of approximately 90% of silica sand, hydrated lime, crushed flint, colouring substances and water [23]. They are durable and resistant to biological degradation and thus contribute to the creation of healthy internal environments. In addition, they reach high levels of compressive strength which makes them ideal for load-bearing masonry. In the Netherlands, sand lime bricks are commonly used, a typical application is the construction of the inner load bearing leaf of cavity walls in Dutch buildings.

They exhibit high compressive strength, high acoustic insulation and good thermal performances. They are fully recyclable and prevent the growth mold and micro-organisms due to their strong alkaline reaction [24]. The compressive strength of standardised calcium silicate bricks can reach 75MPa [25]. Modulus of elasticity values of around 6 GPa, have been found in literature [26]. In comparison to other masonry products they have the least content of radioactive elements [24]. The values of some important parameters of calcium silicate bricks can be seen in relation to the density in Table 3.7. Sand lime bricks that can be found in the market constitute walls with Rw values that can vary from 40 dB to 60 dB depending on the wall thickness (67-300 mm) [27],[28]. Their acoustic absorption coefficient α has been measured to be 0.03 for frequencies between 500 and 1000 Hz [27].

Studies in the Netherlands have shown that buildings made of sand lime bricks account for remarkable lower MPG Values in comparison to buildings made with other structural systems. In the same studies lower costs and construction hours have also been detected Figure 3.4 [29].



(a) Costs

(b) Construction Hours

(c) MPG

Figure 3.4: Costs, construction hours and MPG values, in apartments of different structural systems [29].

Dry density	Thermal conductivity	Emissivity of long wave radiation	Water vapor diffusion resistance factor	Heat capacity
ρ [kg/m^3]	λ [W/(mK)]	ϵ [-]	μ [-]	c [J/(kg×K)]
1200	0.56	0.9	5/10	1000
1400	0.70	0.9	5/10	1000
1600	0.79	0.9	15/25	1000
1800	0.99	0.9	15/25	1000
2000	1.10	0.9	15/25	1000
2200	1.30	0.9	15/25	1000

Table 3.7: Properties of Calcium Silicate Bricks [30].

3.3.5. MATERIAL PROPERTIES - AN OVERVIEW

Some characteristic properties of the materials under scrutiny as collected by the literature review are presented in Table 3.8.

Property	Hempcrete	Autoclaved Aerated Concrete	Sand lime Bricks
General properties			
Density (kg/m^3)	300-600	250-1800	500-2800
Porosity (%)	70% -85%	75% - 85%	~ 30%
Mechanical Properties			
Compressive strength (MPa)	< 1 MPa	1.5 - 14 MPa	5 - 75 MPa
Modulus of elasticity (GPa)	0.07-0.16 GPa	0.18 - 3.58 GPa	~ 6 GPa
Hygrothermal Properties			
Thermal conductivity Dry (W/mK)	0.07 - 0.11	0.07 - 0.21	0.56 - 1.3
Specific Heat Capacity (J/KgK)	1300 - 1600	850 - 1000	850 - 1000
Water Vapour Resistance Factor (-)	2 - 5	8 - 10	10 - 30
Moisture Buffer Value g/m^2..%RH	~ 2.80	~ 1	(-)
Acoustic Properties			
Mean Absorption coefficient (unrendered)	0.27-0.85	0.12-0.35	~ 0.03
Sound reduction index (rendered) (20cm wall)	~ 40 dB	~ 40 dB	~ 50 dB

Table 3.8: Some characteristic properties of Hempcrete, Autoclaved Aerated Concrete and Sand lime bricks .

Bibliography Chapter 3

[1] ISOHemp, *New construction - house and farm - westeremden*, https://www.isohemp.com/en/reference/new-construction-house-and-farm-westeremden, Accessed: 2022-07-26.

[2] ISOHemp, *New construction - modern and ecological housing - sterksel*, https://www.isohemp.com/en/reference/new-construction-modern-and-ecological-housing-sterksel, Accessed: 2022-07-26.

[3] ISOHemp, *Renovation - house and church - westeremden*, https://www.isohemp.com/en/reference/renovation-house-and-church-westeremden, Accessed: 2022-07-26.

[4] ISOHemp, *New build - 10 family houses - chevetogne*, https://www.isohemp.com/en/reference/new-build-10-family-houses-chevetogne, Accessed: 2022-07-26.

[5] ISOHemp, *Interior renovation - lofts - bruxelles*, https://www.isohemp.com/en/reference/interior-renovation-lofts-bruxelles, Accessed: 2022-07-26.

[6] ISOHemp, *Renovation - student housing - anderlecht*, https://www.isohemp.com/en/reference/renovation-student-housing-anderlecht, Accessed: 2022-07-26.

[7] Eurostat, *Hemp production in the eu*, https://ec.europa.eu/info/food-farming-fisheries/plants-and-plant-products/plant-products/hemp_en, Accessed: 2022-07-07.

[8] Marjolein Selten, "An overview of the dutch hemp market," United States Department of Agriculture Foreign Agricultural Service, GAIN Global Agricultural Information Network, Marjolein Selten NL2020-0015, May 15, 2020.

[9] BIA Beton, *Sale hemp blocks by bia beton*, https://www.bia-beton.nl/actueel/verkoop-hennepblokken-door-bia-beton/55, Accessed: 2022-07-26, Mar. 2022.

[10] Wageningen University and research, *Project biobased building materials in the dutch environmental database*, https://www.wur.nl/nl/Onderzoek-Resultaten/Onderzoeksprojecten-LNV/Expertisegebieden/kennisonline/Biobased-Building-materials-in-the-Dutch-Environmental-Database.htm, Accessed: 2022-07-21.

[11] Bouwdetails Online, *Bouwdetails online*, https://bouwdetails.bouwformatie.nl/, Accessed: 2022-06-09.

[12] N. Narayanan and K. Ramamurthy, "Structure and properties of aerated concrete: A review," *Cement and Concrete Composites*, vol. 22, no. 5, pp. 321–329, 2000, ISSN: 0958-9465. DOI: https://doi.org/10.1016/S0958-9465(00)00016-0. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0958946500000160.

3

[13] F. M. Saiyed, A. H. Makwana, J. Pitroda, and C. M. Vyas, "Aerated autoclaved concrete (aac) blocks: Novel material for construction industry," *Int. J. Adv. Res. Eng. Sci. Manag*, vol. 1, no. 2, pp. 21–32, 2014.

[14] E. D. Khanal, A. P. D. A. K. Mishra, and B. Ghimire, "Technical suitability assessment of autoclaved aerated concrete block as alternative building wall construction material; a case of nepal," *Saudi Journal of Civil Engineering*, vol. 4, no. 5, pp. 55–67, 2020.

[15] M. Kalpana and S. Mohith, "Study on autoclaved aerated concrete: Review," *Materials Today: Proceedings*, vol. 22, pp. 894–896, 2020, International Conference on Materials Engineering and Characterization 2019, ISSN: 2214-7853. DOI: https://doi.org/10.1016/j.matpr.2019.11.099. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2214785319337824.

[16] R. Abdul Rahman, A. Fazlizan, N. Asim, and A. Thongtha, "A review on the utilization ofwaste material for autoclaved aerated concrete production†," *Journal of Renewable Materials*, vol. 9, pp. 61–72, Jan. 2021. DOI: 10.32604/jrm.2021.013296.

[17] H.-Q. Jin, X.-L. Yao, L.-W. Fan, X. Xu, and Z.-T. Yu, "Experimental determination and fractal modeling of the effective thermal conductivity of autoclaved aerated concrete: Effects of moisture content," *International Journal of Heat and Mass Transfer*, vol. 92, pp. 589–602, 2016, ISSN: 0017-9310. DOI: https://doi.org/10.1016/j.ijheatmasstransfer.2015.08.103. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0017931015300971.

[18] M. Jerman, M. Keppert, J. Výborný, and R. Černý, "Hygric, thermal and durability properties of autoclaved aerated concrete," *Construction and Building Materials*, vol. 41, pp. 352–359, 2013, ISSN: 0950-0618. DOI: https://doi.org/10.1016/j.conbuildmat.2012.12.036. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0950061812009932.

[19] M. Zhang, M. Qin, and Z. Chen, "Moisture buffer effect and its impact on indoor environment," *Procedia Engineering*, vol. 205, pp. 1123–1129, Dec. 2017. DOI: 10.1016/j.proeng.2017.10.417.

[20] C. Rode, R. Peuhkuri, K. Svennberg, *et al.*, "Moisture buffer value of building materials," *Journal of Astm International*, vol. 4, Jan. 2007. DOI: 10.1520/JAI100369.

[21] A. Laukaitis and B. Fiks, "Acoustical properties of aerated autoclaved concrete," *Applied Acoustics*, vol. 67, no. 3, pp. 284–296, 2006, ISSN: 0003-682X. DOI: https://doi.org/10.1016/j.apacoust.2005.07.003. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0003682X05001015.

[22] A. Chaipanich and P. Chindaprasirt, "9 - the properties and durability of autoclaved aerated concrete masonry blocks," in *Eco-Efficient Masonry Bricks and Blocks*, F. Pacheco-Torgal, P. Lourenço, J. Labrincha, S. Kumar, and P. Chindaprasirt, Eds., Oxford: Woodhead Publishing, 2015, pp. 215–230, ISBN: 978-1-78242-305-8. DOI: https://doi.org/10.1016/B978-1-78242-305-8.00009-7. [Online]. Available: https://www.sciencedirect.com/science/article/pii/B9781782423058000097.

[23] A. Lyons, *Materials for architects and builders*. Routledge, 2014.

[24] R. Dachowski and K. Komisarczyk, "The properties of doped sand-lime products," *E3S Web of Conferences*, vol. 10, p. 00 037, Jan. 2016. DOI: 10.1051/e3sconf/20161000037.

[25] CEN EUROPEAN COMMITTEE FOR STANDARDIZATION, *Nen-en 771-2+a1*, https://connect.nen.nl/standard/openpdf/?artfile=571603&RNR=210517&token=fb567524-6969-47ea-bea4-d29bbc8f4350&type=pdf#pagemode=bookmarks, Accessed: 2022-06-07.

[26] J. Nichols and Y. Totoev, "Experimental determination of the dynamic modulus of elasticity of masonry units," Jan. 1997.

[27] silka, *Brochure les element en silico calcaire*, https://storefrontapi.commerce.xella.com/medias/sys_master/root/hf1/h78/8951315988510/Brochure-les-element-en-silico-calcaire-300422/Brochure-les-element-en-silico-calcaire-300422.pdf, Accessed: 2022-06-09.

[28] Calduran, *Geluidsisolatie*, https://www.calduran.nl/kennisbank/geluid, Accessed: 2022-06-09.

[29] VNK Vereniging Nederlands Kalkzandsteebplatform, *Bouwen? natuurlijk in kalkzandsteen!* https://jimdo-storage.global.ssl.fastly.net/file/9e897fda-48f0-4e1a-b1b7-061d0d2819a3/Brochure%20Bouwen%20Natuurlijk%20in%20kalkzandsteen.pdf, Accessed: 2022-06-09.

[30] Ubakus, *Ubakus: R value calculator*, https://www.ubakus.com/en/r-value-calculator/?, Accessed: 2022-06-07.

3

4

THE RESEARCH INPUT

4.1. THE RESEARCH INPUT AS DEFINED BY THE INTERVIEWS AND THE LITERATURE

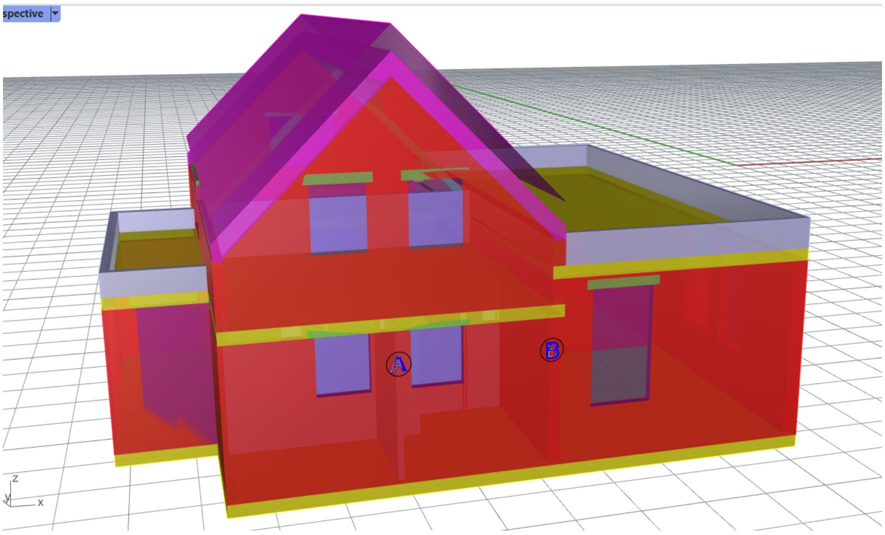
The results of the literature review and the interviews influenced the input of the research and the assessment means according to the following.

Regarding biogenic degradation, the information collected by the existing literature and the interviews indicates that the material is resistant due to the presence of lime. However, hempcrete's performances may decrease when it is inappropriately applied due to long-term water or moisture accumulation. To provide information on this aspect, the long term performances of hempcrete is assessed by simulation means in the most sensitive locations of the case study. These locations can be seen in Figure 4.1. Location A (Detail D1) is regarded as sensitive due to its orientation (North East facade), its position (at the corner of a bathroom) and its configuration (presence of window, infiltration of rain water at the connections with the wall). Non permeable layers such as tiles, may hinder the breathability of the hempcrete wall and as a result may increase the accumulation of moisture. The effect of tiles is assessed in location B (Detail D2). Location C (Detail D3), is regarded as sensitive to rain water infiltration due to its South West orientation, which coincides with the most frequent direction of the wind in the Netherlands and the direct connection of hempcrete with the pitched roof. After running the WUfi 2D simulations, the results for the degradation risks in the five sections depicted in Figures (4.2,4.3)) were assessed. The effect of the driving rain was assessed in Detail D3 (Figure 4.4).

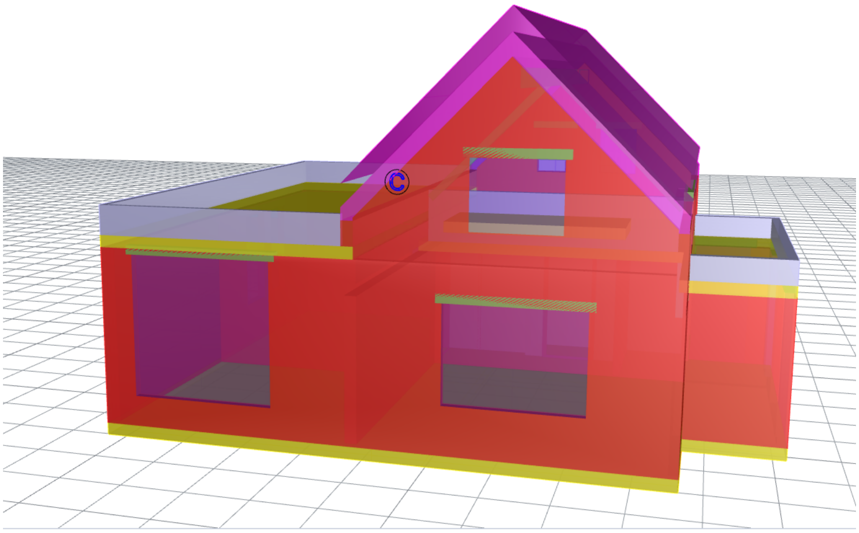
Regarding the costs, hempcrete is relatively expensive in comparison to conventional materials when only the initial costs are taken into consideration. However, it can provide additional value to the building since it is able to increase the indoor comfort conditions which can lead to additional revenue. In addition, the remarkably lower environmental impact of hempcrete can also increase the value of the property in the sense that it provides advantage to hempcrete in projects with high sustainability ambitions. To assess the additional value added to the residence, the levels of the established indoor comfort for the case of hempcrete walls is be compared to those established by conventional wall materials. The difference between the LCA of hempcrete design and those of conventional designs is calculated to assess the level of advantageousness that hempcrete has in projects that require high sustainable solutions.

Long term costs are also expected to be influenced by the application of hempcrete in the case study due to alterations in the energy consumption of the building. A comparison between the energy consumption of the hempcrete and the conventional design options will give an insight on the differences of the long term costs.

4.1.1. THE ASSESSED DETAILS



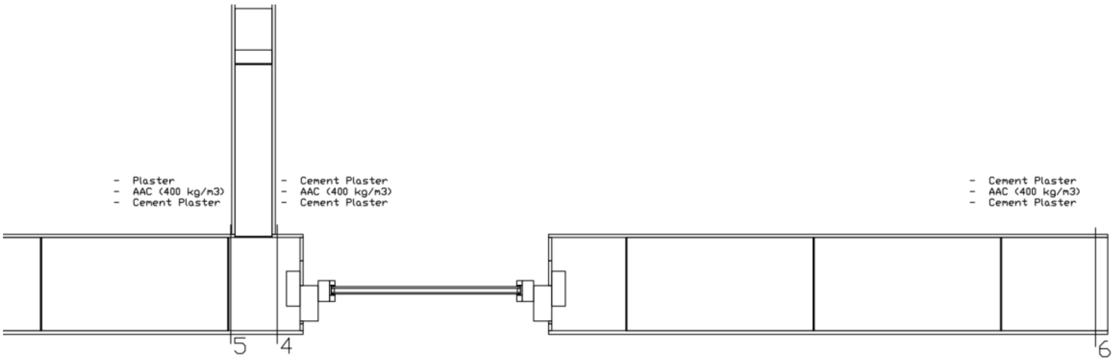
(a) Location of Sections A and B



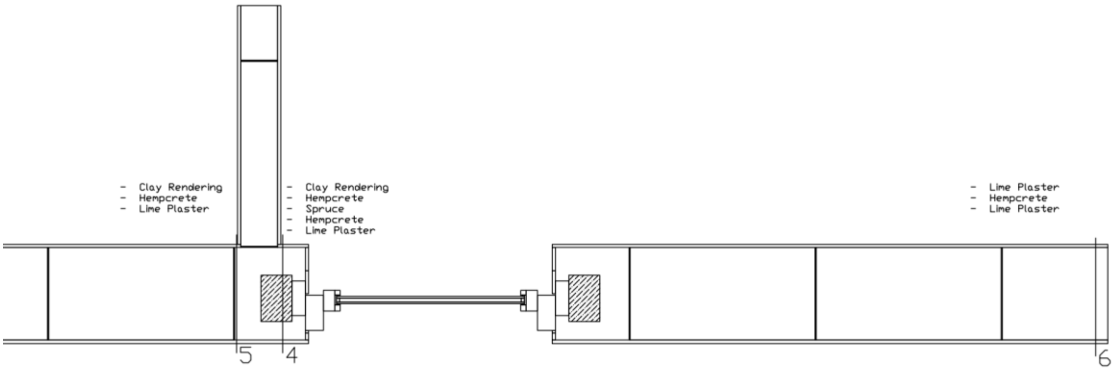
(b) Location of Section C

Figure 4.1: Location of the sensitive sections of the case study which were modelled in WUFI 2D.

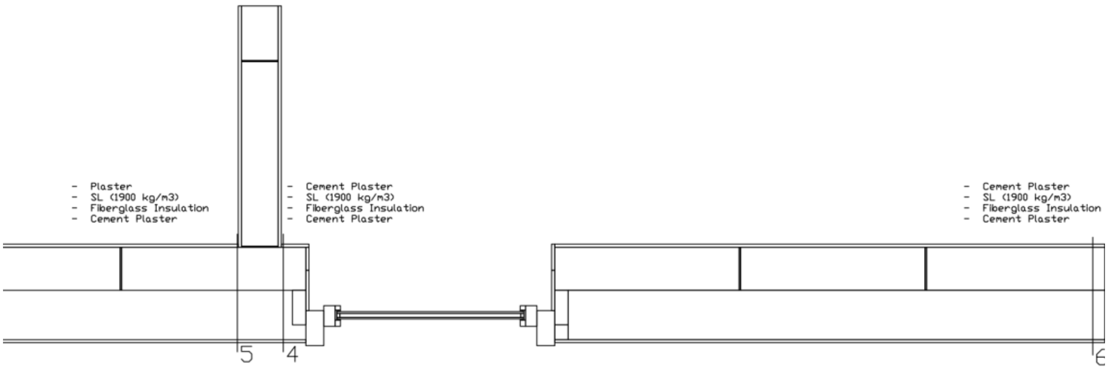
4



D1-AAC

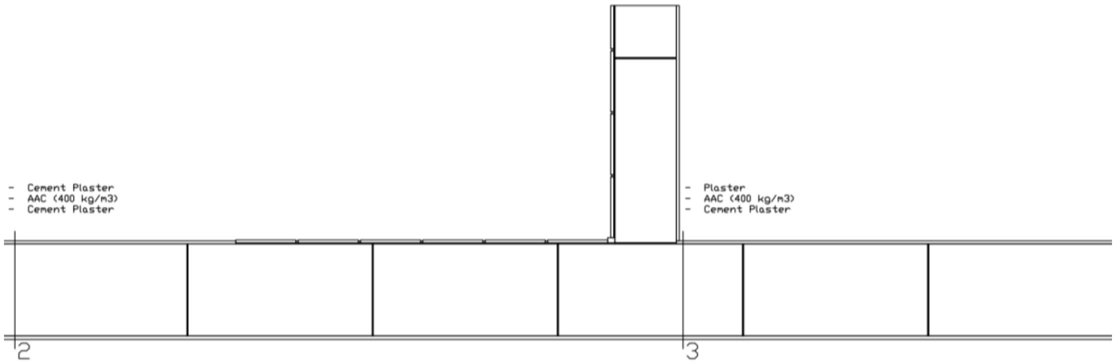


D1-Hempcrete

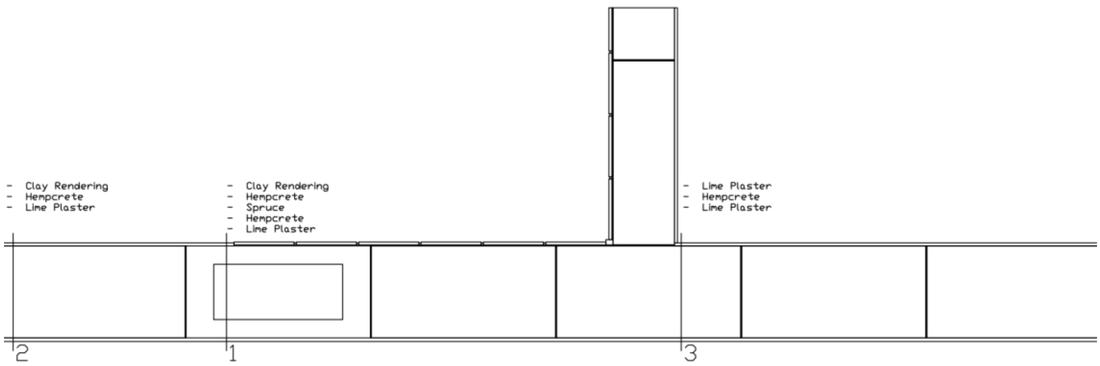


D1-SL

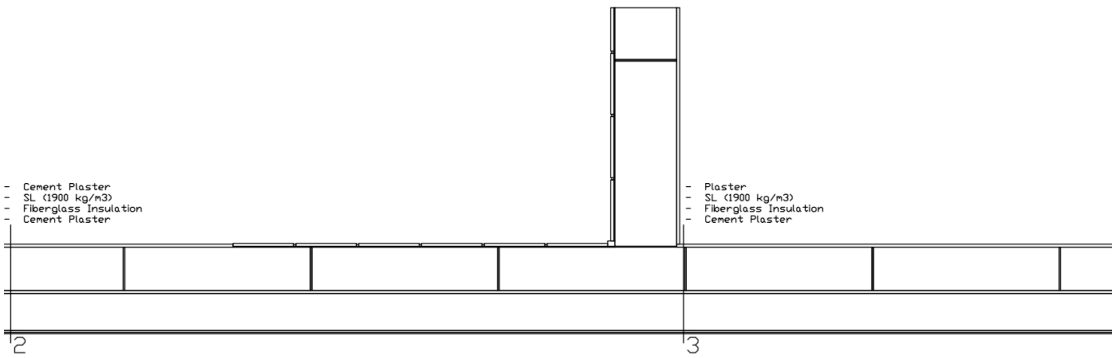
Figure 4.2: The assessed detail 1



D2-AAC



D2- Hempcrete



D2- SL

Figure 4.3: The assessed detail 2

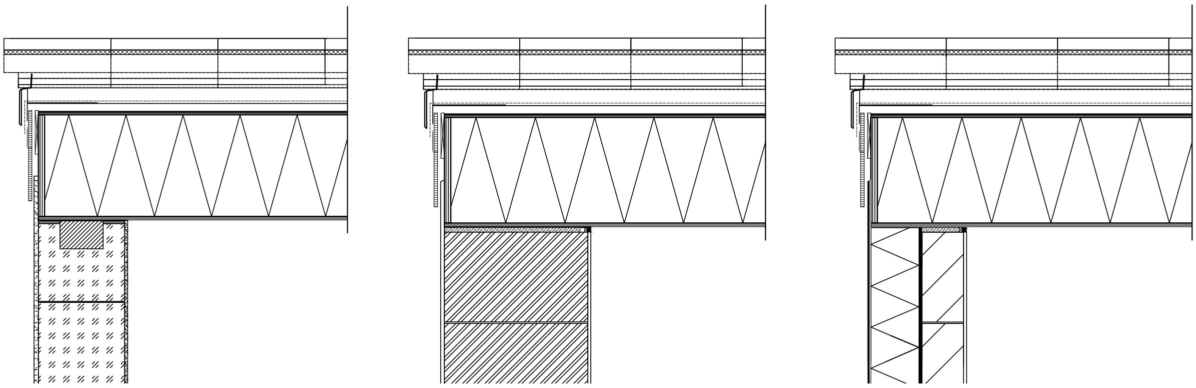


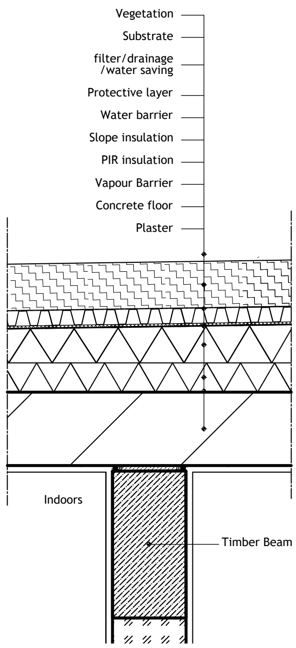
Figure 4.4: The assessed detail 3

4

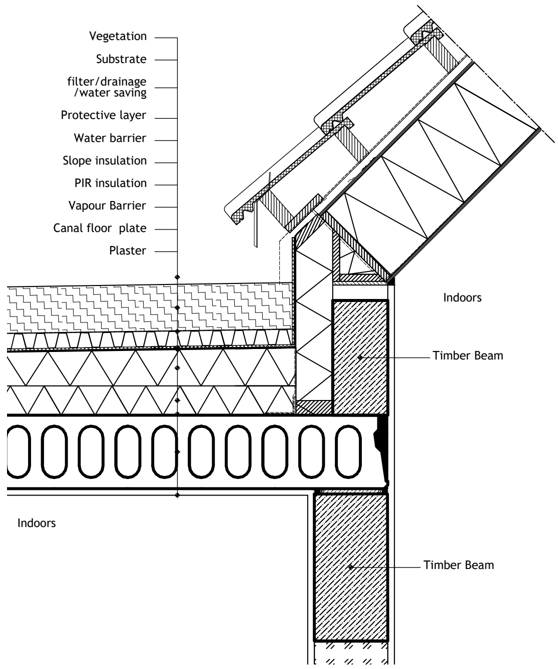
4.1.2. THE CHARACTERISTIC DETAILS OF THE DESIGNS

The characteristic building sections of the case study are depicted in the following section for the options of the hempcrete, the sand lime and the aerated autoclaved concrete designs. These sections were used for the required simulations, and thus the exact thickness of the walls is defined in detail depending on their thermal performances after the analyses.

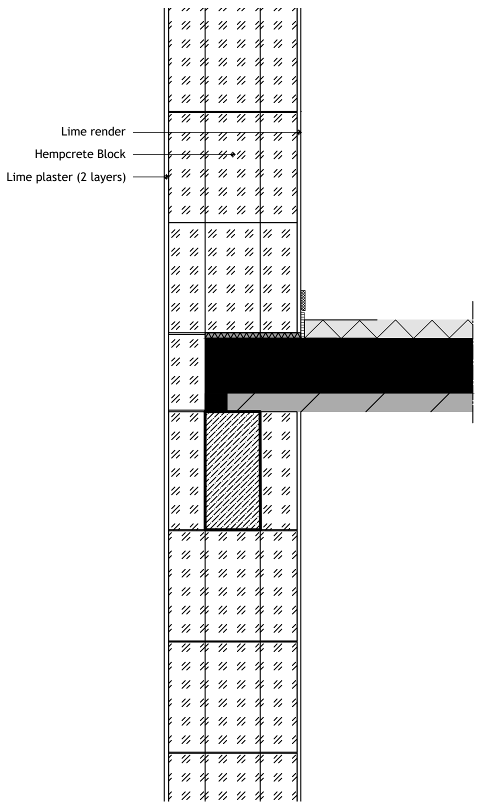
The detached house of the case study (Figure A.5) has been already made of AAC blocks and therefore the structural walls and their thicknesses have been designed. The configuration of the house and the type of the walls (load bearing/non-load bearing) remains the same both for the hempcrete and the sand lime designs. A structural system made of timber is designed for the hempcrete option and the required thickness of the sand-lime structural walls is set the same as that of the AAC. The walls' sequence for each of the design options is depicted in the following figures; the rest features of the house remain the same for all the design options.



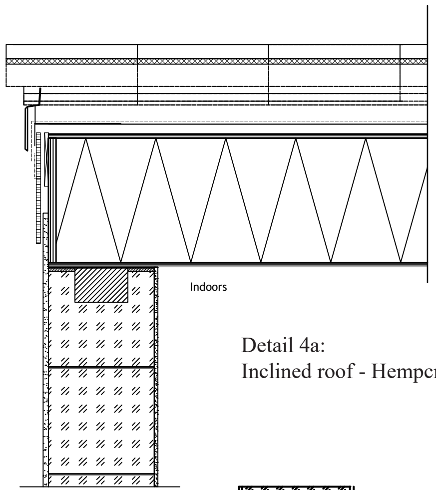
Detail 1a:
Connection internal wall with flat roof - Hempcrete



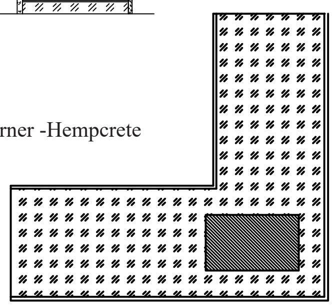
Detail 2a:
Flat roof - Hempcrete



Detail 3a:
Intermediate floor - Hempcrete

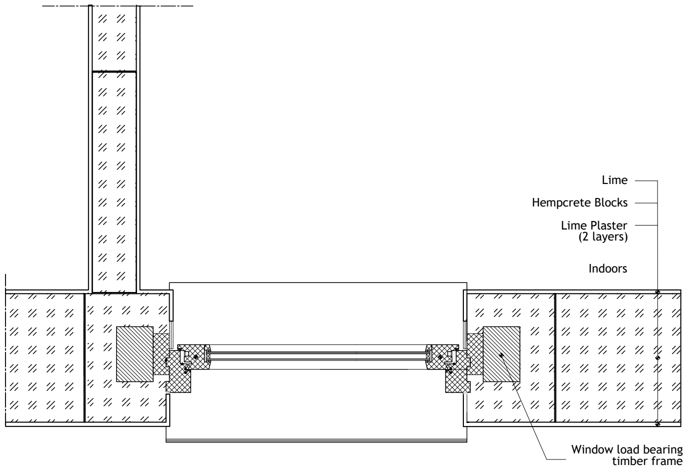


Detail 4a:
Inclined roof - Hempcrete

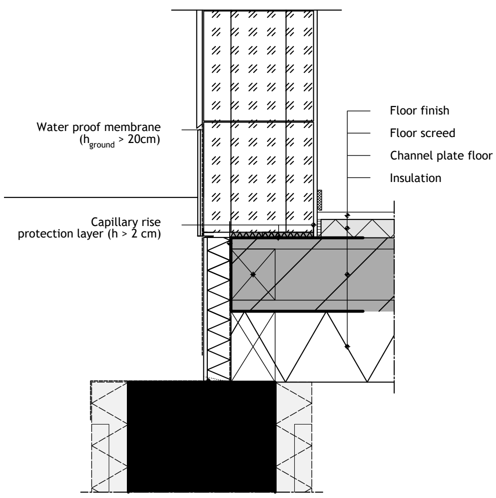


Detail 5a:
Facade corner -Hempcrete

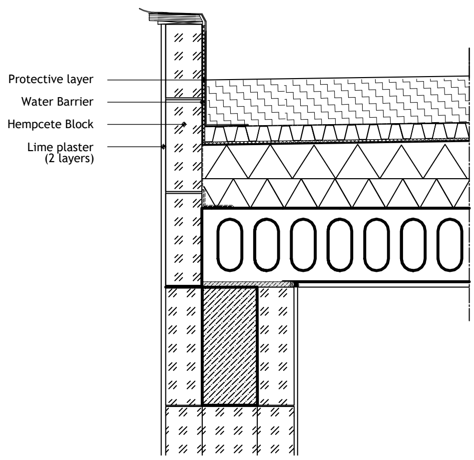
Figure 4.5: Hempcrete Details



Detail 6a:
Window - Hempcrete

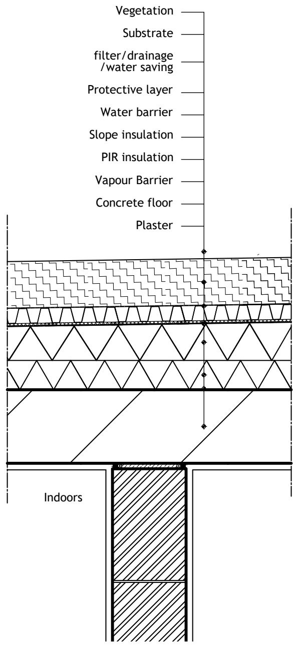


Detail 7a:
Groundfloor level - Hempcrete

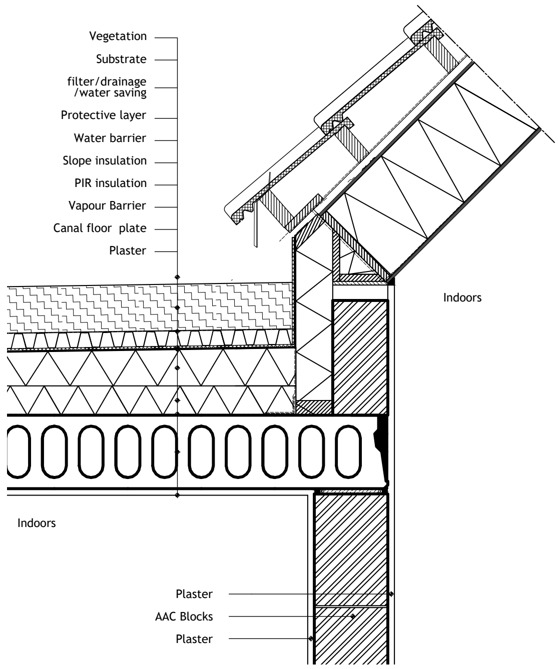


Detail 8a:
Flat roof - Hempcrete

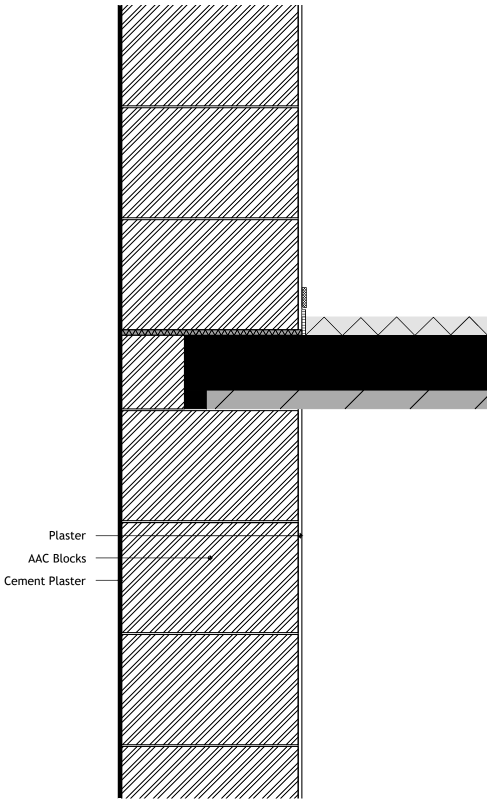
Figure 4.6: Hempcrete Details



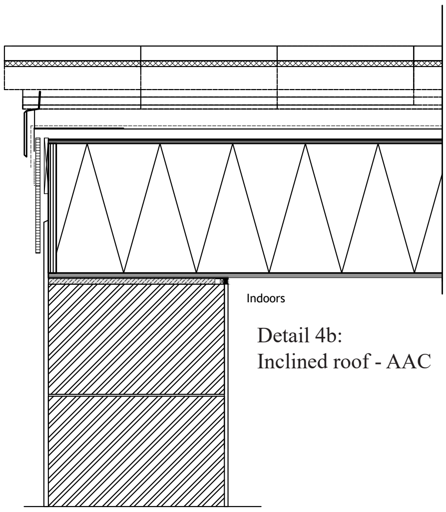
Detail 1b:
Connection internal wall with flat roof - AAC



Detail 2b:
Flat roof - AAC



Detail 3b:
Intermediate floor - AAC



Detail 4b:
Inclined roof - AAC

Detail 5b:
Facade corner -AAC

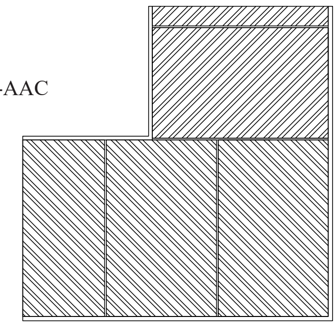
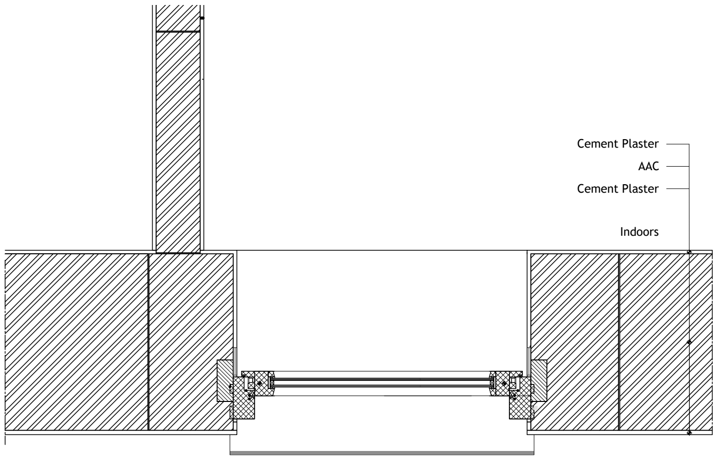
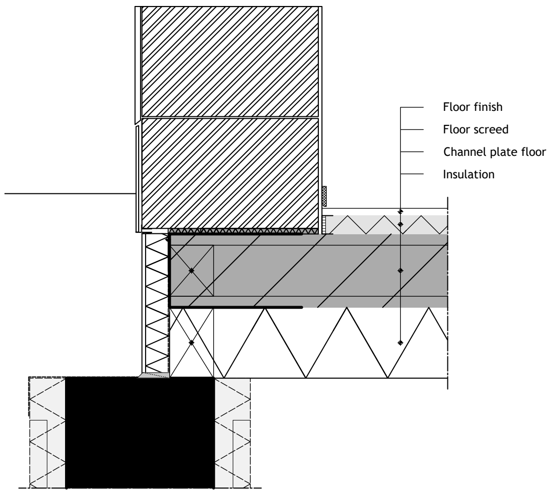


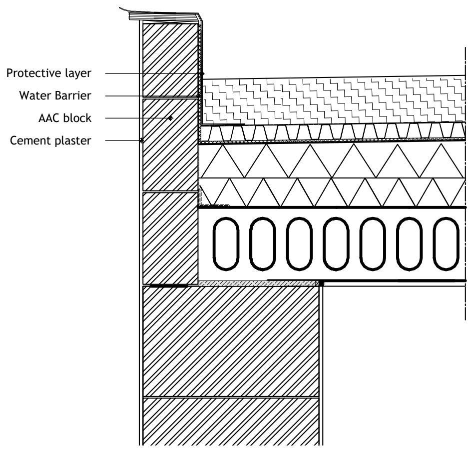
Figure 4.7: AAC Details



Detail 6b:
Window - ACC

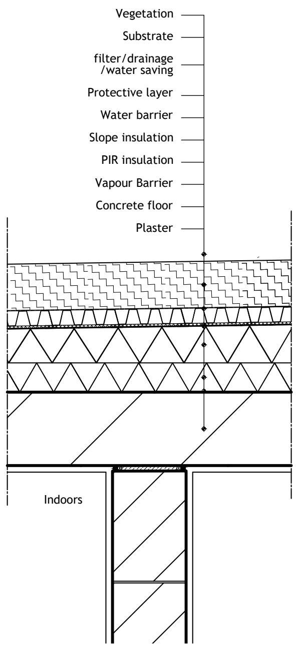


Detail 7b:
Groundfloor level - AAC

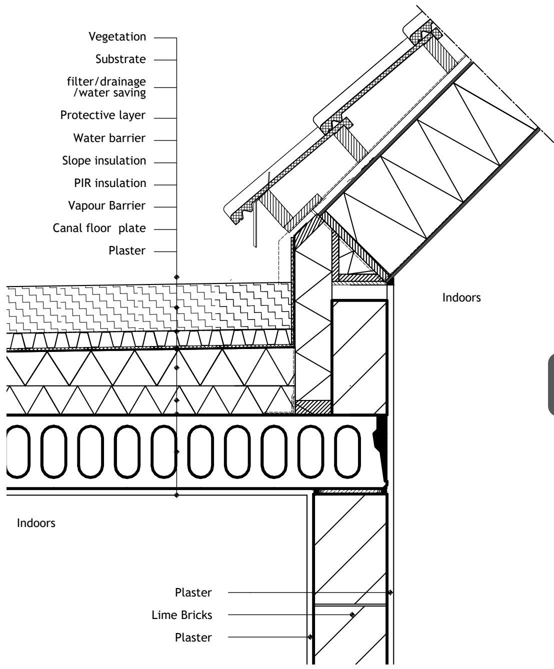


Detail 8b:
Flat roof - AAC

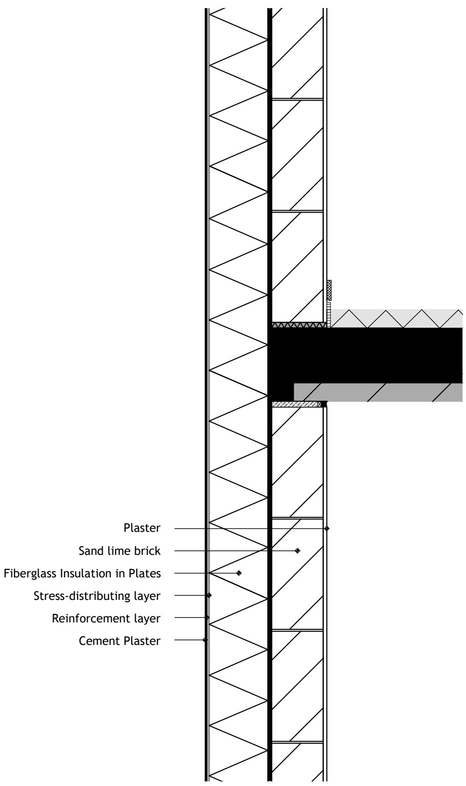
Figure 4.8: AAC Details



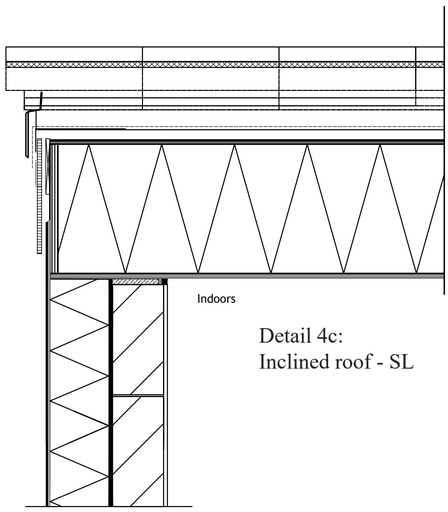
Detail 1c:
Connection internal wall with flat roof - SL



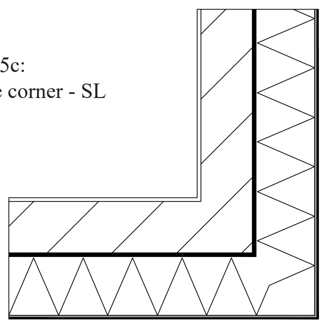
Detail 2c:
Flat roof - SL



Detail 3c:
Intermediate floor - SL



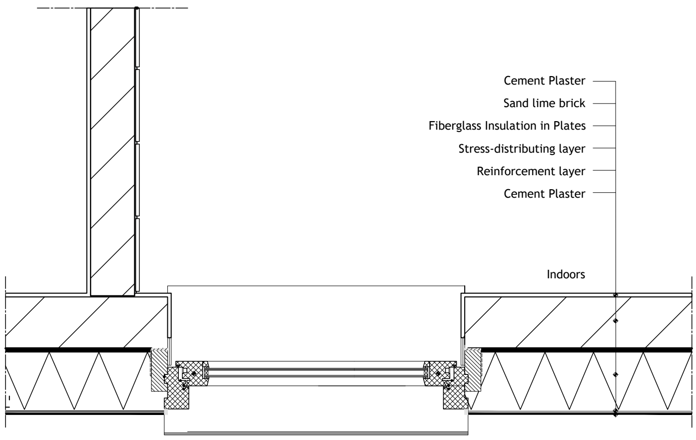
Detail 4c:
Inclined roof - SL



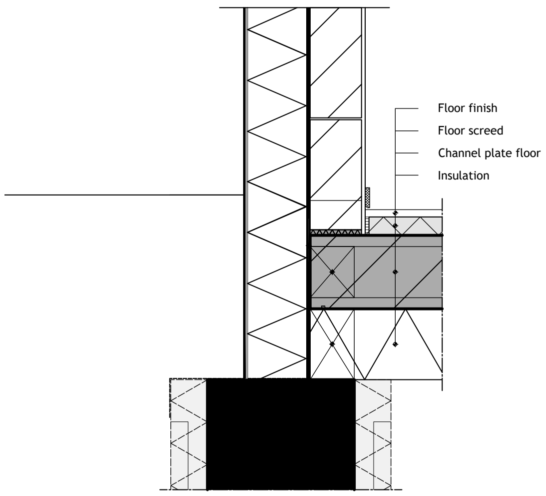
Detail 5c:
Facade corner - SL

Figure 4.9: SL Details

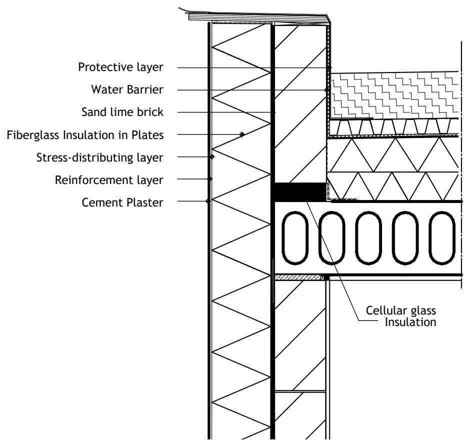
4



Detail 6c:
Window - SL



Detail 7c:
Groundfloor level - SL



Detail 8c:
Flat roof - SL

Figure 4.10: SL Details

5

THE 2D-SIMULATIONS

5.1. THE SIMULATION INPUT

5.1.1. THE PROPERTIES OF THE SIMULATED HEMPCRETE

As it can be summarized from the literature and the interviews, hempcrete properties can differ significantly depending on the composition of the mixture and the way of fabrication. Different factors have been assessed in studies in order to define their impact on the final properties of the materials, however the level of compaction, the binder design, the water content and the binder to hemp ratio were found to be decisive. As already stated, crucial for hempcrete properties as the thermal conductivity, the mechanical strength and the moisture buffering capacity are strongly related to the material's density. An increase in density may result to a desired increase in mechanical strength, however it also affects the thermal conductivity and the moisture buffering capacity negatively.

5

The type of hempcrete selected to be simulated has properties able to provide enough mechanical strength to serve adequately for an infilling wall material and sufficient thermal performances to provide thermal insulation. According to studies, hempcrete compositions with densities in the range between 300-460 kg/m^3 can be characterised by mechanical and thermal properties suitable for infilling material in building applications [1], as they can provide enough mechanical strength (> 0.2 MPa [2] - reference studies: [1], [3], Cerezo,(2005) from [4]) and low thermal conductivity ([5],[3], Mawditt (2008) from [6]).

According to the aforementioned three different hempcrete options were constructed in WUFI in order to perform a sensitivity analysis and acquire a wider image on how hempcrete behaves in the Dutch environment. The density of the hempcrete options was between the range indicated earlier (300-460 kg/m^3: dry density). Apart from the density, three other properties define the suitability of the hempcrete composition for the simulation. These properties are: the specific heat capacity (C_p), the porosity (ϵ) and the thermal conductivity of the material (λ). According to the available literature the aforementioned parameters of mixtures with densities in between the selected range in majority exhibit values that belong to the following ranges:

- C_p **:** ≈ 1500 -1600 J/kgK [6], [7],[8]
- ϵ **:** 71-85% [6],[9],[10], [7],[11]
- λ **:** 0.7 - 0.12 W/(mK) [4],[10], [7],[11]

In addition, different water absorption values were included in order to better approach an adequate value that prevents the overloading of spruce with moisture from the outdoor or indoor conditions but simultaneously facilitates its drying of spruce throughout the years. After defining the target property ranges, the three hempcrete options were simulated according to the following studies:

1. Bioclimatic envelopes made of lime and hemp concrete (Evrard De Herde, 2005 [7]), -

2. Measurement of the thermal properties of Biosourced building materials (Pierre et al., 2013) [5]).

In addition, it was observed that the properties of the hempcrete option that WUFI database offers were compatible with the target properties of the study so it was decided to be also included in the sensitivity analysis. Hence the properties of the defined hempcrete options for the hygrothermal simulations had the following values:

- **Hempcrete 1 - (Evrard De Herde, 2009 [7]):**

  ρ_o: 440 kg/m^3

  ϵ_o: 0.73 (-)

  C_{po}: 1560 J/kgK

  μ_o: 4.85 (-)

  λ_o: 0.115 W/(mK)

  $w_{80\%}$: 33 kg/m^3

  w_f: 546 kg/m^3

  w_{max}: 730 kg/m^3

  A: 0.074 kg/m^2/s$^{0.5}$

- **Hempcrete 2 - Evrard, Arnaud Herde, André (2005) [12],[13],[14].**

  ρ_o: 480 kg/m^3

  ϵ_o: 0.71 (-)

  C_{po}: 1550 J/kgK

  μ_o: 4.85 (-)

  λ_o: 0.11 W/(mK)

  $w_{80\%}$: 36.5 kg/m^3

  w_f: 595.6 kg/m^3

  w_{max}: 710 kg/m^3

  A: 0.170 kg/m^2/s$^{0.5}$

- **Hempcrete 3 - (Pierre et al., 2013) [5]**

  ρ_o: 405 kg/m^3

  ϵ_o: 0.83 (-)

  C_{po}: 1500 J/kgK (assumption: Based on value present often in literature)

  μ_o: 4.85 (-) (taken from literature for hempcrete with density 400 kg/m^3 [15].)

  λ_o: 0.073 W/(mK)

  $w_{80\%}$: 18.8 kg/m^3

  w_f: 503.1 kg/m^3

  w_{max}: 830 kg/m^3

  A: 0.155 kg/m^2/s$^{0.5}$ (taken from literature).

- **Hempcrete 4 - (Pierre et al., 2013) [5]**

  ρ_o: 398 kg/m^3

  ϵ_o: 0.78 (-)

  C_{po}: 1500 J/kgK (assumption: Based on value present often in literature)

  μ_o: 4.85 (-) (taken from literature for hempcrete with density 400 kg/m^3 [15].)

  λ_o: 0.094 W/(mK)

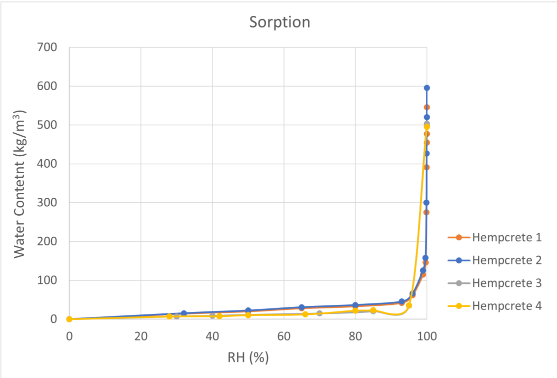
  $w_{80\%}$: 21.9 kg/m^3

  w_f: 495.3 kg/m^3

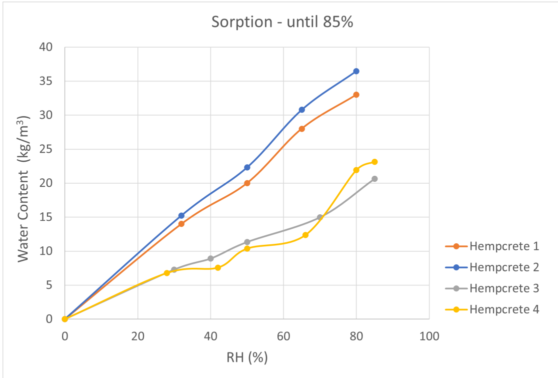
  w_{max}: 780 kg/m^3

  A: 0.155 kg/m^2/s$^{0.5}$ (taken from literature).

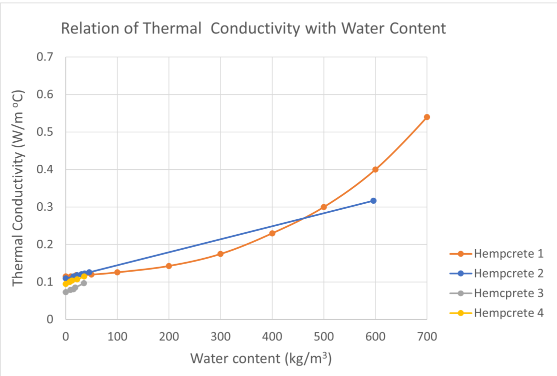
In all the aforementioned studies, there was information regarding the sorption curves of the hempcrete samples. Information on the influence of the temperature and relative humidity on the thermal conductivity was found for hempcrete options 2,3 and 4. This information was also included in the simulation in order to have a close representation of the reality.



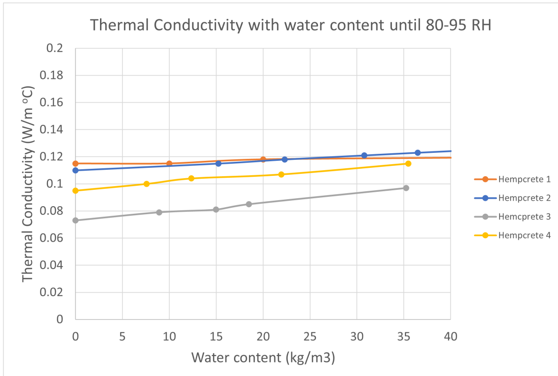
(a) Sorption (Total curve)



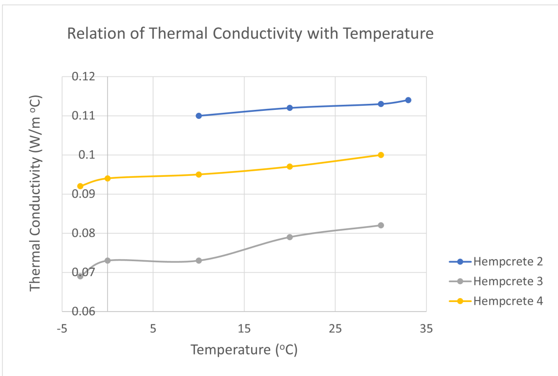
(b) Sorption close-up until 85% RH



(c) Relation of thermal conductivity with water content (Total curve)



(d) Relation of thermal conductivity with water content close-up until 85% RH



(e) Relation of thermal conductivity with temperature

Figure 5.1: Hygrothermal properties of hempcrete options .

5.1.2. THE CLIMATE DATA

For the outdoor conditions, climate data from a measuring station in Schiphol were used. Regarding the indoor conditions, several rooms of the detached house had been monitored in the past. Thus, there was available information on the indoor relative humidity and temperature of the bathroom and the adjacent rooms. An assumption that both the simulated bathroom sections were adjacent to a bedroom was made, in order to derive results of a more generalised case, where the hempcrete wall separates the bathroom from a room with moderate conditions.

In more detail, bathroom indoor conditions had been recorded every five minutes for the period between 01/03/2019 - 19/08/2019. The available data were translated in hourly data. For the case of the bathroom three different ways were examined to convert the temperature and relative humidity values recorded per five minutes to hourly ones. These were:

1. Exporting the average hourly values (Figure A.6- Figure A.9).
2. Exporting the first value recorded in every change of hour (Figure A.10- Figure A.13).
3. Exporting the highest hourly values (Figure A.14- Figure A.17).

Plotting the results of the three aforementioned ways of conversion in the same graph as the actual values recorded per five minutes revealed that in the first two cases a significant number of peaks especially in the case of temperature was excluded. In addition, in general mold appears in conditions when RH levels stay higher than 80% for long periods. As a result including all RH peaks was considered a safer approach to evaluate the situation. Thus, it was decided that the third way of conversion would be more suitable for the simulation, even though it is more conservative, since it is based on the assumption that the maximum hourly recorded values account for the whole timestep of the simulation (an hour).

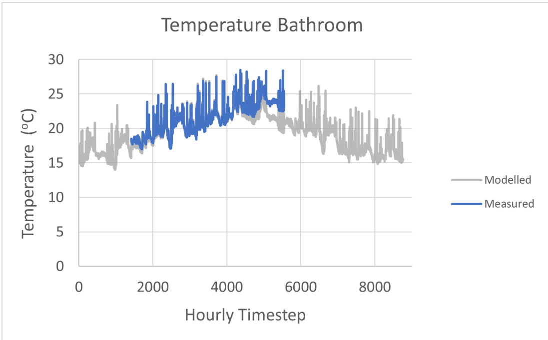
For the case of the adjacent rooms, the indoor conditions were still recorded for the same period, however, with a significantly lower frequency. There was not any standard time step between consecutive recordings and thus there were also dates that only a few or not even any measurements of the indoor conditions were available. Modelling hourly data to cope with the missing data was required for the sake of the simulation. For the modelling two sine formulas were created, for the daily and annual alterations of temperature respectively by making use of the available measurements (Figure 5.2 [a,c]). The same method was followed for the modelling of indoor humidity (Figure 5.2 [b,d]). Hence two formulas, (one for temperature and one for humidity) with the following form were constructed:

$$y = A_1 sin(B_1 x - C_1) + A_{2i} sin(B_{2i} x - C_{2i}) + D \tag{5.1}$$

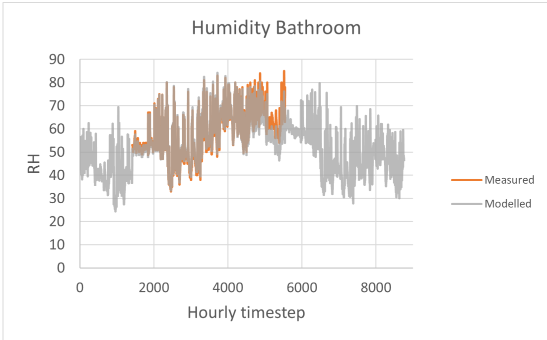
Where:
$_1$: Yearly periodic cosine formula
$_{2i}$: Daily periodic cosine formula, where i = day

For the long-term simulation (10 years period) due to the absence of yearly indoor condition data, at first using the option of the available on Wufi sine curves was considered.

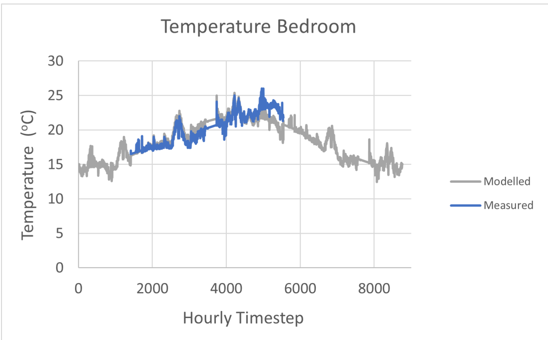
However, with this option the sudden daily alterations in indoor conditions could no be implemented in the model. Thus, new data needed to be modelled for the rest six months. To do so the aforementioned method was used again by assuming that the daily indoor conditions pattern would be the same as in the previous semester.



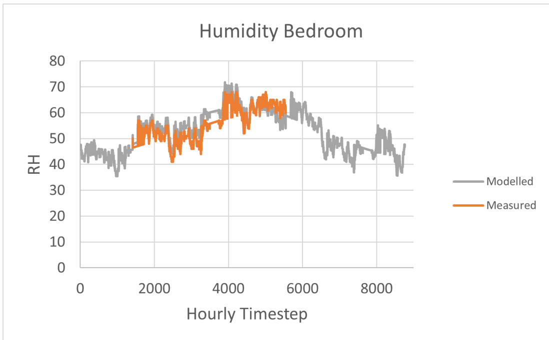
(a) Temperature Bathroom



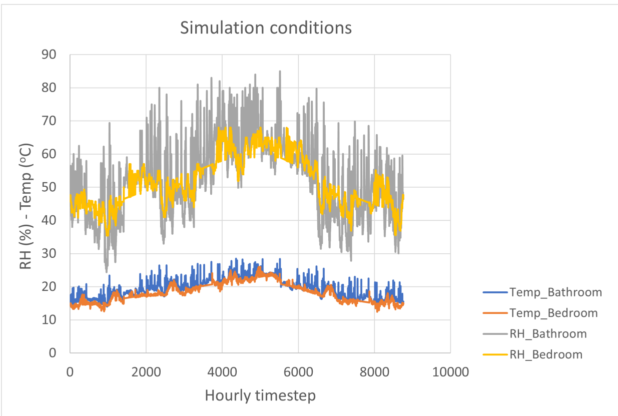
(b) RH Bathroom



(c) Temperature Bedroom



(d) RH Bedroom



(e) Total

Figure 5.2: The modelled and measured indoor conditions.

5

5.2. THE ASSESSMENT OF DEGRADATION RISKS IN THE WALLS

Four different means are used to assess the risks of degradation in the walls for the hempcrete, the sand lime and autoclaved aerated concrete design. The details where these means were assessed are depicted in Section 4.1. These means are:

- The risk of surface condensation.
- The risk of interstitial condensation
- The risk of mold growth in spruce columns (Isopleths)
- The accumulation of water inside the walls of a driving rain facing facade for a long term simulation.

The surface condensation risk is assessed according to the European standard NEN-EN-ISO 13788:2013. The methodology which is followed is described in steps below:

1. Definition of the external mean temperature and relative humidity values for each month of the year from the Schiphol climate data.
2. Definition of the internal mean temperature and relative humidity values of the bathroom for each month of the year from the indoor data.
3. Definition of the external mean humidity for each month by the equation:

$$\overline{p_e} = \overline{\varphi_e} \times p_{sat}(\overline{\theta_e}) \tag{5.2}$$

   Where:

   - $\overline{\varphi_e}$: external mean relative humidity of the month
   - $\overline{\theta_e}$: external mean temperature of the month
   - $p_{sat}(\overline{\theta_e})$: saturation vapour pressure at $\overline{\theta_e}$

   With:

$$p_{sat}(\theta) = 610.5 \times e^{\frac{17.269\times\theta}{237,3+\theta}}, for \theta \geq 0\ C^o \tag{5.3}$$

$$p_{sat}(\theta) = 610.5 \times e^{\frac{21.875\times\theta}{265.5+\theta}}, for < 0\ C^o \tag{5.4}$$

4. Definition of the internal mean humidity for each month by the equation:

$$\overline{p_i} = \overline{p_e} + \Delta p \tag{5.5}$$

   Where: Δp can be given as a monthly mean value $\overline{\varphi_i}$ since the RH is known

5. Definition of $p_{sat}(\theta_{si})$ by the equation:

$$p_{sat}(\theta_{si}) = \frac{\overline{p_i}}{\varphi_{si,crit}} = \frac{\overline{p_i}}{0.8} \tag{5.6}$$

6. Determination of the minimum acceptable surface temperature for the minimum acceptable saturation vapour pressure.

$$\theta = \frac{237.3 \times \ln \frac{p_{sat}(\theta_{si})}{610.5}}{17.269 - ln \frac{p_{sat}(\theta_{si})}{610.5}}, \quad for \;\; p_{sat}(\theta_{si}) \geq 610.5Pa \tag{5.7}$$

$$\theta = \frac{265.5 \times \ln \frac{p_{sat}(\theta_{si})}{610.5}}{21.875 - ln \frac{p_{sat}(\theta_{si})}{610.5}}, \quad for p_{sat}(\theta_{si}) < 610.5Pa \tag{5.8}$$

5

7. Calculate for each month:

$$f_{Rsi,min} = \frac{\theta_{si,min} - \overline{\theta_e}}{\overline{\theta_i} - \overline{\theta_e}} \tag{5.9}$$

8. Define maximum value of:

$$f_{Rsi,min} = f_{Rsi,crit} \tag{5.10}$$

9. Calculate:

$$f_{Rsi} = \frac{\theta_{si} - \overline{\theta_e}}{\overline{\theta_i} - \overline{\theta_e}} \tag{5.11}$$

if $f_{Rsi} > f_{Rsi,max}$, no risk of mold

March was found to be the critical month for the year under scrutiny with:

- $f_{Rsi,min}$=0.507 for the case of the bathroom
- $f_{Rsi,min}$=0.37 for the case of the bedroom

And according to the relevant standard for a static calculation:

- *The temperature factor for this month is the $f_{Rsi,max}$ and the building element shall be designed so that $f_{Rsi,max}$ is always exceeded.*

Mon.	$\overline{\theta_e}$	$\overline{\varphi_e}$	$\overline{\theta_i}$	$\overline{\varphi_i}$	$p_{sat(\theta_e)}$	$p_{sat(\theta_i)}$	$\overline{p_e}$	$\overline{p_i}$	$P_{sat}(\theta_{si,min})$	$f_{Rsi,min}$
1	4.16	0.86	16.36	0.43	822.0	1859.5	799.6	707.0	999.5	0.23
2	4.14	0.80	16.80	0.39	820.9	1912.2	745.8	656.7	932.2	0.14
3	6.20	0.81	18.64	0.54	947.7	2147.3	1159.6	767.6	1449.4	0.51
4	8.77	0.75	20.31	0.49	1129.75	2382.2	1167.3	847.31	1459.1	0.33
5	14.12	0.71	20.38	0.52	1610.2	2392.5	1244.1	1143.3	1555.1	-0.08
6	17.15	0.76	22.22	0.64	19955.1	2678.0	1714.1	1485.9	2142.44	0.29
7	18.23	0.73	23.43	0.64	2092.9	2881.7	1844.3	1527.8	2305.3	0.30
8	18.50	0.75	22.42	0.62	2128.6	2710.8	1680.7	1596.4	2100.9	-0.05
9	15.18	0.78	21.12	0.57	1724.3	2354.4	1342	1344.9	1677.5	-0.09
10	12.00	0.85	18.24	0.41	1401.8	2094.2	858.6	1191.5	1073.3	-0.64
11	7.71	0.85	16.75	0.45	1051.2	1906.2	857.8	893.5	1072.2	0.03
12	5.09	0.9	16.31	0.45	877.4	1853.6	834.1	789.6	1042.6	0.22

Table 5.1: Monthly calculation of the mean $f_{Rsi,min}$ factor in the bathroom according to ISO 13788:201.

Mon.	$\overline{\theta_e}$	$\overline{\varphi_e}$	$\overline{\theta_i}$	$\overline{\varphi_i}$	$p_{sat(\theta_e)}$	$p_{sat(\theta_i)}$	$\overline{p_e}$	$\overline{p_i}$	$P_{sat}(\theta_{si,min})$	$f_{Rsi,min}$
1	4.16	0.86	14.85	0.45	822.0	1688.0	759.6	707.0	949.5	0.19
2	4.14	0.80	15.60	0.42	820.9	1771.4	744.0	656.7	930.0	0.16
3	6.20	0.81	17.19	0.51	947.65	1960.09	999.7	767.6	1249.6	0.37
4	8.77	0.75	18.8	0.49	1129.8	2168.9	1062.8	847.3	1328.5	0.24
5	14.12	071	19.28	0.52	1610.2	2234.8	1162.1	1143.2	1452.6	-0.31
6	17.15	0.76	21.59	0.62	1955.13	2577.1	1597.8	1485.9	1997.2	0.08
7	18.23	0.73	22.62	0.61	2092.9	2743.9	1673.8	1527.8	2092.2	-0.00
8	18.50	0.75	22.14	0.61	2128.6	2665.04	1625.7	1596.4	2032.1	-0.20
9	15.18	0.78	19.14	0.58	1724.3	2215.4	1284.9	1344.9	1606.17	-0.28
10	12.00	0.85	17.28	0.46	1401.81	1971.3	906.8	1191.5	1133.5	-0.60
11	7.71	0.85	15.60	0.45	1051.2	1771.4	797.1	893.5	996.4	-0.10
12	5.09	0.90	15.00	0.46	877.4	1704.4	784.0	789.6	980.0	0.16

Table 5.2: Monthly calculation of the mean $f_{Rsi,min}$ factor in the bedroom according to ISO 13788:201.

The risk of interstitial condensation was assessed graphically according to the Glaser method for every section under scrutiny and every hour in a whole year by making use of Grasshopper. Firstly the vapour pressure lines where calculated in excel and then the results were imported in Grasshopper where the cases when the lines intersect were identified. For the sections under scrutiny the temperature and RH levels at the surface of the materials were derived from the WUFI simulations and used to create the saturation vapour pressure line along the sections. The saturation vapour pressure levels at the contact surface of the materials in the sections were calculated according to the formulas Form.(5.7), Form.(5.8). The partial water pressure line was created by taking into account the vapour resistance factor of each material:

$$P_{contact\ surface_k} = P_{indoor} - \frac{(P_{indoor} - P_{outdoor}) * \sum_{i=1}^{k}(\mu_i * d_i)}{\sum_{i=1}^{n}(\mu_i * d_i)} \tag{5.12}$$

Where:

n=number of materials in the section

k=material sequence number

5.2.1. THE ASSESSMENT FACTORS

The hygrothermal performances of hempcrete in comparison to those of sand lime bricks and AAC bricks have been assessed according to two factors: the thickness and the thermal resistance of the wall. For the first case, walls with a same thickness of around 32 cm were constructed. A thickness of 30-35 cm is typical for the case of Dutch buildings so 32 cm were considered suitable to make a direct comparison between the material performances. Nevertheless, according to the Dutch Building Decree, building walls should be characterised by a thermal resistance higher than 4.7 m^2K/W (Rc > 4.7 m^2K/W) . This requirement is met only for the case of the section composed by the sand lime bricks and the fiber glass board insulation. As a result, additional sections with a thermal resistance of 4.7 m^2K/W and a respective thickness were designed and assessed.

The thickness of the wall was defined by the following formula for the case of the sections for which the configuration in y direction remained the same.

$$R_{total} = R_c + R_{si} + R_{se} = \sum_{i=1}^{n}(\frac{d_i}{\lambda i}) + R_{si} + R_{se} \tag{5.13}$$

Where:

n=number of materials in the section
d= the thickness of the material layer
λ = the thermal conductivity of the material layer
R_c=the thermal resistance of the construction
R_{si}= the thermal resistance at the internal surface (0.13 m^2K/W)
R_{se}= the thermal resistance at the external surface (0.04 m^2K/W)

Material	Thickness (m)	Vapour resistance factor (-)	Thermal Conductivity (W/mK)	Thermal resistance ($m^2 K/W$)
Hempcrete Design				
Clay	0.010	11.30	0.650	0.015
Hempcrete	0.350	4.85	0.073	4.795
Lime	0.012	7.00	0.700	0.017
Total	0.37			5.0*
SL Design				
Cement Plaster	0.010	25	1.20	0.008
Sand lime Bricks	0.15	28	1.00	0.15
Fiber Glass Insulation	0.16	1	0.035	4.57
Cement Plaster	0.012	25	1.20	0.01
Total	0.332			4.9*
AAC Design				
Cement Plaster	0.010	25	1.20	0.005
AAC	0.480	7.9	0.10	4.8
Cement Plaster	0.012	25	1.20	0.01
Total	0.502			5.0*

* Including R_{se}, R_{si}

Table 5.3: Simple Wall constructions.

For the hempcrete detail 2, where the configuration of the external wall does not stay the same but it is interrupted by the spruce column, the approach described in the Dutch standard NTA 8800-2022 was followed to define the required thickness of the wall. This approach accounts for the calculation of the equivalent thermal resistance of walls (R_T) with composite structures and is presented below. In order to include in WUFI 2D equivalent sections of different materials with the same thermal resistance, the calculations have been done for the area of the external wall that is present in the assessed detail (Figure (5.3)). This leads to a slight overestimation of the thickness of the composite hempcrete -spruce wall, since in reality a column spruce corresponds to a slightly higher wall length.

$$R_{T'} = \frac{A_{unit}}{A_a * U_a + A_b * U_b} \tag{5.14}$$

$$\lambda_{j"} = \frac{A_a * \lambda_{aj} + A_b * \lambda_{bj}}{A_{unit}} \tag{5.15}$$

$$R_{T"} = \sum_{i=1}^{n} (\frac{d_i}{\lambda j"}) + R_{si} + R_{se} \tag{5.16}$$

$$R_T = \frac{R_{si} + R_{se} + a' * R_{T'} + R_{T"}}{1 + 1.05 * a'} - R_{si} - R_{se} > 4.7 m^2 K/W \tag{5.17}$$

Where:

A_{unit}= the area of the external wall in the assessed detail in m^2 according to Figure (5.3).
A_a= the area of projected section a in m^2 according to Figure (5.3).
A_b= the area of projected optimal section b in m^2 according to Figure (5.3).
$\lambda_{j''}$= the equivalent thermal conductivity of layer j according to Figure (5.3).
a'= factor defined accordingly to the standard NTA 8800-2022

here a'= 0, since $R_{T'} \leq 1.05 * R_{T''} + R_{si} + R_{se}$

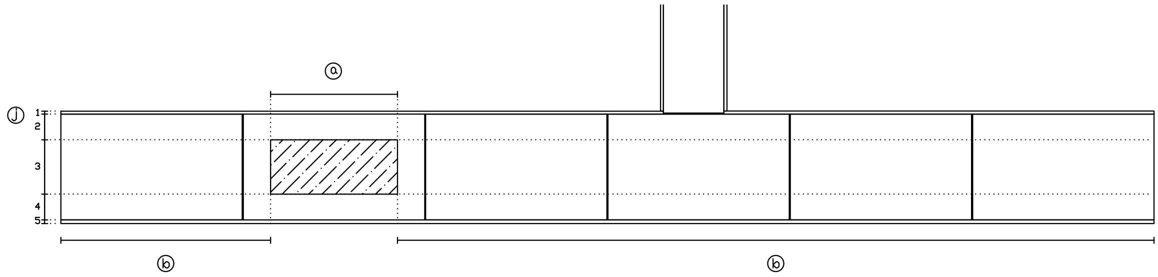


Figure 5.3: Section under assessment.

Material	Thickness (m)	Length (m)	Thermal Conductivity (W/mK)	Area (m^2)	Thermal resistance (m^2K/W)
Section a					
Clay	0.01	0.4	0.65	0.004	0.02
Hempcrete	0.085	0.4	0.073	0.034	1.16
Spruce	0.18	0.4	0.09	0.072	2.00
Hempcrete	0.085	0.4	0.073	0.034	1.16
Lime	0.01	0.4	0.70	0.004	0.02
Total	0.37	0.4	(-)	0.15	4.53 *
Section b					
Clay	0.01	3.215	0.65	0.032	0.02
Hempcrete	0.085	3.215	0.073	0.27	1.16
Hempcrete	0.18	3.215	0.073	0.58	2.47
Hempcrete	0.085	3.215	0.073	0.27	1.16
Lime	0.01	3.215	0.70	0.039	0.02
Total	0.37	3.215	(-)	1.20	5.00 *

* Including R_{se}, R_{si}

Table 5.4: Properties of the sections a and b.

j	$\lambda"_{ji}$	$d_i/\lambda"_{ji}$	$R_{T'}$	$R_{T''}$	R_T
1	0.65	0.02			
2	0.073	1.16			
3	0.073	2.4	4.94	4.94	4.77
4	0.073	1.16			
5	0.7	0.02			

Table 5.5: The final thermal resistance of the composite construction

5.3. THE ASSESSMENT'S RESULTS

5.3.1. THE SURFACE CONDENSATION

5

The time steps during the year that surface condensation occurs were collected and organised in graphs for the Details 2 (Figure: 5.4) and 1 (Figure: 5.5).

The results in the graphs are represented according to the following method:

D_i_M_S_j

Where:

- D accounts for the detail under scrutiny (i=1 or 2)
- M accounts for the respecting type of the wall's assembly, (see also Abbreviations)
- S accounts for the section under scrutiny (j=1-6)

Detail 2

As it can be seen in the graphs of the hempcrete options for the Sections S1, S2 and S3, no surface condensation occurs during the winter for none of the different hempcrete compositions (Figure 5.4 [a1]). In addition, the condensation hours are low (around 30 hours per year) and no consecutive. The hours that condensation occurs remain very close for all Hempcretes under examination however a slight improvement can be noticed as the thermal conductivity of the composition decreases (Figure 5.4 [a1]). Hempcretes with better thermal performances are characterised by less hours of condensation and and frsi values that approximate better the frsi,min. As expected, the better designed $H3_{Rd}$ has a noticeable improvement since the frsi values that approximate better the frsi,min (Figure 5.4 [a1]) and the yearly hours of condensation appear decreased (Figure 5.4 [a2]).

It is worth noticing here, that S1 performs slightly better than S2 in the case of the hempcretes with the higher thermal conductivity (H1,H2,H4), even though it represents the section with the lowest thermal performance in the bathroom due to the presence of timber column (Figure 5.4 [a2]). A possible explanation to the latter could be associated with the presence of the tiles that are close to S1. The tiles work as a barrier to the moisture and prevent excessive moisture to accumulate on the surface of the wall. This is not the case for S2, where eventually higher moisture levels are present and due to the higher thermal conductivity condensate (Figure 5.4 [a2]). When it comes to the Hempcretes with the better thermal performances (H3,H3$_{Rd}$), the temperatures on S2 remain high enough to prevent the excess of moisture to condensate. The effect of the geometry (wall corner) is also noticeable for the hempcretes with the lower thermal performances where Section S3, even though is located in the bedroom displays slightly worst results than those in the bathroom, probably due to the lower temperatures that are present at the corner area (Figure 5.4 [a2]).

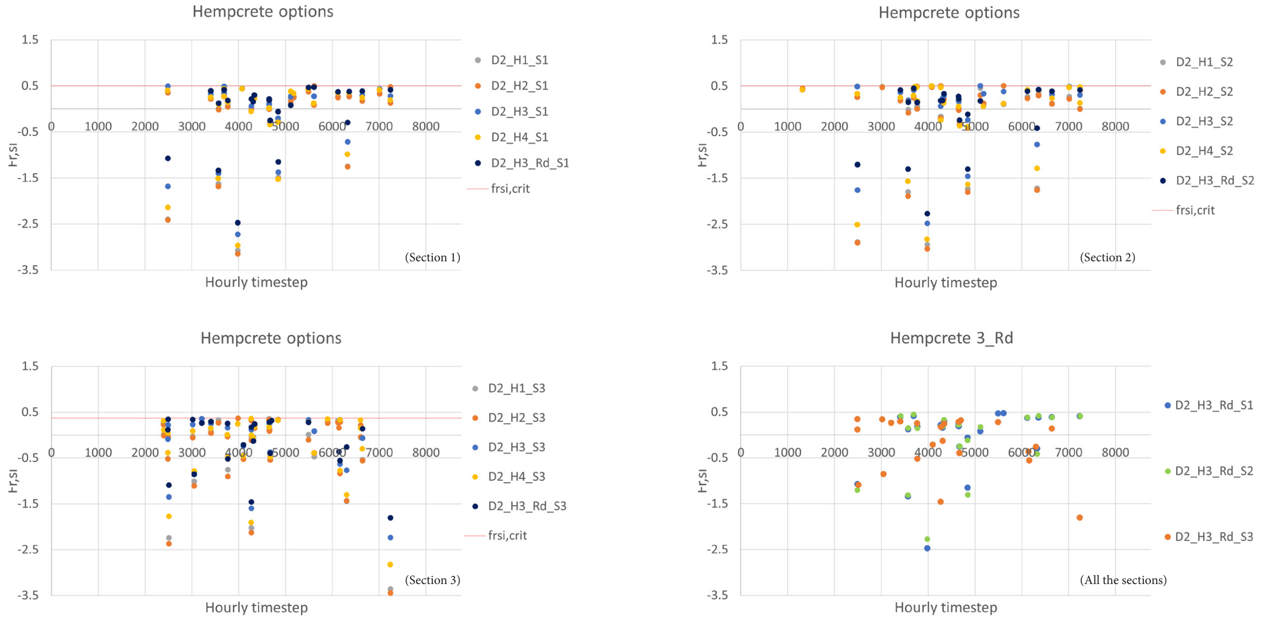
When it comes to a direct comparison between the different materials the results appear to differentiate more. For the case of the same thickness of the wall, Hempcrete appears to approximate remarkably the results of the SL wall assembly despite the difference in the thermal resistance (Figure 5.4 [b]) and (Figure 5.4 [a2] (For H3-SL)). The difference in the hygrothermal performances of the materials becomes noticeable also in the case of AAC. For a wall with a same thickness, H3 and AAC display a great difference in performances for the section located in the Bathroom, where for the case of AAC, surface condensation appears already in winter (Figure 5.4 [b] - Pink) and (Figure 5.4 [a2], For H3-AAC). For walls with the same thermal resistance hempcrete still outperforms AAC in high moisture environments (Figure 5.4 [a2] (For H3$_R d$-AAC$_R d$)). The results between the Hempcrete and the SL design are the same.

5

Detail 1

The same pattern regarding the relationship between thermal conductivity and the surface condensation can be detected in the case of the Detail 1, too (Figure 5.5,5.6). Surface condensation is remarkably decreased in S4, S5, S6 as the thermal conductivity of the simulated hempcrete wall decreases (Figure 5.5 [d,e]). S4 which is located at the bathrooms corner appears to have higher surface condensation than than all the sections under scrutiny and for the majority of the materials and thicknesses under examination (Figure 5.5 [e,f]). An exemption appears however for the case of the wall assemblies with the higher thermal conductivities. (H1,H2 Figure 5.5 [e] S6>S4) Nevertheless, the results for S4 are remarkably worse for the case of SL configuration (Figure 5.5 [e] SL_S4: 59 hours), even though in comparison to Hempcretes and AAC, only SL meets the thermal resistance requirement of the Dutch Building Decree for the same wall thickness .

For the case of H3$_{Rd}$, the local effect of the thermal bridge due to the presence of the timber supporting frame leads to a slightly worse performance than the one detected in the case of AAC. Nevertheless, even with lower thermal performance, all the simulated hempcrete options still outperform SL at S4 due to the moisture buffering capacity of the material. The effect of the window (thermal bridge) is more noticeable for the hempcretes with the lower thermal conductivity (H1,H2,H4) which can be seen in the sections S4 and S5 (Figure (5.5 [d,e]). Nevertheless, for the optimised case of H3$_{Rd}$ the effect is remarkably decreased in the Section S4 - e.g. 33 hours for H3$_{Rd}$ and 52 hours for H1 - (Figure (5.5 [d,e]) and disappears for the corner of the bedroom, since same hours of condensation (23 hours) appear in the respective corners of the two assessed details (Section S5 for H3$_{Rd}$: Figure (5.5 [d,e] and Section S3 for H3$_{Rd}$: Figure (5.4 [a1,a2]).

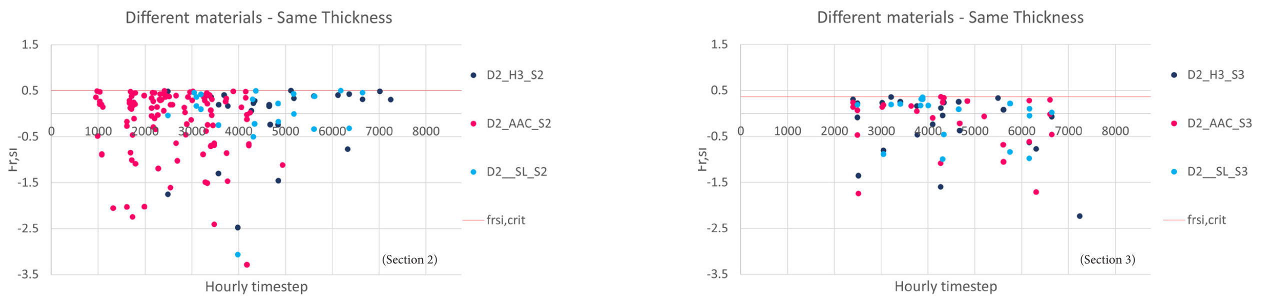


(a1): The surface condensation - Comparison between the hempcrete options - Detail 2

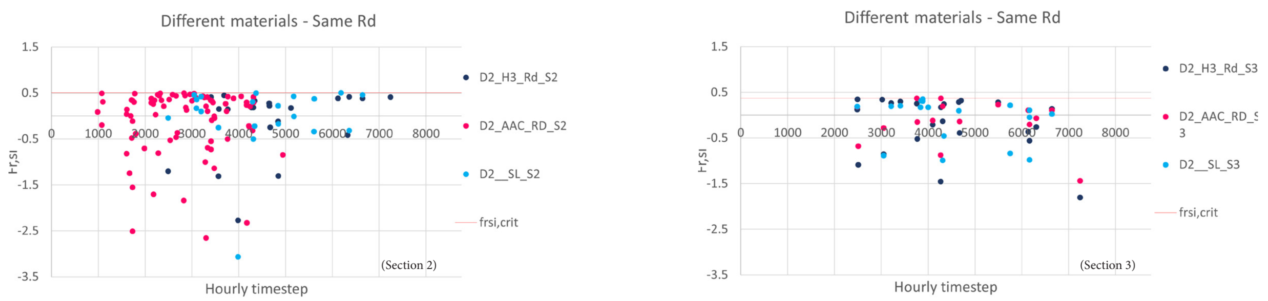
	S1	S2	S3
H1	30	32	33
H2	30	34	35
H3	25	25	23
H4	28	31	30
H3_Rd	23	21	23

	S1	S2	S3
H3	25	25	23
AAC	(-)	112	26
H3_Rd	23	21	23
AAC_Rd	(-)	81	16
SL	(-)	21	19

(a2): The surface condensation - Yearly Hours of surface condensation per material and section - Detail 2

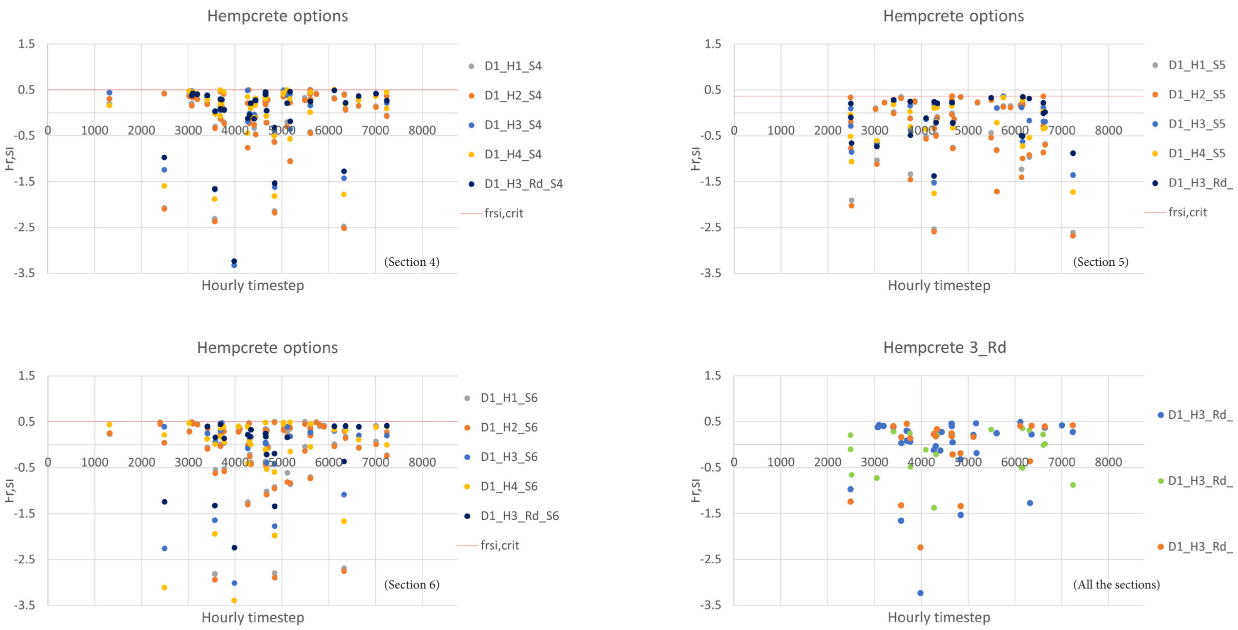


(b): The surface condensation - Comparison between the materials (same thickness) - Detail 2



(c): The surface condensation - Comparison between the materials (same Rd) - Detail 2

Figure 5.4: Surface condensation - (Detail 2).

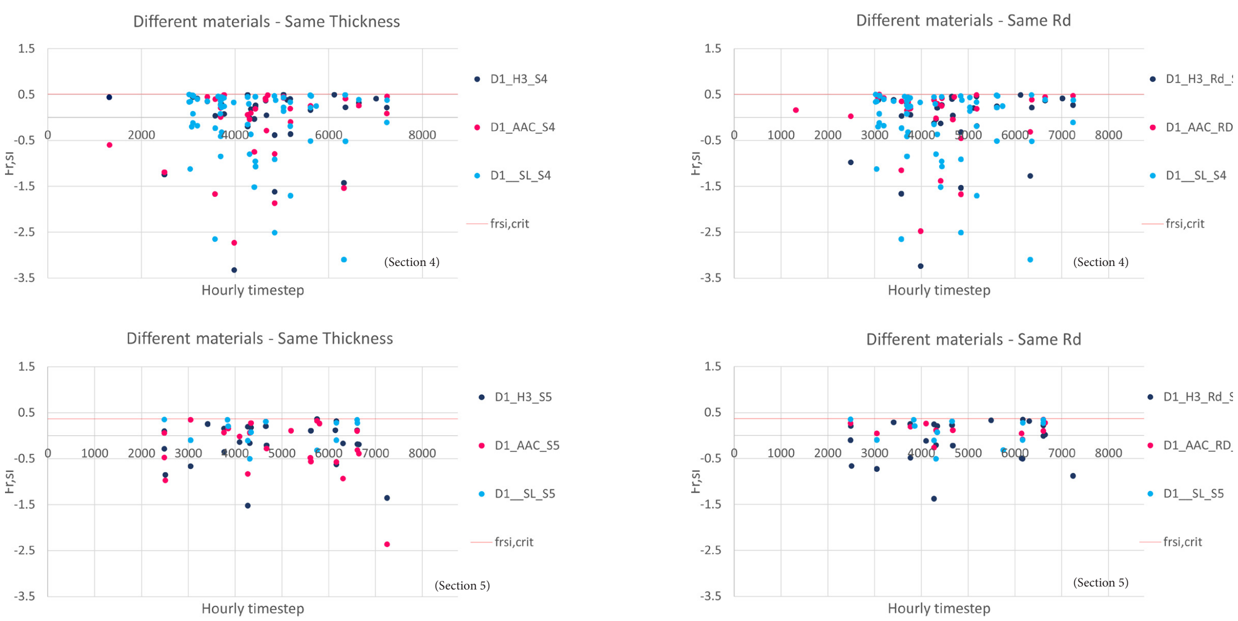


(d): The surface condensation - Comparison between the hempcrete options - Detail 1

	S4	S5	S6
H1	52	41	59
H2	53	42	60
H3	37	24	27
H4	41	24	37
H3_Rd	33	23	21

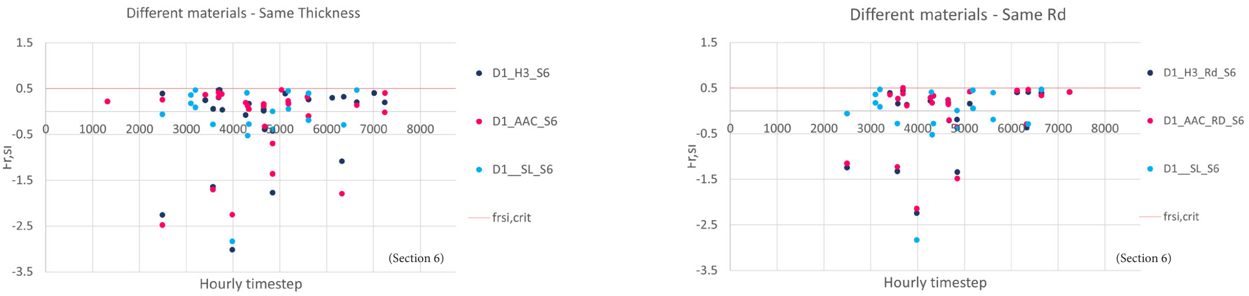
	S4	S5	S6
H3	37	24	27
AAC	32	22	27
H3_Rd	33	23	21
AAC_Rd	28	12	22
SL	59	13	18

(e): The surface condensation - Yearly Hours of surface condensation per material and section- Detail 1



(f): The surface condensation - Comparison between the materials Section S4, S5 -Detail 1

Figure 5.5: Surface condensation - (Detail 1).



	S4	S5	S6
H3	37	24	27
AAC	32	22	27
H3_Rd	33	23	21
AAC_Rd	28	12	22
SL	59	13	18

(g): The surface condensation - Comparison between the materials section S6 -Detail 1

Figure 5.6: Surface condensation - (Detail 1).

5.3.2. THE INTERSTITIAL CONDENSATION

Wall of the same thickness						
	Detail 2			Detail 1		
Material	Section 1	Section 2	Section 3	Section 4	Section 5	Section 6
H1	68	0	0	51	0	0
H2	72	0	0	52	0	0
H3	71	0	0	57	0	0
H4	67	0	0	43	0	0
SL	(-)	3	0	3	0	1
AAC	(-)	29	5	0	0	0

Table 5.6: Condensation hours during the 10th year of the simulation a wall with the same thickness (d= 32 cm).

Wall of the same R_T						
	Detail 2			Detail 1		
Material	Section 1	Section 2	Section 3	Section 4	Section 5	Section 6
$H3_{Rd}$	68	0	0	48	0	0
SL	(-)	3	0	0	0	0
AAC_{Rd}	(-)	13	0	0	0	0

Table 5.7: Condensation hours during the 10th year of the simulation in a wall with the thermal resistance ($R_T = 5\ m^2K/W$)).

According to Table 5.6, small differences regarding the hours of condensation per year can be observed between the different hempcrete options when they are compared in walls with the same thicknesses, even though the thermal conductivity of the hempcretes under scrutiny differs (from λ=0.073 - 0.115 W/(mK)). When compared to the SL and AAC design in the monolithic hempcrete sections (S2,S3, S5, S6) hempcrete shows in general equal or better performances. In Table 5.6, only the SL design meets the thermal resistance requirement of the Bouwbesluit. However, no interstitial condensation appears in the monolithic sections of hempcrete for both the cases of the Bathroom (S2, S6) and the Bedroom (S3, S5) even for the case of hempcrete walls with significantly lower thermal resistance (H1, H2: Table 5.7).

In the case of the Section S1 of the Detail 2 (D2) (Table 5.6), which accounts for the section with the timber column close to the bathroom tiles, no particular conclusions can be derived regarding a possible higher performance of any hempcrete option, since the number of condensation hours for the different hempcrete design options remains quite close. Nevertheless, the latter indicates a smaller sensitivity of the possibility of condensation to the thermal conductivity value of the hempcrete in the current location. A higher sensitivity to the thermal conductivity however can be detected for untiled wall in the Section S4 of the Detail 1, (Table 5.6), where again a timber column is present for the support of the window, and in general the hempcrete options H1 and H2 with almost similar thermal conductivities (λ_{H1}=0.11 W/(mK) - λ_{H2}=0.115 W/(mK)) are characterised by similar condensation hours (51,52).

It is also worth mentioning here that the hempcrete H3 which has the lower thermal conductivity (λ_{H3}=0.073 W/(mK)) is characterised by the poorest performance, whereas the hempcrete H4, which has a slightly higher thermal conductivity (λ_{H4}=0.09 W/(mK)) shows better performances even when compared to the hempcrete wall that meets the thermal resistance requirement of the Bouwbesluit (Table 5.7). Both the aforementioned hempcrete compositions are characterised by similar characteristics. The main difference in their performance can be therefore attributed to their sorption curves (Figure 5.1). H4 is characterised by a higher sorption curve which can result to a more efficient buffering of high RH levels.

5.3.3. THE ISOPLETHS

In order to assess the risk of growing mould on the spruce column of Detail 2, the isopleths of two of its sides which are more exposed to moisture (sides towards the exterior and the interior) were plotted. Parts of the graph with lighter colours (yellow) account for time steps close to the start of the simulation, whereas darker colours (black) represent the conditions close to the end of the simulation (10 years). The risk limits are represented by the lines LIM I (Biological materials) and LIM II (Porous building materials). For the case of the risk in the spruce, the risk limit according to LIM I is taken into account.

Regarding the side towards the interior, the spruce's isopleths show no remarkable differences between the four hempcrete options. They are characterised by a very low risk, which decreases rapidly with time as the spruce dries out. The isopleth diagram for hempcrete 1 and 3 can be seen in the Figure 5.7. The diagrams for the other two options can be found in the Annexes (Figure A.18).

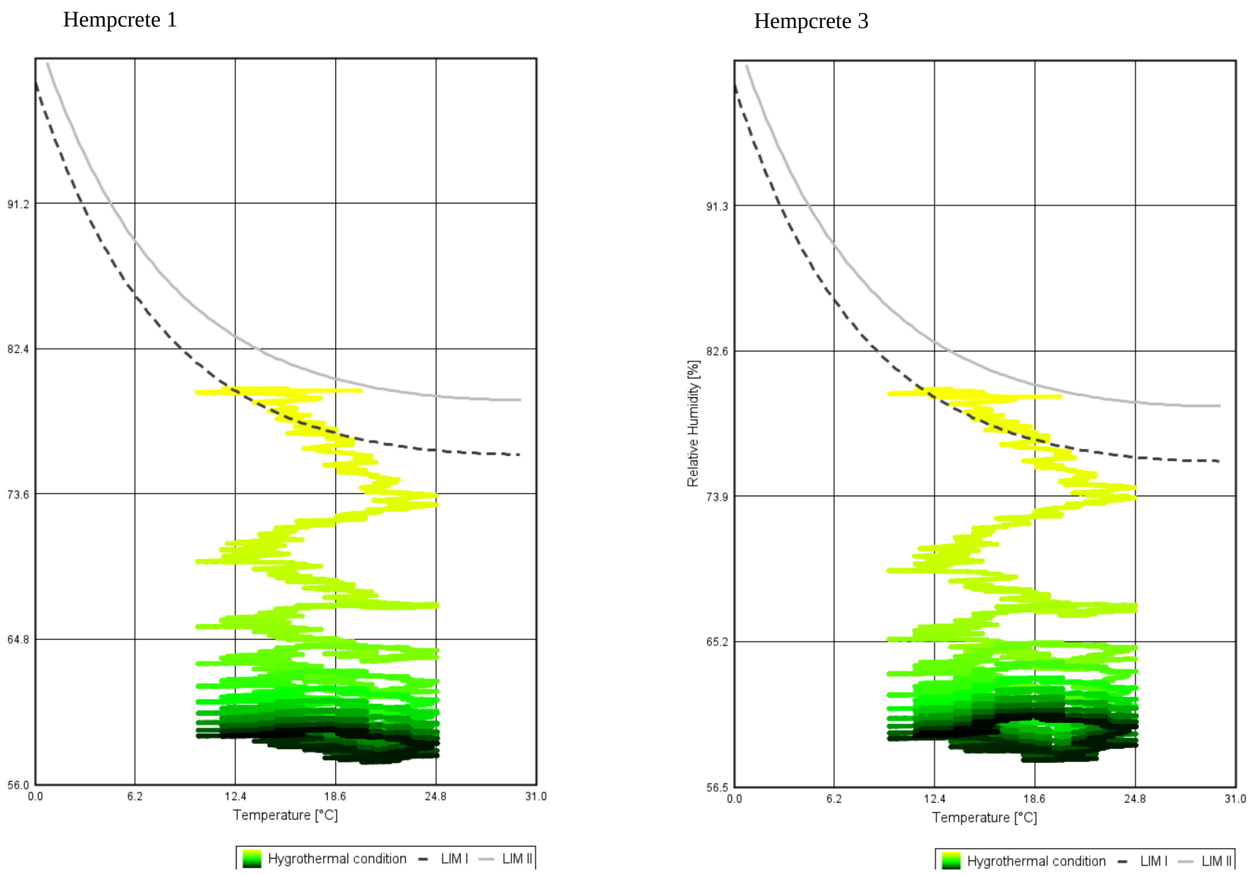


Figure 5.7: Isopleths on the inner side of the spruce column - Detail 2.

Nevertheless, some differences in the performance of the spruce column can be detected for the case of the side towards the exterior which is subjected to higher moisture loads due to rain (Figure 5.9). In this case the water absorption of the hempcrete plays a crucial role and influences the risk of mould growth remarkably. Even though the spruce in all four hempcrete options remains in general under the critical lines with only a few exceptions which are recorded early in the simulation (yellow colour) when the section is still highly influenced by the initial conditions (RH=80%), someone can still detect the better performance of the spruce column which is surrounded by Hempcrete 1. The lower water absorption of the respective hempcrete hinders the propagation of rain water towards the spruce, which would create favourable conditions for mold growth. The isopleth graph quickly comes away from the critical lines in comparison to the other three hempcrete options where values close to the critical lines are still detected also later in the simulation (darker colours close to critical lines). This high influence of the water absorption can be better understood when the isopleth diagrams between Hempcrete 1 and Hempcrete 2 are compared (Figure 5.9),in which case the thermal conductivity between the materials is almost the same (around $0.11 W/(mK)$) but the water absorption potentials are more than doubled ($H_1 : 0.074\ kg/m^2/s^{0.5}$ - $H_2 : 0.17\ kg/m^2/s^{0.5}$). In general, spruce column performs the worst when it is combined with the Hempcrete 2 (Figure 5.9), due to its lower thermal conductivity and higher water absorption. Regarding the influence of the thermal conductivity of hempcrete, some conclusions can be drawn, by assessing the isopleth diagrams for the Hempcrete 3 and Hempcrete 4 designs (Figure 5.9) which have are characterised by the same water absorption but different thermal conductivity values. The performance of spruce in the Hempcrete 3 design appears to be slightly better, as the graph approaches the critical lines less frequently than that of the spruce which is surrounded by Hempcrete 4.

The same features as described above can be detected in the case of the spruce frame which supports the window in Detail 1. The respective isopleth graphs are displayed in the Annexes (Figure A.19, Figure A.20).

The isopleth graphs for the optimised case in which hempcrete is characterised by the lowest thermal conductivity, enough thickness to meet the requirements of the Bouwbesluit and adequate absorbance to protect the wooden columns from the external moisture without hindering its drying capacity are depicted in Figure 5.8. The results appear improved regarding the risks, since the risk of mold on the spruce decline even more throughout the years.

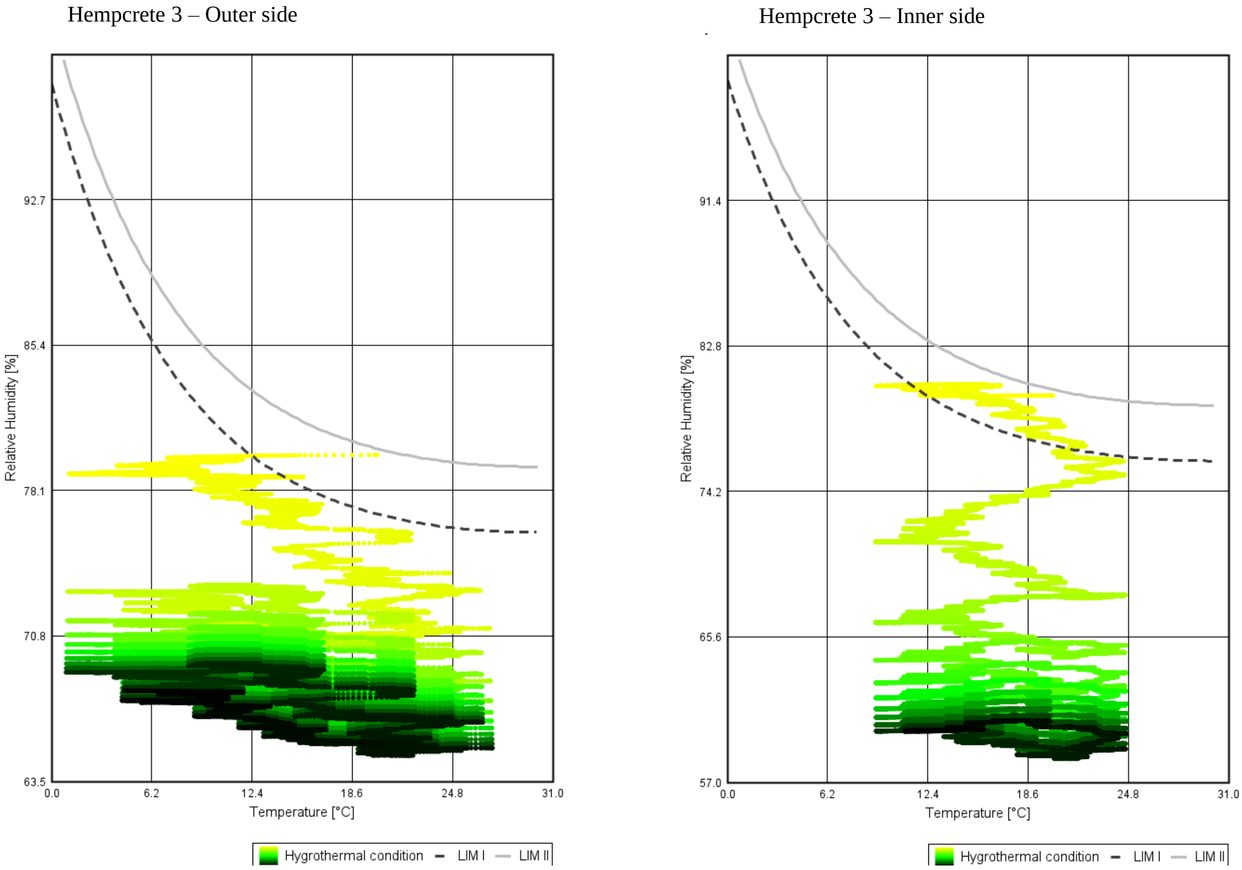


Figure 5.8: Isopleths for the inner and outer side of the spruce column in the optimised case - Detail 2.

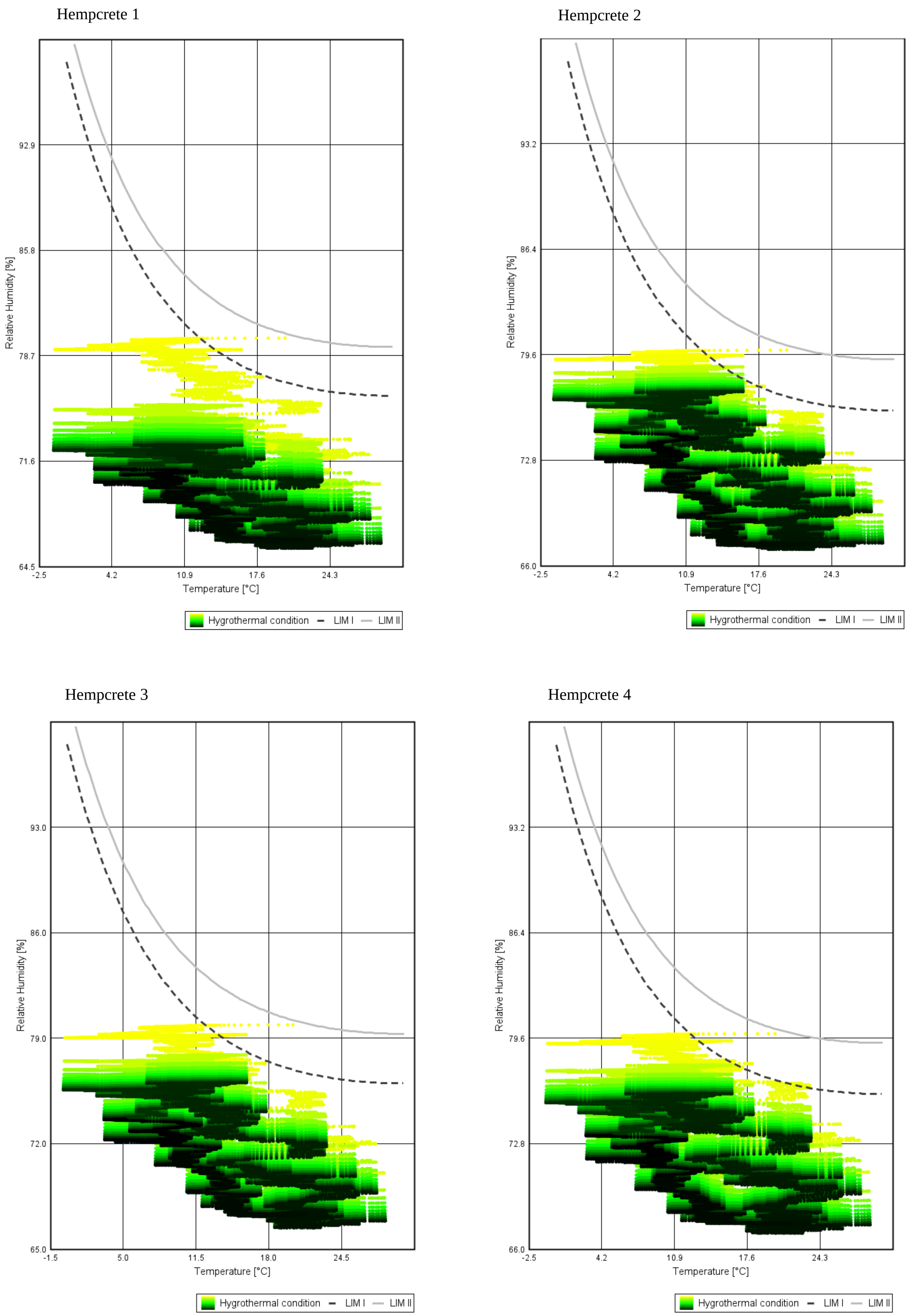


Figure 5.9: Isopleths on the side of the spruce column towards the exterior - Detail 2.

5.3.4. THE WATER CONTENT AND RH

Two important factors that can influence the thermal performances of a material are the water content and the RH that are present inside it. Both these factors had been assessed in the details under scrutiny for the three different material assemblies. For the details D1 and D2, the results show that the walls are properly designed since the water content decreases after time both inside the wall and in the spruce. By looking on the water content graph of the hempcrete options, it can be observed that for H3 and H4 the water content lines remain in ranges that account for around the half of the respective ranges for hempcretes H1 and H2. This aspect reflects the image of their sorption graphs. For the optimised H3$_{R}d$ option where the thickness of the material is higher (35cm instead of 30cm) the real difference in the results of the walls water content is not clearly shown by the graph. Therefore, dividing the value derived in the last timestep by the walls thickness shows:

- For H3: 15.55 (kg/m^3)/0.30 (m) = 51.83 kg/m^2
- For H3$_{Rd}$:14.99 (kg/m^3)/0.35 (m) = 42.83 kg/m^2

In addition, in the spruce's graph of the optimised H3$_{RD}$, three important features can be detected. The first one is regarding the overall decrease in the water content of the spruce which in comparison to the rest of the hempcrete option is the sharpest. Regarding the second feature, the water content gains during the winter period appear milder in comparison to the rest of the hempcrete options. Lastly regarding the third feature, the difference between the graph of of the spruce in the case of H3$_{R}D$ increase as the simulation time passes, which means that even with the decrease in the water absorption capacity of the hempcrete (in comparison to H2,H3,H4), the spruce's drying due to the initial conditions of the simulation is not impeded.

Both the aforementioned improved features can be attributed to two factors: the decreased water absorption capacity (in comparison to hempcrete options H2,H3,H4) and the increased thickness of the hempcrete layer before the column (+2.5 cm).

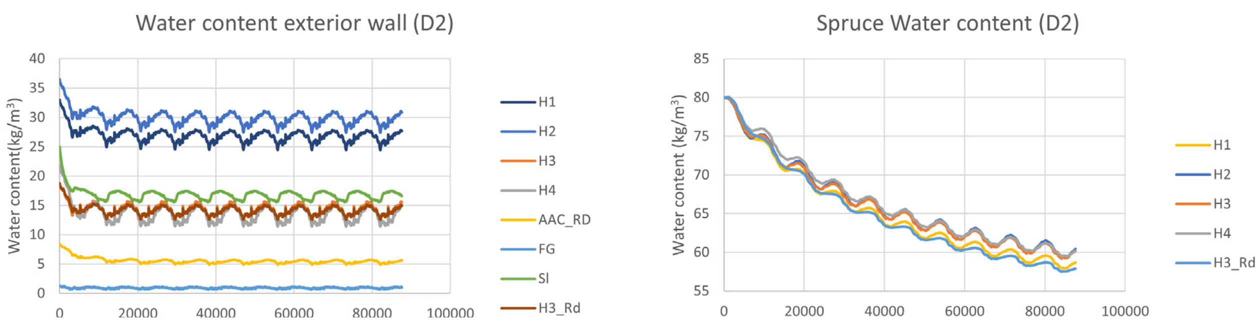


Figure 5.10: Water content for materials in detail D2 - Hempcrete wall (left) and spruce (right).

The relative humidity on the inter layers between the materials for the sections of the detail D2 and section S4 of detail 1 is presented in the following figures. The same characteristics as in the water content graphs can be also detected here. The hempcrete options with the higher water absorption capacity allow higher amounts of moisture to reach the outer surface of the spruce column (Table 5.10), whereas the lower maximum RH level is detected in the optimised $H3_{RD}$ case (69.3 %). Nevertheless, for none of the hempcrete options in details D2, RH on the outer layer of the spruce surpasses 80% - which is a critical value frequently associated with mold growth and degradation -. When RH on the layer between the clay and the hempcrete is compares for S1 and S2, it can be seen that the tiles which work as a water barrier influence slightly the RH, and therefore higher values are detected at the S1 which is close to the tiles. For the case of the AAC, the RH levels on the surface towards the exterior, between the AAC and the mortar appear decreased in comparison to the other options. The same characteristic can be seen in the hempcrete options with the lower sorption curves (H3,H4). That shows the influence of the sub-layer's water capacity on the moisture that eventually passes the mortar.

The same trends can be observed also in the case of the Section S4 (Table 5.10). However, in this case, where the timber column is more exposed to the outdoor environment, RH levels higher than 80% eventually manage to reach the supporting timber column for the case of H2.

Detail D2									
	Section 1			Section 2			Section 3		
Design option	Surface	Max RH(%)	Hours*	Surface	Max RH(%)	Hours	Surface	Max RH(%)	Hours *
H1	Clay	86.6	18	Clay	85.9	14	Lime	69.8	0
	Clay Hempcr.	67.9	0	Clay Hempcr.	68.9	0	Clay Hempcr.	64.6	0
	Hempc. Spruce	61.5	0	Hempcr. Lime	96.2	3488	Hempcr. Lime	96.2	3488
	Spruce Hempc.	72.5	0	Lime	99.1	4110	Lime	99.1	4123
	Hempc. Lime	96.2	3476	-	-	-	-	-	-
	Lime	99.1	4115	-	-	-	-	-	-
H2	Clay	86.8	22	Clay	86.1	13	Lime	69.9	0
	Clay Hempcr.	67.8	0	Clay Hempcr.	68.9	0	Clay Hempcr.	64.6	0
	Hempc. Spruce	62.7	0	Hempcr. Lime	96.1	3481	Hempcr. Lime	96.1	3471
	Spruce Hempc.	77.1	0	Lime	99.1	4099	Lime	99.1	4118
	Hempc. Lime	96.1	3462	-	-	-	-	-	-
	Lime	99.1	4104	-	-	-	-	-	-
H3	Clay	86.0	13	Clay	85.2	6	Lime	69.5	0
	Clay Hempcr.	69.6	0	Clay Hempcr.	69.9	0	Clay Hempcr.	65.3	0
	Hempc. Spruce	62.7	0	Hempcr. Lime	95.3	3568	Hempcr. Lime	95.3	3566
	Spruce Hempc.	75.9	0	Lime	99.1	4170	Lime	99.1	4187
	Hempc. Lime	95.3	3523	-	-	-	-	-	-
	lime	99.1	4161	-	-	-	-	-	-
H4	Clay	86.3	15	Clay	85.6	11	Lime	69.8	0
	Clay Hempcr.	68.8	0	Clay Hempcr.	69.1	0	Clay Hempcr.	66.0	0
	Hempc. Spruce	62.6	0	Hempcr. Lime	95.3	3396	Hempcr. Lime	95.3	3396
	Spruce Hempc.	75.8	0	Lime	99.1	4143	Lime	99.1	4158
	Hempc. Lime	95.3	3383	-	-	-	-	-	-
	lime	99.1	4140	-	-	-	-	-	-

*Hours when RH>80
The results are presented from the interior towards the exterior

Table 5.8: Rh at the interface of the hempcrete layers.

5

Detail D2									
	Section 1			Section 2			Section 3		
Design option	Surface	Max RH(%)	Hours*	Surface	Max RH(%)	Hours*	Surface	Max RH(%)	Hours *
H3$_{Rd}$	Clay	86.0	12	Clay	85.2	6	Lime	69.3	0
	Clay Hempcr.	69.4	0	Clay Hempcr.	69.9	0	Clay Hempcr.	65	0
	Hempc. Spruce	62.2	0	Hempcr. Lime	95.3	3555	Hempcr. lime	95.3	3547
	Spruce Hempc.	69.3	0	lime	99.1	4188	lime	99.1	4199
	Hempc. Lime	95.3	3519	-	-	-	-	-	-
	Lime	99.1	4180	-	-	-	-	-	-
AAC$_{Rd}$	-	-	-	Cement Plaster	84.1	6	Cement Plaster	69.3	0
	-	-	-	Cement Plaster AAC	67.5	6	Cement Plaster AAC	66	0
	-	-	-	AAC Cement Plaster	86	3456	AAC Cement Plaster	85.8	3409
	-	-	-	Cement Plaster	99.9	3950	Cement Plaster	99.9	3959
SL	-	-	-	Cement Plaster	90.1	50	Cement Plaster	71.2	0
	-	-	-	Cement Plaster SL	68.9	0	Cement Plaster SL	67.4	0
	-	-	-	SL FG Ins.	78.1	0	SL FG Ins.	78.9	0
	-	-	-	FG Ins. Cement Plaster	96.9	3145	FG Ins. Cement Plaster	96.5	31270
	-	-	-	Cement Plaster	96.2	3998	Cement Plaster	96.2	4007

*Hours when RH>80

The results are presented from the interior towards the exterior

Table 5.9: Rh at the interface of the material layers - same R$_d$.

Detail D1									
Section 4									
	H1			H2			H3		
	Surface	Max RH(%)	Hours*	Surface	Max RH(%)	Hours	Surface	Max RH(%)	Hours *
	Clay	85.9	14	Clay	86.1	16	Clay	85.2	11
	Clay Hempcr.	68.6	0	Clay Hempcr.	68.5	0	Clay Hempcr.	69.7	0
	Hempc. Spruce	63.9	0	Hempc. Spruce	63.9	0	Hempc. Spruce	64.8	0
	Spruce Hempc.	76.3	0	Spruce Hempc.	80	54	Spruce Hempc.	77.8	0
	Hempc. Lime	96.6	3964	Hempc. Lime	96.5	4034	Hempc. Lime	95.3	3514
	Lime	99.2	4457	Lime	99.2	4448	Lime	99.2	4170

	H4				$H3_{RD}$		
	Surface	Max RH(%)	Hours*		Surface	Max RH(%)	Hours *
	Clay	85.4	11		Clay	85.2	10
	Clay Hempcr.	68.9	0		Clay Hempcr.	68.8	0
	Hempc. Spruce	64.8	0		Hempc. Spruce	63.6	0
	Spruce Hempc.	78.1	0		Spruce Hempc.	69.4	0
	Hempc. Lime	95.3	3383		Hempc. Lime	92.1	3294
	Lime	99.2	4153		Lime	94.6	4171

	AAC_{RD}				SL		
	Surface	Max RH(%)	Hours*		Surface	Max RH(%)	Hours *
	Cement Plaster	79.8	6		Cement Plaster	84.2	25
	Cement Plaster AAC	66.4	0		Cement Plaster SL	68.5	0
					SL FG Ins.	76.8	0
					FG Ins. SL	68.6	0
	AAC Cement Plaster	85.3	2884		SL Cement Plaster	98.5	3140
	Cement Plaster	95.9	3886		Cement Plaster	96.1	3954

*Hours when RH>80

The results are presented from the interior towards the exterior

Table 5.10: Rh at the interface of the hempcrete layers.

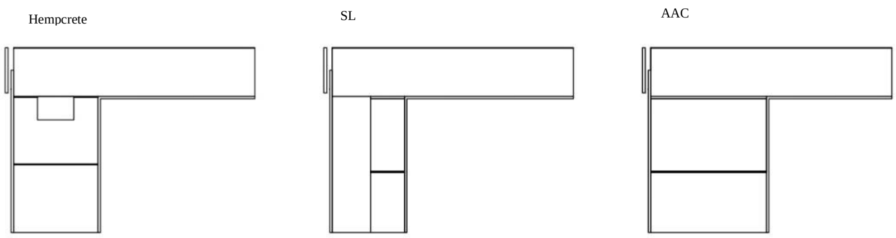
5

5.3.5. THE DRIVING RAIN

The biobased nature of hempcrete creates the necessity to assess its performances under high rain loads. For this reason the optimised option of hempcrete ($H3_{Rd}$), as it was formulated from the conclusions derived by the Details 1 and 2, was assessed in Detail 3 (Roof connection - Driving rain facade) in comparison to the equally thermal resistant SL and the AAC walls.

In order to reduce the computational time and the complexity of the model in WUFI-2D, the layers above the insulation, namely the air-layer between the insulation and the tiles, the wooden roof battens and the tiles, were not included in the model. This simplification is regarded acceptable for the following reasons:

- The ommitance of the three aforementioned layers influences slightly the thermal resistance of the roof.
- The ommitance serves towards the safe conservative side. Ommiting these layers leads to a slight decrease of the thermal resistance of the roof. As a result, the results will be slightly more conservative than the reality.
- The section which is assessed is part of the external wall and not part of the roof it self. Hence, the influence of such ommitance is considered negligible.



Material	Thickness (m)	Conductivity (W/mK)	Vapour resistance factor (-)
Gypsum Plaster	0.01	0.20	8.3
PIR Insulation	0.20	0.024	72
Water resistant layer	0.001	2.3	200
Rc (m^2/KW)	8.4		

Figure 5.11: Configuration of the simulated Detail 3 - Roof (Vertical section).

Nevertheless, the insulation in the reality is protected from the direct water rain by the tiles. This aspect needs to be included in the simulation. As a result, the direct rain was excluded from the external boundary condition that was assigned to the roof and during a rain incident, the insulation is affected only by the the high moisture levels and not by a direct water contact. According to the aforementioned the assessed detail was formed according to the Figure 5.11.

After running the simulations for the case of the Hempcrete and the AAC, it was observed that the high amounts of rain vertical to the facade resulted in accumulation of water in the walls which indicates that the current design could be problematic. According, to the literature the amount of moisture that remains inside the material after summer, should not exceed a maximum value depending each time on the type and thickness of the material. This maximum value for hempcrete is:

- $30 \times \rho \times d$ [g/m^2]: for hempcrete as an organic material [16]
- Which for the case of the current wall is equal to: $30 \times 405 \times 0.35 = 4.25$ [kg/m^2]
- The amount of water content that remains in the material after summer (Figure (5.13) is : $(116 - 60) \times 0.35 = 19.6 > 4.25$ [kg/m^2]
- The amount of water content that remains in the material after summer when water protection is used (Figure (5.13) is: $(10.8\text{-}8.7) \times 0.35 = 0.74 << 4.25$ [kg/m^2]

5

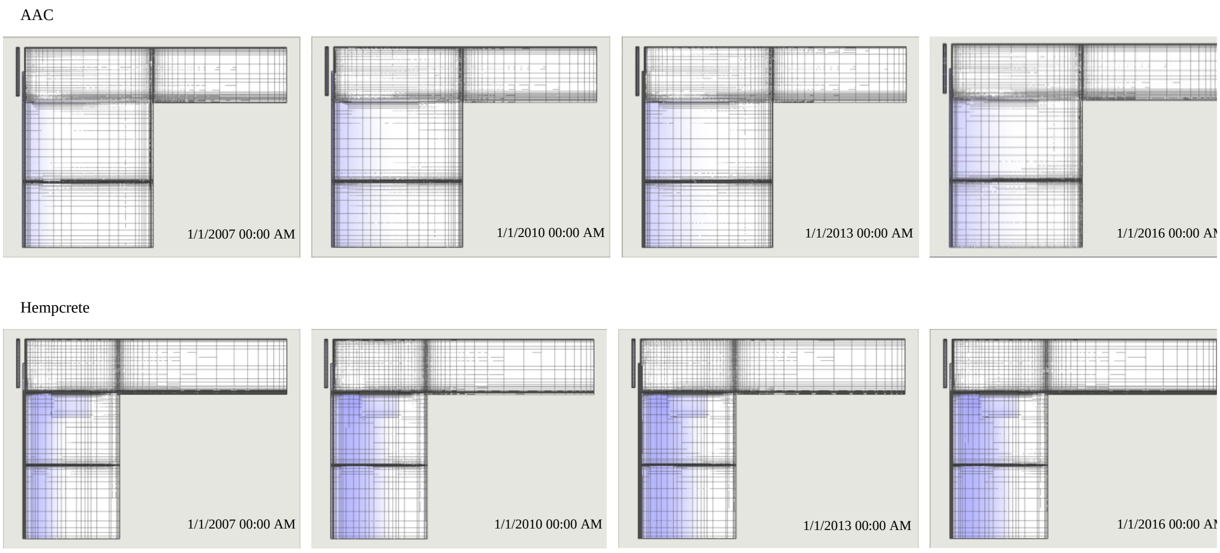


Figure 5.12: Water accumulation in the simulated details for the case of AAC and Hempcrete.

Thus, a cladding or a mortar that is waterproof enough to act as a barrier for the liquid water but simultaneously vapour permeable is needed to protect the wall from the driving rain. The protecting effect of cladding was implemented in the simulation in the same way as the effect of ceramic roof tiles, and the rain was excluded from the external boundary condition. Hence, during a rain incident the wall is influenced by the high moisture level but not by a direct contact with the rain water. The water content in Hempcrete is indeed declined and stabilised after the influence of the initial conditions has finished. The water content decrease after the implementation of the cladding effect in the simulation was around 90% (from more than 105 [kg/m^3] to less than 11 [kg/m^3]). The aforementioned results showed that if the amount of rain is high, a water barrier or cladding might be needed.

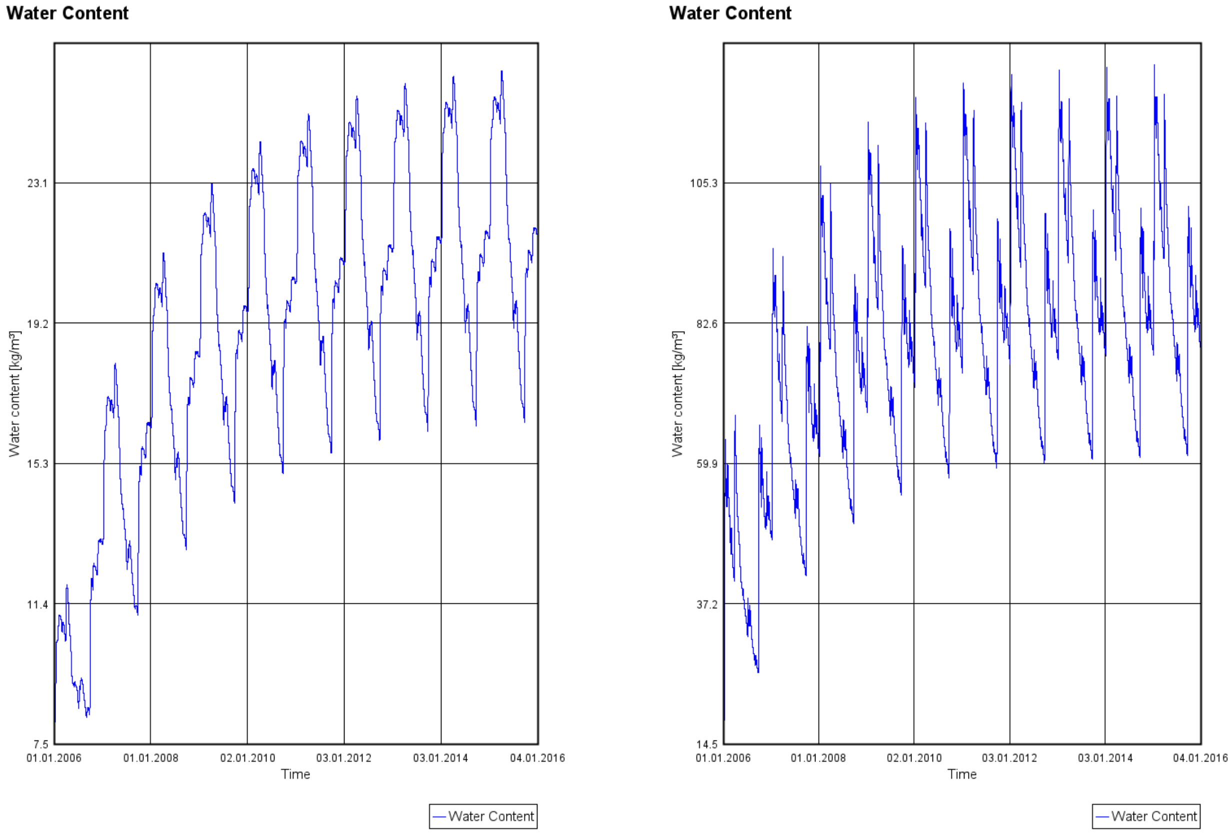


Figure 5.13: Water content in the simulated details for the case of AAC (left) and Hempcrete (right).

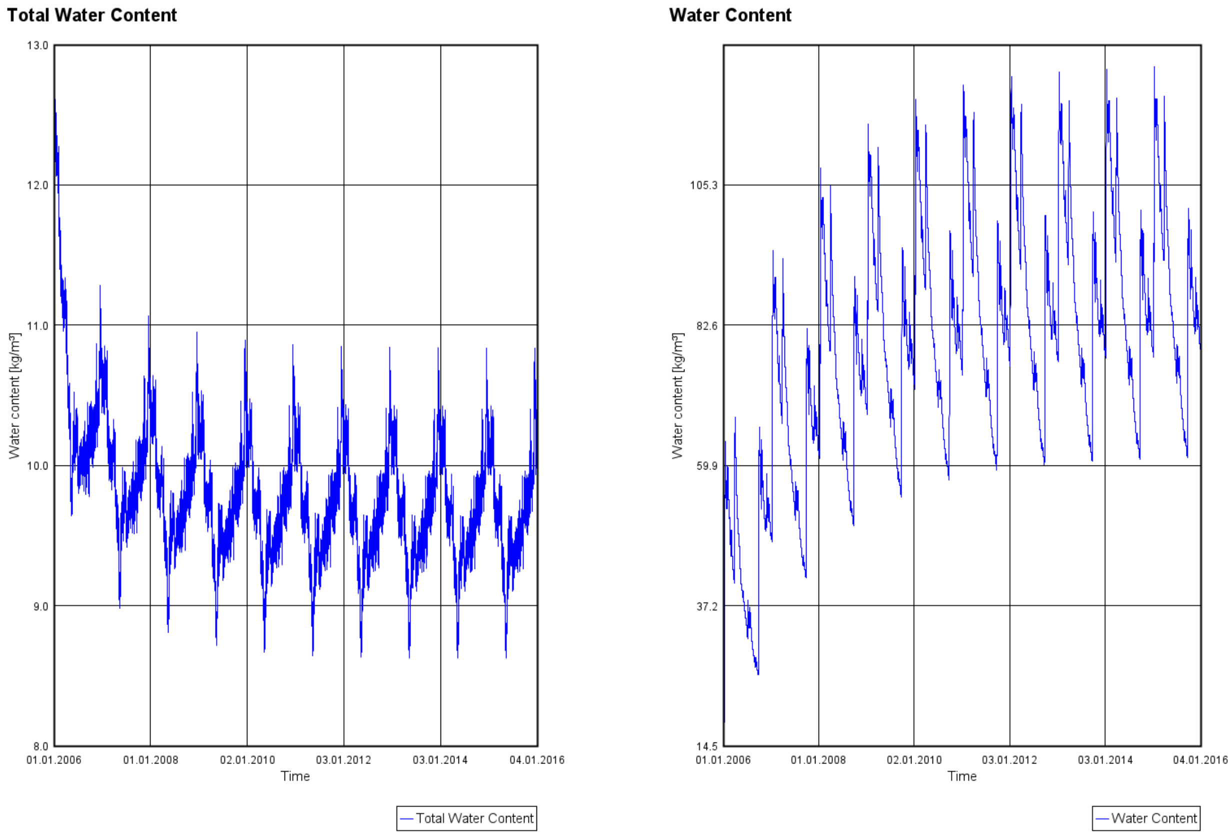


Figure 5.14: Water content in the simulated details for the case of of hempcrete $H3_{Rd}$. Protected case (left) and initial case (right).

5.4. THE ASSESSMENT OF HYGROTHERMAL BEHAVIOR OF THE DIFFERENT MATERIALS

In order to visualise the hygrothermal behaviour of the different materials WUFI RH isolines were exported for one date in the year during the critical month (March) when a shower and precipitation occurred simultaneously. High levels of driving rain on the facade (0.9) before the assessed period (31/3/2015 7:00 AM -12:00 PM) have led to high RH levels (around 84%) on the facade. In the following section only the figures that contribute to the relevant discussion are present. The rest can be found in the Annexes (Figures A.29-A.52).

The four hempcrete options

5

When the four hempcrete options are compared to each other, the influence of the composition and the production process is noticeable, as hempcretes that have been created by the same researcher show more hygrothermal behavior similarities (H1 with H2 and H3 with H4). In addition, some differences in their moisture regulation capacities can be observed. Hempcretes which are characterised by the higher sorption curves (H1,H2 - Figures 5.15-5.20) show a slightly increased moisture buffering capacity as the respective isolines appear to have moved deeper in the facade (e.g. Figure 5.15 - Isoline 60% RH). This moisture buffering capacity can be beneficial for the regulation of the indoor RH levels and the establishment of comfort. In addition, in the case of the same hempcretes (H1,H2), moisture seems to be better distributed inside the wall. The latter can be understood by the shape of the isolines which appear smoother than in the case of H3 and H4, where sometimes even local areas with lower RH levels can be detected (e.g. Figures 5.18-5.20 H3, Figure 5.15-H4 corner). This characteristic can be beneficial in the areas where hempcrete is in contact with timber, since higher moisture levels which may be present in timber due to rain, can be buffered and absorbed faster by the hempcrete wall. An example of the latter can be observed in Figure 5.15, in the area under the window where timber is in contact with the hempcrete wall. For H3, slightly higher levels of RH seem to be present in the area. On the other hand however, RH levels in the respective area appear smoother even though H4 is still characterised by a lower sorption curve in comparison to H1 and H2. The main reason for that is the thermal conductivity of H4 which in comparison to the other hempcrete options approaches closer to that of the wood. Despite the aforementioned differences in the hygrothermal performance of the hempcretes under scrutiny and the higher capacity of moisture absorption of H1,H2, it is worth mentioning here that eventually the moisture levels in the middle of the wall remain the same for all the hempcretes under scrutiny. The latter can be detected by observing the isoline of 66% RH which stays stable in the same location for all the hempcretes and time moments under scrutiny. Therefore the higher moisture which is absorbed by H1 and H2 is eventually distributed along the wall and not accumulated.

The same characteristics can be detected in Detail 2. However, in this case the influence of the water absorbance of the hempcrete can be noticeable too. In Figure 5.23, H1 which is characterised by lower water absorption capacity but similar thermal conductivity and sorption curve to those of H2, has resulted to lower RH levels to be present within the spruce column. The Isoline of 73% RH remains in the hempcrete area before the spruce whereas for the rest of the hempcrete options, the respective Isoline creates a circular high RH area within the spruce. The influence of the shower is slightly noticeable for the hempcretes H3, H4 (Figures 5.24, 5.25).

The different materials

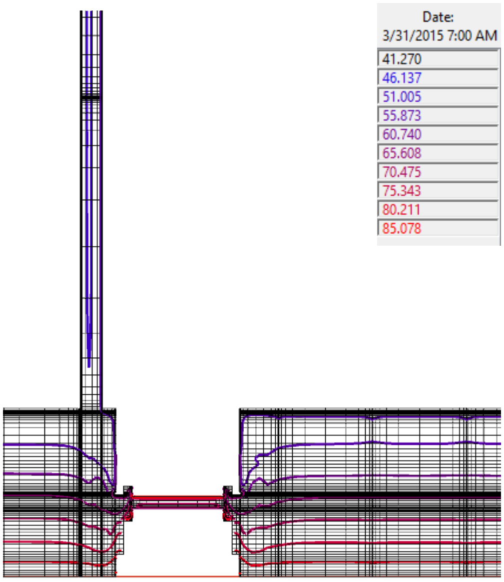
A different image is detected when the different designed walls (Hempcrete, SL, AAC) are compared to each other. For the case of the materials with the highest moisture buffering capacity (Hempcrete and AAC) the RH humidity levels are gradually decreased from the exterior to the interior. This is not the case for the SL designed wall however. The differences in the vapour resistance values (μ) between the FG insulation (μ=1 (-)) and the SL bricks (μ= 25(-)) restrict the RH which is easily undertaken by FG (due to its low moisture resistance value) inside the insulation. As a results high amounts of RH are present inside the insulation (Red Isolines of 76% RH with the same colour: Figure 5.26) which can decrease its insulating capacity. The SL Bricks are not eventually influenced by the RH levels and the central low RH areas inside them remain stable (Figure 5.21, Figure 5.22). In general, RH levels inside the SL are remarkably lower than the ones in the case of AAC and Hempcrete. A characteristic example is the again detected in the central low RH area of the SL design, where the Isoline detected accounts for 43%, in the case of the other two designs however the Isoline of 59% is present at the same location.

When the hempcrete wall is compared to the AAC, the differences become more difficult to be distinguished. Again the later can be attributed to the vapour resistance factor (μ) which for the case of these two materials is very close (Hempcrete: 4.85 - AAC: 7.9). Both the aforementioned materials have a similar response to the shower incident (31.3.2015 at 10:00). The latter can be understood by observing the Isoline of 55% RH, which starts to be influenced by the indoor RH increase at 10:00 AM, moves deeper inside the wall until 11:00 AM and eventually returns at its initial location at 12:00 PM (Figures 5.26-5.27). The walls made of these two materials are able to absorb the additional moisture and stabilise the indoor environment. The SL wall has a slower response as the Isoline of 47% RH appears in the wall behind the tiles at 11:00 and remains in that place also at 12:00 PM (Figures 5.26-5.27). The extensive moisture in the case of the SL brick appears to be buffered inside the wall, as the respective Isoline goes deeper in the external wall of the adjacent room (Figure 5.27). The same feature is not present in the Hempcrete design where the Isolines do not incline but remain stable in the external wall of the adjacent room (Figure 5.27).

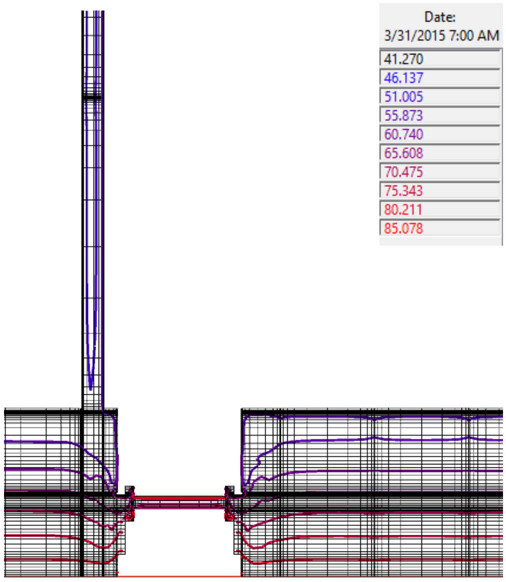
5.4.1. DETAIL 1

The four hempcrete options - 31/3/2015

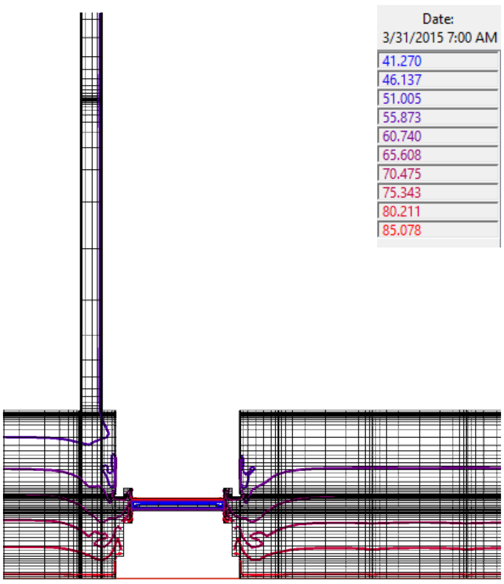
- Bathroom conditions: RH 57%, Temperature: 19.9 ^{o}C
- Bedroom conditions: RH 53%, Temperature: 17.5 ^{o}C
- Outdoor conditions: RH 75%, Temperature: 9.2 ^{o}C, precipitation: 0.2 (Driving rain)



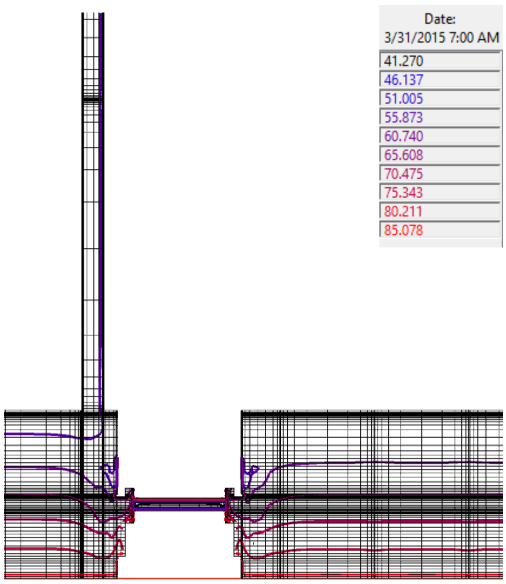
(a) Hempcrete 1



(b) Hempcrete 2



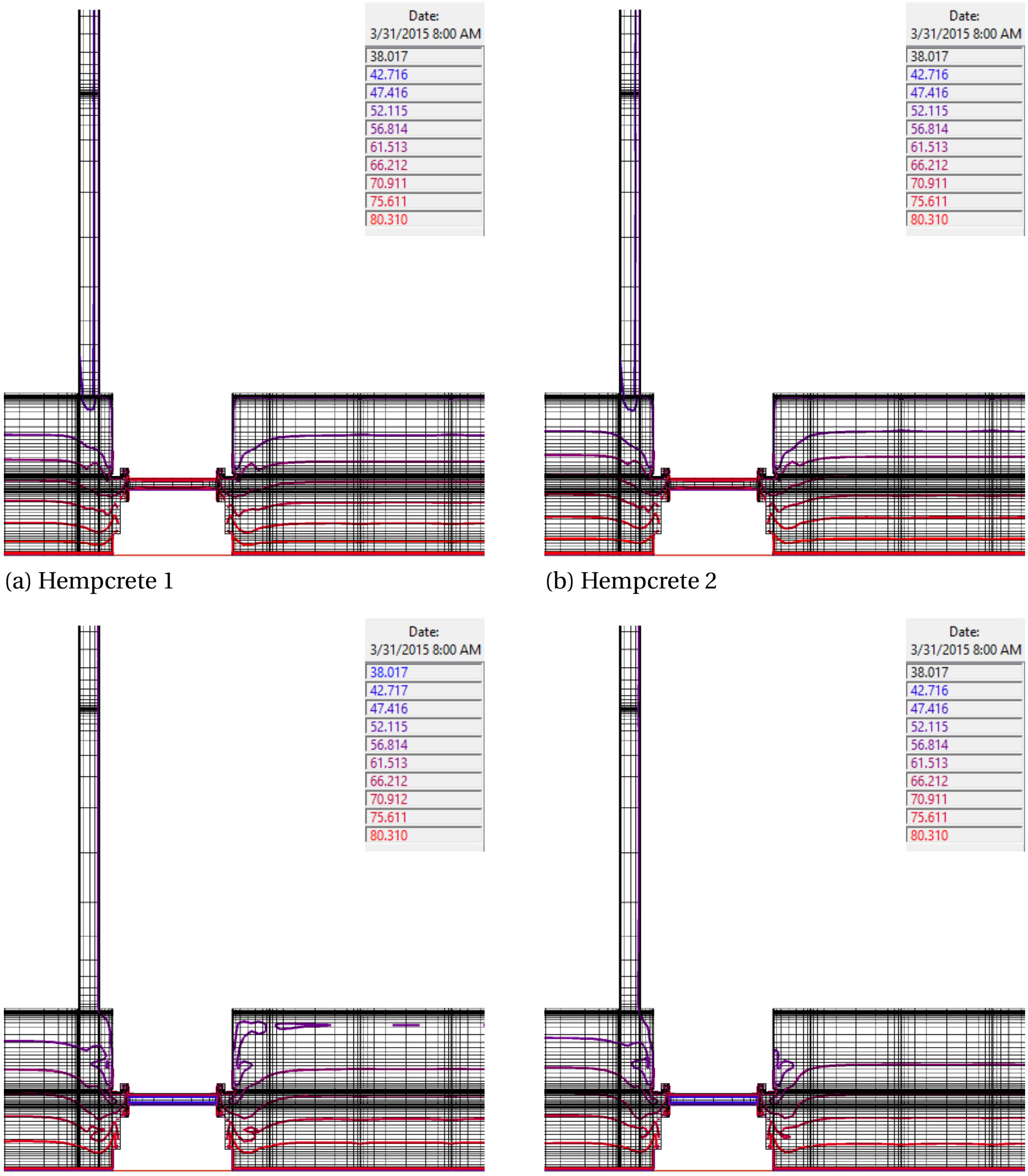
(c) Hempcrete 3



(d) Hempcrete 4

Figure 5.15: Hempcrete behaviour - Date 31/3/2015 at 7:00.

- Bathroom conditions: RH 57%, Temperature: 20 ^oC
- Bedroom conditions: RH 53%, Temperature: 17.4 ^oC
- Outdoor conditions: RH 72%, Temperature: 9.4 ^oC, precipitation: 0.1 (Driving rain)

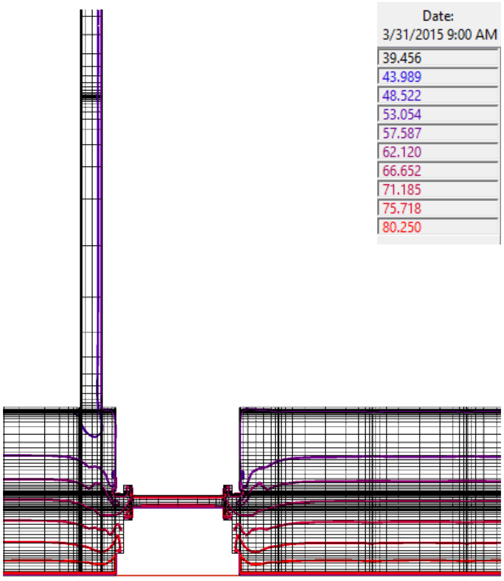


(a) Hempcrete 1 (b) Hempcrete 2

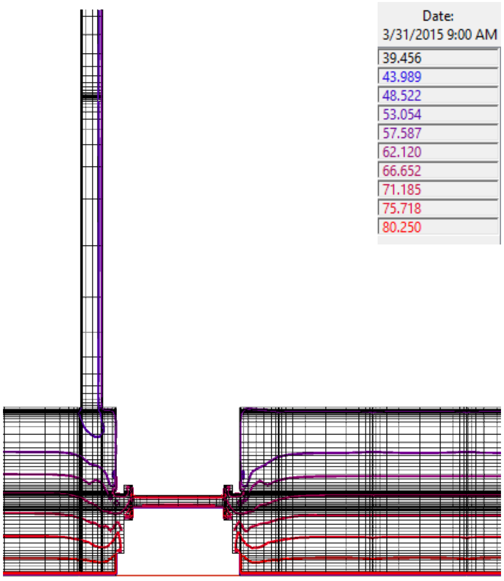
(c) Hempcrete 3 (d) Hempcrete 4

Figure 5.16: Hempcrete behaviour - Date 31/3/2015 at 8:00.

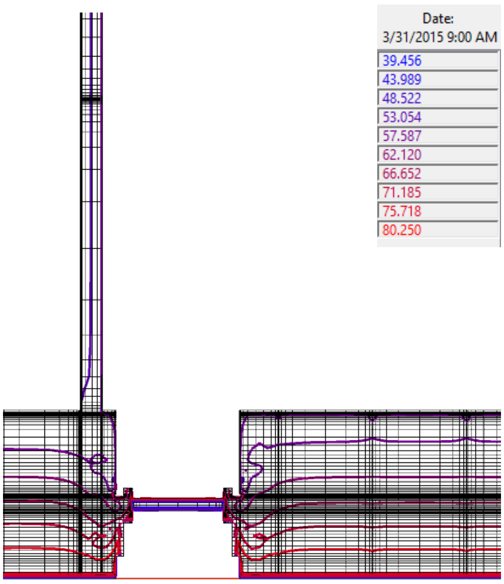
- Bathroom conditions: RH 57%, Temperature: 20.3 ^oC
- Bedroom conditions: RH 53%, Temperature: 17.4 ^oC
- Outdoor conditions: RH 69%, Temperature: 9.2 ^oC, precipitation: 0.1 (Driving rain)



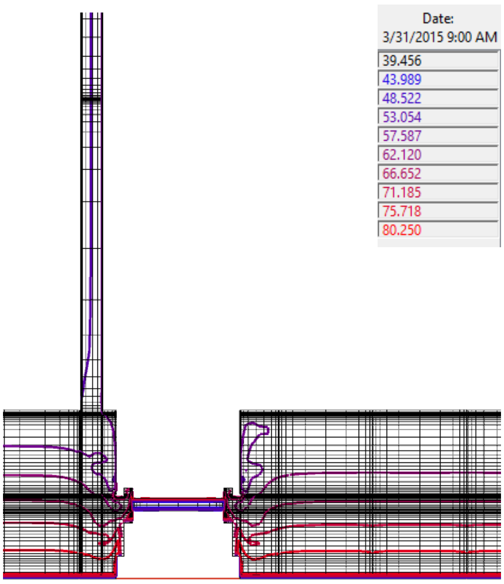
(a) Hempcrete 1



(b) Hempcrete 2



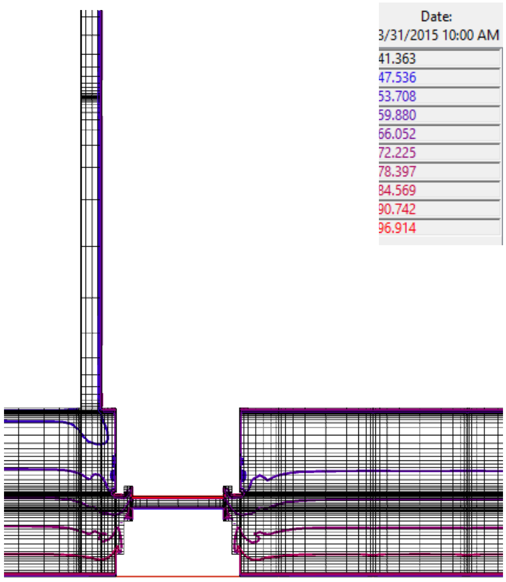
(c) Hempcrete 3



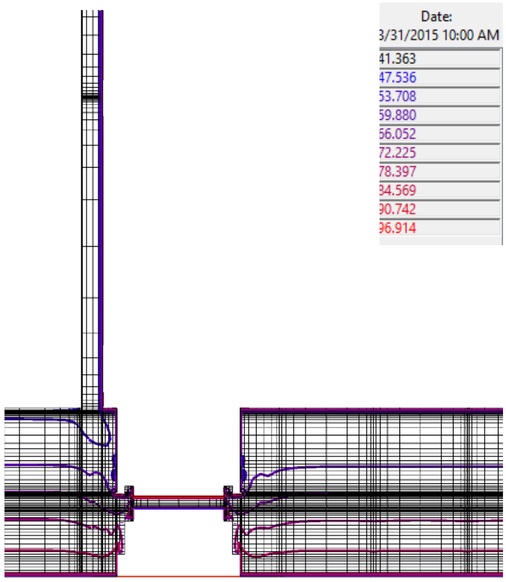
(d) Hempcrete 4

Figure 5.17: Hempcrete behaviour - Date 31/3/2015 at 9:00.

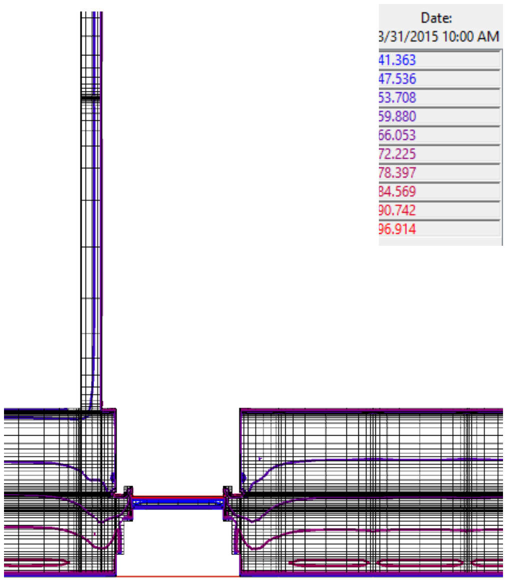
- Bathroom conditions: RH 73%, Temperature: 24.8 ^{o}C
- Bedroom conditions: RH 53%, Temperature: 17.5 ^{o}C
- Outdoor conditions: RH 69%, Temperature: 9.5 ^{o}C, precipitation: 0.4 (Driving rain)



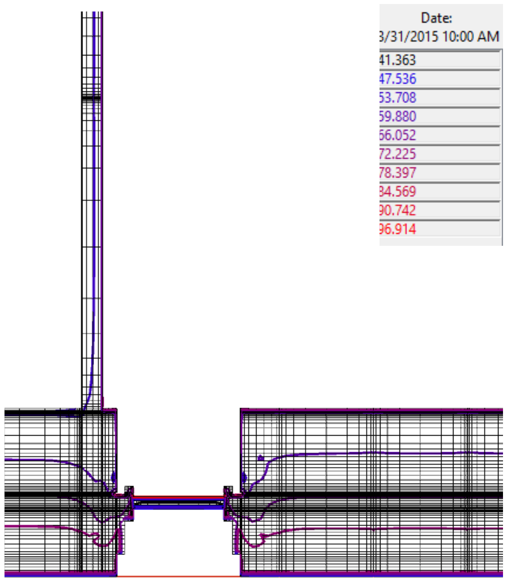
(a) Hempcrete 1



(b) Hempcrete 2



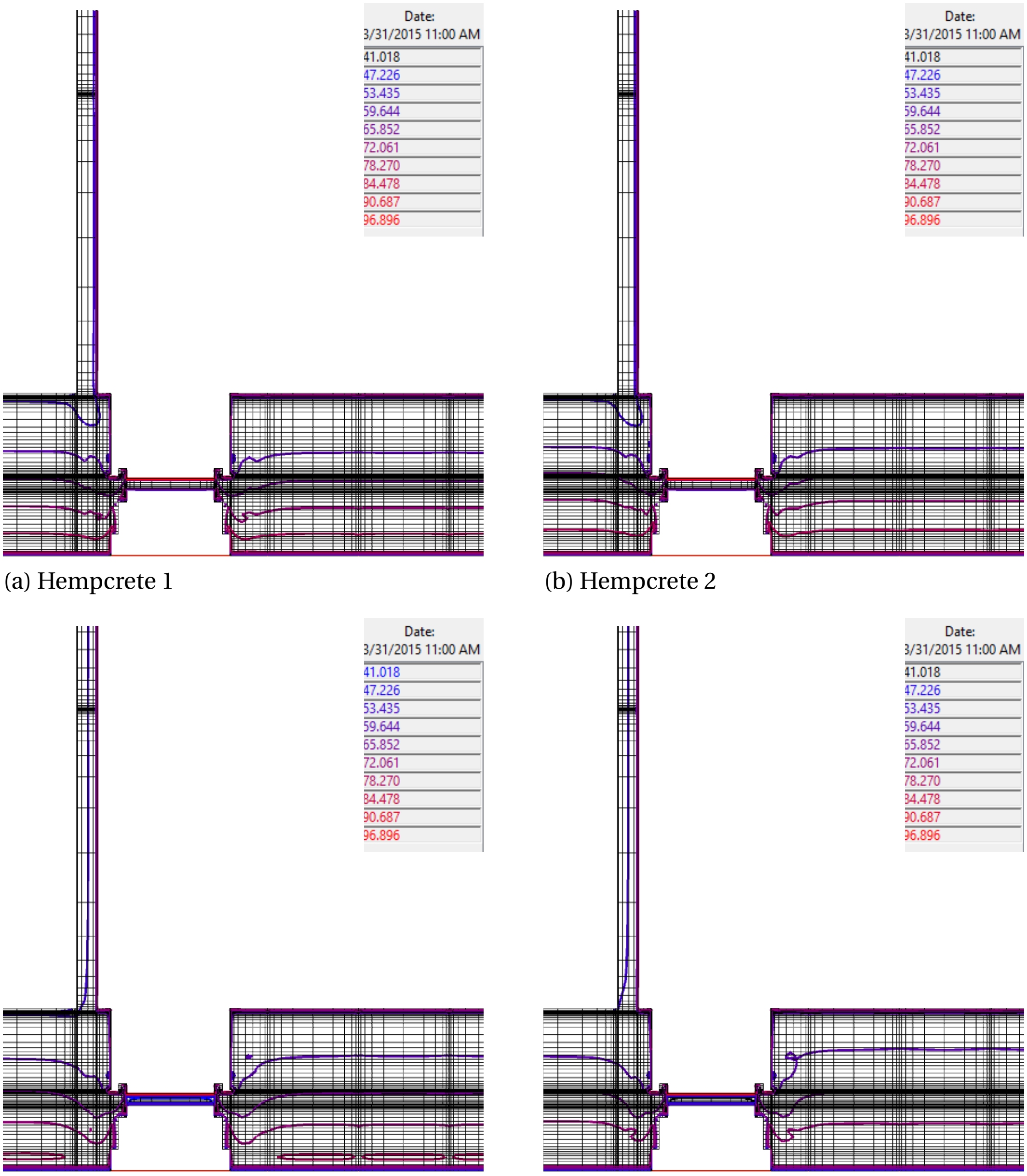
(c) Hempcrete 3



(d) Hempcrete 4

Figure 5.18: Hempcrete behaviour - Date 31/3/2015 at 10:00.

- Bathroom conditions: RH 75%, Temperature: 22 ^{o}C
- Bedroom conditions: RH 53%, Temperature: 17.4 ^{o}C
- Outdoor conditions: RH 66%, Temperature: 9.8 ^{o}C, precipitation: 0.3 (Driving rain)



(a) Hempcrete 1

(b) Hempcrete 2

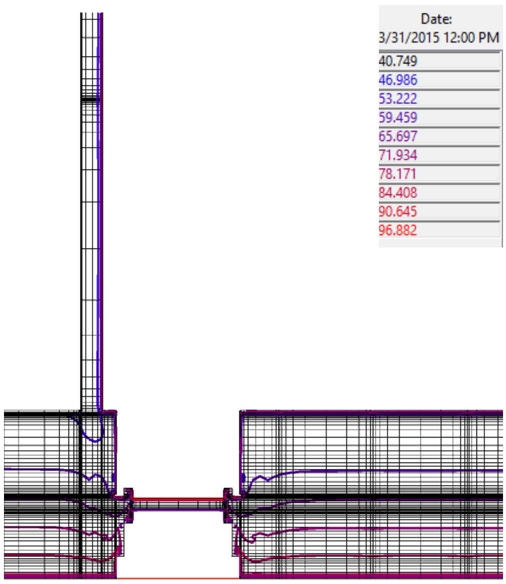
(c) Hempcrete 3

(d) Hempcrete 4

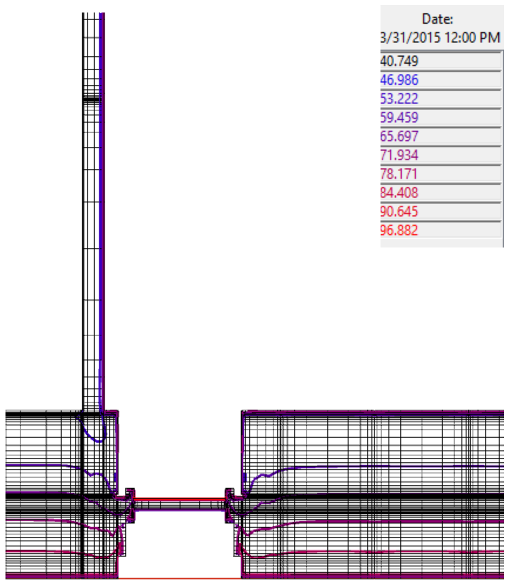
Figure 5.19: Hempcrete behaviour - Date 31/3/2015 at 11:00.

5

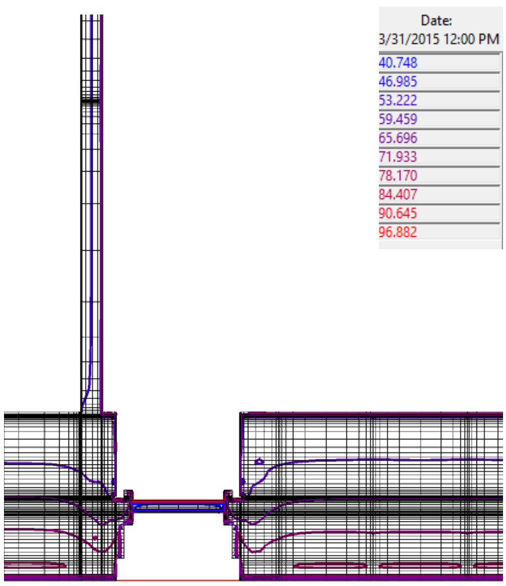
- Bathroom conditions: RH 75%, Temperature: 21.2 ^{o}C
- Bedroom conditions: RH 53%, Temperature: 17.5 ^{o}C
- Outdoor conditions: RH 69%, Temperature: 9.2 ^{o}C, precipitation: 0.1 (Driving rain)



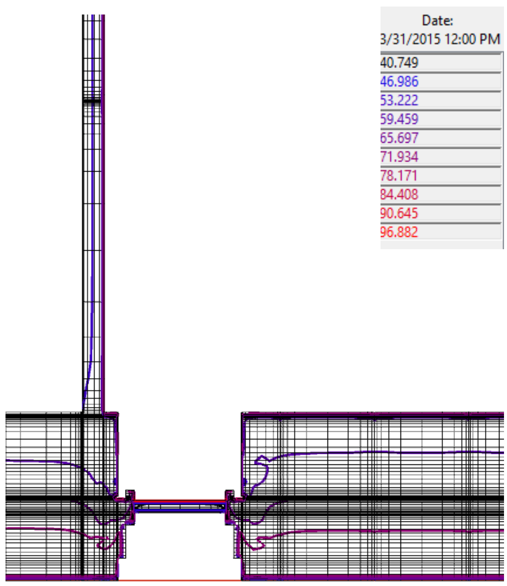
(a) Hempcrete 1



(b) Hempcrete 2



(c) Hempcrete 3

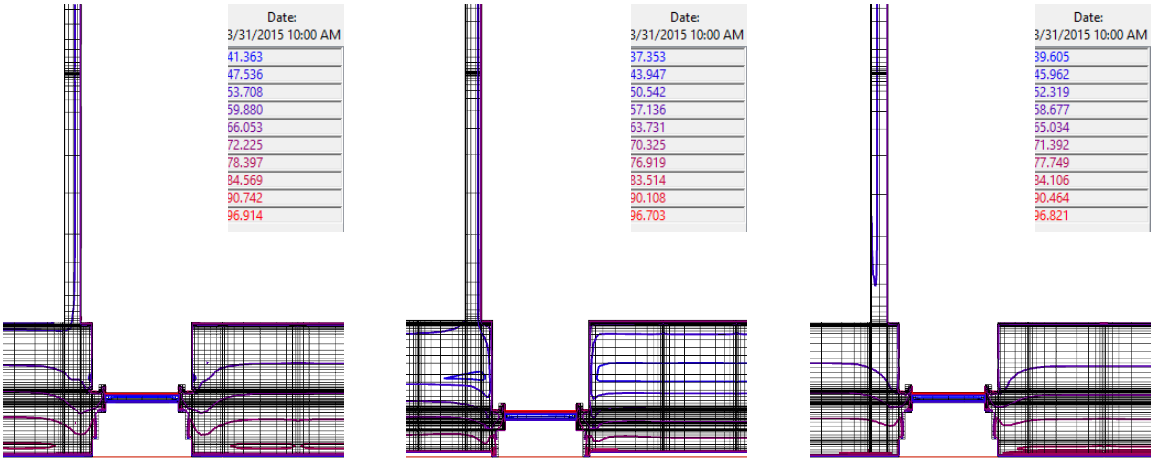


(d) Hempcrete 4

Figure 5.20: Hempcrete behaviour - Date 31/3/2015 at 12:00.

The different materials same thickness - 31/3/2015

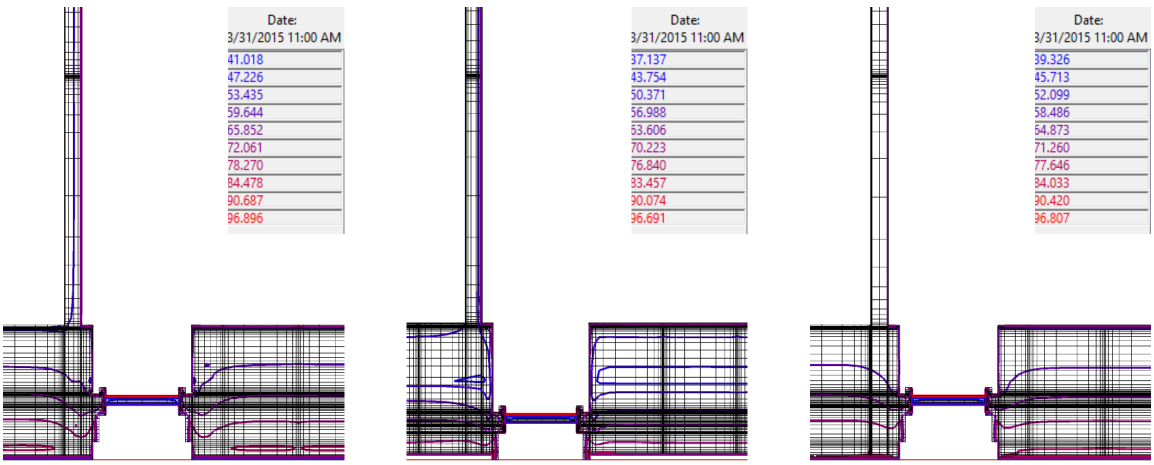
- Bathroom conditions: RH 73%, Temperature: 24.8 ^{o}C
- Bedroom conditions: RH 53%, Temperature: 17.5 ^{o}C
- Outdoor conditions: RH 69%, Temperature: 9.5 ^{o}C, precipitation: 0.4 (Driving rain)



(a) Hempcrete 3 (b) Sand Lime Bricks (c) AAC

Figure 5.21: Comparison between materials (Same thickness) - Date 31/3/2015 at 10:00.

- Bathroom conditions: RH 75%, Temperature: 22 ^{o}C
- Bedroom conditions: RH 53%, Temperature: 17.4 ^{o}C
- Outdoor conditions: RH 66%, Temperature: 9.8 ^{o}C, precipitation: 0.3 (Driving rain)



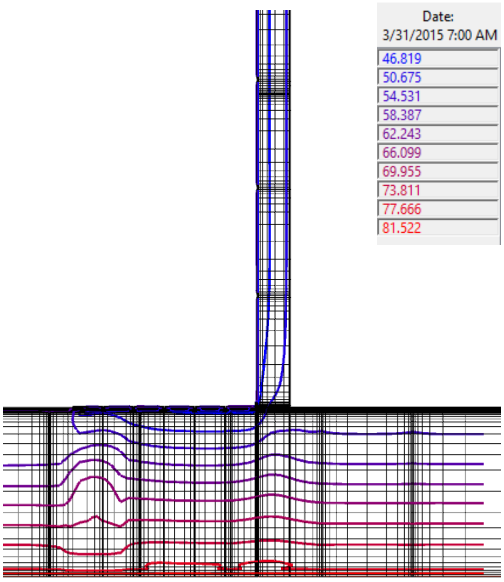
(a) Hempcrete 3 (b) Sand Lime Bricks (c) AAC

Figure 5.22: Comparison between materials (Same thickness) - Date 31/3/2015 at 11:00.

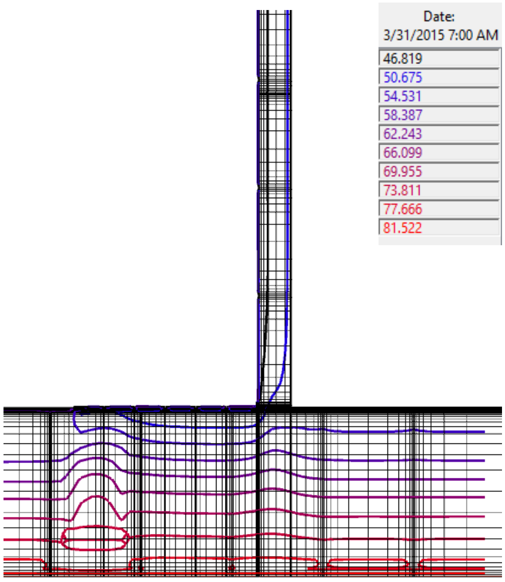
5.4.2. DETAIL 2

The four hempcrete options - 31/3/2015

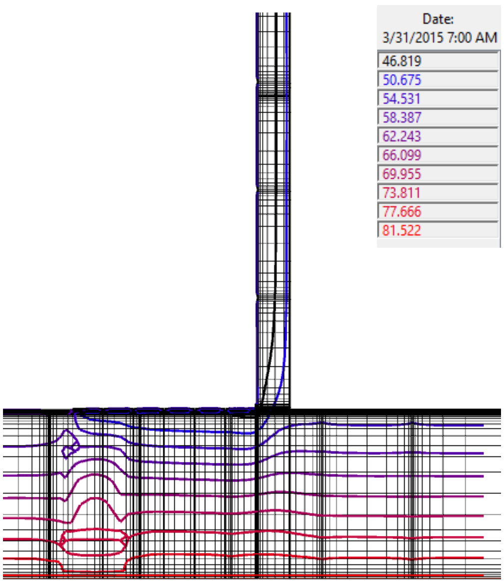
- Bathroom conditions: RH 57%, Temperature: 19.9 ^{o}C
- Bedroom conditions: RH 53%, Temperature: 17.5 ^{o}C
- Outdoor conditions: RH 75%, Temperature: 9.2 ^{o}C, precipitation: 0.2 (Driving rain)



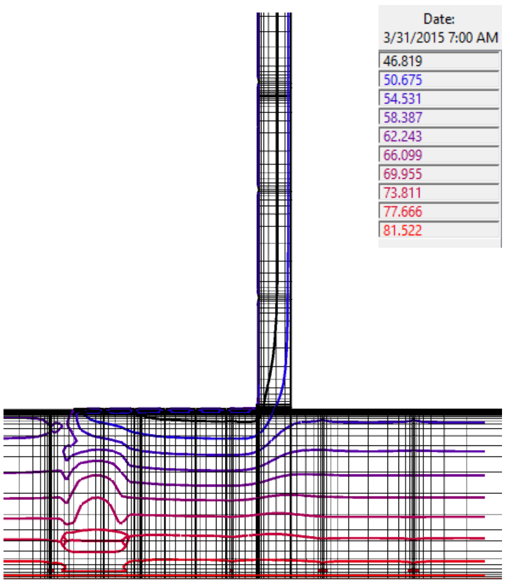
(a) Hempcrete 1



(b) Hempcrete 2



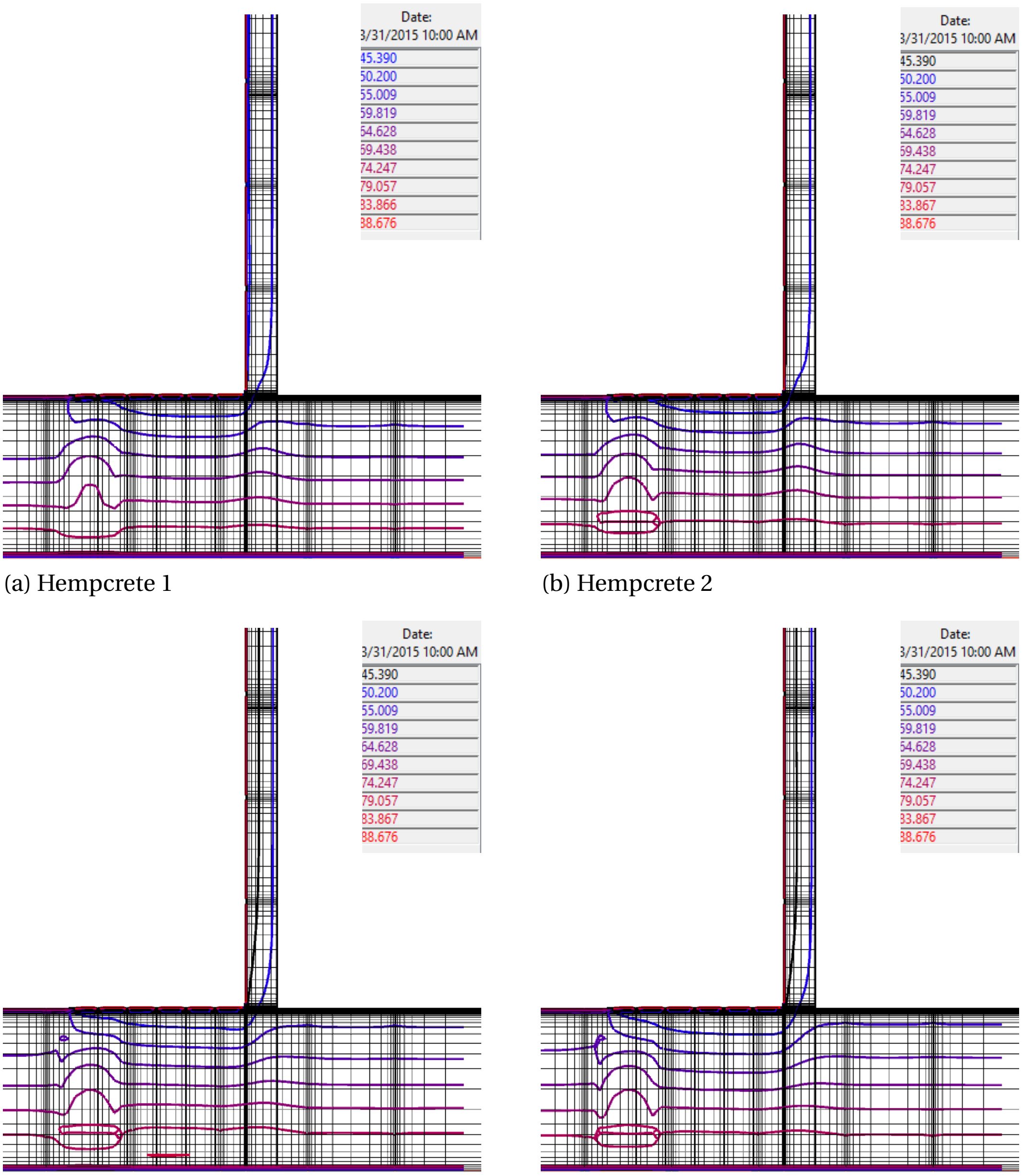
(c) Hempcrete 3



(d) Hempcrete 4

Figure 5.23: Hempcrete behaviour - Date 31/3/2015 at 7:00.

- Bathroom conditions: RH 73%, Temperature: 24.8 ^{o}C
- Bedroom conditions: RH 53%, Temperature: 17.5 ^{o}C
- Outdoor conditions: RH 69%, Temperature: 9.5 ^{o}C, precipitation: 0.4 (Driving rain)



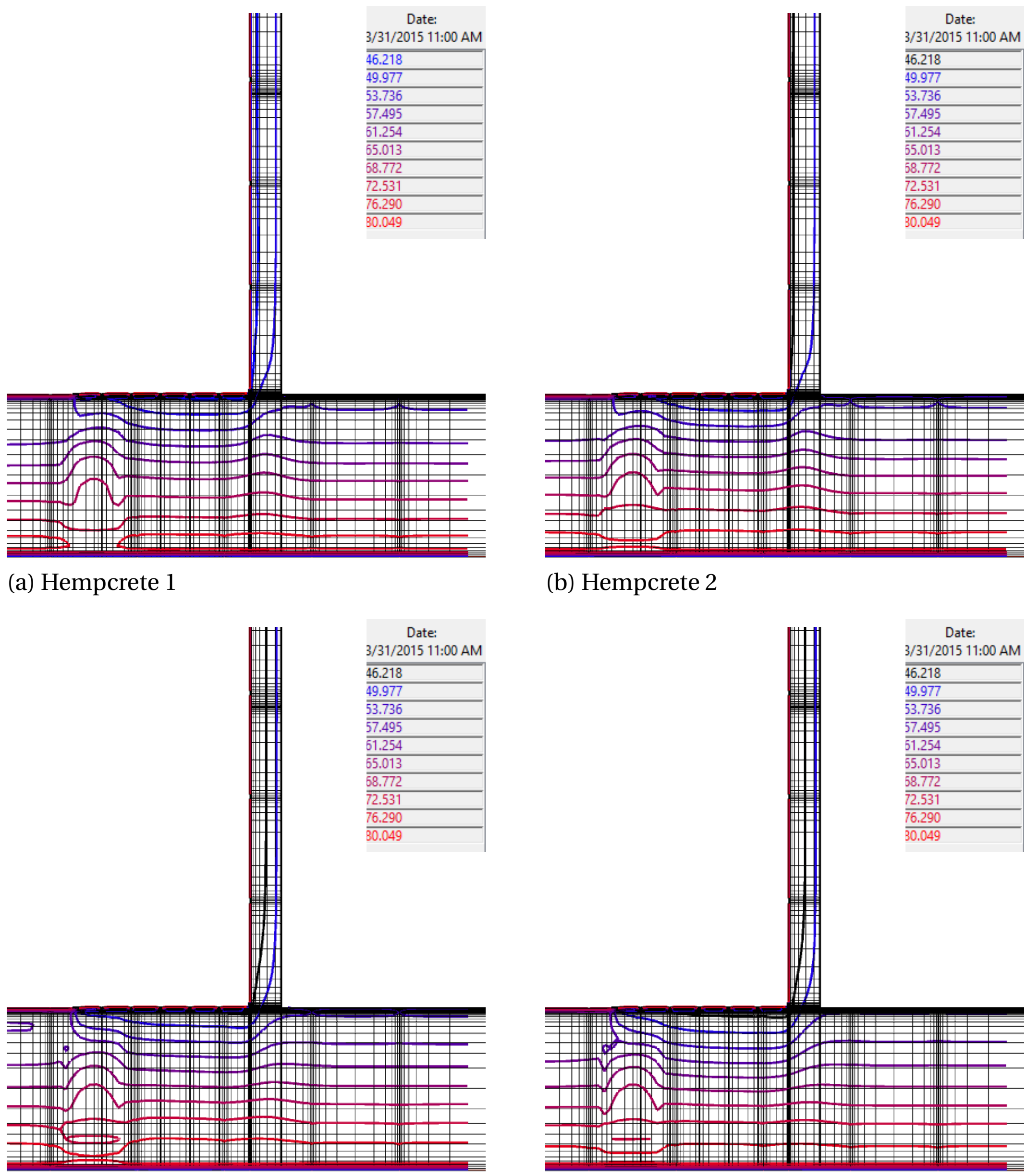
(a) Hempcrete 1 (b) Hempcrete 2

(c) Hempcrete 3 (d) Hempcrete 4

Figure 5.24: Hempcrete behaviour - Date 31/3/2015 at 10:00.

5

- Bathroom conditions: RH 75%, Temperature: 22 ^oC
- Bedroom conditions: RH 53%, Temperature: 17.4 ^oC
- Outdoor conditions: RH 66%, Temperature: 9.8 ^oC, precipitation: 0.3 (Driving rain)



(a) Hempcrete 1

(b) Hempcrete 2

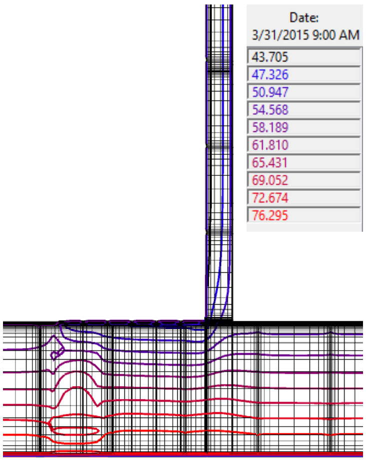
(c) Hempcrete 3

(d) Hempcrete 4

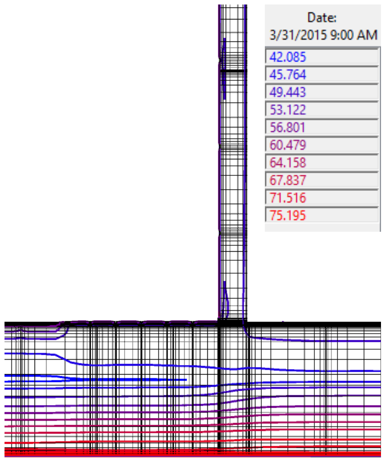
Figure 5.25: Hempcrete behaviour - Date 31/3/2015 at 11:00.

The different materials same thickness - 31/3/2015

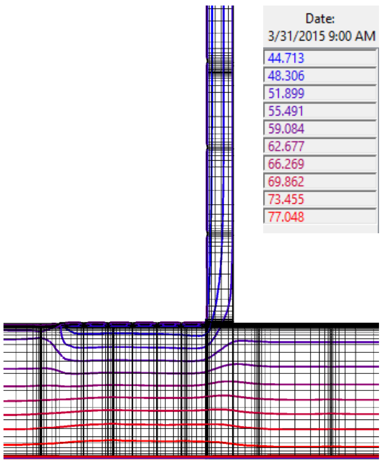
- Bathroom conditions: RH 57%, Temperature: 20.3 ^{o}C
- Bedroom conditions: RH 53%, Temperature: 17.4 ^{o}C
- Outdoor conditions: RH 69%, Temperature: 9.2 ^{o}C, precipitation: 0.1 (Driving rain)



(a) Hempcrete 3



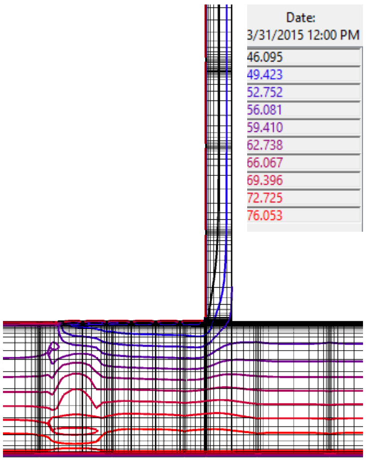
(b) Sand Lime Bricks



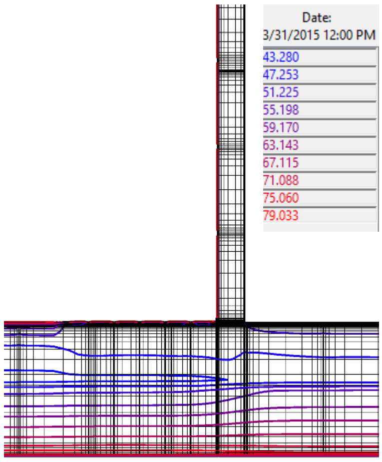
(c) AAC

Figure 5.26: Comparison between materials (Same thickness) - Date 31/3/2015 at 9:00.

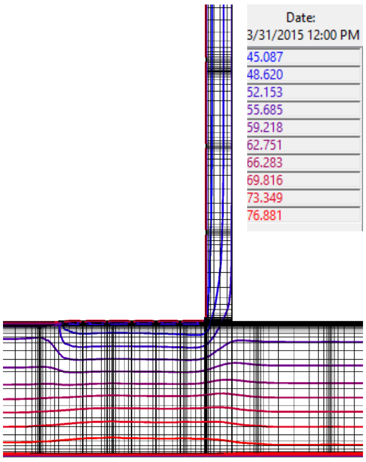
- Bathroom conditions: RH 75%, Temperature: 21.2 ^oC
- Bedroom conditions: RH 53%, Temperature: 17.5 ^oC
- Outdoor conditions: RH 69%, Temperature: 9.2 ^oC, precipitation: 0.1 (Driving rain)



(a) Hempcrete 3



(b) Sand Lime Bricks



(c) AAC

Figure 5.27: Comparison between materials (Same thickness) - Date 31/3/2015 at 12:00.

Bibliography Chapter 5

[1] Y. Abdellatef, M. A. Khan, A. Khan, M. I. Alam, and M. Kavgic, "Mechanical, thermal, and moisture buffering properties of novel insulating hemp-lime composite building materials," *Materials*, vol. 13, no. 21, 2020, ISSN: 1996-1944. DOI: 10.3390/ma13215000. [Online]. Available: https://www.mdpi.com/1996-1944/13/21/5000.

[2] S. Amziane and L. Arnaud, *Bio-aggregate-based building materials. applications to hemp concrete. iste ltd and wiley*, 2013.

[3] UBAtc, *Atg technical approval for certification - isohemp*, Accessed: 2022-09-23. [Online]. Available: %5Curl%7Bhttps://api.butgb-ubatc.be/api/public/file/ATG3169E.pdf%7D.

[4] T. Jami, S. Karade, and L. Singh, "A review of the properties of hemp concrete for green building applications," *Journal of Cleaner Production*, vol. 239, p. 117 852, 2019.

[5] T. Pierre, T. Colinart, and P. Glouannec, "Measurement of thermal properties of biosourced building materials," *International Journal of Thermophysics*, Jun. 2013. DOI: 10.1007/s10765-013-1477-0.

[6] U. Dhakal, U. Berardi, M. Gorgolewski, and R. Richman, "Hygrothermal performance of hempcrete for ontario (canada) buildings," *Journal of cleaner production*, vol. 142, pp. 3655–3664, 2017.

[7] A. Evrard and A. D. Herde, "Hygrothermal performance of lime-hemp wall assemblies," *Journal of Building Physics*, vol. 34, no. 1, pp. 5–25, 2010. DOI: 10.1177/1744259109355730. [Online]. Available: https://doi.org/10.1177/1744259109355730.

[8] ISOHemp, *What is the specific heat of a hemp block?* Accessed: 2022-09-23. [Online]. Available: %5Curl%7Bhttps://www.isohemp.com/en/what-specific-heat-hemp-block#:~:text=The%5C%20specific%5C%20heat%5C%20of%5C%20the%5C%20IsoHemp%5C%20block%5C%20is%5C%201600%5C%20J%5C%2FKgK.%7D.

[9] B. Seng, C. Magniont, and S. Lorente, "Characterization of a precast hemp concrete. part i: Physical and thermal properties," *Journal of Building Engineering*, vol. 24, p. 100 540, 2019, ISSN: 2352-7102. DOI: https://doi.org/10.1016/j.jobe.2018.07.016. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2352710218303760.

[10] E. Gourlay, P. Glé, S. Marceau, C. Foy, and S. Moscardelli, "Effect of water content on the acoustical and thermal properties of hemp concretes," *Construction and Building Materials*, vol. 139, pp. 513–523, 2017, ISSN: 0950-0618. DOI: https://doi.org/10.1016/j.conbuildmat.2016.11.018. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S095006181631772X.

[11] F. Collet and S. Pretot, “Thermal conductivity of hemp concretes: Variation with formulation, density and water content,” *Construction and Building Materials*, vol. 65, pp. 612–619, 2014, ISSN: 0950-0618. DOI: https://doi.org/10.1016/j.conbuildmat.2014.05.039. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0950061814005224.

[12] A. Evrard, “Dynamical interactions between heat and mass flows in lime-hemp concrete,” 2006. [Online]. Available: %5Curl%7Bhttps://www.semanticscholar.org/paper/Dynamical-interactions-between-heat-and-mass-flows-Evrard/11b5f20a6f897ff00d9b69cec1cff777bdf6db4a#paper-header%7D.

[13] A. Evrard, “Sorption behaviour of lime-hemp concrete and its relation to indoor comfort and energy demand,” Sep. 2006. [Online]. Available: %5Curl%7Bhttps://umanitoba.ca/faculties/engineering/departments/ce2p2e/alternative_village/media/6_Sorption_behaviour_lime_hemp_concrete_and_relation_to_indoor_comfort.pdf%7D.

[14] A. Evrard and A. Herde, “Bioclimatic envelopes made of lime and hemp concrete,” Sep. 2005. [Online]. Available: %5Curl%7Bhttps://www.researchgate.net/publication/266467019_Bioclimatic_envelopes_made_of_lime_and_hemp_concrete%7D.

[15] R. Walker and S. Pavia, “Moisture transfer and thermal properties of hemp–lime concretes,” *Construction and Building Materials*, vol. 64, pp. 270–276, 2014.

[16] A. van der Linden, P. Erdtsieck, I. Kuijpers-van Gaalen, A. Zeegers, and T. Selten, *Building Physics*. ThiemeMeulenhoff, 2013.

6

The Energy Simulation

6.1. THE SIMULATION INPUT

6.1.1. THE THERMAL BRIDGES

Thermal bridges play an important role in the energy efficiency of buildings and as a result in order to derive realistic results their effect should be included in the energy simulation. For this reason, the thermal bridges that are present in the house under scrutiny have been identified. Thermal bridges that remain the same for the three design options, have a fractional influence or are expected to be equal for the three design options have been omitted from the simulation. The determination of the ψ factor, a factor which indicates the linear thermal heat loss that is present at the junction of different materials, was necessary for the incorporation of the thermal bridging effects in the simulation. For the conventional SL design, the ISO-SBR-Woningbouw details have been used as a reference for the determination of the linear thermal transmittance factor (Figure: A.25). For the case of the AAC and the hempcrete design, the factor was calculated by making use of the THERM software. Eventually, the thermal bridges that have been simulated and the linear thermal transmittance factors (ψ) are presented in Figure 6.1 and Table 6.4. The methodology followed is presented below:

6

1. The thermal bridges were designed in Therm and the respective materials were assigned.
2. The U_{factor} of the indoor surface which was calculated by the software was used in combination with the indoor surface length to define the total heat flow through the section (L_D).
3. The ideal U_{factor} of the section without the thermal bridge was calculated from the total thermal resistance of the ideal section.
4. The ψ factor was derived by the formula:

$$\psi = L_D - U_c * A_c \tag{6.1}$$

   Where:
   U_c: thermal transmittance in the ideal section.
   A_c: the area of the ideal section.

At this point, it is worth noting how the effect of the timber beams was incorporated in the energy simulation. The thickness of the timber beams was defined by the structural analysis and was kept the same (at 150 mm) for the total number of the exterior beams. However, due to the different loading it was not possible to keep the beams' height the same without overestimating the needed material. In order to simplify the input for the simulation, a weighted average beam height was calculated by taking into account the beams' length at the facade. The respective height was calculated to be around 0.26 m. A beam with the aforementioned dimensions was eventually used to simulate the thermal bridge at first floor height in Therm, the results of which were later incorporated in the energy simulation.

In the cases of the two conventional designs, the configuration of the external walls (sequence and thickness of materials) does not change and as a result the thermal resistance of the wall remains constant in the totality of the facade. In the hempcrete design however, the hempcrete wall is interrupted by timber beams and columns. The latter, results in the creation of parts on the building envelop with lower thermal performances, the effect of which should be also considered in the energy simulation.

Firstly, the required thickness of the wall in order for the totality of the hempcrete facade to meet the thermal resistance requirement (Rc>4.7 m^2 K/W) of the Dutch Building Decree was calculated. The approach followed was the same as the one described in the Section 5.2.1 *The Assessment factors*, which can be found in the Dutch standard NTA 8800-2022. For the calculation, the thickness of the timber columns and beams remained the same (150 mm) as it had been already defined from the structural analysis. That made possible to include the totality of the timber volume in an equivalent section (Section A) The equivalent length on the facade for each of the two sections (Section with 15 cm of timber, and monolithic Section with hempcrete) was measured and then the required wall thickness was defined (Table 6.1 and Table 6.2). A hempcrete wall with the defined thickness was designed in the Energy simulation. Adding manually the wall sections at the position of each of the columns and beams was decided to be avoided to not overload the simulation. As a result the thermal effect of the timber elements was taken into account by increasing the thermal conductivity of the hempcrete in order to acquire a wall with the same thermal resistance and thickness as of those calculated according to the Dutch standard (Table 6.3).

Material	Thickness (m)	Length (m)	Thermal Conductivity (W/mK)	Area (m^2)	Thermal resistance (m^2K/W)
Section a					
Lime	0.01	4.31	0.700	0.043	0.01
Hempcrete	0.10	4.31	0.073	0.431	1.37
Spruce	0.15	4.31	0.090	0.647	1.67
Hempcrete	0.10	4.31	0.073	0.431	1.37
Lime	0.012	4.31	0.700	0.051	0.02
Total	0.372	4.31	(-)	1.60	4.61 *
Section b					
Lime	0.01	34.51	0.700	0.345	0.01
Hempcrete	0.10	34.51	0.073	3.451	1.37
Hempcrete	0.15	34.51	0.073	5.176	2.05
Hempcrete	0.10	34.51	0.073	3.451	1.37
Lime	0.012	34.51	0.700	0.414	0.02
Total	0.372	34.51	(-)	12.83	5.00 *

* Including R_{se}, R_{si}

Table 6.1: Properties of the sections a and b.

j	$\lambda"_{ji}$	$d_i/\lambda"_{ji}$	$R_{T'}$	$R_{T"}$	R_T
1	0.70	0.01			
2	0.073	1.37			
3	0.075	2.00	4.95	4.94	4.8
4	0.073	1.37			
5	0.7	0.02			

Table 6.2: The final thermal resistance of the composite wall

Equivalent wall section			
Material	Thickness (m)	Thermal Conductivity (W/mK)	Thermal resistance (m^2K/W)
Lime	0.01	0.700	0.01
Hempcrete	0.10	0.0734	4.77
Lime	0.012	0.700	0.02
Total	0.372	(-)	4.80

Table 6.3: Properties of the equivalent wall.

ψ values (W/mK)								
Hempcrete			AAC			SL & FG		
Corner	Floor	Roof	Corner	Floor	Roof	Corner	Floor	Roof
0.032	0.117	0.179	0.041	0.079	0.165	0.075	0.00	0.188

Table 6.4: The ψ values.

6

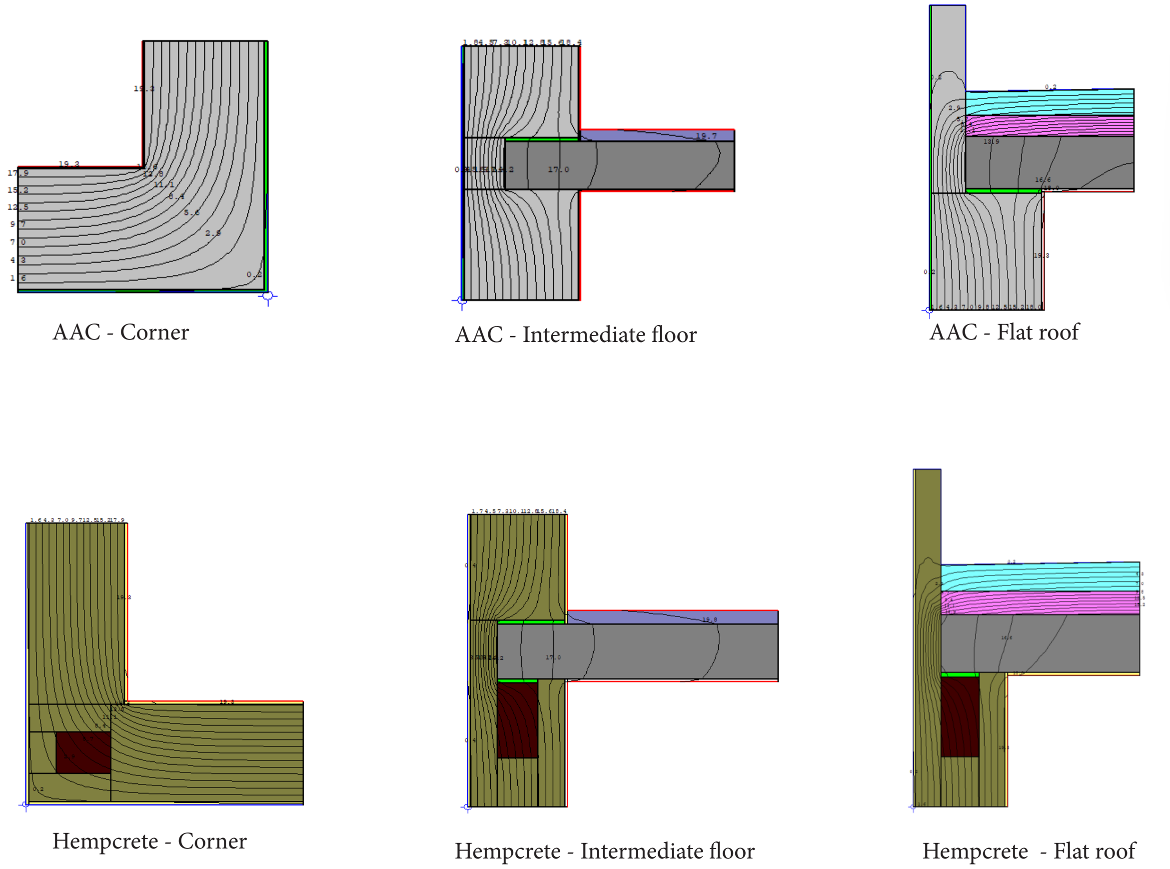


Figure 6.1: The simulated thermal bridges.

6.1.2. THE SIMULATION INPUT

The geometry of the residence was imported in WUFI PLUS and the sections of the elements were defined for the three different designs with respect to the drawings that can be found in the Annexes. An exception was made for the Flat roof, where section was simulated as a conventional roof, and therefore the green roof layers were not included in the simulation. The same climate data (For a typical year in the Netherlands) was used as in the case of the 2D simulations. For the sake of consistency the same materials as the ones used in the 2D simulation were also applied. For the case of hempcrete, the optimised hempcrete option ($H3_{RD}$) was applied.

Different thermal zones were defined for each of the rooms. Different schedules according each time to the room's type were assigned in order to simulate the residents behavior. For the latter, the WUFI Plus library was used. In order to also include the effect of clothing, for the comfort analysis, different levels of clo were attached depending each time on the season of the year, (1 clo for winter, 0.7 clo for spring and autumn and 0.4 clo for summer). The unoccupied space next to the bathroom was simulated as an unheated space. However, since in reality this room is occupied with the residence's installations, a constant heat source with a radiative heat flow of 100 W had been added .

The residence does not make use of mechanical cooling for the summer. As a result no cooling installations have been added to the model. To avoid overheating, blinds were enabled to close automatically when indoor temperature surpasses 25 ^{o}C. In addition, night cooling during the summer months was also introduced by the means of natural ventilation. To do so, a schedule for natural ventilation was applied for the summer months. Natural ventilation with a flow of 8 l/s was assumed to take place in all the occupied zones during the summer from 20:00 h-10:00 h every day. The adequacy of this modeling method for the representation of the ventilation was checked after the simulation was finished, by checking the results of the total heating of the residence. No heating was required for the months that the night cooling ventilation was applied (Start of June - End of August) which means that the way that natural ventilation was modeled did not led to uncomfortable indoor temperatures below the heating set points of the rooms (Figure -A.21).

For the heating of the house, a heat pump with a power of 5kW was added to the model. The heat pump was combined with mechanical ventilation with heat recovery (0.90). The heating capacity was divided to each room proportionally to its surface. For the heating of rooms, the same temperature set point values as of the actual residence were used. The temperature set points can be found in the Annexes (Figure -A.21). Nevertheless, the schedules were adjusted lightly to correspond better to the occupancy schedules of the WUFI profiles.

6

The residence is mechanically ventilated. The ventilation system's capacity was set to the minimum allowed by the Dutch Building Decree (0.9 l/s/m^2). Then for each of the rooms, the ventilation flow was again defined by the Dutch Building Decree according to the room's type.

- Living room: 0.7 l/s/m^2
- Bedroom: 0.7 l/s/m^2
- Bathroom: 14 l/s
- Kitchen: 21 l/s

The mechanical ventilation schedule was adjusted again to the occupancy schedules to decrease energy losses when people are not in the house and CO2 control was also enabled as an activation factor for all the rooms except the Bathroom, where humidity control was selected.

Two simulations have been performed in order to get a broader idea on the energy performances and the related differences of the materials. The first analysis included the thermal bridges which have been described previously, whereas the second one excluded their effect. The first analysis, represents the design of the residence as it has been derived from the current study, which had as an objective to only make use of the materials under scrutiny. However, in reality, the effect of thermal bridging, can be decreased by applying locally thermal insulation with higher performances. The second analyses, was based therefore on the assumption that additional insulation means are used at the location of the thermal bridges in an efficient way that alleviates the differences between the three design options.

6.1.3. THE SIMULATION RESULTS

The simulation results for the three more frequently occupied rooms have been plotted. The actual residence has an annual requirement for heating of around 24 kWh/m^2. The results of the simulations approach and the actual results of the simulated residence and therefore are accepted as a realistic representation of the reality.

AAC			
Heating	24.2 KWh/m2		
	Bedroom ground floor	Bedroom first floor	Living room
Max temp (C°)	27.5	29.9	32.8
Mean temp (C°)	19.8	20.8	22.3
Min temp (C°)	12.6	13.6	17
Max RH (%)	70.2	65	72.7
Mean RH (%)	51.7	49.1	48.4
Min RH (%)	25.9	26.9	27

AAC			
Heating	22.42 KWh/m2		
	Bedroom ground floor	Bedroom first floor	Living room
Max temp (C°)	27.7	30.1	33.3
Mean temp (C°)	20	20.9	22.7
Min temp (C°)	12.9	13.7	17
Max RH (%)	68.9	65	73.3
Mean RH (%)	51	47.8	47.3
Min RH (%)	25.9	26.9	25.9

Hempcrete			
Heating	24.9 KWh/m2		
	Bedroom ground floor	Bedroom first floor	Living room
Max temp (C°)	27.6	29.5	32
Mean temp (C°)	19.9	20.7	22.1
Min temp (C°)	13	13.8	17
Max RH (%)	70.8	67.8	73.2
Mean RH (%)	52	48.6	48.7
Min RH (%)	31.6	29.5	31.3

Hempcrete			
Heating	23.35 Kwh/m2		
	Bedroom ground floor	Bedroom first floor	Living room
Max temp (C°)	27.8	29.7	32.4
Mean temp (C°)	20.1	20.8	22.5
Min temp (C°)	13.2	13.9	17
Max RH (%)	70.5	67.8	73
Mean RH (%)	52.3	48.1	47.7
Min RH (%)	31.4	29.5	30.3

SL			
Heating	23.9 KWh/m2		
	Bedroom ground floor	Bedroom first floor	Living room
Max temp (C°)	27.5	28.8	30.1
Mean temp (C°)	20.4	21	21.8
Min temp (C°)	14.4	15	17
Max RH (%)	66.1	64.4	72.2
Mean RH (%)	48.1	47.2	50.3
Min RH (%)	25.9	27.2	29.2

SL			
Heating	21.8 KWh/m2		
	Bedroom ground floor	Bedroom first floor	Living room
Max temp (C°)	27.7	29	304
Mean temp (C°)	20.7	21.1	22.2
Min temp (C°)	14.6	15	17
Max RH (%)	65.5	64.4	71.9
Mean RH (%)	48.4	46.8	49.4
Min RH (%)	25.9	27.2	29.1

Figure 6.2: Results of WUFI Plus Analysis

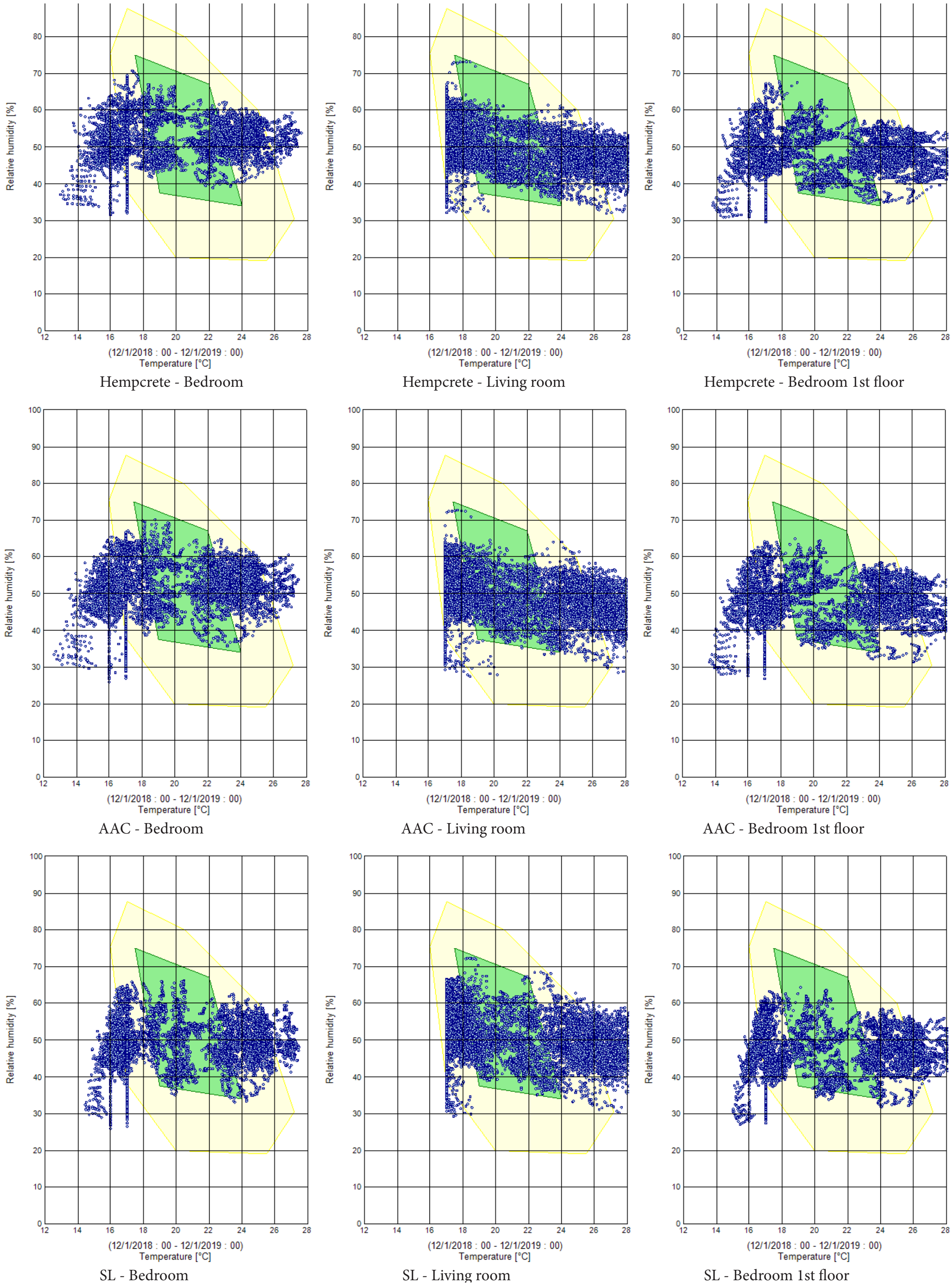


Figure 6.3: Results of WUFI Plus Analysis - Indoor comfort with thermal bridges

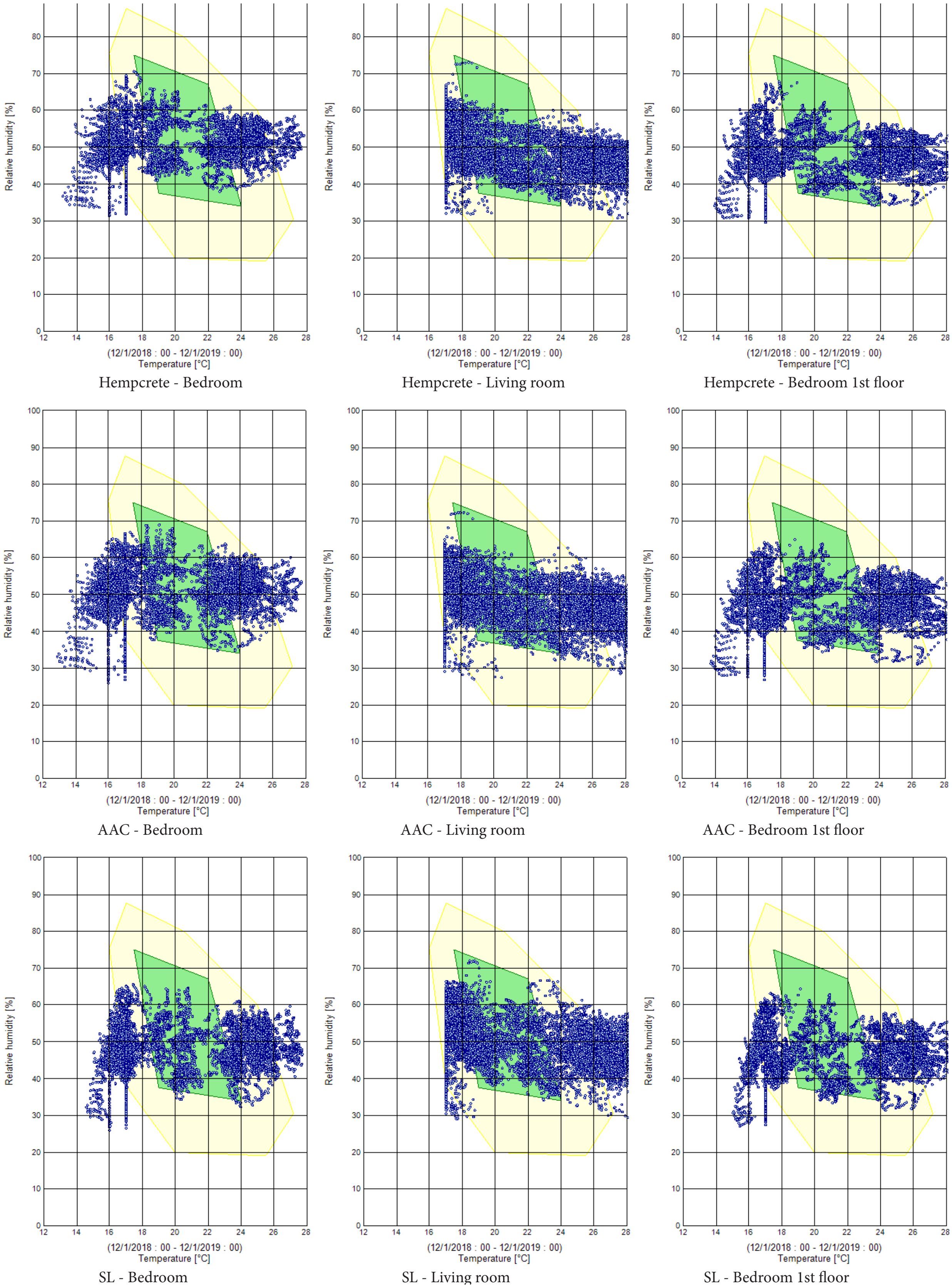


Figure 6.4: Results of WUFI Plus Analysis - Indoor comfort without thermal bridges

The influence of the volumetric heat capacity can be observed in the results of the simulation. For the case of SL and AAC designs, which are characterised by higher volumetric heat capacity, the energy appears slightly decreased in comparison to the Hempcrete design for both the analyses. The effect of the thermal bridging seems to influence more the SL design, which can be attributed to the thermal bridge which is present at the connection of the flat roof. This thermal bridge is the one with the higher presence at the residence, and for SL bricks has the highest linear transmittance factor in comparison to the other designs.

Volumetric heat capacity

- $C_{p,AAC} * \rho = 850 * 400 = 340 \ \ kJ/m^3$

- $C_{p,Hempcrete} * \rho = 1500 * 405 = 607.5 \quad kJ/m^3$

- $C_{p,SL} * \rho = 850 * 1900 = 1615 \quad kJ/m^3$

6

It is worth noticing here the differences between the AAC and the hempcrete design. The volumetric heat capacity of the AAC per m^3 is significantly lower than the one of the hempcrete design. In order for the AAC to deliver similar thermal and energy performances to those of the Hempcrete design the AAC volume of material used reached in total 76.4 m^3, whereas the respective total volume of material used for the residence made of hempcrete was calculated at 56.8 m^3 (Table 7.8).

The comfort graphs (Figure 6.3, Figure 6.4) appear quite similar for the cases under scrutiny, where the values belong towards the comfortable side. A slight better performance towards the temperature threshold can be seen for the case of the SL brick design, where the temperature values appear lower temperatures during the summer and slightly higher during the winter. Hempcrete on the other hand, shows a better performance when it comes to the case of the RH threshold, where more RH values appear to belong to the comfortable RH range (40%-70%) in comparison to the conventional designs.

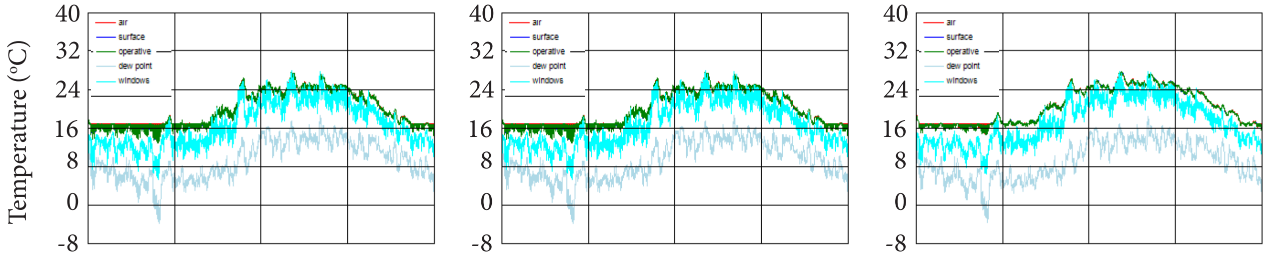
The aforementioned can be also detected in the indoor temperature (Figure 6.5) and RH (Figure 6.6) graphs of the three rooms under scrutiny as they have been derived by WUFI-plus simulation. The indoor operative temperature (in dark green colour) between the AAC design and the hempcrete design does not differentiate in general, higher temperatures however can be detected for the case of the AAC during the temperature peaks in the summer months in the case of the living room (due to its orientation) (Figure 6.4-living room). When hempcrete is compared to the SL brick design, the SL performs slightly better, as the operative temperature of the SL design appears to fluctuate less during the year. Nevertheless, the pattern and the minimum values of the indoor temperature during winter do not in general differentiate considerably. A noticeable difference is observed for the case of the living room, when the temperatures appear to be noticeably lower, due to the external insulation (Figure 6.4-living room).

Hempcrete appears to perform better in terms of moisture regulation in all the rooms under scrutiny. The latter is expressed by two main features (Figure 6.6).

- The graph which accounts for hempcrete fluctuates less than these of the AAC and SL during the year.
- The trend line of the hempcrete graph appears be be characterised by smoother inclinations.

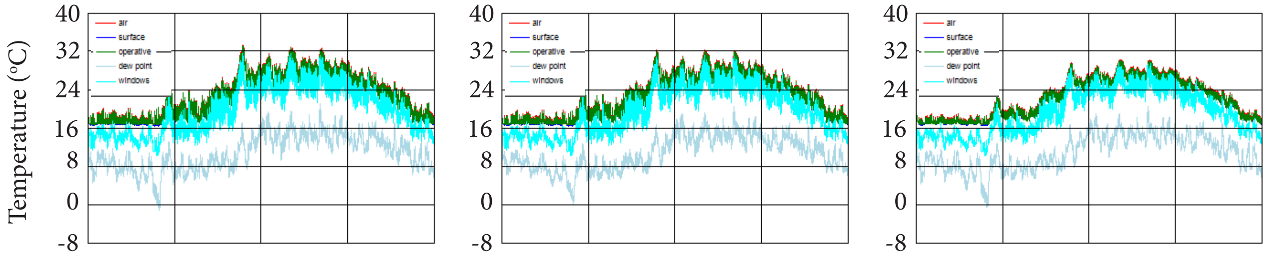
This effect of better stabilised RH levels should not be overlooked. Moisture regulation creates a feeling of indoor comfort to the residents even if lower or higher temperatures are detected during winter and summer respectively. In addition, it is an important benefit in designs that strive for stabilised indoor humidity levels.

Bedroom



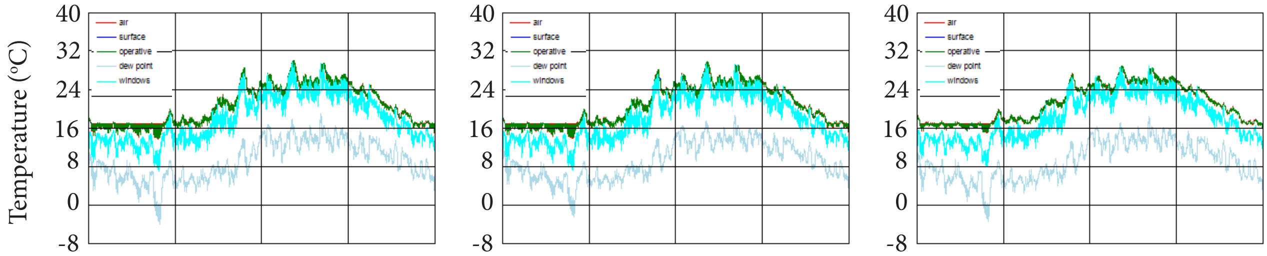
AAC Hempcrete SL

Living room



AAC Hempcrete SL

Bedroom 1st floor



AAC Hempcrete SL

Figure 6.5: Results of WUFI Plus Analysis - Indoor temperatures for one simulated year (1/12/2018-1/12/2019): case without the thermal bridges

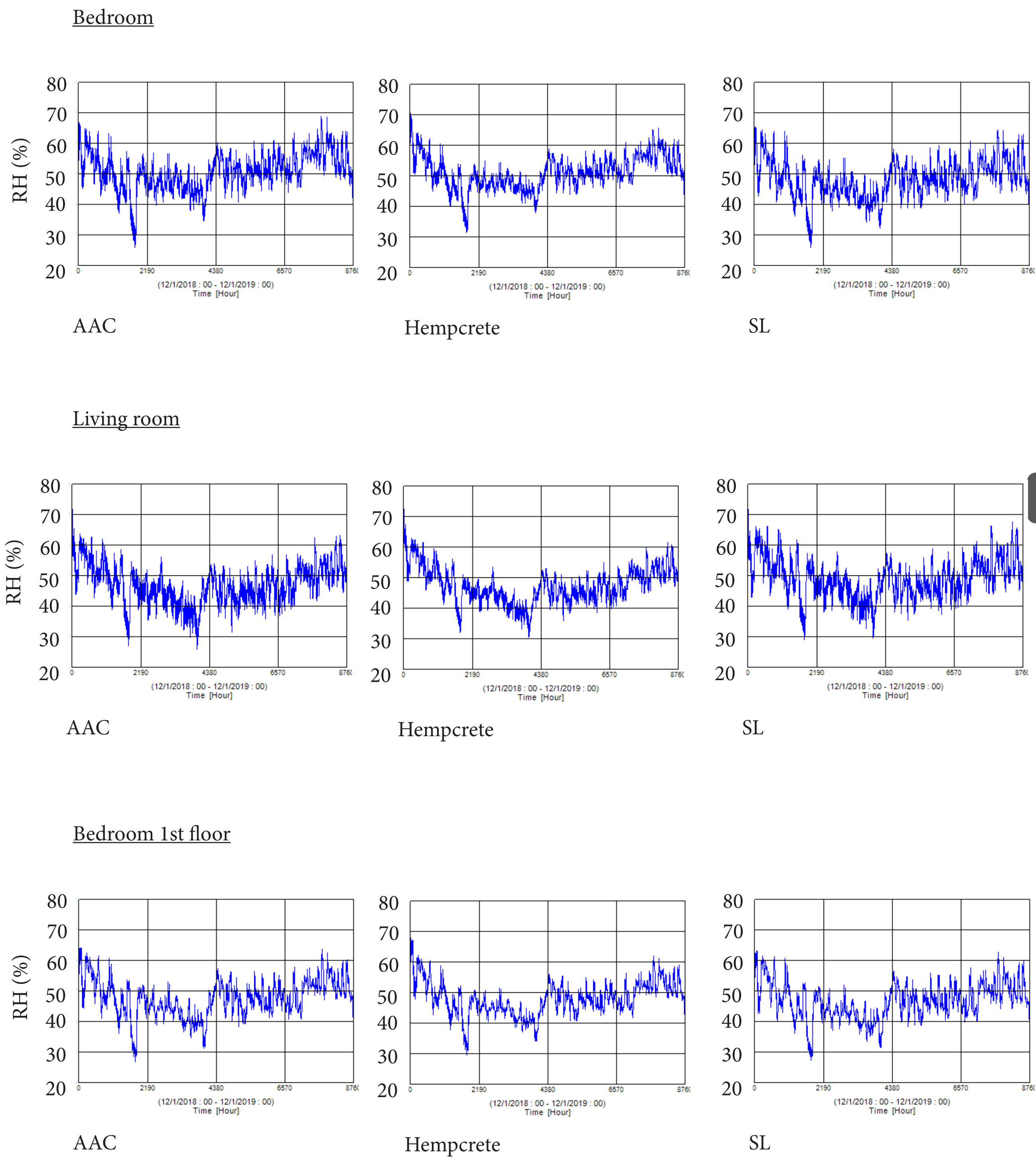


Figure 6.6: Results of WUFI Plus Analysis - Indoor RH (for one simulated year (1/12/2018-1/12/2019): case without the thermal bridges

7

THE ENVIRONMENTAL AND FINANCIAL COSTS

7.1. THE SYSTEM AND ITS BOUNDARIES

In order to be able to derive fair conclusions about the differences in the environmental performances of the three different material designs, it is important to define the requirements that the design systems under scrutiny should be able to cover. These requirements, define the type and the quantity of materials that are used and eventually determine the unit factor of the environmental analyses.

The scope of this research was to compare a hempcrete designed residence with two conventional Dutch construction designs. From an environmental perspective, this comparison concerns the configuration of the walls since the rest of the building's elements as namely the floors, the roofs, the foundations and the openings remained the same for the three design options and as a result were excluded from the LCA.

The differences in the performances of the materials regarding some critical for the buildings aspects as the structural strength, the thermal resistance and the acoustic insulation, do not allow a monolithic direct comparison between them. On the contrary, they create the necessity to construct performance based equal wall systems. This approach was followed from the beginning of this graduation project and accounts also for the environmental comparison. In the residence, the following three types of wall can be observed, for each of the aforementioned types a critical factor that determined the wall thickness and consequently the material usage was defined:

- Load bearing facade walls - Thermal resistance + structural stability
- Load bearing internal walls - Structural stability
- Non load bearing separation walls - Acoustic insulation

For the load bearing masonry cases (SL and AAC) the critical factors which influence the wall's strength the most are the nature of the mortar and the imposed deformations due to settlements or dilatations combined with inappropriate detailing. The residence is already constructed so the walls are assumed adequately designed with regard to these factors. Since the residence is already designed additional use of materials is not needed to provide additional compressive strength. Nevertheless, additional material improves the thermal resistance of the wall which needs to cover the requirements of the Dutch building Decree, as a result the latter is considered as the critical factor which determined the thickness of the wall.

For the hempcrete construction on the other hand both the thermal resistance and the structural strength defined the configuration of the facade. The timber structural frame was designed to support the loads according to the Eurocode. The loads remained the same as in the cases of the masonry systems. No assumptions were required for the permanent loads of the slabs which are transported to the frames, since they were taken from the actual structural report of the residence. The critical structural verification for each of the structural elements, defined their sections, more information on these verifications can be found in the following section. The thickness of the infilling hempcrete was defined according to the Dutch standard NTA 8800-2022, in order to cover the requirement of the Dutch Building Decree for thermal resistance higher than 4.7 m^2 K/W, including the effect of the thermal bridges due to the structural timber frame inside the hempcrete wall. More information on the calculation method can be found in the Section (4.2.1. The Assessement Factors).

Placing the structural timber frame in between the hempcrete blocks, as it can been seen in Figure(7.1) can provide some considerable advantages. The loads from the hempcrete walls can directly be transported to the floors and then to the structural frame without needing any additional supporting structure and brackets to connect the facade with the structural system. That creates some financial advantages since it optimises the material usage and the time needed for construction. In addition, the fire proofing properties of hempcrete can be exploited and give to the hempcrete-timber wall system, some fire safe performances comparable to those of SL and AAC, without the need of using plaster boards for protection. Nevertheless, as it is already stated in previous chapters, it is important to evaluate the risk of moisture for the confined wood. In addition, this construction method creates some additional thermal bridges to the building envelop at the height of the 1st floor and at the points where hempcrete is interrupted by the structural timber. These thermal bridges need to be taken into account in the thermal resistance of the wall and in the energy consumption simulation and therefore are presented in Section 6.

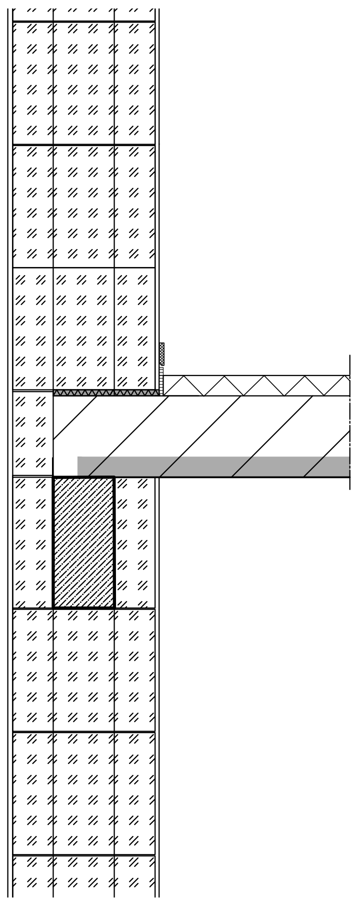


Figure 7.1: The construction method.

7.2. THE STRUCTURAL SYSTEM

A structural analysis defined the sections and amount of timber that is needed to support the loads of the detached house. The dimensions of the sections were defined by the critical strength verification according to the structural element's type. According to the later, beams were checked to be able to withstand the imposed moment and shear whereas the columns were checked to withstand flexural buckling.

Frame structural systems are more sensible to lateral loading (e.g. wind loads) in comparison to masonry systems. In addition, timber constructions are prone to buckling and as a result most of the time stability to lateral loading cannot be achieved only by increasing the area section of the frames, a measure that eventually mainly contributes to the support of the construction's vertical loads. Additional means such as braces are needed to increase the stiffness of the structure and ensure the stability of the system. Due to its low height however, the house under scrutiny will not be subjected to high wind-loads, as a result the amount of bracing that could be needed is expected to be very low to have a noticeable impact on the LCA. Therefore, vertical loads were defined as the critical loading for the determination of the material usage. As a result, the structure was subjected to vertical loads which were applied according to the combinations which are described in the Eurocodes. More information can be found in the Annexes.

Sawn spruce timber was selected as the structural timber for the design. This selection was made for environmental reasons since sawn timber is subjected to lower treatment in comparison to other timber products. Furthermore, spruce is highly available in Europe, so environmental emissions related to the transportation of the product are highly attenuated. The environmental superiority of the solid timber in comparison to GLT however can be debated in some cases, since GLT is characterised by higher strength which can lead to smaller sections. Nevertheless, due to the small scale of the project it was assumed that the solid timber would be able to cover the strength requirements when higher strength classes are used while maintaining similar to GLT sections. Since the difference in the strength class does not affect the environmental emissions in timber products, spruce could eventually perform environmentally better than the GLT.

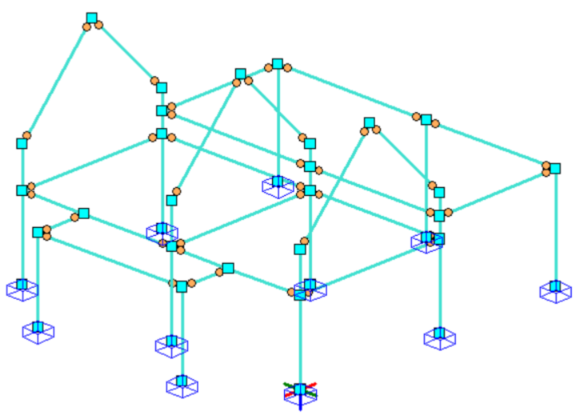


Figure 7.2: The structural system.

An optimisation on the structural system has an influence on the environmental performances since it minimises the material use. Structural optimisation is related to the properties of the material and the systems' geometry. The required degree of static indeterminacy plays a crucial role as it influences the distribution of internal loads in the system and therefore the level of performance that the sections should be able to cover. Increasing the degree of static indeterminacy can have both positive and negative results. Selecting rigid connections between the elements, can partially relieve beams from high moments and decrease the required section area, nevertheless it simultaneously creates imposed moments in columns, which can create a difference in the dimensions when the material is susceptible to buckling.

Finding the most optimised structural system is a complex procedure that goes beyond the scope of this research. Nevertheless, the aforementioned considerations regarding the material capabilities were taken into account in order to design a structure that performs well in terms of material exploitation. Timber is characterised by a moderate stiffness so rigid connections between beams and columns cannot be achieved [1]. In addition due to its sensitivity to buckling, hinges at the ground supports were selected to decrease its buckling length. As a result of the aforementioned, the structural system depicted in Figure (7.2) was designed.

In order to facilitate the building process it was decided to keep the same thickness in the beams and columns. The thickness selected was 15 cm. That would allow 20 cm of hempcrete insulation, so namely 10 cm around each side of the timber frame. It was assumed that the different design options are have renderings with the similar environmental impacts and thus the rendering was not taken into account in the LCA Analysis.

7.3. THE EPDS

For the calculation of the environmental performances of the three design options, the EPDs for the different materials have been collected. All the EPDs used have been drawn according to the European standard EN 15804+A2 and include the effect of the packaging too. The vast majority of the EPDs was a the type cradle to grave, with the exception of the EPD used for the mortar adhesive (cradle to gate) between the blocks in the AAC and SL designs. Since they have been drawn according to the same standard, the boundary conditions, the criterion for the total or individual input flows and the calculation procedures were analogous. However, due to the different nature of the materials some stages were not taken into account in the some EPDs.

Consideration has been given to whether the transportation stages (A2, A4 and C2) should be included in the comparison. The latter, aroused from the fact that different transportation scenarios (lorry type, distances, loading factor) can be taken into account in the EPDs. The transportation information for stage A4 was present in the EPDs and therefore due to some high differences in the transportation distances it was decided to be excluded from the comparison. Regarding the stage C2, information on the transportation was difficult to be derived for all the materials, however it was assumed that the waste center distance is based on analogous scenarios and therefore was included in the comparison. When it comes to stage A2, information on the transportation type and distance was again sometimes difficult to be derived for all the materials. In addition, the emission results were given in an aggregated form for the whole stage in some of the EPDs. Nevertheless, since the transportation of the raw material to the manufacturing site is highly connected with the production site and therefore with the production scenario itself, A1 and A2 stages are interconnected and cannot be taken into account separately. Hence, A2 was also included in the comparison. The declaration of stage D has become compulsory according to the EN-15804+A2. In this stage the benefits and expenses beyond the system's limits are expressed. Such benefits can be the energy generation from biomass, which is an important asset of biobased materials when compared to conventional materials, therefore this stage is also included in the LCA.

Some stages are optional and hence were not included in some of the EPDs. These stages were the stages in level B (Use phase) and the stage A5 (Installation). As a result consideration was also given to whether they should be included in the comparison. The different end uses which accounted for some materials as the sawn timber has been one reason. However, carbonisation of lime is an important advantage of the Sand-lime blocks and the hempcrete blocks which takes place in Level B. As a result it was decided to include Level B in the comparison. In order to do so, it was assumed that no maintenance, water use or energy is required during the life time of the different wall designs. Hence, zero emissions were assigned to the rest of materials (except hempcrete and SL) during the whole B Level. Installation (A5) emissions were not available in the case of AAC and the spruce. Since the AAC blocks have similar density and installation procedure as those of the hempcrete blocks, an assumption was made that the emissions which account for the stage A5 of the AAC design are the same as those of the hempcrete wall when it comes to $1m^3$ of masonry. For the case of the spruce it was initially considered to increase the the final emissions related to stage A5 of the hempcrete design by the percentage of timber's presence on the selected unit factors. However, the results showed that the emissions related to A5 are only fractional and thus such implementation would not eventually have influenced the results. All the aforementioned information is depicted in Figure 7.3. More information on the EPDs can be found in the Annexes.

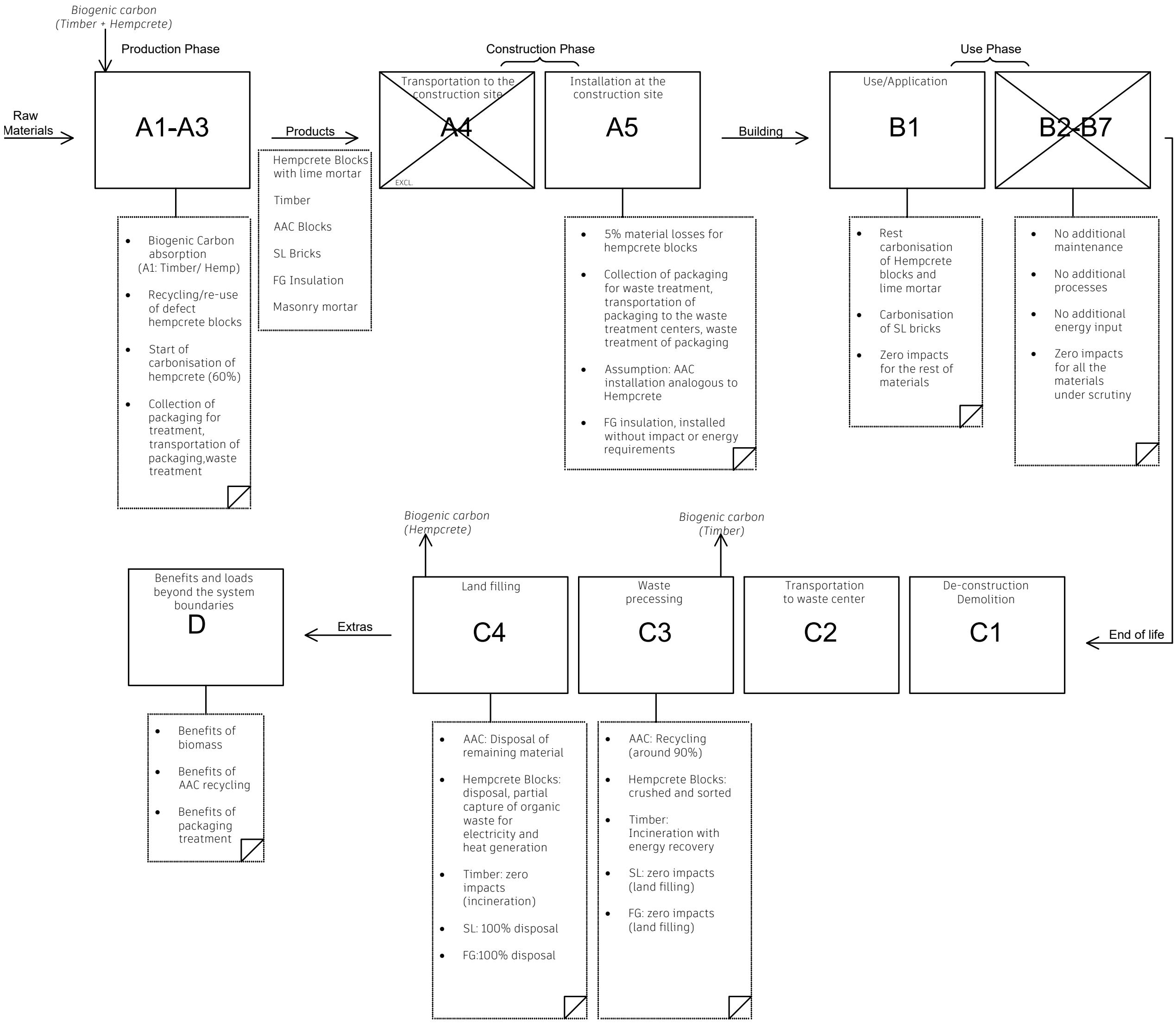


Figure 7.3: The features of the LCA stages.

7.4. THE UNIT FACTORS

The critical aspects that eventually formed the unit factors for each of the different designs have been explained in Section 7.1. For the facade walls, apart from meeting the structural requirements, the assemblies were designed to have a thermal resistance R_c= 4.80 m^2 K/W. Regarding the internal loadbearing walls, they have been designed to cover the structural requirements as already explained in the previous sections of this chapter. The separation walls were designed to be able to deliver an acoustic insulation of R_w= 37 dB. Eventually, all the aforementioned led to the creation of walls with the following thicknesses:

Thickness of walls (m) (excluding renderings)			
Type of wall	Hempcrete	AAC blocks	SL bricks with FG insulation
Facade	0.35	0.48	0.15 & 0.16 (SL/FG)
Internal load bearing walls	0.075	0.165*	0.158 *
Separation walls	0.075	0.10	0.07

* The conventional load bearing walls have different thicknesses in the residence under scrutiny, hereby the weighted value is presented

Table 7.1: The thickness of the walls.

In order to derive a wider image on the differences of the walls' environmental performances apart from calculating the environmental emissions on a whole building level, it was decided to also estimate the difference in a unit factor level. Therefore, unit factors of 1 m^2 of wall for each type of walls (facade, separation, internal loadbearing) were created. This procedure was quite straight forward for the case of the conventional materials, where the configuration of the assembly remained the same in the totality of the wall and thus allowed a unit factor of 1 m^2 with a thickness respective to the wall's type to (true thickness for Facade & separation walls, and weighted thickness for the loadbearing internal walls) be considered. However, for the case of the hybrid hempcrete walls a different approach was followed.

Comparable unit factors should be able to deliver the same performances in the aspects under scrutiny. As a result in the case of the loadbearing hempcrete walls, it is important to identify the amount of timber which needs to be included in order to deliver a wall unit with equivalent structural properties as those of the conventional loadbearing masonry designs. The amount of structural timber in the residence had been defined by the structural analysis. Additional timber was included for the support of the windows and doors, since in general hempcrete is a non load bearing material. However, the structural analysis and the differences in the presence of windows led to a different percentage of timber on the different oriented building facades. Therefore, two different approaches were followed to deliver a unit factor that better represents the case study.

For the first approach (M1), the amount of timber which accounted for the timber studs, columns and beams was measured separately on each of the four facade orientation parts and the respective percentage of timber for each facade part and element (studs, columns, beams) was found. The average percentages for the presence of studs, columns and beams were calculated. Then, the timber presence in the unit factor was assumed to be equivalent to the sum of the averages percentages of the elements. This approach was considered to deliver better fit unit factors in buildings with different proportions of timber on the facade, since the difference between the actual amount of timber on a facade part and the estimated one can be decreased. However, according to this method an over/underestimation of the total environmental emissions can occur.

For the second approach (M2) the percentage of timber's presence in the unit factor was assumed to be equivalent to the one of the whole building envelop. The emissions which account for the facade of the residence were calculated by multiplying the equivalent timber and hempcrete emissions with the respective volumes. Then the calculated emissions were then assigned to each of the facade parts proportionally to their surface. The second approach does not lead to an over/underestimation of the total environmental emissions of the building. Nevertheless, it can lead to higher differences between the actual emissions in a facade part and the estimated by the unit factor ones, since in this case the timber is assumed to be evenly spread on the whole facade, which is not a good representation of reality in some cases. According to the aforementioned, this approach was considered to better apply on buildings which are characterised by a more balanced distribution of timber on the facade.

The final environmental emissions for the four different oriented parts (W1, W2, W3, W4) were estimated by the two methods described above and the results were compared to the actual environmental emissions of the facade parts in order to find the overestimation/underestimation percentage in each case. The results showed that the second method (M2) was more appropriate for the current case study, since the differences from the actual emissions appear to be decreased in comparison to the respective differences of method 1 for the vast majority of the orientations. The percentage of timber on three out of four facade orientations was found to be quite evenly shared, which supports the consideration about the appropriateness of this method for facades with a balanced distribution of timber. An small exception appears when it comes to facade W4, where the first method seems to be slightly more appropriate, due to to differentiation of timber presence in comparison to the rest facade parts. However, since the differences between the two methods for W2 were only small, it was considered acceptable to use method M2 for the creation of the hempcrete's facade unit factor.For the formation of the unit factor of the separation and internal load bearing walls the same method as in the case of the facade was followed. The characteristics of the compared unit factors are presented in Table 7.3.

Figure 7.4: The facade orientation parts (Front and Back view).

W1																			
Over/Underestimation (%)	M1 A1	M2 A1	M1 A2	M2 A2	M1 A3	M2 A3	M1 A5	M2 A5	M1 B1	M2 B1	M1 C1	M2 C1	M1 C2	M2 C2	M1 C3	M2 C3	M1 C4	M2 C4	M1 D
GWP-Total	15.13%	6.62%	-0.35%	-0.15%	-1.02%	-0.45%	-0.88%	-0.39%	-0.96%	-0.42%	-0.70%	-0.31%	0.63%	0.28%	10.93%	4.78%	-0.96%	-0.42%	23.38%
GWP-Fossil	-0.84%	-0.37%	-0.36%	-0.16%	-1.06%	-0.46%	-0.83%	-0.36%	-0.96%	-0.42%	-0.71%	-0.31%	0.62%	0.27%	6.51%	2.85%	-0.96%	-0.42%	6.43%
GWP-Biogeneic	2.91%	1.27%	2.71%	1.18%	-0.97%	-0.42%	-0.96%	-0.42%	0.00%	0.00%	1.08%	0.47%	5.82%	2.55%	11.05%	4.84%	-0.96%	-0.42%	-1.02%
GWP-Luluc	2.81%	1.23%	10.78%	4.72%	-0.34%	-0.15%	-0.95%	-0.42%	0.00%	0.00%	9.95%	4.35%	10.96%	4.80%	2.75%	1.20%	-0.96%	-0.42%	0.35%
ODP	-0.51%	-0.22%	-0.96%	-0.42%	-0.91%	-0.40%	-0.96%	-0.42%	0.00%	0.00%	-0.96%	-0.42%	-0.96%	-0.42%	-0.96%	-0.42%	-0.96%	-0.42%	-0.96%
AP	-0.79%	-0.35%	-0.35%	-0.15%	0.19%	0.08%	-0.96%	-0.42%	0.00%	0.00%	-0.85%	-0.37%	0.54%	0.23%	6.72%	2.94%	-0.96%	-0.42%	4.13%
EP-Freshwater	-0.59%	-0.26%	1.85%	0.81%	2.23%	0.97%	-0.96%	-0.42%	0.00%	0.00%	0.09%	0.04%	4.77%	2.09%	3.66%	1.60%	-0.96%	-0.42%	0.03%
Ep-Seawater	-0.82%	-0.36%	-0.14%	-0.06%	0.97%	0.42%	-0.96%	-0.42%	0.00%	0.00%	-0.84%	-0.37%	1.06%	0.46%	5.90%	2.58%	-0.96%	-0.42%	3.63%
EP-land	-0.75%	-0.33%	-0.13%	-0.05%	0.70%	0.31%	-0.96%	-0.42%	0.00%	0.00%	-0.84%	-0.37%	1.10%	0.48%	6.70%	2.93%	-0.96%	-0.42%	3.91%
POCP	0.32%	0.14%	-0.39%	-0.17%	0.59%	0.26%	-0.96%	-0.42%	0.00%	0.00%	-0.85%	-0.37%	0.44%	0.19%	5.60%	2.45%	-0.96%	-0.42%	3.74%
ADP-Elements	1.79%	0.78%	0.01%	0.00%	-0.71%	-0.31%	-0.96%	-0.42%	0.00%	0.00%	-0.91%	-0.40%	1.51%	0.66%	2.95%	1.29%	-0.96%	-0.42%	3.72%
ADP - Comb. & Fossils	-0.64%	-0.28%	-0.39%	-0.17%	0.35%	0.15%	-0.96%	-0.42%	0.00%	0.00%	-0.73%	-0.32%	0.52%	0.23%	5.40%	2.36%	-0.96%	-0.42%	5.55%
WDP	-0.71%	-0.31%	-3.81%	-1.67%	-0.15%	-0.06%	-0.80%	-0.35%	0.00%	0.00%	0.01%	0.01%	-15.34%	-6.72%	10.96%	4.80%	-0.96%	-0.42%	0.05%

W2																			
Over/Underestimation (%)	M1 A1	M2 A1	M1 A2	M2 A2	M1 A3	M2 A3	M1 A5	M2 A5	M1 B1	M2 B1	M1 C1	M2 C1	M1 C2	M2 C2	M1 C3	M2 C3	M1 C4	M2 C4	M1 D
GWP-Total	17.55%	10.23%	-0.42%	-0.22%	-1.22%	-0.64%	-1.05%	-0.55%	-1.15%	-0.61%	-0.84%	-0.44%	0.76%	0.40%	12.78%	7.25%	-1.15%	-0.61%	26.71%
GWP-Fossil	-1.01%	-0.53%	-0.43%	-0.23%	-1.27%	-0.66%	-0.99%	-0.52%	-1.15%	-0.61%	-0.84%	-0.44%	0.74%	0.39%	7.67%	4.23%	-1.15%	-0.61%	7.58%
GWP-Biogeneic	3.46%	1.86%	3.21%	1.73%	-1.15%	-0.61%	-1.15%	-0.61%	0.00%	0.00%	1.28%	0.68%	6.87%	3.77%	12.92%	7.33%	-1.15%	-0.61%	-1.22%
GWP-Luluc	3.34%	1.80%	12.61%	7.14%	-0.40%	-0.21%	-1.14%	-0.60%	0.00%	0.00%	11.65%	6.57%	12.81%	7.27%	3.27%	1.76%	-1.15%	-0.61%	0.42%
ODP	-0.61%	-0.32%	-1.15%	-0.61%	-1.09%	-0.57%	-1.15%	-0.61%	0.00%	0.00%	-1.15%	-0.61%	-1.15%	-0.61%	-1.15%	-0.61%	-1.15%	-0.61%	-1.15%
AP	-0.95%	-0.50%	-0.42%	-0.22%	0.23%	0.12%	-1.15%	-0.60%	0.00%	0.00%	-1.01%	-0.53%	0.64%	0.34%	7.91%	4.37%	-1.15%	-0.61%	4.89%
EP-Freshwater	-0.70%	-0.37%	2.20%	1.18%	2.65%	1.42%	-1.15%	-0.61%	0.00%	0.00%	0.11%	0.06%	5.64%	3.08%	4.33%	2.35%	-1.15%	-0.61%	0.04%
Ep-Seawater	-0.98%	-0.52%	-0.16%	-0.09%	1.16%	0.61%	-1.15%	-0.61%	0.00%	0.00%	-1.01%	-0.53%	1.26%	0.67%	6.96%	3.82%	-1.15%	-0.61%	4.30%
EP-land	-0.89%	-0.47%	-0.15%	-0.08%	0.83%	0.44%	-1.15%	-0.60%	0.00%	0.00%	-1.01%	-0.53%	1.31%	0.70%	7.89%	4.36%	-1.15%	-0.61%	4.63%
POCP	0.39%	0.21%	-0.46%	-0.24%	0.70%	0.37%	-1.15%	-0.60%	0.00%	0.00%	-1.02%	-0.53%	0.53%	0.28%	6.61%	3.62%	-1.15%	-0.61%	4.44%
ADP-Elements	2.13%	1.14%	0.01%	0.01%	-0.85%	-0.45%	-1.15%	-0.61%	0.00%	0.00%	-1.09%	-0.57%	1.80%	0.96%	3.50%	1.89%	-1.15%	-0.61%	4.41%
ADP - Comb. & Fossils	-0.76%	-0.40%	-0.46%	-0.24%	0.41%	0.22%	-1.15%	-0.60%	0.00%	0.00%	-0.87%	-0.46%	0.62%	0.33%	6.38%	3.49%	-1.15%	-0.61%	6.56%
WDP	-0.85%	-0.45%	-4.58%	-2.37%	-0.17%	-0.09%	-0.96%	-0.51%	0.00%	0.00%	0.01%	0.01%	-18.88%	-9.08%	12.81%	7.27%	-1.15%	-0.61%	0.06%

W3																			
Over/Underestimation (%)	M1 A1	M2 A1	M1 A2	M2 A2	M1 A3	M2 A3	M1 A5	M2 A5	M1 B1	M2 B1	M1 C1	M2 C1	M1 C2	M2 C2	M1 C3	M2 C3	M1 C4	M2 C4	M1 D
GWP-Total	17.93%	10.74%	-0.43%	-0.23%	-1.25%	-0.67%	-1.08%	-0.58%	-1.19%	-0.64%	-0.86%	-0.46%	0.77%	0.42%	13.07%	7.61%	-1.19%	-0.64%	27.22%
GWP-Fossil	-1.03%	-0.56%	-0.44%	-0.24%	-1.30%	-0.70%	-1.02%	-0.55%	-1.19%	-0.64%	-0.87%	-0.47%	0.76%	0.41%	7.86%	4.44%	-1.19%	-0.64%	7.77%
GWP-Biogeneic	3.54%	1.95%	3.30%	1.82%	-1.19%	-0.64%	-1.18%	-0.64%	0.00%	0.00%	1.32%	0.72%	7.04%	3.96%	13.21%	7.70%	-1.19%	-0.64%	-1.26%
GWP-Luluc	3.43%	1.89%	12.90%	7.50%	-0.41%	-0.22%	-1.17%	-0.63%	0.00%	0.00%	11.92%	6.89%	13.11%	7.63%	3.35%	1.85%	-1.19%	-0.64%	0.43%
ODP	-0.62%	-0.34%	-1.19%	-0.64%	-1.11%	-0.60%	-1.19%	-0.64%	0.00%	0.00%	-1.19%	-0.64%	-1.19%	-0.64%	-1.18%	-0.64%	-1.19%	-0.64%	-1.18%
AP	-0.97%	-0.52%	-0.43%	-0.23%	0.24%	0.13%	-1.18%	-0.63%	0.00%	0.00%	-1.04%	-0.56%	0.66%	0.36%	8.11%	4.59%	-1.19%	-0.64%	5.01%
EP-Freshwater	-0.72%	-0.39%	2.26%	1.24%	2.71%	1.49%	-1.18%	-0.64%	0.00%	0.00%	0.12%	0.06%	5.79%	3.23%	4.44%	2.46%	-1.19%	-0.64%	0.04%
Ep-Seawater	-1.01%	-0.54%	-0.17%	-0.09%	1.19%	0.65%	-1.18%	-0.64%	0.00%	0.00%	-1.03%	-0.56%	1.29%	0.70%	7.13%	4.01%	-1.19%	-0.64%	4.41%
EP-land	-0.92%	-0.49%	-0.15%	-0.08%	0.86%	0.47%	-1.18%	-0.63%	0.00%	0.00%	-1.03%	-0.56%	1.34%	0.73%	8.09%	4.58%	-1.19%	-0.64%	4.75%
POCP	0.40%	0.22%	-0.47%	-0.26%	0.72%	0.39%	-1.18%	-0.63%	0.00%	0.00%	-1.04%	-0.56%	0.54%	0.30%	6.78%	3.81%	-1.19%	-0.64%	4.55%
ADP-Elements	2.18%	1.19%	0.01%	0.01%	-0.87%	-0.47%	-1.18%	-0.64%	0.00%	0.00%	-1.11%	-0.60%	1.85%	1.01%	3.59%	1.98%	-1.19%	-0.64%	4.52%
ADP - Comb. & Fossils	-0.78%	-0.42%	-0.48%	-0.26%	0.42%	0.23%	-1.18%	-0.63%	0.00%	0.00%	-0.89%	-0.48%	0.63%	0.34%	6.54%	3.67%	-1.19%	-0.64%	6.72%
WDP	-0.87%	-0.47%	-4.71%	-2.49%	-0.18%	-0.10%	-0.99%	-0.53%	0.00%	0.00%	0.01%	0.01%	-19.47%	-9.53%	13.10%	7.63%	-1.19%	-0.64%	0.06%

W4																			
Over/Underestimation (%)	M1 A1	M2 A1	M1 A2	M2 A2	M1 A3	M2 A3	M1 A5	M2 A5	M1 B1	M2 B1	M1 C1	M2 C1	M1 C2	M2 C2	M1 C3	M2 C3	M1 C4	M2 C4	M1 D
GWP-Total	-27.66%	-28.80%	0.43%	0.63%	1.21%	1.80%	1.05%	1.56%	1.15%	1.71%	0.84%	1.25%	-0.78%	-1.13%	-17.52%	-20.40%	1.15%	1.71%	-58.95%
GWP-Fossil	1.00%	1.49%	0.43%	0.64%	1.26%	1.87%	0.99%	1.47%	1.15%	1.71%	0.84%	1.25%	-0.76%	-1.10%	-9.24%	-11.91%	1.15%	1.71%	-9.12%
GWP-Biogeneic	-3.78%	-5.24%	-3.50%	-4.87%	1.15%	1.71%	1.15%	1.71%	0.00%	0.00%	-1.34%	-1.92%	-8.12%	-10.62%	-17.78%	-20.64%	1.15%	1.71%	1.21%
GWP-Luluc	-3.65%	-5.06%	-17.21%	-20.11%	0.41%	0.60%	1.14%	1.69%	0.00%	0.00%	-15.50%	-18.49%	-17.59%	-20.46%	-3.56%	-4.95%	1.15%	1.71%	-0.43%
ODP	0.61%	0.90%	1.15%	1.71%	1.08%	1.61%	1.15%	1.71%	0.00%	0.00%	1.15%	1.71%	1.15%	1.71%	1.15%	1.71%	1.15%	1.71%	1.15%
AP	0.95%	1.40%	0.42%	0.62%	-0.24%	-0.34%	1.14%	1.70%	0.00%	0.00%	1.01%	1.50%	-0.66%	-0.96%	-9.59%	-12.30%	1.15%	1.71%	-5.52%
EP-Freshwater	0.70%	1.04%	-2.34%	-3.31%	-2.84%	-3.99%	1.15%	1.71%	0.00%	0.00%	-0.12%	-0.17%	-6.48%	-8.66%	-4.84%	-6.61%	1.15%	1.71%	-0.04%
Ep-Seawater	0.98%	1.45%	0.17%	0.24%	-1.20%	-1.73%	1.15%	1.70%	0.00%	0.00%	1.00%	1.49%	-1.31%	-1.89%	-8.24%	-10.76%	1.15%	1.71%	-4.79%
EP-land	0.89%	1.32%	0.15%	0.22%	-0.86%	-1.25%	1.14%	1.70%	0.00%	0.00%	1.00%	1.49%	-1.37%	-1.96%	-9.56%	-12.27%	1.15%	1.71%	-5.20%
POCP	-0.40%	-0.58%	0.47%	0.69%	-0.72%	-1.04%	1.14%	1.70%	0.00%	0.00%	1.01%	1.51%	-0.55%	-0.79%	-7.77%	-10.20%	1.15%	1.71%	-4.96%
ADP-Elements	-2.26%	-3.20%	-0.01%	-0.02%	0.85%	1.26%	1.15%	1.71%	0.00%	0.00%	1.08%	1.61%	-1.90%	-2.71%	-3.83%	-5.31%	1.15%	1.71%	-4.92%
ADP - Comb. & Fossils	0.76%	1.13%	0.47%	0.69%	-0.42%	-0.62%	1.14%	1.70%	0.00%	0.00%	0.87%	1.29%	-0.63%	-0.92%	-7.46%	-9.83%	1.15%	1.71%	-7.69%
WDP	0.85%	1.26%	4.27%	6.66%	0.18%	0.26%	0.96%	1.42%	0.00%	0.00%	-0.01%	-0.02%	13.92%	25.56%	-17.58%	-20.46%	1.15%	1.71%	-0.06%

Figure 7.5: Formation of the UF - The over/underestimation of emissions per surface and method.

Timber percentages (%)				
	W1	W2	W3	W4
Percentage on facade	8.03 %	8.20 %	8.23 %	6.06%
Percentage for columns	1.90 %	2.18 %	2.02 %	1.06%
Percentage for beams	4.22 %	3.24 %	4.41 %	3.51%
Percentage for studs	1.91 %	2.78 %	1.80 %	0.95%
M1 - Average per timber element type(%)				
Columns	Beams	Studs		
3.85 %	1.81 %	1.48 %		
M1 - Mean timber percentage on the facade parts (%)			M2 - Timber percentage on the facade (%)	
7.14 %			7.64 %	

Table 7.2: Timber percentages on each facade parts.

		Surface	Thickness	Features
Hempcrete	Facade	1 m^2	0.35 m	7.64% / 92.36 % (Timb./Hempcr.)
	Separation	1 m^2	0.075 m	8.54% / 91.46 % (Timb.*/Hempcr.)
	Internal loadbearing	1 m^2	0.075 m	30.20*% / 69.80 % (Timb./Hempcr.)
Sand lime bricks	Facade	1 m^2	0.31 m	0.16cm/0.15cm ((FG / SL**)
	Separation	1 m^2	0.07 m	SL**
	Internal loadbearing	1 m^2	0.158 m	SL** (Weighted mean thickness)
AAC	Facade	1 m^2	0.48 m	AAC **
	Separation	1 m^2	0.10 m	AAC **
	Internal loadbearing	1 m^2	0.165 m	AAC** - Weighted mean thickness

*Timber for studs around doors

**98.2% Block & 1.8 % Mortar

Table 7.3: Compared unit factors.

7

7.5. THE BIOGENIC CARBON STORAGE AND THE POTENTIAL OF BIOBASED MATERIALS

Plants have the ability to store CO_2 during their lifetime. This CO_2 storage is part of the biogenic terrestrial carbon cycle and can be proven beneficial for the reduction of the green house gas emissions.

In more detail, the global carbon cycle is characterised by its carbon pools and fluxes. Among others, which include the earth crust (c.100,000,000 Pg C), the fossil fuels (c. 4000 Pg C), the oceans (c. 38,000 Pg C), the atmosphere (c. 750 Pg C) and the soils (c. 1500 Pg C), biomass (c. 560 Pg C) is also part of the earth's pools. Through different processes carbon travels from one pool to another which sometimes can cause imbalances in the terrestrial systems as for example in the case of global warming (atmosphere) and acidification (oceans). The carbon which is stored in biomass is characterised by the term biogenic carbon. Biogenic carbon is stored in plants through the process of photosynthesis, however it can eventually move to a different carbon pool by two main mechanisms: the respiration and the degradation of the biomass. In comparison to the other types of carbon as for instance the fossils, biogenic carbon is characterised by a significantly lower carbon cycle and therefore can be an efficient means for carbon sequestration [2].

7

This aspect of the biogenic carbon has been noticed by the modern scientific community and steps towards the exploitation of the advantages that offers have been already taken. A recent example is the introduction of the Biogenic Global Warming Potential in the LCA related European standards (EN15804+A2, EN 15978:2021). The initiative behind these steps is to increase the low carbon sequestration potential of the biomass and soils, which can be done by the introduction of the bio energy in the carbon cycle. Such introduction has the ability to increase the biogenic carbon storage potential, decrease the GHG emissions originated by fossils and limit the carbon losses from soil due to land use changes (LUC) [2]. Bio-based construction materials after their lifetime can be used to substitute fossils for the generation of heat and electricity. This advantage can be taken into account in stage D of the LCA analysis.

The biogenic carbon storage was taken into account in the biobased hempcrete design. For the hempcrete blocks, the carbon content in a unit factor equal to the one of the case study facade was calculated with respect to the information provided by the EPD. The main features are presented below:

- The biogenic carbon which is stored in the shiv during the cultivation of the hemp, is estimated to 0.47 kg C per Kg of dry hemp. The humidity in the material is estimated at approximately 12%, thus for 1 kg of hemp shiv, the remaining dry material includes 88% * 0.47 Kg C= 0.4136 kg C/kg of hemp shiv.
- For the carbon conversion to CO_2, the Carbon content is multiplied by the molar ratio of the two components (44/12=3.667). Thus, C= 0.4136 kg C/kg of hemp -> 0.4136 * 3.667 = 1.517 kg CO_2/kg of hemp shiv (at 88% dry material).
- With similar composition's proportions, 1 UF of 35 cm contains 33.3 kg of hemp shiv, which is translated to:

→ 13.73kg C/UF
→ 50.52kg CO_2/UF

- However in a UF of 35 cm only the 92.36% accounts for hempcrete, since the rest is timber. Therefore eventually:
  → $13.73 * 0.92 = 12.68$kg C/UF
  → $50.52 * 0.92 = 46.48$kg CO_2/UF (taken into account in stage A1 - Biogenic-GWP)

- It is considered that the total of carbon storage in hempcrete eventually decomposes and is released in the atmosphere in the form of GHG emissions (stage C4 - Biogenic-GWP) . For the bio-gas potential, only 15% of shiv is assumed to be decomposed after land-filling, 50% in the form of CO_2 and 50% in the form of methane. A proportion of 70% of bio-gas (30% losses), is captured in a co-generation unit and eventually is being converted to electricity and heat (module D).

  → $22.90 * 0.92 = 21.16$ MJ/UF(electricity)
  → $40.01 * 0.92 = 36.95$ MJ/UF(heating)

7

- The part of the packaging, namely the wooden pallets and the protection corner pieces of the blocks, includes biogenic carbon which is also taken into account in the calculation and accounts for 3.695 kg C/UF -> 13.55 kg CO_2/UF (taken into account in stage A3 - Biogenic-GWP). After use the pallets are partly re-used, recycled, and incinerated (taken into account in stage A5 and D - Biogenic-GWP).

Regarding the wooden part of the unit factor the carbon storage is calculated as shown below. The packaging of the material does not contain any biogenic content.

- The biogenic carbon which is stored in 1 m^3 of spruce is 212 KgC. Again for the carbon conversion to CO_2, the Carbon content is multiplied by the molar ratio of the two components (44/12=3.667).

  → $C = 212kg\ C/m^3$ of spruce -> 212 * 3.667 = 777.4 kg CO_2/m^3 of spruce

- Eventually the carbon content for a unit factor of 0.35 m^3 with a 7.64% presence of timber:

  → $777.4kg\ CO_2/m^3$ * 0.35 * 0.076 = 20.70 kg CO_2/UF

- Incineration is concerned as a waste treatment scenario (stage C3). The energy gain related to the timber proportion for heating and electricity per UF of facade is:

→ 36.18 MJ/UF (electricity)
→ 64.9 MJ/UF (heating)

Eventually the total carbon storage and energy gain of the UF of the biobased facade (exl. packaging) is calculated at:

→ $46.48 + 20.70 = 67.18$ kg CO_2/UF
→ $21.16 + 36.18 = 57.34$ MJ/UF (electricity)
→ $36.95 + 64.9 = 101.8$ MJ/UF (heating)

7.6. THE CARBONISATION OF THE LIME

As it has been already stated in the Literature review, hempcrete and sand lime bricks have the ability to store CO_2 during their life time through the process of the carbonisation. This ability is also taken into account in the EPDs.

7

The carbonisation potential of hempcrete
The amount of the CO_2 capturing by this process is strongly related to the presence of calcium oxide in the binder, as it is the result of reaction of the carbon dioxide which is present in the atmosphere with the calcium hydroxide ($Ca(OH)_2$) which is contained in the aerial lime and the natural cement of the hempcrete wall. The equation of this reaction is described below:

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O \tag{7.1}$$

According to the Formula (7.1), 1 kmol of $Ca(OH)_2$ (74.09 kg/kmol) sequestrates 1 kmol of CO_2 (44.01 kg/kmol).

The carbonisation lasts from three to five years, it is a non linear process which allows the majority of CO_2 to be sequestrated during the first months after the production of the material. For 35 cm blocks, the same approach as in the EPD has been followed. It was estimated that around 60% of sequestration takes place during the first 2 months after production and the rest sequestration potential in a five year period after that. The configuration of the hemp network and the high porosity of the material, allows the air to circulate within the hempcrete blocks. The later makes almost the entire amount of the lime available to carbonisation (80-90%). In the relevant EPD, a carbonisation potential of 90% was indicated. According to the aforementioned the sequestration due to carbonisation for the UF was calculated to:

- 19.08 kg CO_2/UF in stage A3 (Factory gate)
- 12.63 Kg CO_2/UF in stage B1 (Use Phase)

However due to the substitution of hempcrete by an amount of timber the carbonisation potential must be accordingly converted:

- 19.08 * 0.92 = 17.62 kg CO_2/UF →in stage A3 (Factory gate)
$-12.63 * 0.92 = 11.66 KgCO_2$/UF →in stage B1 (Use Phase)

The carbonisation potential of the SL bricks

Again for carbonisation potential of the SL bricks the estimation approach as the one presented in the perspective EPD was used.

- 90.25 kg CO_2/m^3 → 13.54kg $CO_2/UF \rightarrow in$stage B1 (Use Phase)

7.7. THE ENVIRONMENTAL PERFORMANCES OF THE MATERIALS

In order to acquire a wider image on how each material contributes to the environmental performance of the composite sections under scrutiny, the following bar charts with the breakdown of the environmental emissions per material, environmental category and LC stage were constructed.

According to Figure 7.9, some patterns related to the nature of the materials and the environmental impacts can be detected. In general masonry materials appear to have the highest environmental impact in the majority of the categories under scrutiny. An exception can be observed in the categories of GWP-Luluc and WDP (Water depletion potential) where timber and FG insulation respectively are characterised by a significantly high environmental impact. As expected, bio-based materials show higher benefits in stage D, due to the their biogenic carbon storage, which allows some further exploitation for energy generation after their life time. For all the materials under scrutiny, the production stages A1-A3, account for the higher environmental impact in all the categories under examination.

The activities that are required for the mining of raw materials (Sand in SL and AAC blocks) and the production of the binder (cement/lime) for the masonry blocks, are known to be energy consuming and demand high levels of fossil fuel combustion. The latter is reflected on the high scores' of the masonry materials in the categories of GWP-Fossil and ADP-fossil fuels combustibles, which are related to the environmental impacts originated by the degradation or transformation of fossil fuels. The production of lime binder is less energy intensive than that of the cement since lime can be produced in lower temperatures than cement. Hempcrete, in terms of energy combustion combines the advantages of the lime binder and its natural aggregate (hemp) which results to the lowest environmental impact between the masonry materials in these two aforementioned categories. The environmental impact of hempcrete in these categories is further decreased when biogenic carbon is taken into account as a substitution of fossil carbon (stage D).

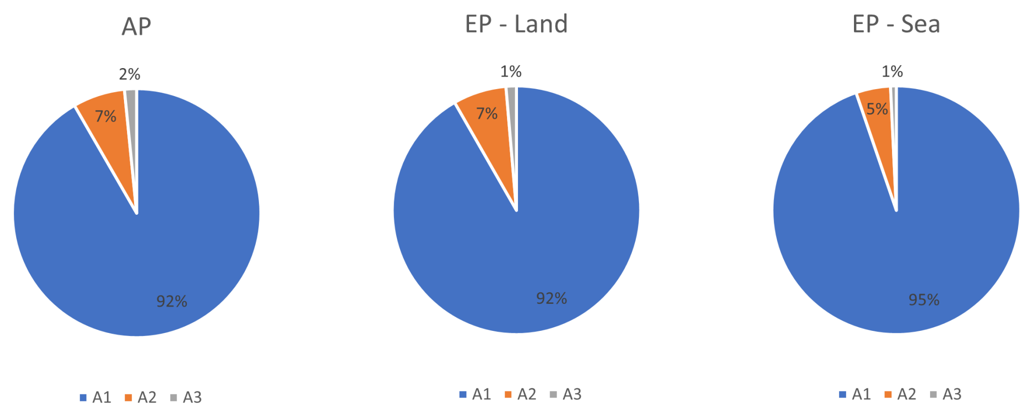


Figure 7.6: Proportional contribution of sub-stages A1-A3 in the total product stage of hempcrete for the impact categories of sea and land eutrophication and acidification .

Hempcrete performs better than the conventional masonry materials in the majority of the environmental categories. Apart from the impact categories of the GWP-Fossil and ADP combustibles, hempcrete exhibits exceptional performances in comparison to the rest materials in the impact categories of ADP Elements and GWP Luluc. ADP-elements category reflects the environmental costs which are related to the extraction of minerals, which for the case of hempcrete and timber remain limited due to their biobased nature. Regarding the environmental impact category of GWP Luluc, even though hempcrete is a biobased material, which are known to have high contribution in this category, its impact remains considerably lower in comparison to the majority of the material under examination (excl. FG Insulation). According to the bar charts (Figure 7.9), the use of timber in the UF is expected to increase the environmental impact in the categories of GWP Luluc and ADP-elements.

Nevertheless, hempcrete appears to be characterised by lower performances in the environmental categories of AP (Acidification potential), EP - Seawater (eutrophication potential), EP land (eutrophication potential) and ODP (ozone layer depletion potential). For the measurement of the impact levels in both the aforementioned eutrophication categories, nitrogen levels are taken into account. The cultivation of industrial hemp is known to be dependent on nitrogen fertilization, which has a positive influence on important factors as the biomass yield, the height of the plant and the stem's and inflorescence weight [3]. According to studies, in the case of hemp, fertilizers can be responsible for around 90% of the environmental impact detected in the eutrophication category [4], a feature which could be responsible for the hempcrete's results in the respective category. Nitrogen based fertilizers can also be the main reason behind the high environmental impact in the category of acidification, as nitrogen has a higher influence on the soil's pH in comparison to other types of nutrients [5]. It is worth mentioning here that for the aforementioned categories of eutrophication and acidification, stage A1 (raw material supply) accounts for a significantly high proportion (> 90%), a feature that can also be an indicator for the contribution of the fertilizers in the environmental results (Figure 7.6).

7

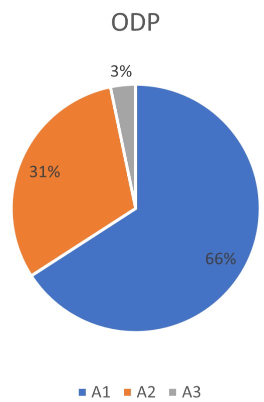


Figure 7.7: Proportional contribution of sub-stages A1-A3 in the total product stage of hempcrete for the impact category of ozone depletion .

Regarding the ozone depletion (ODP), higher impact levels of hempcrete in comparison to conventional materials as AAC, have been also detected in other studies , nevertheless the reason behind it remains unclear [6]. In this case, sub-stage A1 accounts for a lower percentage in comparison to the aforementioned eutrophication and acidification categories (66%) and the sub-stage A2 (Transportation) accounts for a noticeable proportion too (31%).

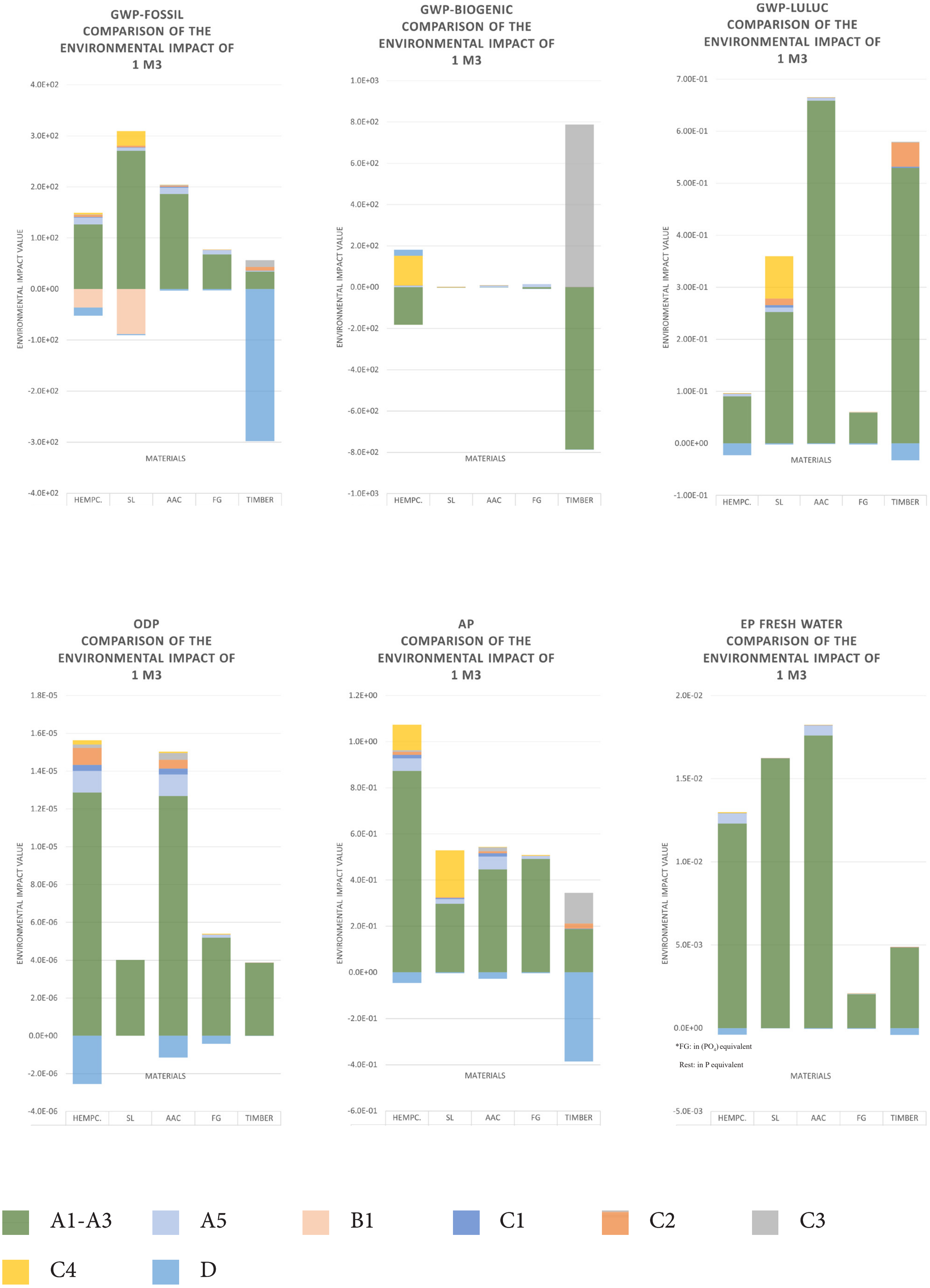


Figure 7.8: The environmental impact of 1 m^3 - Comparison between the materials under scrutiny.

Figure 7.9: The environmental impact of 1 m^3 - Comparison between the materials under scrutiny.

7.8. THE ENVIRONMENTAL RESULTS PER UNIT FACTOR

7.8.1. THE FACADE

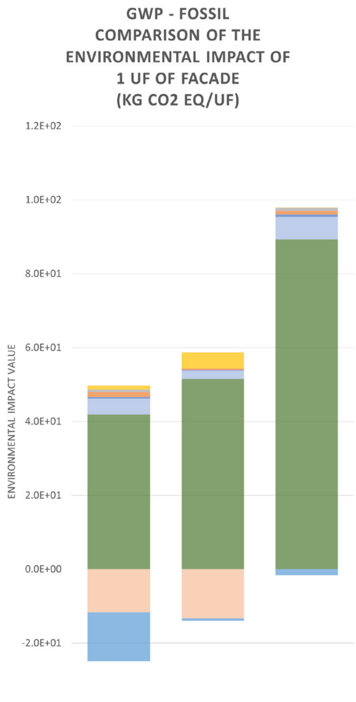
The environmental impact of the facade's UF was calculated for the assemblies under scrutiny. The results are presented in total in Table 7.4 and in aggregated form per stage in Figures 7.10-7.11. For the sake of brevity the term Hempcrete is used for the hybrid Hempcrete-Timber facade, and the term SL for the hybrid Sand-lime and Fiberglass facade.

Assembly		Hempcrete		SL& FG		AAC	
Impact category		Excl. stage D	Incl. stage D	Excl. stage D	Incl. stage D	Excl. stage D	Incl. stage D
GWP Fossil	(kg CO2 eq/UF)	3.81 E+01	2.48 E+01	4.54 E+01	4.47 E+01	9.79 E+01	9.63 E+01
GWP Biogenic	(kg CO2 eq/UF)	-9.54 E+00	-6.21 E-02	7.98E-01	7.88 E-01	3.25 E+00	3.25 E+00
GWP luluc	(kg CO2 eq/UF)	4.67 E-02	3.84 E-02	6.35E-02	6.29 E-02	3.19 E-01	3.19 E-01
ODP	(kg CFC11 eq/UF)	5.16 E-06	4.33 E-06	1.47E-06	1.40 E-06	7.21 E-06	6.66 E-06
AP	(mol H+eq/UF)	3.56 E-01	3.31 E-01	1.61E-01	1.60 E-01	2.61 E-01	2.47 E-01
EP Fresh water	(kg P eq/UF)	4.33 E-03	4.19 E-03	2.44E-03	2.44 E-03	8.75 E-03	8.73 E-03
	(kg PO4 eq/UF)	(-)	(-)	3.34 E-04	3.27 E-04	(-)	(-)
EP Sea water	(kg N eq/UF)	1.55 E-01	1.47 E-01	2.78E-02	2.75 E-02	6.47 E-02	6.0 E-02
EP Land	(mol N eq/UF)	1.27 E-00	1.20 E-00	5.55E-01	5.53 E-01	7.93 E-01	7.42 E-01
POCP	(kg NMVOC eq/UF)	1.45 E-01	1.24 E-01	9.96E-02	9.89 E-02	2.07 E-01	1.92 E-01
ADP Elements	(kg Sb eq/UF)	9.21 E-06	6.06 E-06	7.79E-05	7.58 E-05	8.33 E-04	8.1 E-04
ADP Fossils	(MJ/UF)	4.75 E+02	2.20 E+02	5.46E+02	5.31 E+02	6.87 E+02	6.49 E+02
WDP	(m3 water/UF)	7.42 E+00	6.40 E+00	9.32E+03	9.00 E+03	1.24 E+01	1.10 E+01

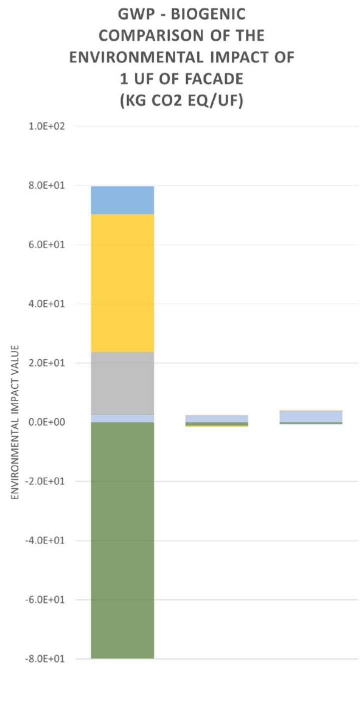
Table 7.4: Compared unit factors.

The Hempcrete assembly performs better than the AAC one in the vast majority of the impact categories under scrutiny with the exception in the categories of Acidification, Eutrophication Land and Eutrophication Seawater. The possible reasons behind the lower environmental performances in these categories have been already discussed in Section 7.7. The contribution of timber in the biobased design UF, had partly decreased the environmental impact of the biobased design in the category of the Ozone depletion. The emission differences between the two materials are highly distinguishable.

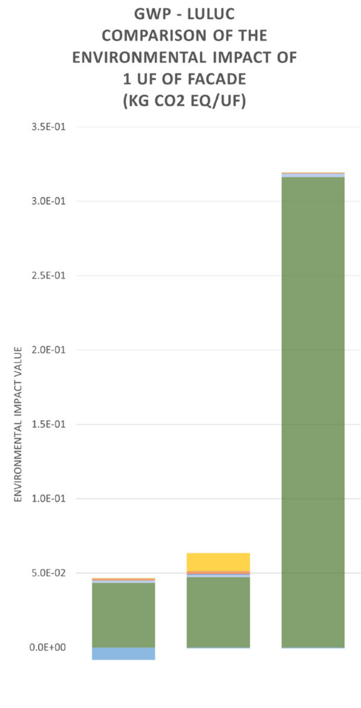
The results of the SL and Hempcrete design seem divided when all the environmental impact categories are taken into account and thus do not allow a clear environmental ranking between the two options. The hempcrete design displays superior environmental performances in the global warming categories (GWP), where the biogenic carbon potential is taken into account, even though no carbon storage is considered and the total amount of stored CO2 in hempcrete is assumed to be emitted (Figure 7.10 - GWP - Biogenic carbon, stage C4) after the declared service life (60 years). The latter is a rather conservative scenario, since in reality the biogenic carbon storage in hempcrete has a higher duration that can reach more than 100 years. Eventually the total of CO^2 emissions for the sum of the GWP-categories (Fossil, Biogenic, Luluc), in the case of the Hempcrete design is almost the half of that of SL when also stage D is considered (2.48 E+01 and 4.55E+01 CO2 eq., for Hempcrete and Sl respectively). The higher amounts of the carbonisation of the lime for the case of hempcrete (Section 7.6) and the benefits of the exploitation of biomass in stage D have contributed considerably in the aforementioned results. For the impact categories of Abiotic Depletion potential of Fossil fuels and Elements, again the hempcrete design performs better. A remarkable difference between the SL and the hempcrete option can be detected in the environmental category of Water depletion, where the Hempcrete design impact is accounts for 0.07% of the respective impact of the SL design. This difference is attributed to the FG insulation. In the rest environmental categories, SL design appears to perform better, the lower environmental impact of the FG insulation (Section 7.7), has attenuated the impact of the SL bricks.



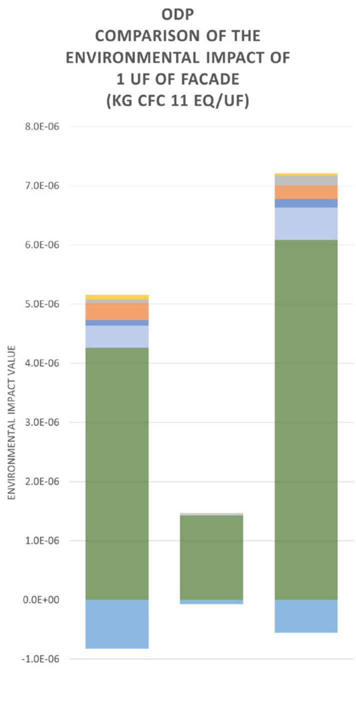
	HEMPCRETE	SL	AAC
D	-1.3E+01	-6.9E-01	-1.6E+00
C4	1.1E+00	4.3E+00	8.9E-02
C3	5.9E-01	0.0E+00	7.8E-01
C2	1.5E+00	4.7E-01	9.6E-01
C1	4.4E-01	1.8E-01	7.0E-01
B1	-1.2E+01	-1.3E+01	0.0E+00
A5	4.2E+00	2.2E+00	6.1E+00
A1-A3	4.2E+01	5.1E+01	8.9E+01



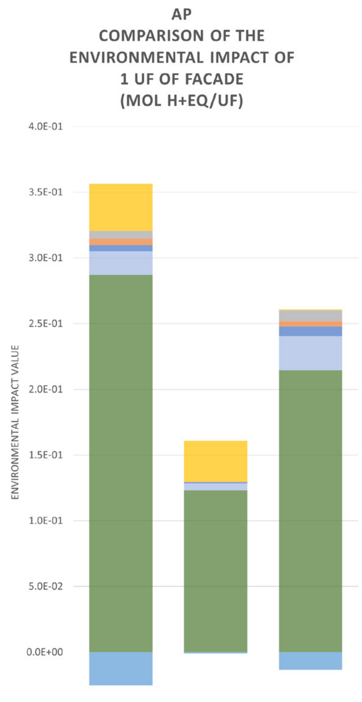
	HEMPCRETE	SL	AAC
D	9.5E+00	-1.4E-03	-2.9E-03
C4	4.7E+01	-3.4E-01	1.8E-04
C3	2.1E+01	0.0E+00	2.2E-04
C2	1.2E-03	1.8E-04	7.0E-04
C1	1.9E-04	-7.6E-03	1.9E-04
B1	0.0E+00	0.0E+00	0.0E+00
A5	2.6E+00	2.2E+00	3.8E+00
A1-A3	-8.0E+01	-1.1E+00	-6.0E-01



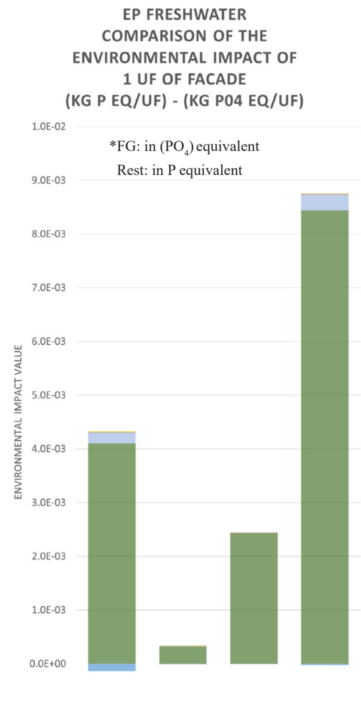
	HEMPCRETE	SL	AAC
D	-8.3E-03	-6.5E-04	-6.1E-04
C4	1.8E-04	1.2E-02	2.7E-05
C3	1.6E-04	0.0E+00	6.6E-05
C2	1.2E-03	1.9E-03	2.9E-04
C1	6.5E-05	7.1E-04	5.9E-05
B1	0.0E+00	0.0E+00	0.0E+00
A5	1.7E-03	1.4E-03	2.5E-03
A1-A3	4.3E-02	4.7E-02	3.2E-01



	HEMPCRETE	SL	AAC
D	-8.2E-07	-6.8E-08	-5.5E-07
C4	7.3E-08	6.4E-09	3.7E-08
C3	5.5E-08	0.0E+00	1.7E-07
C2	3.0E-07	8.4E-10	2.3E-07
C1	9.7E-08	4.2E-17	1.5E-07
B1	0.0E+00	0.0E+00	0.0E+00
A5	3.7E-07	2.6E-08	5.5E-07
A1-A3	4.3E-06	1.4E-06	6.1E-06

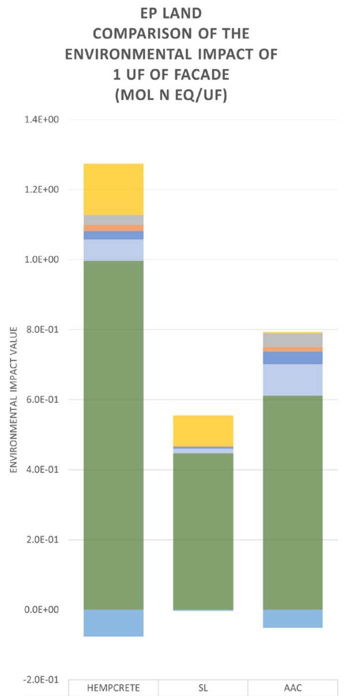


	HEMPCRETE	SL	AAC
D	-2.5E-02	-1.1E-03	-1.3E-02
C4	3.6E-02	3.1E-02	8.5E-04
C3	5.7E-03	0.0E+00	8.1E-03
C2	5.0E-03	5.4E-04	4.0E-03
C1	4.7E-03	8.4E-04	7.3E-03
B1	0.0E+00	0.0E+00	0.0E+00
A5	1.8E-02	5.1E-03	2.6E-02
A1-A3	2.9E-01	1.2E-01	2.1E-01

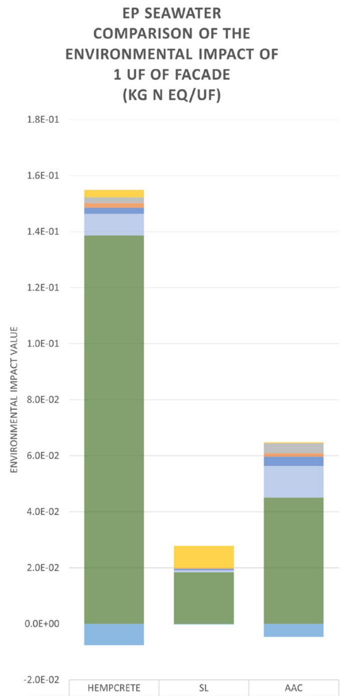


	HEMPCRETE	FG	SL	AAC
D	-1.4E-04	-6.8E-06	-5.3E-07	-2.1E-05
C4	1.7E-05	5.0E-07	7.3E-16	1.1E-06
C3	1.2E-06	0.0E+00	0.0E+00	3.2E-06
C2	1.4E-06	2.2E-07	9.9E-07	7.8E-06
C1	3.7E-07	0.0E+00	3.7E-07	2.8E-06
B1	0.0E+00	0.0E+00	0.0E+00	0.0E+00
A5	2.0E-04	8.6E-06	6.9E-07	3.0E-04
A1-A3	4.1E-03	3.2E-04	2.4E-03	8.4E-03

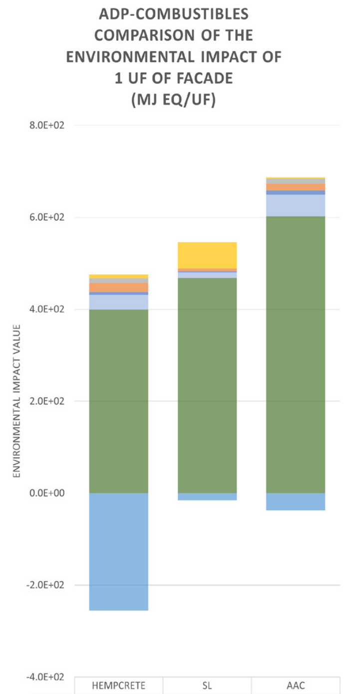
Figure 7.10: The environmental impact of 1 facade UF - Comparison between the assemblies under scrutiny.



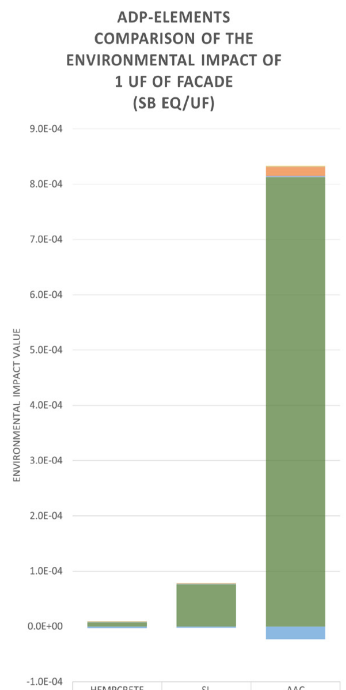
	HEMPCRETE	SL	AAC
D	-7.7E-02	-2.4E-03	-5.1E-02
C4	1.5E-01	8.8E-02	3.2E-03
C3	2.7E-02	0.0E+00	4.0E-02
C2	1.9E-02	2.2E-03	1.3E-02
C1	2.3E-02	4.4E-03	3.5E-02
B1	0.0E+00	0.0E+00	0.0E+00
A5	6.2E-02	1.3E-02	9.0E-02
A1-A3	1.0E+00	4.5E-01	6.1E-01



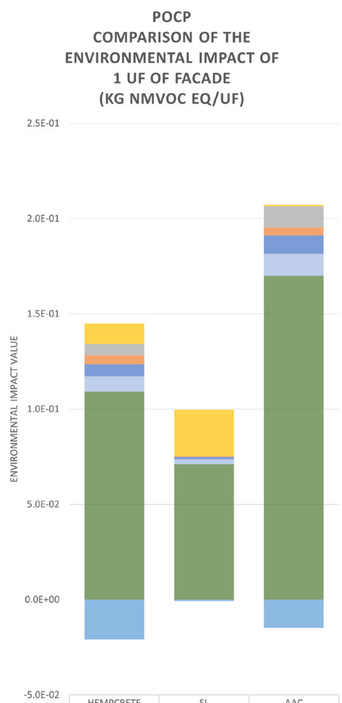
	HEMPCRETE	SL	AAC
D	-7.6E-03	-2.2E-04	-4.7E-03
C4	2.6E-03	8.0E-03	2.9E-04
C3	2.1E-03	0.0E+00	3.6E-03
C2	1.7E-03	1.8E-04	1.2E-03
C1	2.1E-03	4.0E-04	3.2E-03
B1	0.0E+00	0.0E+00	0.0E+00
A5	7.8E-03	8.1E-04	1.1E-02
A1-A3	1.4E-01	1.8E-02	4.5E-02



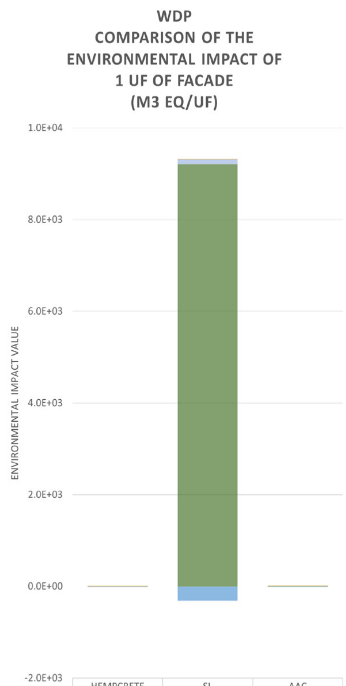
	HEMPCRETE	SL	AAC
D	-2.6E+02	-1.5E+01	-3.8E+01
C4	7.4E+00	5.7E+01	2.5E+00
C3	1.0E+01	0.0E+00	1.1E+01
C2	2.0E+01	6.3E+00	1.5E+01
C1	6.1E+00	2.3E+00	9.6E+00
B1	0.0E+00	0.0E+00	0.0E+00
A5	3.2E+01	1.2E+01	4.7E+01
A1-A3	4.0E+02	4.7E+02	6.0E+02



	HEMPCRETE	SL	AAC
D	-3.1E-06	-2.1E-06	-2.3E-05
C4	2.7E-07	4.4E-07	8.1E-07
C3	1.5E-07	0.0E+00	1.2E-06
C2	9.3E-08	7.7E-08	1.6E-05
C1	1.9E-07	1.4E-08	1.1E-06
B1	0.0E+00	0.0E+00	0.0E+00
A5	7.1E-07	1.1E-06	1.0E-06
A1-A3	7.8E-06	7.6E-05	8.1E-04



	HEMPCRETE	SL	AAC
D	-2.1E-02	-7.4E-04	-1.5E-02
C4	1.1E-02	2.4E-02	9.3E-04
C3	5.9E-03	0.0E+00	1.1E-02
C2	4.8E-03	5.1E-04	4.3E-03
C1	6.3E-03	1.1E-03	9.7E-03
B1	0.0E+00	0.0E+00	0.0E+00
A5	7.9E-03	2.5E-03	1.2E-02
A1-A3	1.1E-01	7.1E-02	1.7E-01



	HEMPCRETE	SL	AAC
D	-1.0E+00	-3.1E+02	-1.4E+00
C4	2.0E-02	3.3E+00	1.2E-01
C3	2.6E+00	0.0E+00	2.0E-02
C2	-1.9E-03	7.9E-01	5.6E-02
C1	1.3E-03	7.4E-04	1.8E-02
B1	0.0E+00	0.0E+00	0.0E+00
A5	3.2E-01	1.1E+02	4.7E-01
A1-A3	4.4E+00	9.2E+03	1.2E+01

Figure 7.11: The environmental impact of 1 facade UF - Comparison between the assemblies under scrutiny.

The different measurement units and results' scales in the environmental categories under examination create some difficulties regarding the derivation of final conclusions on the sustainability of the materials. In order to overcome these difficulties, different normalisation and weighting schemes are used as a means during Life Cycle Assessment worldwide, which allow the translation of results in a single score. In literature five different weighting approaches are found: the Single item based, the distance to target, the panel based, the monetary valuation and the meta models [7]. Each of the aforementioned assessment schemes are inherently dependent on choices influenced by aspects as policy, culture and therefore are not directly derived by science. For this reason, an equal weighting approach is sometimes preferably followed. In the Netherlands however the monetary valuation approach is followed and therefore the same approach has been chosen for this graduation project. The new standard EN 15978:2021 is still under development and therefore monetary values have not yet been assigned to the emission equivalents of the new environmental categories [8]. As a result, the monetary valuation in this graduation project is based on values derived by the Dutch literature (Table 7.5).

Impact category		cost per eq. (€)	Hempcrete	SL	AAC	Source
GWP Fossil	(kg CO2 eq/UF)	0.05	1.24 E+00	2.24 E+00	4.81 E+00	[9]
GWP Biogenic	(kg CO2 eq/UF)	0.05	-3.10 E-03	3.94E-02	1.62 E-01	[9]
GWP luluc	(kg CO2 eq/UF)	0.05	1.92 E-03	3.14 E-03	1.59E-02	[9]
ODP	(kg CFC11 eq/UF)	30.0	1.30 E-04	4.2 E-05	2.0 E-04	[9]
AP	(mol H+eq/UF)	4.0	1.32 E+00	6.39 E-01	9.90 E-01	[10]
EP Fresh water	(kg P eq/UF)	1.90	7.96E-03	4.63E-03	1.66E-02	[10]
EP Fresh water	(kg PO4 eq/UF)	9.0	(-)	2.95E-03	(-)	[9]
EP Sea water	(kg N eq/UF)	3.11	4.58 E-01	8.56 E-02	1.87 E-01	[10]
EP Land	(mol N eq/UF	0.04	5.22 E-02	2.41 E-02	3.23 E-02	[10]
POCP	(kg NMVOC eq/UF)	2.0	2.48 E-01	1.98 E-01	3.85 E-01	[9]
ADP Elements	(kg Sb eq/UF)	0.16	9.70 E-07	1.21 E-05	1.3 E-04	[9]
ADP Fossils	(MJ/UF)	7.70E-05	1.69 E-02	4.08 E-02	5.0 E-02	[9]**
WDP	(m3 water/UF)	1 E-04	1 E-03	9 E-01	1 E-03	Assump.
Total		(€)	3.35E+00	3.27E+00	6.65E+00	(exl. WDP)
Total		(€)	3.35 E+00	4.17 E+00	6.65 E+00	(incl. WDP)

*conversion: 1 mol N =0.014 kg N

** conversion: MJ/UF x 4.81E-04 = kg Sb-eq

Table 7.5: The final environmental costs per UF of facade

Due to the high difference in the results of the three assemblies in the category of WDP, two different approaches were used, one including and one excluding the the WDP category (Table 7.5).

In the case where the WDP was excluded from the final results, the SL brick facade UF appears to perform slightly better than that of Hempcrete. Nevertheless, the environmental image between the SL and the Hempcrete facade UF differs in the case of the second approach (incl. WDP) and the hempcrete option exhibits higher environmental performances. The environmental costs of the AAC UF, appear doubled in comparison to the rest two options for both the aforementioned approaches.

In order to derive a clearer image regarding the performances of the SL brick and the Hempcrete UF some further discussion on the results and the methods which were followed is needed. Regarding the second approach (incl. WDP), no environmental monetary valuation regarding the amount of water used was found in the available literature. Assigning a monetary value equal to the current net price of 1 m^3 of water in the Netherlands (around 1 €/ m^3) and assuming that the water use of the materials belong to the same range (E+00 - E+01) turned out to be an inappropriate method since eventually the costs of the rest environmental categories were overshadowed by the high volume and price of water use. In order to overcome this issue a normalisation approach was applied and the current water price in the Netherlands was divided by 1 E+04, which is the conversion factor for the case that the water use in the SL UF is assumed to belong to the same range as the other two assemblies (1 E+00). This approach can be an underestimation of the weight of the WDP category on the final results, since the shadow price is eventually remarkably low, however due to the better performances of hempcrete in the respective category is considered to be towards the safe conservative side for the comparison.

Another feature that is worth noticing here is the considerably lower environmental prices per kg of substance emission that are assigned to the environmental categories in which the hempcrete facade U.F. exhibits better performances (GWP, ADP elements and ADP combustibles). This feature attenuates the differences regarding the environmental performance of hempcrete and SL especially when biogenic carbon of the hempcrete design is assumed to be released back in the environment after the service life of the material (as in the case of this research). The weighting factors used in the current project were in their majority the ones defined in the Environmental Performance Assessment Method for Construction Works in the Netherlands (NMD -Nationale milieu database), which however have been formed in accordance with the previous version of the standard for the creation of EPDs in the Netherlands (NEN 15804+A1). The aforementioned feature has been noticed, and as a result some alterations will be incorporated in the new environmental determination method with the aim to attribute higher weighting on the ADP categories [8], which according to the current version of the environmental method do not contribute significantly in the determination of the environmental cost. New monetary weighting factors are currently under development in order to comply with the new version of the EPD standard and adequately lead towards a circular economy. Consideration is also given to the GWP-biogenic category and how it should be included in the new environmental method in order to allow a fair comparison between materials and products [8].

The way that the impact of categories of Eutrophication and Acidification is estimated may also be not ideal for the case of hempcrete, since nitrogen fertilization seems to overshadow other aspects of hemp that could be beneficial for the environment and the health of the soils as its low need for pesticides and herbicides, the prevention of soil erosion, the promotion of biodiversity [11] and its high phytoremediation potential for heavy metal contaminated soils [12].

Taken all the aforementioned into account it can be understood that the approach followed for the calculation of the environmental costs of the assemblies is conservative for the case of the hempcrete facade. However, even in this case the hempcrete results outperform (Table 7.5 - Incl. WDP) or significantly approach the SL UF results (Table 7.5 - Excl. WDP). The latter statement can be better understood when a different weighting approach, as for instance the one developed by the EU ([7]) which assigns higher weighting factors in GWP and ADP categories, or an equal weighting approach is followed. For the case of an equal weighting approach, the total amount of impact is expressed as the sum of the impact equivalents and following results are delivered:

- 1 UF of hempcrete facade: 2.47 E+02 impact equivalents *
- 1 UF of SL facade: 5.76 E+02 impact equivalents *
- 1 UF of AAC facade: 7.49 E+02 impact equivalents *

*excluding WDP

7.8.2. THE INTERNAL WALLS

The internal load bearing walls

The same method as the one described in Section 7.8.1 was followed for the determination of the environmental costs for the internal load bearing walls. Information about the characteristics of the UF can be found in Table 7.3. The results are presented in an aggregated form per stage in Figure 7.12 and Figure 7.13 and in total in Table 7.6.

Assembly		Hempcrete		SL		AAC	
Impact category		Excl. stage D	Incl. stage D	Excl. stage D	Incl. stage D	Excl. stage D	Incl. stage D
GWP Fossil	(kg CO2 eq/UF)	7.2 E+00	-4.02 E-01	3.49 E+01	3.46 E+01	3.36 E+01	3.31 E+01
GWP Biogenic	(kg CO2 eq/UF)	-1.52 E+00	-1.96 E-02	-3.57E-01	-3.58 E-01	1.12 E+00	1.12 E+00
GWP luluc	(kg CO2 eq/UF)	1.82 E-02	1.62 E-02	5.69E-02	5.66 E-02	1.1 E-01	1.09 E-01
ODP	(kg CFC11 eq/UF)	9.06 E-07	7.72 E-07	6.35E-07	6.35 E-07	2.48 E-06	2.29 E-06
AP	(mol H+eq/UF)	6.40 E-02	5.29 E-02	8.36E-02	8.31 E-02	8.96 E-02	8.50 E-02
EP Fresh water	(kg P eq/UF)	7.91 E-04	7.61 E-04	2.57E-03	2.57 E-03	3.0 E-03	3.0 E-03
EP Sea water	(kg N eq/UF)	2.75 E-02	2.44 E-02	2.09E-02	2.08 E-02	2.22 E-02	2.06 E-02
EP Land	(mol N eq/UF)	2.36 E-01	2.02 E-01	2.59E-01	2.58 E-01	2.73 E-01	2.552 E-01
POCP	(kg NMVOC eq/UF)	3.30 E-02	2.42 E-02	7.09E-02	7.06 E-02	7.12 E-02	6.61 E-02
ADP Elements	(kg Sb eq/UF)	2.45 E-06	1.13 E-06	6.1E-05	5.89 E-05	2.86 E-04	2.78 E-04
ADP Fossils	(MJ/UF)	9.18 E+01	-4.21 E+01	3.88E+02	3.84 E+02	2.36 E+02	2.23 E+02
WDP	(m3 water/UF)	3.06 E+00	2.84 E+00	3.91E+00	3.89 E+00	4.28 E+00	3.79 E+00

Table 7.6: Compared unit factors.

In the case of the load bearing walls the environmental superiority of the hempcrete timber design becomes clearer. The biobased design performs better than the two conventional designs in the vast majority of the environmental categories, with an exception for the case of the ozone depletion potential (ODP) and the Eutrophication - Seawater. Three main factors contributed to the different image of the environmental results in the case of the load bearing walls: the higher amounts of material needed for the structural support of the residence's loads for the case of the conventional loadbearing masonry, the absence of the FG insulation, which for the case of the facade attenuated the environmental impact of the SL designed facade and the higher amounts of timber which are present in the load bearing walls (30.2% instead of 7.64 %).

The difference in the UF results regarding environmental categories that of GWP and ADP between the biobased design and the other two conventional options is highly distinguishable. The SL design proved to be more competitive for the case of the facade and thus it is worth mentioning here the differences in some key impact categories between the performances of the SL and the biobased design in the case of the facade and load bearing walls. Regarding the GWP fossil impact category, the proportional difference between the two designs accounted for 17% (excluding stage D) and 44% (Including stage D) for the case of the facade. For the case of the load bearing wall however this difference reached 80% (excluding stage D) and 112% (Including stage D). The differences in the nature and the volume of the required materials for the loadbearing support of the residences created some highly favorable conditions for the biobased design, these conditions were further improved when the scenario of incineration of the timber is taken into account and part of the fossil combustion is substituted. The benefit of including the incineration potential of the biomass is eventually high enough to lead to a negative environmental footprint for the case of the biobased design (Table 7.6: -4.02 E-01 kg CO2 eq/ UF). A similar image can be observed for the case of ADP-combustibles.

Regarding the environmental categories of Acidification and Eutrophication an improved image can be detected for the case of the loadbearing walls. For the vast majority of the aforementioned categories hempcrete performs better than the two conventional options, even when the benefits of stage D are excluded. The high influence of the production stage in these categories is still however noticeable especially in the categories when nitrogen equivalents are used as impact indicators. In more detail, the sensibility of the biobased design in the nitrogen related categories appears to be high, since even with a remarkable less use of material (7.5 cm thickness of walls for Hempcrete and around 15 cm for the conventional options), the influence of the production stages (A1-A3) is significant. The scenario of deposition after use has a detectable influence in the case of the SL design, for the majority of the aforementioned categories. Nevertheless, for the case of the biobased design, the scenario of the deposition of the hempcrete blocks appear to mainly influence the Acidification and Euphtrophication of Land. For the case of the AAC concrete, where a less conservative scenario was assumed for the end of the life (Recycling of the blocks), the environmental impact is still higher than the rest options in the majority of the categories. Regarding the Water Depletion potential (WDP), the scenario of incineration of timber is responsible for a considerable impact which even surpasses this of the production stages.

According to the aforementioned it is worth assessing the sensibility of the environmental performances of the design in the different proportions of timber and hempcrete especially in the categories of the eutrophication and the acidification. The influence of the increased percentage of timber in the the UF of the biobased design when stage D is excluded, can be observed in Figures 7.14,7.14. An increase of 22.4% in the timber percentage (from 7.6% in the case of the facade to 30 % in the case of the load bearing walls) as expected did not influenced proportionally the environmental impacts of the unit factors due to the different impacts that characterise Hempcrete and Timber when compared to the same unit of volume. Increasing the timber percentage by 22.4% eventually led to a higher increase in the respective percentage of the UF's emissions that account for the timber in the environmental categories of GWP Land Use, Abiotic depletion of raw materials, Photochemical ozone depletion and water use. For the rest of the categories, the increase in the percentage of impacts that account for timber was lower than 22.4%, which indicates a higher sensitivity to hempcrete. As a resul, the difference between the environmental results of the facade UF and the UF of the load bearing walls for the Eutrophication and Acidification categories can be mainly attributed to the decrease on the amount of hempcrete used due to the different thickness of the wall and not the proportion of the wall which was substituted by timber.

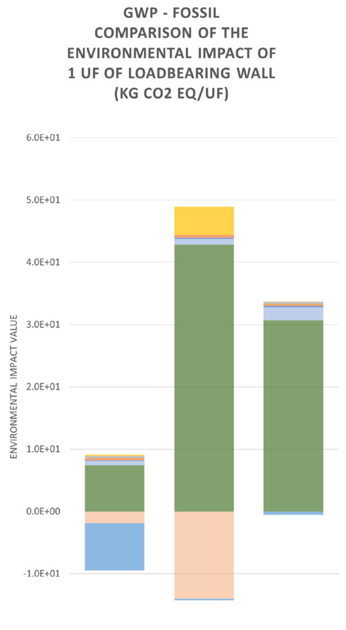
The final environmental costs of the loadbearing UF were calculated and are depicted in Table 7.7. The difference between the UF in the final costs has increased significantly, the costs of the environmental design barely surpass 0.3 € whereas for the conventional masonry the final cost exceeds 2 €. For the impact category of ADP fossils and GWP fossil the benefits of biomass leaded to even negative costs.

Impact category		cost per eq. (€)	Hempcrete	SL	AAC	Source
GWP Fossil	(kg CO2 eq/UF)	0.05	-2.01 E-02	1.73 E+00	1.65 E+00	[9]
GWP Biogenic	(kg CO2 eq/UF)	0.05	-9.78 E-04	-1.79E-02	5.58 E-02	[9]
GWP luluc	(kg CO2 eq/UF)	0.05	8.12 E-04	2.83 E-03	5.47E-03	[9]
ODP	(kg CFC11 eq/UF)	30.0	2.32 E-05	1.9 E-05	6.87 E-05	[9]
AP	(mol H+eq/UF)	4.0	2.11 E-01	3.32 E-01	3.4 E-01	[10]
EP Fresh water	(kg P eq/UF)	1.90	1.45E-03	4.48E-03	5.69E-03	[10]
0 EP Sea water	(kg N eq/UF)	3.11	7.58 E-02	6.47 E-02	6.42 E-02	[10]
EP Land	(mol N eq/UF	0.04	8.82 E-03	1.12 E-02	1.11 E-02	[10]
POCP	(kg NMVOC eq/UF)	2.0	4.85 E-02	1.41 E-01	1.32 E-01	[9]
ADP Elements	(kg Sb eq/UF)	0.16	1.81 E-07	9.42 E-06	4.45 E-05	[9]
ADP Fossils	(MJ/UF)	7.70E-05	-3.24 E-03	2.96 E-02	1.72 E-02	[9]**
WDP	(m3 water/UF)	1 E-04	2.84 E-04	3.89 E-04	3.79 E-04	Assump.
Total		(€)	3.23 E-01	2.30 E+00	2.29 E+00	(incl. WDP)

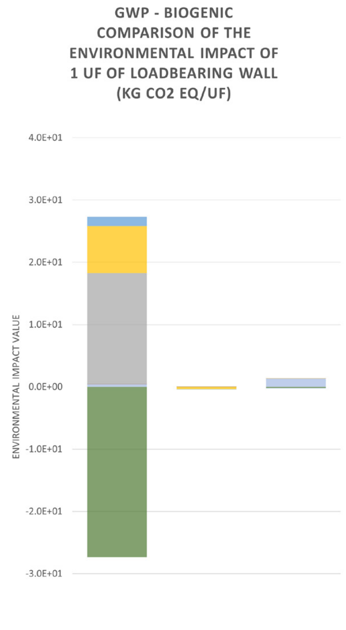
*conversion: 1 mol N =0.014 kg N

** conversion: MJ/UF x 4.81E-04 = kg Sb-eq

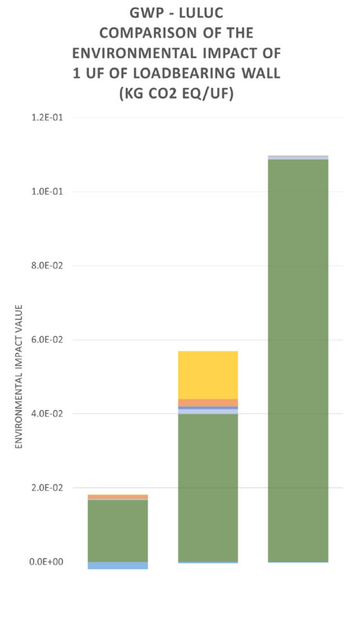
Table 7.7: The final environmental costs per UF of loadbearing walls



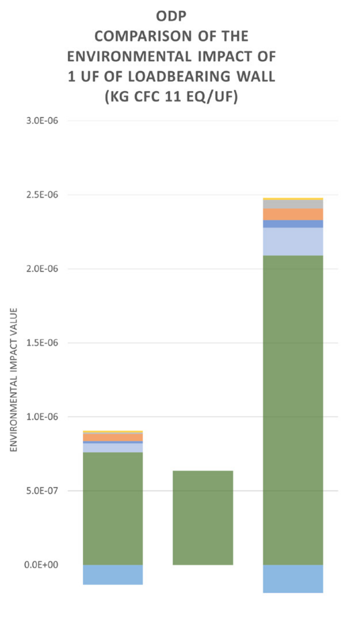
	HEMPCRETE	SL	AAC
D	-7.6E+00	-2.7E-01	-5.6E-01
C4	1.8E-01	4.5E+00	3.1E-02
C3	3.4E-01	0.0E+00	2.7E-01
C2	3.6E-01	4.8E-01	3.3E-01
C1	7.8E-02	1.9E-01	2.4E-01
B1	-1.9E+00	-1.4E+01	0.0E+00
A5	7.1E-01	9.0E-01	2.1E+00
A1-A3	7.4E+00	4.3E+01	3.1E+01



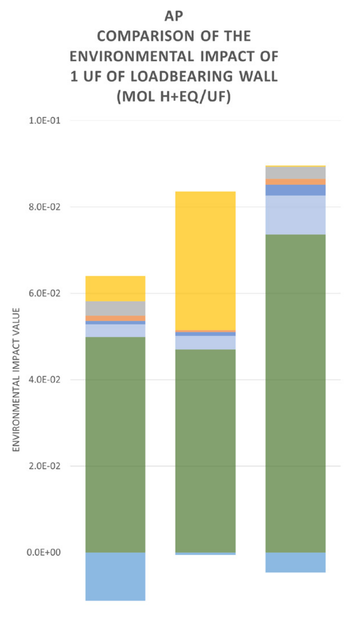
	HEMPCRETE	SL	AAC
D	1.5E+00	-9.8E-04	-1.0E-03
C4	7.5E+00	-3.5E-01	6.1E-05
C3	1.8E+01	0.0E+00	7.5E-05
C2	6.3E-04	1.9E-04	2.4E-04
C1	5.1E-05	-8.0E-03	6.7E-05
B1	0.0E+00	0.0E+00	0.0E+00
A5	4.3E-01	-2.3E-03	1.3E+00
A1-A3	-2.7E+01	7.0E-03	-2.1E-01



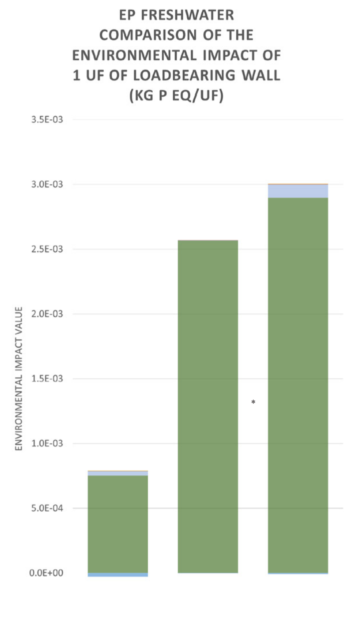
	HEMPCRETE	SL	AAC
D	-1.9E-03	-3.5E-04	-2.1E-04
C4	3.0E-05	1.3E-02	9.1E-06
C3	5.8E-05	0.0E+00	2.3E-05
C2	1.0E-03	2.0E-03	1.0E-04
C1	5.1E-05	7.5E-04	2.0E-05
B1	0.0E+00	0.0E+00	0.0E+00
A5	2.8E-04	1.3E-03	8.5E-04
A1-A3	1.7E-02	4.0E-02	1.1E-01



	HEMPCRETE	SL	AAC
D	-1.3E-07	-3.9E-15	-1.9E-07
C4	1.2E-08	1.7E-14	1.3E-08
C3	8.9E-09	0.0E+00	5.8E-08
C2	4.8E-08	1.2E-16	7.8E-08
C1	1.6E-08	4.4E-17	5.2E-08
B1	0.0E+00	0.0E+00	0.0E+00
A5	6.1E-08	3.7E-16	1.9E-07
A1-A3	7.6E-07	6.3E-07	2.1E-06



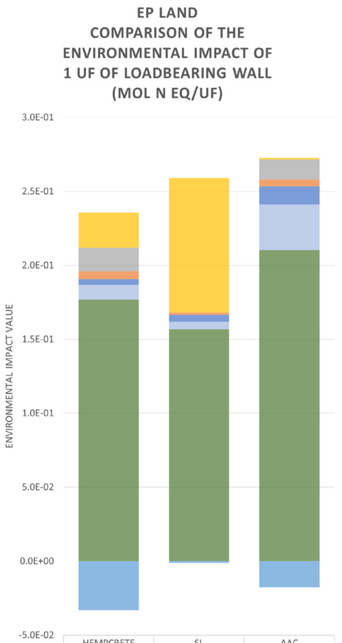
	HEMPCRETE	SL	AAC
D	-1.1E-02	-5.7E-04	-4.6E-03
C4	5.8E-03	3.2E-02	2.9E-04
C3	3.4E-03	0.0E+00	2.8E-03
C2	1.2E-03	4.5E-04	1.4E-03
C1	7.9E-04	8.9E-04	2.5E-03
B1	0.0E+00	0.0E+00	0.0E+00
A5	2.9E-03	3.1E-03	8.9E-03
A1-A3	5.0E-02	4.7E-02	7.4E-02



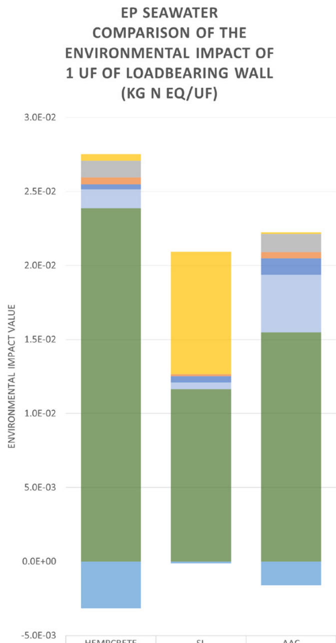
	HEMPCRETE	SL	AAC
D	-2.9E-05	-5.6E-07	-7.3E-06
C4	2.7E-06	7.7E-16	3.7E-07
C3	5.1E-07	0.0E+00	1.1E-06
C2	6.8E-07	1.0E-06	2.7E-06
C1	8.1E-08	3.9E-07	9.7E-07
B1	0.0E+00	0.0E+00	0.0E+00
A5	3.3E-05	7.3E-07	1.0E-04
A1-A3	7.5E-04	2.6E-03	2.9E-03

7

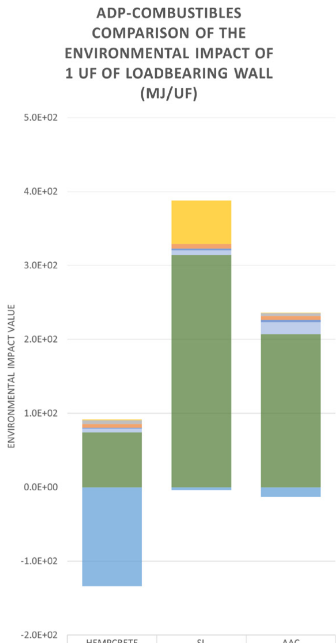
Figure 7.12: The environmental impact of 1 UF of load bearing wall- Comparison between the assemblies under scrutiny.



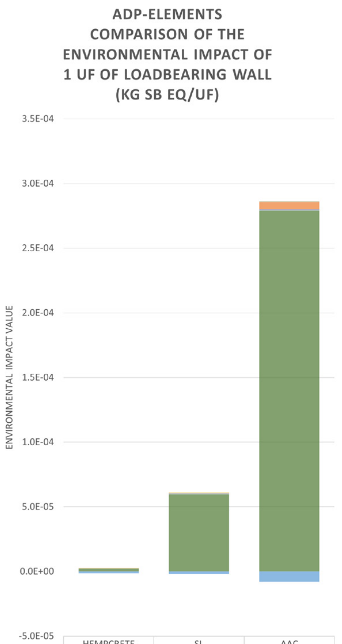
	HEMPCRETE	SL	AAC
D	-3.3E-02	-1.3E-03	-1.8E-02
C4	2.4E-02	9.1E-02	1.1E-03
C3	1.6E-02	0.0E+00	1.4E-02
C2	5.1E-03	1.7E-03	4.6E-03
C1	3.9E-03	4.6E-03	1.2E-02
B1	0.0E+00	0.0E+00	0.0E+00
A5	1.0E-02	5.0E-03	3.1E-02
A1-A3	1.8E-01	1.6E-01	2.1E-01



	HEMPCRETE	SL	AAC
D	-3.2E-03	-1.2E-04	-1.6E-03
C4	4.2E-04	8.3E-03	1.0E-04
C3	1.1E-03	0.0E+00	1.2E-03
C2	4.6E-04	1.4E-04	4.2E-04
C1	3.6E-04	4.2E-04	1.1E-03
B1	0.0E+00	0.0E+00	0.0E+00
A5	1.3E-03	4.5E-04	3.9E-03
A1-A3	2.4E-02	1.2E-02	1.5E-02

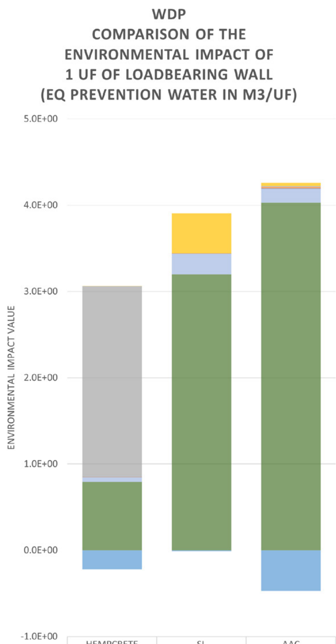


	HEMPCRETE	SL	AAC
D	-1.3E+02	-3.8E+00	-1.3E+01
C4	1.2E+00	5.9E+01	8.6E-01
C3	5.2E+00	0.0E+00	3.7E+00
C2	5.0E+00	6.4E+00	5.1E+00
C1	1.1E+00	2.4E+00	3.3E+00
B1	0.0E+00	0.0E+00	0.0E+00
A5	5.2E+00	6.1E+00	1.6E+01
A1-A3	7.4E+01	3.1E+02	2.1E+02



	HEMPCRETE	SL	AAC
D	-1.3E-06	-2.1E-06	-7.9E-06
C4	4.3E-08	4.0E-07	2.8E-07
C3	5.5E-08	0.0E+00	4.1E-07
C2	2.8E-08	4.0E-08	5.6E-06
C1	3.2E-08	1.5E-08	3.7E-07
B1	0.0E+00	0.0E+00	0.0E+00
A5	1.1E-07	7.3E-07	3.5E-07
A1-A3	2.2E-06	6.0E-05	2.8E-04

	HEMPCRETE	SL	AAC
D	-8.8E-03	-3.2E-04	-5.1E-03
C4	1.7E-03	2.5E-02	3.2E-04
C3	3.1E-03	0.0E+00	3.7E-03
C2	1.1E-03	3.7E-04	1.5E-03
C1	1.1E-03	1.2E-03	3.4E-03
B1	0.0E+00	0.0E+00	0.0E+00
A5	1.3E-03	1.4E-03	4.0E-03
A1-A3	2.5E-02	4.3E-02	5.8E-02



	HEMPCRETE	SL	AAC
D	-2.2E-01	-1.1E-02	-4.7E-01
C4	3.3E-03	4.7E-01	4.0E-02
C3	2.2E+00	0.0E+00	6.9E-03
C2	1.1E-03	2.1E-03	1.9E-02
C1	2.7E-04	7.8E-04	6.2E-03
B1	0.0E+00	0.0E+00	0.0E+00
A5	5.5E-02	2.4E-01	1.6E-01
A1-A3	7.9E-01	3.2E+00	4.0E+00

Figure 7.13: The environmental impact of 1 UF of load bearing wall - Comparison between the assemblies under scrutiny.

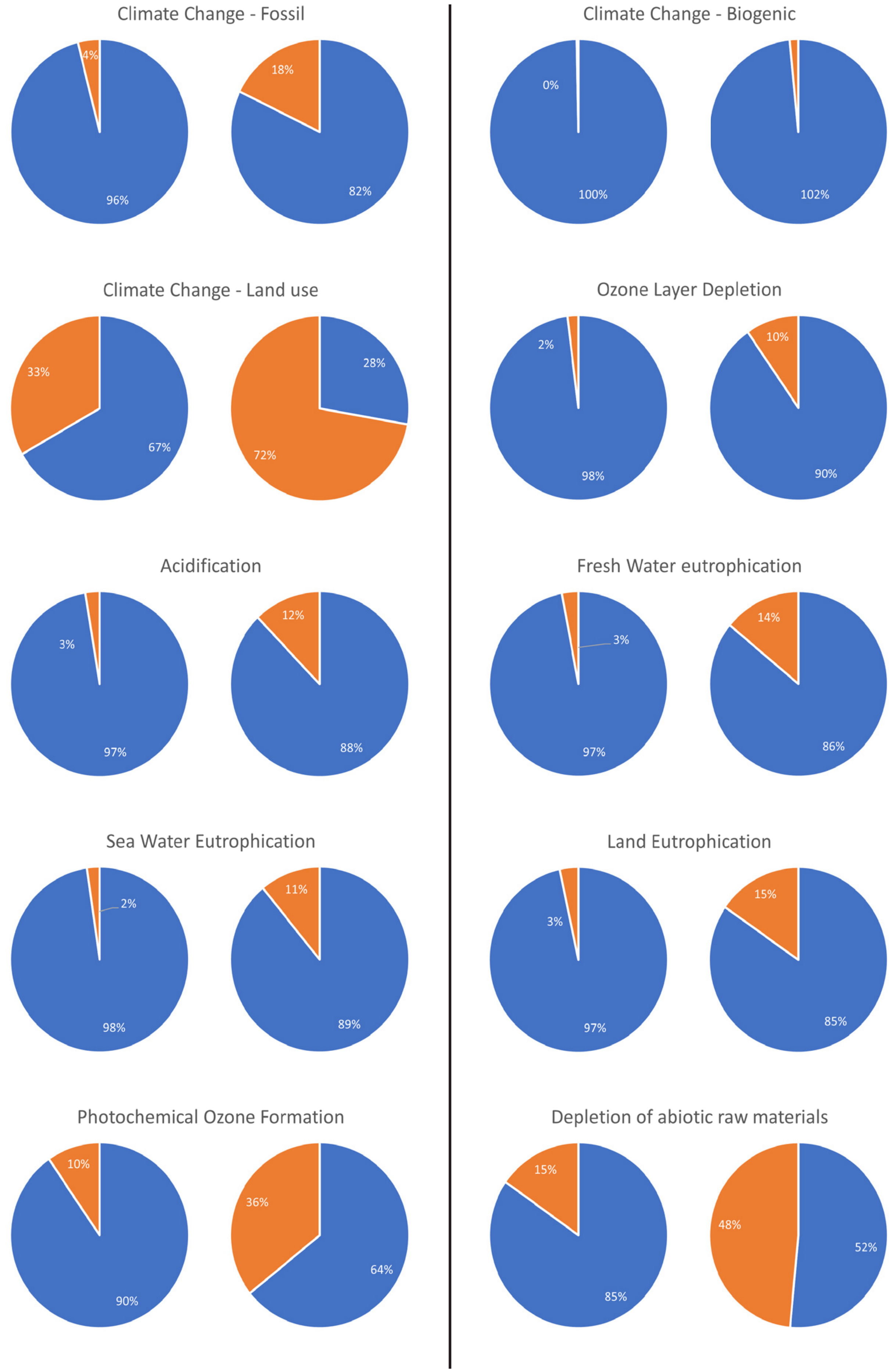


Figure 7.14: The influence of timber in the unit factor - For each category depicted, left side pie charts: Facade (7% Timber) - right side pie charts: Loadbearing walls (30% Timber).

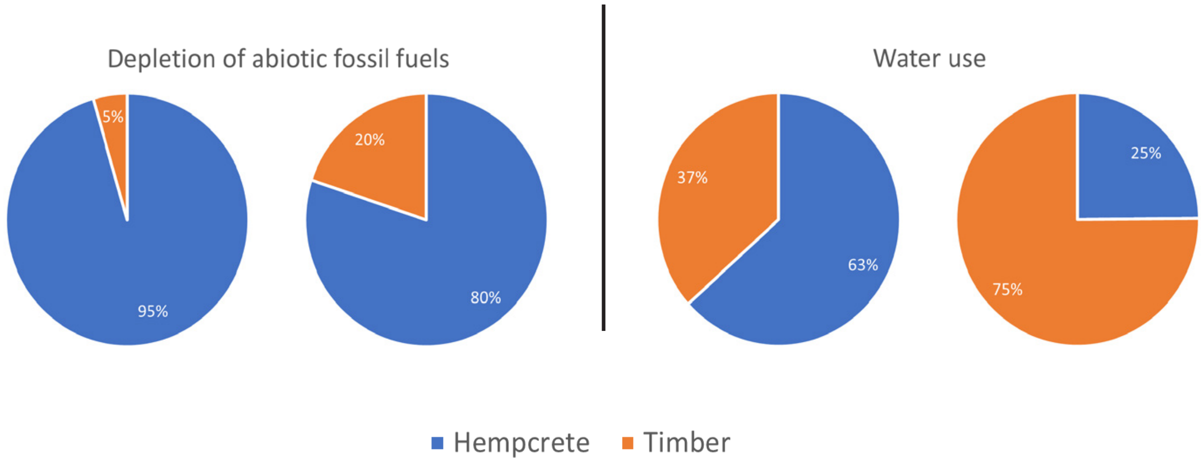


Figure 7.15: The influence of timber in the unit factor - For each category depicted, left side pie charts: Facade (7% Timber) - right side pie charts: Loadbearing walls (30% Timber).

The separation walls

The same method was used for the calculation of the environmental costs of the UF for the separation walls. Due to the similar thicknesses between the selected wall unit factors (Table 7.3) and the similar timber percentage to that of the facade, the same observations as the ones described in Section 7.7 and Section 7.8.2 - *Internal load bearing walls* can be detected. For the sake of brevity the results are presented in the Annexes (Table A.2, Figure A.26 and Figure A.27).

7.9. The total environmental costs of the residence

The environmental costs of the residence related to the three different wall designs have been calculated by following the same methodology as the one explained in the previous sections, the calculation includes stage D. The volumes of the materials that were taken into account for the calculation of the final costs are presented in Table (7.8). The relevant tables for the results that are present in Figure (7.16) can be found in the Annexes in combination with the assigned respective monetary values and the contribution of each wall type to the final results (Figure A.28).

Type of wall	Unit	Hempcrete		SL		AAC
Facade	m^3	48.8	(7.64% /93.36%) (Timb./Hempcr)	43.2	(52% FG / 48% SL)	66.96
Separation	m^3	2.31	(8.54 % /91.46%) (Timb.*/Hempcr)	2.28		2.97
Load bearing internal	m^3	5.5	(30.2% /69.8%) (Timb./Hempcr)	6.5		6.4
Final Env. Costs	€	5.14E+02		7.10E+02		1.06E+03

* Timber for studs around doors

Table 7.8: The volumes of the materials used in the residence design.

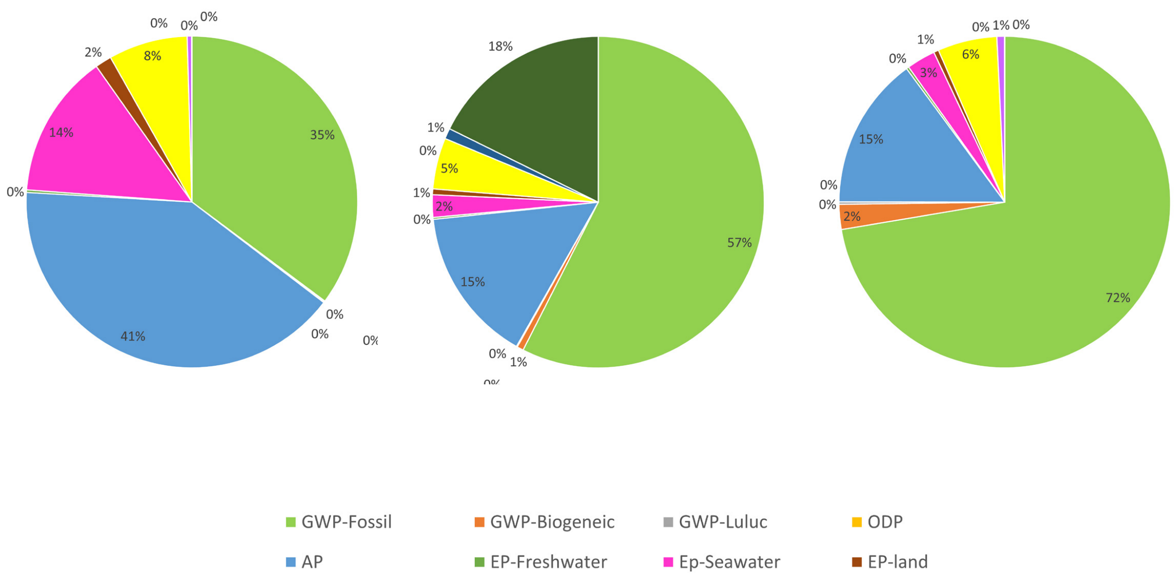


Figure 7.16: Total environmental costs per design

The results show a clear better environmental image for the case of the hempcrete design, which can be mainly attributed to the lowest impact associated with the environmental category of the GWP Fossil. Other environmental categories that contribute noticeably to the final environmental costs of the design are, as expected by the results of the wall's unit factors, the Acidification and the Eutrophication Sea water.

7.10. THE FINANCIAL COSTS

The prices of the materials depend on many different aspects as the market conditions, the price set by different producers and the distributors, the dimensions of the block, the amount of the material ordered etc. For the purpose of the current research the financial cost of the materials were estimated. The calculation was based on average prices of the materials in the Dutch market as they have been calculated by prices on the internet. For the calculation the following prices were taken into account:

- Autoclaved Aerated concrete (Cellenbeton) : 235 € / m^3
- Sandlime bricks (Kalkzandstees lijm blokken): 359 €/ m^3
- Fiberglass Insulation board: 11 € / m^2
- Hempcrete blocks: 442 €/m^3

Timber prices differ depending on the required length of the beam, the range of the required section dimensions and the strength class. Due to the complexity, the price of the timber was excluded from the calculation. The final costs were estimated according to the volumes that are present in Table 7.8 and then translated per m2 of floor area of the residence.

- AAC = 235 € $*$76.33 = 17938€ -> 145 € / m^2
- SL+FG = (43.2 $*$ 52% + 2.28 + 6.5) $*$ 359€ +(43.2/0.31) $*$ 11 €= € 12840 -> 107 € / m^2
- Hempcrete: 442 € $*$((48,8 $*$ 93%) + (2.31 $*$ 91.5%) + (5.5 $*$ 70%)) = 442 $*$ 51.36 = 22700 € -> 190 €/m^2

The net floor area is also an important factor that is considered during the design of the residence. The respective net floor areas for the three different designs are presented in Table 7.9. The final net area of the hempcrete design is eventually slightly higher than that of the SL, which can be attributed to the thinner internal walls that are possible due to the structural frame system.

	Unit	Hempcrete	SL	AAC
Net Floor Area	m^2	99.9	100.07	92.03

Table 7.9: The net floor area.

Bibliography Chapter 7

[1] O. Hegeir, T. Kvande, H. Stamatopoulos, and R. A. Bohne, “Comparative life cycle analysis of timber, steel and reinforced concrete portal frames: A theoretical study on a norwegian industrial building,” *Buildings*, vol. 12, Apr. 2022. DOI: 10.3390/buildings12050573.

[2] Z. M. Harris, S. Milner, and G. Taylor, “Chapter 5 - biogenic carbon—capture and sequestration,” in *Greenhouse Gas Balances of Bioenergy Systems*, P. Thornley and P. Adams, Eds., Academic Press, 2018, pp. 55–76, ISBN: 978-0-08-101036-5. DOI: https://doi.org/10.1016/B978-0-08-101036-5.00005-7. [Online]. Available: https://www.sciencedirect.com/science/article/pii/B9780081010365000057.

[3] P. PAPASTYLIANOU, I. KAKABOUKI, and I. TRAVLOS, “Effect of nitrogen fertilization on growth and yield of industrial hemp (cannabis sativa l.),” *Notulae Botanicae Horti Agrobotanici Cluj-Napoca*, vol. 46, no. 1, pp. 197–201, Jan. 2018. DOI: 10.15835/nbha46110862. [Online]. Available: https://www.notulaebotanicae.ro/index.php/nbha/article/view/10862.

[4] S. González-García, A. Hospido, G. Feijoo, and M. Moreira, “Life cycle assessment of raw materials for non-wood pulp mills: Hemp and flax,” *Resources, Conservation and Recycling*, vol. 54, no. 11, pp. 923–930, 2010, ISSN: 0921-3449. DOI: https://doi.org/10.1016/j.resconrec.2010.01.011. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0921344910000297.

[5] Fertiliser Technology Research Centre, *Technical bulletin: Fertilizers and soil acidity*, Accessed: 2022-12-22. [Online]. Available: https://set.adelaide.edu.au/fertiliser/system/files/media/documents/2020-01/factsheet-fertilizers-and-soil-acidity.pdf.

[6] P. Aversa, B. Daniotti, G. Dotelli, *et al.*, “Thermo-hygrometric behavior of hempcrete walls for sustainable building construction in the mediterranean area,” *IOP Conference Series: Earth and Environmental Science*, vol. 296, p. 012 020, Jul. 2019. DOI: 10.1088/1755-1315/296/1/012020.

[7] S. S, C. A, and P. R, “Development of a weighting approach for the environmental footprint,” no. KJ-NA-28562-EN-C (print),KJ-NA-28562-EN-N (online), 2017, ISSN: 1018-5593 (print),1831-9424 (online). DOI: 10.2760/945290(online),10.2760/446145(print). [Online]. Available: %5Curl%7Bhttps://publications.jrc.ec.europa.eu/repository/handle/JRC106545%7D.

[8] Ecochain, *The determination method (mki) has been adjusted: What the en15804 + a2 means for your company*, Accessed: 2022-12-22. [Online]. Available: %5Curl%7Bhttps://ecochain.com/nl/knowledge-nl/wat-en15804-a2-voor-jou-betekent/%7D.

[9] STICHTING NATIONAL ENVIRONMENTAL DATABASE, “Environmental performance assessment method for construction works, version 1.1.,” May 2022. [Online]. Available: %5Curl%7Bhttps://milieudatabase.nl/wp-content/uploads/2022/05/Bepalingsmethode_Milieuprestatie_Bouwwerken_maart_2022_Engels.pdf%7D.

[10] d. B. Sander, A. Saliha, B. Marijn, *et al.*, “Handboek milieuprijzen 2017 methodische onderbouwing van kengetallen gebruikt voor waardering van emissies en milieuimpacts,” Jul. 2017. [Online]. Available: %5Curl%7Bhttps://cedelft.eu/publications/environmental-pricing-manual-2017/%7D.

[11] European commission, *Hemp production in the eu*, Accessed: 2022-12-25. [Online]. Available: %5Curl%7Bhttps://agriculture.ec.europa.eu/farming/crop-productions-and-plant-based-products/hemp_en%7D.

[12] G. Todde, G. Carboni, S. Marras, M. Caria, and C. Sirca, “Industrial hemp (cannabis sativa l.) for phytoremediation: Energy and environmental life cycle assessment of using contaminated biomass as an energy resource,” *Sustainable Energy Technologies and Assessments*, vol. 52, p. 102 081, 2022, ISSN: 2213-1388. DOI: https://doi.org/10.1016/j.seta.2022.102081. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2213138822001333.

8

Conclusions and discussion

8.1. CONCLUSIONS AND DISCUSSION

The research sub-questions that define the research question are answered in the following section according to the current research's results.

- *What are the properties and the related parameters that need to be examined to guarantee that hempcrete blocks are safely and adequately applied with regard to their intended use in the case study?*

According to the research results, hempcrete is a bio-based material that is characterised by considerable potential in building applications. Among others hempcrete incorporates a substantial hygrothermal behaviour due to its high vapour permeability, low thermal conductivity and high specific heat capacity. In addition, it is characterised by good acoustic properties (in terms of sound absorption and sound insulation) and considerably good fire safety performances. The beneficial properties of the material can be mainly attributed to its high porosity (and low density), which combines the advantages of both macro and micro porosity due to its natural aggregate (hemp shives) and the type of the binder (lime). Its high carbon sequestration capacity and its hygrothermal performances are the main aspects that have distinguished it from other building materials.

Hempcrete is a non-loadbearing material, however in order to be used in building applications, for safety reasons an adequate mechanical strength is required (> 0.2 MPa) . According to studies, increasing the mechanical strength of the material can have a negative impact on the beneficial properties of hempcrete since it can be be mainly achieved by increasing the composition's density and the amount of the binder. Among other factors, the level of compaction, the nature of the binder, the water content and the binder to shiv ration have been found to be decisive in the definition of the final properties of the material. According to the literature review, hempcretes which are characterised by densities that belong to the range between 300-460 kg/m^3 can be suitable for building applications since they are able to provide to the wall enough mechanical strength for integrity and self support and an adequate thermal conductivity (around 0.07 W/(mK)), able to meet the requirements of the modern building codes in reasonable wall thicknesses.

Regarding its application in buildings, hempcrete can be mainly found in three forms: in-situ sprayed and poured or in the form of the prefabricated blocks. The in-situ forms of hempcrete are generally characterised by higher porosities and thus lower thermal conductivities. However, they are also come with some disadvantages when compared to the prefabricated blocks. In more detail, in situ-forms are know to be associated with higher risks and costs, as they are more labour intensive and require higher levels of expertise in order to be adequately applied. In addition, they require significant time for drying in order for the rendering to be applied. The risks are mainly related to insufficient level of mixting, which can lead to uncoated hemp shives or parts of the wall with different properties and hence can create some biodegradability, fire safety or shrinkage issues. However, in the case of hempcrete blocks, these issues are not present anymore since the material is fabricated in monitored and protected conditions. Furthermore, no high levels of expertise is required since hempcrete blocks' application, is highly similar to that of conventional the masonry, which is a frequent construction method in the Netherlands. As a result, contractors can easily learn how to apply the material by following short workshops.

Hempcrete comes with some important application features. It should be used in breathable walls, without vapour barriers. For this reason, consideration must be given to the type and properties of the rendering. Renderings should be also vapour permeable and for this reason cement plasters are not adequate for hempcrete. Clay or lime renders have been found to be good choices as an alternative. Clay plasters are preferably used in rooms with higher moisture due to their good moisture buffering capacity. Lime plasters are better for general applications due to their lower costs and higher strengths. In addition, hempcrete must be protected from water capillary movement. For this reason a capillary protection layer between the hempcrete blocks and the concrete floor is also needed to protect the blocks from capillary movement. A water proof membrane should also reach at least 20 cm above ground to protect the material from pond rain water. During construction, it is important to cover the upper-side of unfinished hempcrete walls to avoid vertical water intrusion.

Furthermore, hempcrete is a non load bearing material so a structural frame system is always needed for the support of the the building loads. The sustainability of the design can be further enhanced when a timber structure is selected. The hygrothermal properties of hempcrete and its PHA levels allow the breathability of the timber, create some unfavourable conditions for the creation of mould and thus permit the placement of the timber structure inside the hempcrete wall. In addition, the fire safe performance of hempcrete can protect the timber construction in case of a fire without additional means to be required. This type of design, can offer some benefits since the loads of the walls can be directly transported to the floor slabs without requiring additional external structure for the support of the facade. Nevertheless, the results of the current research show that some considerations should be taken into account when this construction method is selected. These considerations include: the water absorptivity of hempcrete and the thickness of the wall section around the timber. Hempcrete's water absorptivity should be low enough to limit the amount of of rainwater that enters the wall, while simultaneously allows the drying of the timber through out the years. Regarding the wall's thickness, it should be enough to prevent high levels of humidity to reach the timber. The results of these research showed that if this aspects are properly consider no particular degradation risks can arouse for timber. The aforementioned considerations, can play a higher role in facades that are facing towards the driving rain direction, where hempcrete may accommodate higher water content levels. These higher content levels may no influence hempcrete itself, but may burden the encased timber. Adding a cladding or a render with appropriate properties to the driving rain facade can eliminate the risk. The influence of the render in this aspect, was not considered in the current research since the same lime rendering was taken into account in all the simulations. Defining however the ideal properties of such a rendering could contribute to better performances of the biobased wall and therefore could be a recommendation for some future research.

Standardisation does not yet exist for hempcrete so DoPs cannot be composed. European standards of other biobased materials or conventional materials with similar applications as AAC can be used as references to get an insight on the application requirements that the material should meet in order to be adequately tested and applied. Types of certification based on the tests that have been performed in accordance with European standards already exists for the case of hempcrete blocks. Despite the lack of standardisation, hempcrete's properties and performance characteristics have been already widely researched in Europe, especially in countries as France and the UK. Hempcrete buildings have been already constructed since decades in Europe, while regulation regarding the composition and application requirements of hempcrete is already into force in France since 2012. The results of available literature and application provide enough information about the behaviour of the material and the way that it should be applied in buildings. However, its application in the Netherlands remain limited. According to the interviews, biobased buildings in the Netherlands only account for 2-5% of the total amount of annual constructed buildings in the Netherlands. From this percentage only a small proportion corresponds to hempcrete constructions which mainly refers to individual projects. Some bigger projects of hempcrete which include 10-15 hempcrete houses can be found in the Netherlands, nevertheless their number is extremely limited.

- *What are the current restraints in hempcrete's use in the Netherlands and how can they affect the decision of using hempcrete in building constructions?*

According to the interviews results, the most important barriers for the hempcrete use in the Netherlands are: the biased perspective of people regarding biobased materials, the legislation and the additional costs.

The available knowledge on the material can already provide information which can be used as a reference to cover the lack of the standardisation of the material. In addition, the existence of buildings already constructed in hempcrete can already provide stimulation for the performances of the material. However, the biased image of people regarding the sensitivity of biobased materials in aspects as moisture, bio-degradation and fire, currently restricts the propagation of hempcrete in the Netherlands, even though hempcrete has proven to exhibit some good performances in these aspects. The established masonry construction tradition in the Netherlands which was influenced by the high presence of clay in rivers, also limits the use of biobased materials in the Netherlands in comparison to neighbouring countries where biobased materials are more frequently present in traditional architecture.

The current regulation reality in the Netherlands also discourages the use of biobased materials to some extent. When it comes to hempcrete, this discouragement is related to bureaucracy requirements and not performance based requirements, since hempcrete is able to meet the strict fire safety and thermal requirements that the Dutch regulation imposes. The current Dutch market is characterised by a limited presence of hempcrete blocks which may be unable to support big residential projects. Producers outside the Netherlands, are required to re-test their products according to the NEN Norms in order to be admitted into the National Environmental Database (NMD) even though the products have been already tested according to EU standards (EN Norms). The latter creates additional costs to the producers and discourages their actions. In addition, it creates uncertainty about the receivement of a building permit since the decision needs to be based to methods of proofing the performances of the material that are not part of Dutch NEN standards. The difficulties that the Dutch regulation imposes have already acknowledged to an extent. The development of the new version of the environmental method (Bepalingsmethode MKI) according to the new European standards will offer more international opportunities.

In addition, building physics and energy efficiency related regulations are only based on static calculation methods. These methods fail to give prominence to some of the most beneficial aspects of hempcrete, namely its moisture buffering capacity and its high specific heat capacity, which can actively contribute to the establishment of indoor comfort and lead to constructions that meet the energy efficiency and condensation requirements even with walls that are characterised by lower thermal resistance values than those set by the Dutch building Decree. A characteristic example is the results of the condensation analysis performed in the current graduation project, where no particular surface or interstitial condensation were detected in hempcrete sections with thermal resistance values lower than the Decree requirements.

When it comes to costs hempcrete is a more costly option. This aspect is mainly influenced by the low availability of the material in the market. Taking steps to increase the material availability will also affect its price. The presence of hemp production in the Netherlands is limited, producers tend to be hesitant to increase the production and contractors tend to be hesitant to go for hempcrete due to the absence of a steady flow supply - an issue which however can be solved if international supply is facilitated by the means of Dutch regulation -. The current regulation fails to give prominence to important benefits of hempcrete as already stated above and as a result and the choice on the material is only with regard to the most cost efficient option that meets static calculations requirements. The new Bepalingsmethode (MKI) is expected to promote biobased materials as hempcrete.

- *How does the hempcrete block design perform in the analyses relevant to the required building aspects in comparison to the AAC design option and the sand-lime option?*

AND

- *What impact does choosing a hempcrete block design instead of the two predefined conventional Dutch masonry design options will have on the environmental and financial costs of the residence?*

When hempcrete is compared to its equivalent conventional material AAC (400 kg/m3), it exhibits better performances. The condensation and environmental analysis performed in the current research showed more favorable results for the case of hempcrete. An additional thickness of 13 cm was needed in order for the monolithic AAC design to meet the current requirements of the Bouwbesluit. The latter decreased the net surface of the residence and increased the required amount of material remarkably in comparison to the hempcrete design. Both the aforementioned aspects are detrimental in financial and environmental terms. Regarding the energy and indoor comfort analysis two main aspects were observed: the high thickness of the AAC walls increased the thermal mass of the residence which slightly improved the energy consumption of the residence, it simultaneously however hindered natural cooling in the summer.

The SL brick design with the FG insulation appeared to be more competitive for hempcrete. The FG insulation on the facade attenuated the impact of the SL bricks in the majority of the environmental categories. It highly influenced however the environmental category of the water depletion. Eventually hempcrete showed better environmental performances even with the conservative scenario of the release of the total amount of CO2 in the atmosphere after the service life of the building. The net surface of the residence did not eventually differentiate for the two design options (Hempcrete: 99,9 m^2, SL:100.07 m^2), since the surface missed by the higher hempcrete facade thickness was eventually compensated by the thinner internal walls. The condensation analysis showed no particular differences between the design options in most of the cases for walls with the same thermal resistance. Nevertheless, hempcrete walls with lower thermal resistance were able to exhibit same results as those of the better thermally designed SL wall. Hempcrete showed better moisture buffering capacities in the bathroom simulation. Regarding the energy analysis, the high density of the SL brick design was able to compensate for the lower specific heat capacity and result to lower energy performances and slightly better cooling in summer. The hempcrete designed building showed better response in the moisture regulating capacity as more values of RH remained in the comfortable range. The SL design however due to its higher thermal mass corresponded better to temperature alterations.

When it comes to the sustainability of the material, both the natural aggregate and the lime binder have contributed to its high performances. The high sequestration potential of hemp and the carbonisation process of the lime contribute to the high carbon storage ability of hempcrete. Hempcrete Facade unit factors of 1 m2 with a thermal resistance of Rc=4.8 m^2 K/W offer in total a carbon storage potential of 96.5 kg CO2/UF (48% hemp shivs, 0.31 % carbonisation of the lime and 21% timber presence). The benefits of the biobased nature can be further enhanced when biomass is partly exploited for the generation of energy. The lower energy intensive processes required for the production of the material give also an advantage in hempcrete when it comes to the Abiotic depletion impact categories for fossil fuels and elements. The latter is not reflected of the current NMD method where low monetary values are assigned to these categories, this issue however is already detected and will be taken into account in the new LCA method. The benefits of the low water needs of the hemp plant are expected to be reflected on the new EU LCA approach in the category of water depletion. The material environmental performance seems however to be sensible to the environmental categories that are influenced by nitrogen presence as those of the Acidification, EP seawater and EP land. The latter could be attributed to the needs of hemp for nitrogen fertilisation. This sensibility is magnified when high monetary values are assigned to the aforementioned categories.

The hempcrete design was estimated to be more expensive in comparison to the other two design options. However, when it comes to the financial costs of the residence more aspects than just the material supply related costs should be considered. Such cost could be any costs related to potential maintenance, any potential construction delay, or cost related to the net surface value. It is also important however to consider any potential added value to the design.

According to the research results hempcrete in the form of blocks is a durable material which in comparison to other biobased materials is not sensible to risks as fire or biodegradation. Regarding the condensation (both interstitial and surface) no particular risks have been detected after the dynamical hygrothermal simulation, which eliminates the related degradation risks. In addition, adequately designed hempcrete walls allow the encasement of structural timber without imposing mould growth risks. The latter offers some potential, since such method could allow a faster and less resource demanding construction.

In general, hempcrete blocks are not associated with particular delay related risks. Producers of hempcrete blocks with certified facilities already exist in neighbouring countries of the Netherlands. An advance notice of around 12-14 weeks is enough to allow sufficient supply, in case the available stocks are not enough for a project. The installation of the blocks is similar to that of the conventional masonry and as a result contractors only require brief workshops to get familiarised with the material. Nevertheless, hempcrete blocks have not been introduced yet to the Environmental database of the Netherlands, so the methods which are required for the material's proof of performances may differ per project case. The procedures for the introduction of hempcrete blocks in the Dutch Environmental Database have been already started, thus the aforementioned aspect is expected to not be an issue anymore soon.

The additional value that hempcrete may add to a construction should not be overlooked. Hempcrete blocks are able to provide energy efficient and comfortable constructions. Their high hygroscopicity and high specific heat capacity can be beneficial for buildings. In addition, hempcrete is associated with social and environmental aspects on which its industrialised competitors fall behind. Some of these aspects are not reflected in the modern building regulation and therefore are frequently forgotten. Nevertheless, they provide a considerable advantage to the option of selecting hempcrete in the case of projects which aim for high sustainability scores or for indoor environments with controlled RH fluctuations.

8.2. LIMITATIONS

The wide research question of the current graduation study required numerous aspects to be investigated in order for adequate conclusions to be drawn. The latter did not allow the incorporation of many sensitivity analyses in general in the research, which its also its main limitation. However, some sensitivity analyses were included in parts of the study where the author considered important in order for a broader image to be generated. These parts were:

- The assessment of the different hempcrete compositions in order to investigate the sensitivity of the degradation risks to the material properties.

- The assessment of the suitability of the method followed to the generate a hempcrete facade UF which adequately reflects the actual total environmental impact of the design.

- The influence of the different proportions of timber per unit factor in the impact categories results of the hempcrete design.

Despite its limitations the current research contributes to the distribution of knowledge regarding the main aspects that characterise the use of hempcrete blocks for the construction of residences in the Netherlands. Findings of the research give insight on the main aspects of the material that should be considered when hempcrete is applied and how they can be improved to further decrease degradation risks. It provides information the current barriers that are present in the Netherlands and how they should be addressed in order to facilitate the use of sustainable biobased materials and succeed to incorporate their true value.

8.3. RECOMMENDATIONS

According to the aforementioned, some recommendations for additional research can be:

- Research on the influence of the rendering's properties on hempcrete facades with encased timber in the case of driving rain orientation.
- Research on the potential means to increase the thermal mass of hempcrete while sustaining high porosity and adequate binder proportions. A possible research on the incorporation of phase changing materials in the composition.
- Research including a sensitivity analysis regarding the level on which the differences in the hygrothermal properties of different hempcrete compositions can influence the final environmental and financial costs.
- Research on the required thermal resistance and properties of hempcrete walls in order to meet the BENG regulation energy requirements by means of dynamic hygrothermal simulations. Comparison to the hygrothermal dynamic response and required thermal resistance of conventional construction materials.
- Research on how moisture accumulation inside the material can influence its thermal properties in long term conditions by means of long term experiments.
- Research on how the image regarding the energy performances of hempcrete in comparison to other materials differs between static and dynamic calculation methods.
- Research on the potential factors that influence the sensitivity of hempcrete in the environmental categories of the Acidification, Eutrophication of Land and Eutrophication of Sea-water.
- Research on the environmental performances of hempcrete according to different LCA weighting methods. Identification of the highest influencing impact categories.

A

Annexes

Section	Section Number	Parameter	Value	Description
Fire Reaction	2.9	Smoke class	s2	Indoor air surface
		Fire class	B	Residential Building Indoor surface in escape route
		Indoor surface	D	Residential Building General Indoor surface
		”	C	Residential Building Outdoor surface in escape route
		Fire class	D	Residential Building General Outdoor surface
		Outdoor surface	B	The height of the construction >13 m
		”	B	Fire class for at least 2.5 m in building with floor at height > 5m,
Limitation of fire spread and smoke spread	2.10	Fire resistance between compartments	60 min.	Between two compartments
			30 min.	Between a compartment and an enclosed space through which an extra protected escape route leads
”	2.11	Fire resistance between sub-compartments	20 min.	Between a fire sub-compartment and a protected fire sub-compartment located in another fire sub-compartment
			30 min.	Between a protected fire sub-compartment and another space in the fire compartment
”	”	Resistance to smoke penetration	R200	From a fire sub-compartment to a protected fire sub-compartment located in another fire sub-compartment.
				From a fire sub-compartment to an enclosed space through which an extra protected escape route leads.
				From a protected fire sub-compartment to another protected fire sub-compartment is R200
”	”	Resistance to smoke penetration	Ra	From a fire sub-compartment to another fire sub-compartment

Sound from outside	3.1.	Sound insulation	20 dB	Characteristic sound insulation of residential area
	”	Sound insulation in case of industrial, road or railway noise	35dB(A)	Industrial Noise
			33 dB(A)	Railway or road noise
			AND	
			> difference	Between the highest permissible noise exposure for industrial, road or railway noise included in that decree
Reverberation	3.3.	Reverberation Limitation	> 1/8 V	Total sound absorption of a closed communal traffic space for opening up a residential function that is adjacent to a non-communal space of a residential function
Soundproofing between rooms	3.4.	Characteristic air-sound level difference with another plot within residential area	> 52 dB	Sound transmission from a confined space to a residential area of an adjacent functional function on another plot
				Sound transmission from a confined space to a residential area of an adjacent residential function on the same plot
”	”	Characteristic air-sound level difference with another space with residential function within the same plot in a residential area	> 52 dB	Sound transmission from a confined space to a residential area of an adjacent residential function on the same plot
”	”	Weighted contact sound level between plots in residential area	< 54 dB	Sound transmission from a confined space to a residential area of an adjacent use on another plot
”	”	Weighted contact noise level	< 54 dB	Sound transmission from a confined space to a residential area of an adjacent residential function on the same plot
Moisture resistance	3.5	Protection of moisture from the outside	Watertight NEN2778	External partition construction of a residential area a toilet room or a bathroom
				Partition between a living area, a toilet room or a bathing space, and a crawl space
				Internal partition construction of a residential area, a toilet room or a bathing room, that is not adjacent to another residential area, another toilet room or another bathing room

”	”	Average Water Absorption	< 0.01	On bathroom wall up to a height of 1.2 m above the floor
”	”	Maximum Water Absorption	< 0.2	[In kg/(m².s 1 /2)]
”	3.10	Protection against rats and mice	(-)	Structure has to be built in a way that prevents the intrusion of rats and mice
NZEB	5.2.	Energy Demand (Residential use **)	65	If Als/Ag ≤ 1.83
			55+30×(Als/Ag – 1.5)	If 1.83 ≤Als/Ag ≤ 3
			100+50×(Als/Ag – 3)	If Als/Ag ≥ 3
”	”	Primary fossil energy use (Residential use **)	50 [Kw / m2 · yr]	(-)
”	”	Share of renewable energy (Residential use **)	40 [%]	(-)
Thermal Insulation	5.3.	Thermal Resistance	4.7 [m² x K/W]	For vertical external partition
			3.7 [m² x K/W]	For partition which forms the separation with a crawl space
Sustainable Building	5.9.	Environmental Performance (MPG)	0.8	Residences

** When the simulations are performed in an apartment level (same use). Otherwise, the weighted values must be calculated.

Table A.1: Building requirements according to Bouwbesluit 2012

MSc Track: Building Engineering
Civil Engineering and Geosciences
Delft University of Technology

Graduation Study:

The effectiveness of hempcrete in the reduction of environmental and financial costs of residences

(A case study in the Netherlands)

Alexandra Vontetsianou

Abstract

The introduction of a new unstandardised material in the market is a complex procedure. The material performances must be able to compensate for the difficulties and the risks associated with the lack of applicational experience in order to attract the interest parties. Hempcrete is a natural, healthy, and sustainable material with high performances in main aspects that define indoor comfort and sustainability. However, despite its advantages, it has not yet established its place into the Dutch building industry. This graduation study will account for a stimulation research for the developers and will cope with the lack of produced and distributed knowledge on the material. Hempcrete's use will be approached in a multidimensional way as different aspects like the application requirements (e.g as a façade material), the energy performances, the indoor comfort regulation levels, financials (benefits and losses e.g. net surface) and sustainability will be assessed by means of simulations and interviews.

The current interview will be a semi-structured interview and will focus on four main aspects::

- The properties of hempcrete
- Possible points of improvement
- The application of hempcrete in France
- The future of hempcrete in Europe after its standardisation

Interview Questions

1. Which are the most important benefits of hempcrete in your point of view?
   (Regarding the hygrothermal performances of hempcrete, what are the relevant studies in which the university of Reims has been focused on in order to investigate how aspects as conductivity, moisture content, density change depending on the RH? What other aspects can be influenced by different levels of RH?).

2. Hempcrete is a very convertible material with properties that can differ remarkably according to composition. Are there specific mixture compositions that the University of Reims has been focusing on during the past years? What are the characteristics of these compositions?
   (With the aim to influence which aspects? With what kind of intended use? Are the limits of other properties apart from those of the governing ones are taken into account? Are any additives required? What performance you aim to achieve in the case of hempcrete blocks? Are the environmental performances taken into account in the selection of those compositions? How does the different components influence the LCA?

3. Biobased materials are regarded as sensitive to moisture, mould, pests, insects and fire. What is the sensitivity of hempcrete regarding these risks?
   (Are there other risks? Are there specific compositions or additives that can decrease or increase these risks?)

4. Are there any properties of hempcrete that require additional research in your point of view? What happens in the case of application in the building industry?
   (Which? Why? How?) (Scientific research aims to cover all the different aspects, in what aspects should the research when it is related to application in the market?)

5. In France, hempcrete related guidelines already exist (so standardisation is not an issue). Is hempcrete often chosen for building projects?

(Why/Why not?, What kind of projects, form of hempcrete in these projects? if not, is the regulation an issue? Would you say that constructing with hempcrete has become a systematic procedure, Are still practical issues which are encountered in practice?What is the role of the current regulation?)

6. What are the most common causes for the failure of hempcrete applications in France?
(What are the reasons behind those failures? What are the means to limit them? What are the types of proof of performances that are required when hempcrete is used?)

7. Why hempcrete is not yet standardised in Europe in your point of view?
(What are the issues to overcome?)

8. Do you have any additional remarks or experience about the material that you would like to share?

Figure A.1: Interview guide for the interview with Chadi Maalouf

MSc Track: Building Engineering
Civil Engineering and Geosciences
Delft University of Technology

Graduation Study:

The effectiveness of hempcrete in the reduction of environmental and financial costs of residences

(A case study in the Netherlands)

Alexandra Vontetsianou

Abstract
The introduction of a new unstandardised material in the market is a complex procedure. The material performances must be able to compensate for the difficulties and the risks associated with the lack of applicational experience in order to attract the interest parties. Hempcrete is a natural, healthy, and sustainable material with high performances in main aspects that define indoor comfort and sustainability. However, despite its advantages, it has not yet established its place into the Dutch building industry. This graduation study will account for a stimulation research for the developers and will cope with the lack of produced and distributed knowledge on the material. Hempcrete's use will be approached in a multidimensional way as different aspects like the application requirements (e.g as a façade material), the energy performances, the indoor comfort regulation levels, financials (benefits and losses e.g. net surface) and sustainability will be assessed by means of simulations and interviews.

The current interview will be a semi-structured interview and will focus on four main aspects:

- Type of projects and experience from practice
- Required process for projects in the Netherlands
- Properties of hempcrete, strengths limitations and procedures
- Clients concerns

Interview Questions

1. In how many projects and what types of projects have you participated? What is your experience projects in the Netherlands?
   (What kind of projects were they, how did you get this projects, form of hempcrete, place of hempcrete, were any Dutch projects, what is the essential documentation for trading in the Netherlands, have you experienced any delay due to bureaucracy issues in the Netherlands? Would you say that local requirements account for current barriers?)

2. Were there any projects that hempcrete was considered to be used but eventually another material was selected? Why?
   (What material was that? And for what reasons was it preferred?, how the choice was made?)

3. How did you cope with the absence of EAD for hempcrete?
   (Do you intend to apply for an EAD in order to draw a DoP? Why do you not have already one?, How does the absence of DoP affects the contractors?)

4. Hempcrete is a very convertible material (its properties can differ a lot depending to the composition of the mixture). In what kind of mixtures have you been focusing on?
   (with what intended use, what properties you aim to enhance?, did that had an influence on the environmental properties of the material, what risks are limited with the current compositions,)

5. Hempcrete is biobased. How do you ensure that the hempcrete blocks have the expected properties?
   (Have hempcrete building sections been constructed, tested and monitored in different ambient conditions? , How is your quality control set up?, what is the accepted difference between expected and actual values of the hempcrete blocks).

6. What are the strongest points and risks of hempcrete as you have experienced in building applications so far? How can you limit these risks?
   (Are there any mould growth risks, any other risks(insects pests, fire safety)? How these risks are limited? Have tests been performed to be able to incorporate the hygrothermal properties of hempcrete (e.g. conductivity, moisture content, density changes due to RH, Is a high level of expertise required to limit these risk?)

7. What are your means to enhance the environmental performances of the material?
   (*Was the environmental footprint taken into account in the composition?, How the environmental performance is influenced by the composition?)*

8. What are your clients' views regarding biobased materials?
   (*Are there any particular concerns? What distinguishes hempcrete from other biobased materials?)*

9. Do you have any additional remarks or experience about the material that you would like to share?

Figure A.2: Interview guide for the interview with ISOHEMP producers

MSc Track: Building Engineering
Civil Engineering and Geosciences
Delft University of Technology

Graduation Study:

The effectiveness of hempcrete in the reduction of environmental and financial costs of residences

(A case study in the Netherlands)

Alexandra Vontetsianou

Abstract

The introduction of a new unstandardised material in the market is a complex procedure. The material performances must be able to compensate for the difficulties and the risks associated with the lack of applicational experience in order to attract the interest parties. Hempcrete is a natural, healthy, and sustainable material with high performances in main aspects that define indoor comfort and sustainability. However, despite its advantages, it has not yet established its place into the Dutch building industry. This graduation study will account for a stimulation research for the developers and will cope with the lack of produced and distributed knowledge on the material. Hempcrete's use will be approached in a multidimensional way as different aspects like the application requirements (e.g as a façade material), the energy performances, the indoor comfort regulation levels, financials (benefits and losses e.g. net surface) and sustainability will be assessed by means of simulations and interviews.

The current interview will be a semi-structured interview and will focus on four main aspects:

- Hempcrete projects in the Netherlands
- Required Documentation
- Material related challenges and current barriers
- Clients' concerns

Interview Questions

1. Was it the first hempcrete project that you have participated?
   (If not in what kind of other hempcrete projects have you participated? Was any other project where applying hempcrete was considered but eventually a different choice was made? If yes, why? Who was the supplier?)

2. Why hempcrete in this specific design? Were there any other materials considered?
   (Were these materials considered as a backup for the case that hempcrete was failing to fulfil the requirements? Which were those? Why they were not chosen?)

3. What is required as a proof of performance (to get a building permit) for the municipality for hempcrete projects?
   (Would you say that collecting and preparing such documentation was demanding? What is the difference between such documentation and the one required for conventionally built buildings?)

4. What were the types of performance assessment means?
   (E.g. Simulations? on site monitoring? thermal conductivity in different relative humidity conditions? just for dry state?)

5. Does hempcrete perform as intended in the building applications?
   (Were the final building physics results as expected? Did you experience any delay or unforeseen issue that needed to be resolved?)

6. What were the material related challenges and risks?
   (sensibility to moisture, mould, insects, pests, fire, other risks? How can these risks be eliminated? Is it difficult?)

7. According to your experience which are the current barriers for using hempcrete in building applications in the Netherlands?
   (Availability of the material, liabilities, types of contract, municipality rules? Costs? Effects of lack in standardisation? What is the role of the engineer when an unstandardised material is used for a project? For what kind of properties would you as an engineer request for proof.? Eventually would you recommend hempcrete? Why/Why not?)

8. Do clients express interest in hempcrete constructions? What are their concerns?

9. Do you have any additional remarks or experience about the material that you would like to share?

Figure A.3: Interview guide for the interview with Frank Lambregts - Renovation of the municipality of Voorst

MSc Track: Building Engineering
Civil Engineering and Geosciences
Delft University of Technology

Graduation Study:

The effectiveness of hempcrete in the reduction of environmental and financial costs of residences

(A case study in the Netherlands)

Alexandra Vontetsianou

Abstract

The introduction of a new unstandardised material in the market is a complex procedure. The material performances must be able to compensate for the difficulties and the risks associated with the lack of applicational experience in order to attract the interest parties. Hempcrete is a natural, healthy, and sustainable material with high performances in main aspects that define indoor comfort and sustainability. However, despite its advantages, it has not yet established its place into the Dutch building industry. This graduation study will account for a stimulation research for the developers and will cope with the lack of produced and distributed knowledge on the material. Hempcrete's use will be approached in a multidimensional way as different aspects like the application requirements (e.g as a façade material), the energy performances, the indoor comfort regulation levels, financials (benefits and losses e.g. net surface) and sustainability will be assessed by means of simulations and interviews.

The current interview will focus on three main aspects:

- Hempcrete projects in the Netherlands
- Material related advantages, challenges and current barriers
- Current interest for hempcrete in the Netherlands

Interview Questions

1. What is the interest for hempcrete in the Netherlands?
   (In what kind of projects hempcrete is primary used? How often? In which form (in situ/prefabricated)? Why?)
2. Were there any projects that you know in which hempcrete was considered to be applied but eventually a different choice was made? If yes, why?
   (Which were the alternatives? Why?)
3. Apart from the indoor comfort (moisture buffering capacity, thermal comfort, acoustics) and a low MPG, is hempcrete associated with other benefits?
   (For which reason(s) would you recommend hempcrete?)
4. What are the technical challenges and risks related to the nature of the material and its application?
   (Degradation by fire, moisture accumulation, mould, insects and pest, other? How can these risks be eliminated? Is it difficult?)
5. What are the required proof of performances related to hempcrete that need to be handed to the local authorities to acquire a building permit?
   (Would you say that the bureaucracy for the case of hempcrete is demanding in comparison to other conventional materials?)
6. Do hempcrete buildings in the Netherlands perform as expected?
   (Are there any monitored hempcrete buildings in the Netherlands? By what kind of (other) means is ensured that hempcrete buildings perform as expected? What are the main types of hempcrete failures in building applications in the Netherlands?)
7. According to your experience which are the current barriers for using hempcrete in building applications in the Netherlands? Is the material sufficiently available in the Netherlands in your point of view?

(Availability of the material / liabilities / types of contract / municipality rules / Costs / Possible delays / Effects of lack in standardisation?
What is the role of the engineer when an unstandardised material is used for a project? For what kind of properties would you request for proof?)

8. How can the absence of standardisation affect the involved parties in case of a damage in terms of liabilities?

9. Are there any aspects of hempcrete that need to be further explored in your point of view? Is there any additional information related to hempcrete that you would like to know?

10. In your experience which are the main concerns of the interest parties when considering the application of hempcrete?

11. Why hempcrete is not yet more widely applied? What are the issues that it needs to overcome?

12. Do you have any additional remarks or experience about the material that you would like to share?

Figure A.4: Interview guide for the interview with Ralf van Tongeren - Specialised architect in biobased design and Secretariat of the Dutch hempcrete association

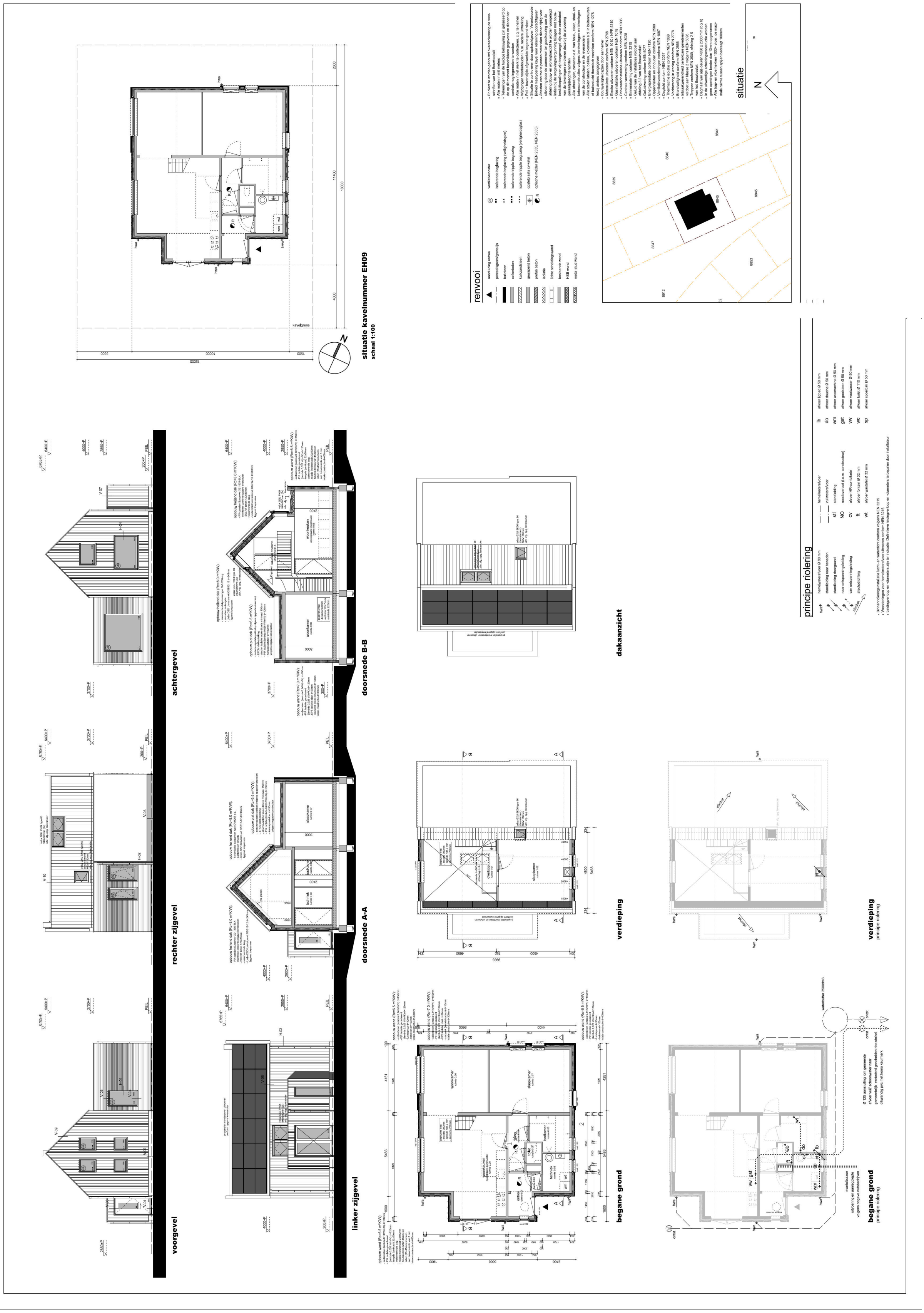


Figure A.5: The case study residence

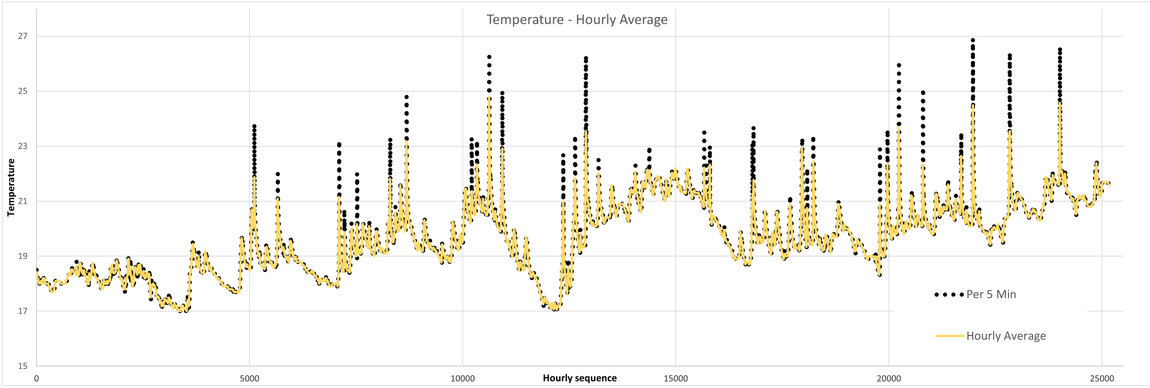


Figure A.6: Bathroom - Plotted values for Temperature (01/03/2019-30/05/2019)- per 5 minutes and hourly average

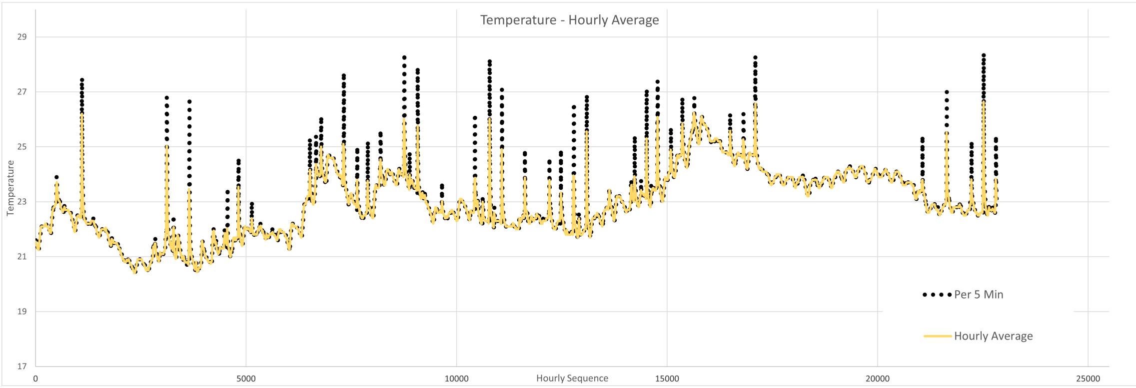


Figure A.7: Bathroom - Plotted values for Temperature (01/06/2019-19/08/2019)- per 5 minutes and hourly average

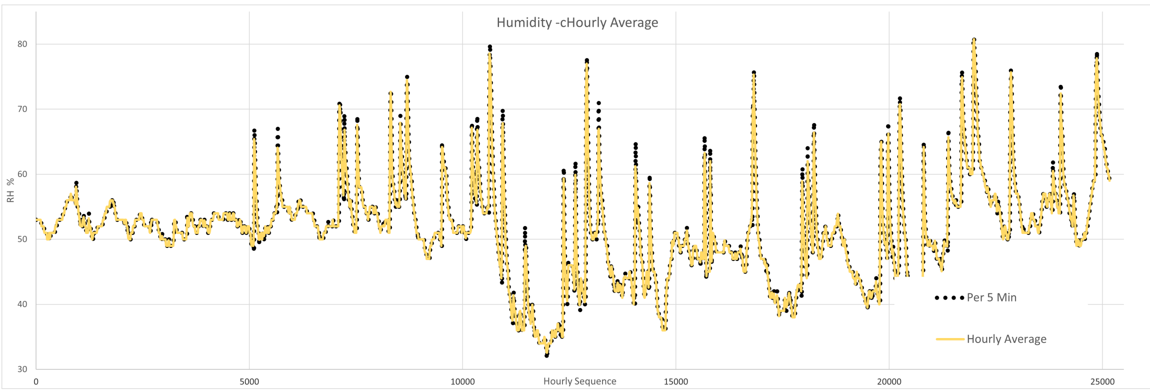


Figure A.8: Bathroom - Plotted values for RH (01/03/2019-30/05/2019)- per 5 minutes and hourly average

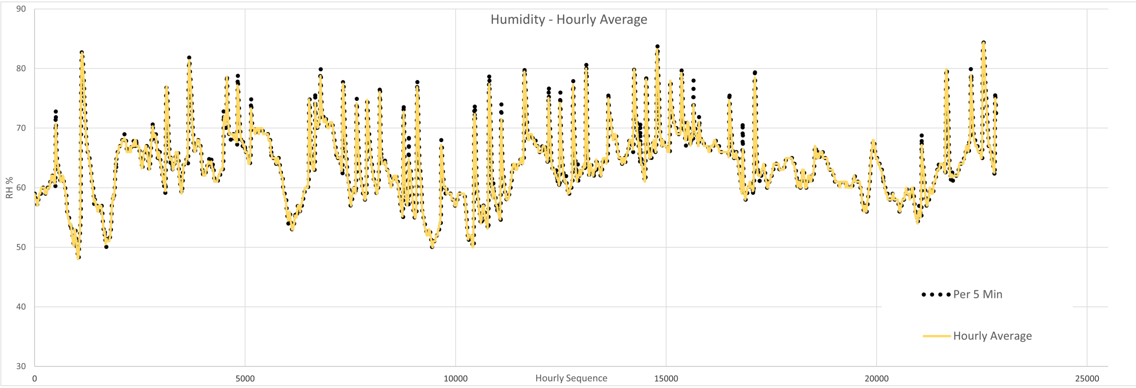


Figure A.9: Bathroom - Plotted values for RH (01/06/2019-19/08/2019)- per 5 minutes and hourly average

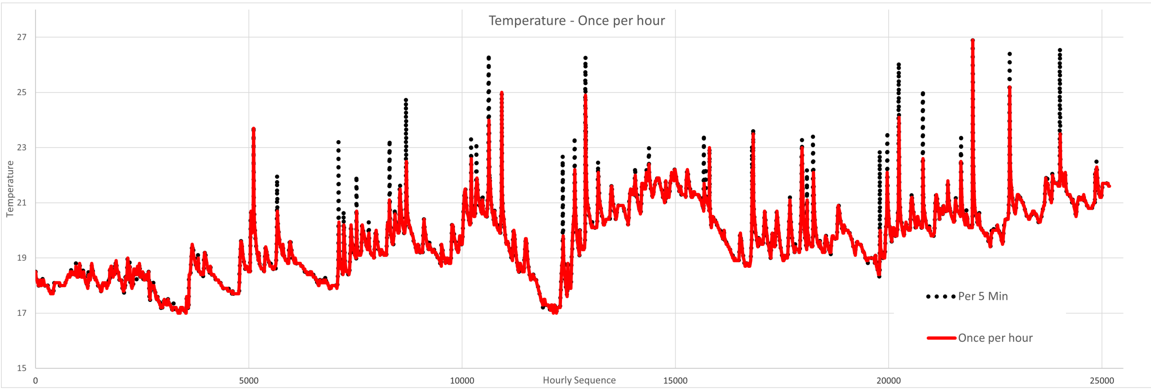


Figure A.10: Bathroom - Plotted values for Temperature (01/03/2019-30/05/2019)- per 5 minutes and once per hour

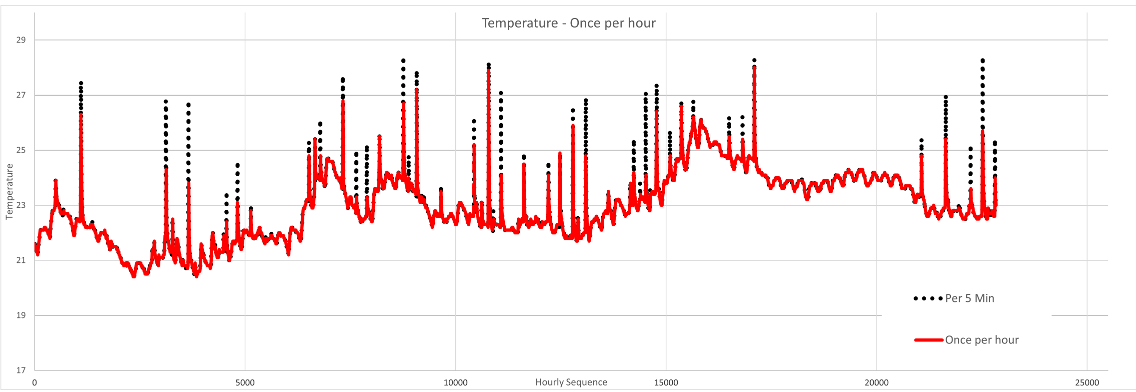


Figure A.11: Bathroom - Plotted values for Temperature (01/06/2019-19/08/2019)- per 5 minutes and once per hour

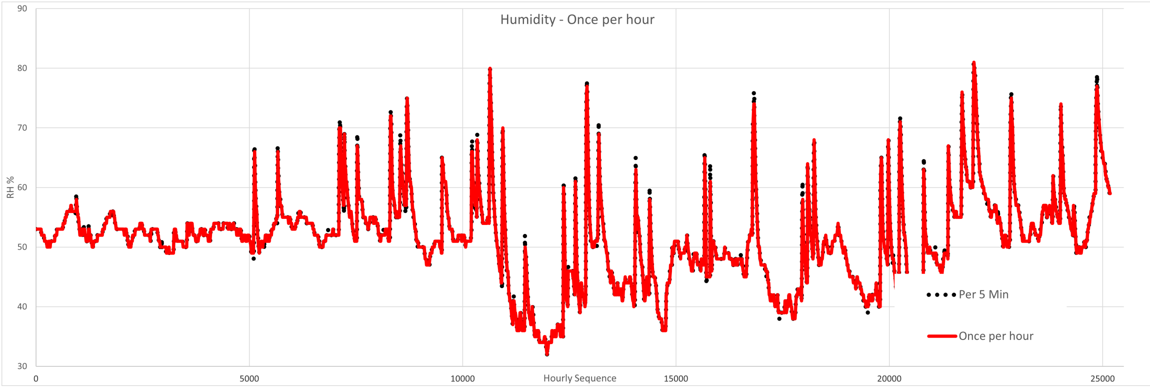


Figure A.12: Bathroom - Plotted values for RH (01/03/2019-30/05/2019)- per 5 minutes and once per hour

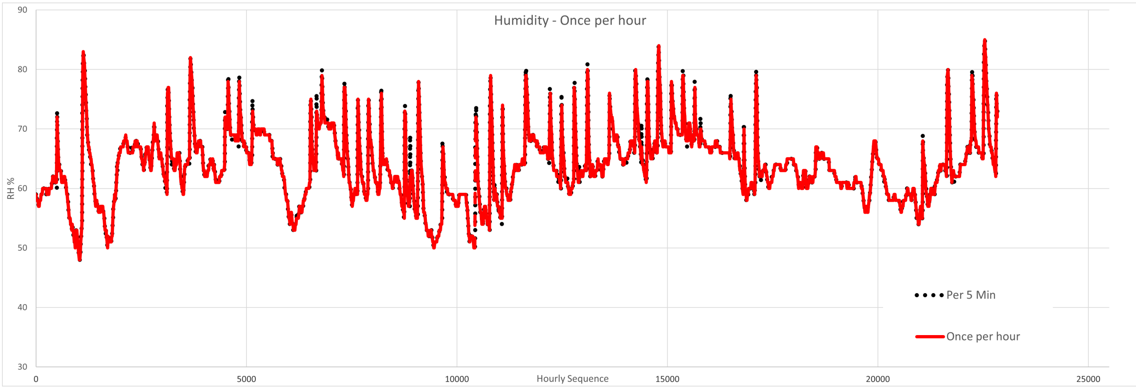


Figure A.13: Bathroom - Plotted values for RH (01/06/2019-19/08/2019)- per 5 minutes and once per hour

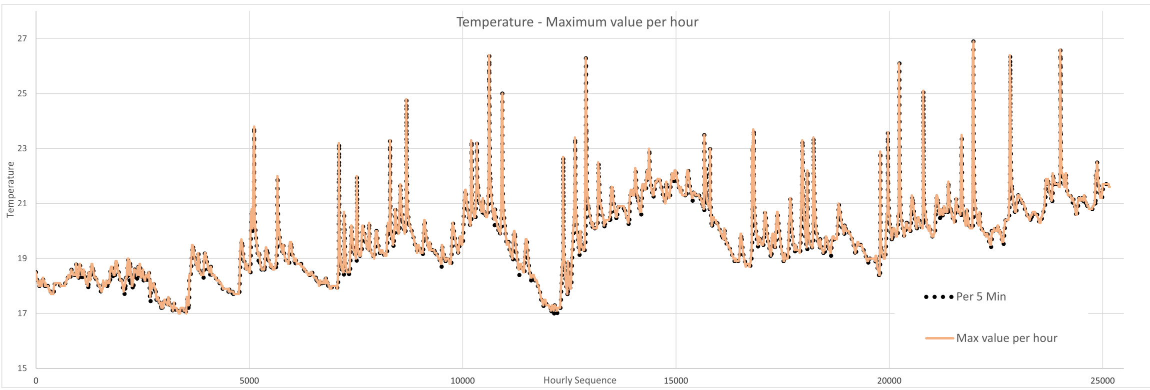


Figure A.14: Bathroom - Plotted values for Temperature (01/03/2019-30/05/2019)- per 5 minutes and maximum hourly values

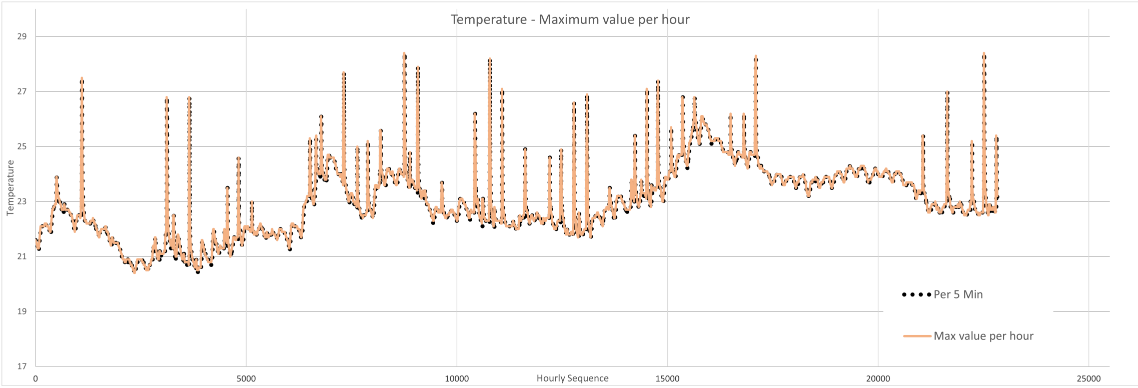


Figure A.15: Bathroom - Plotted values for Temperature (01/06/2019-19/08/2019)- per 5 minutes and maximum hourly values

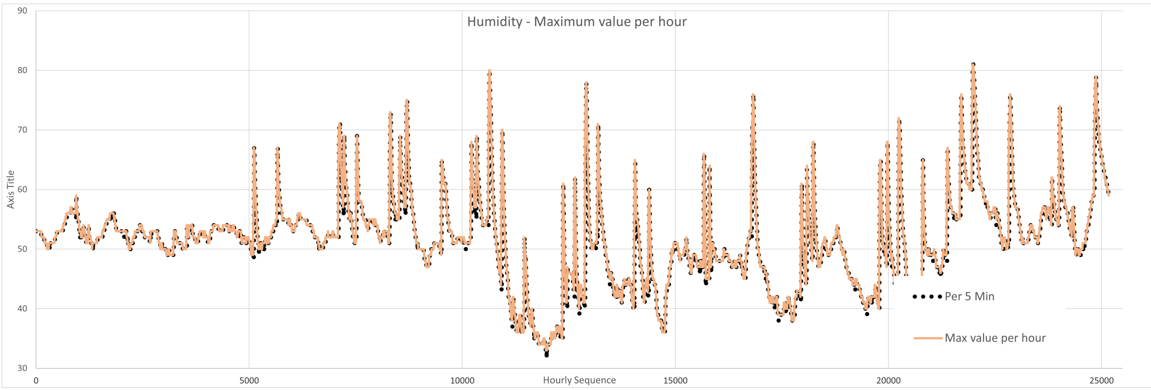


Figure A.16: Bathroom - Plotted values for RH (01/03/2019-30/05/2019)- per 5 minutes and maximum hourly values

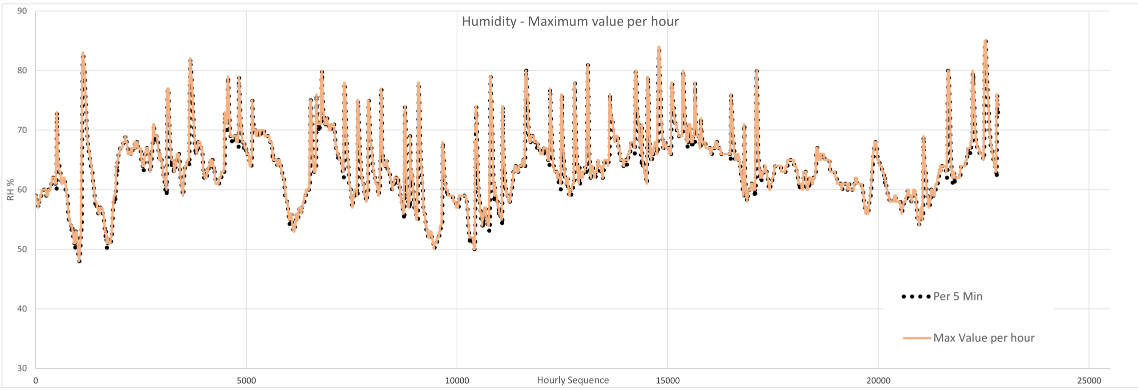


Figure A.17: Bathroom - Plotted values for RH (01/06/2019-19/08/2019)- per 5 minutes and maximum hourly values

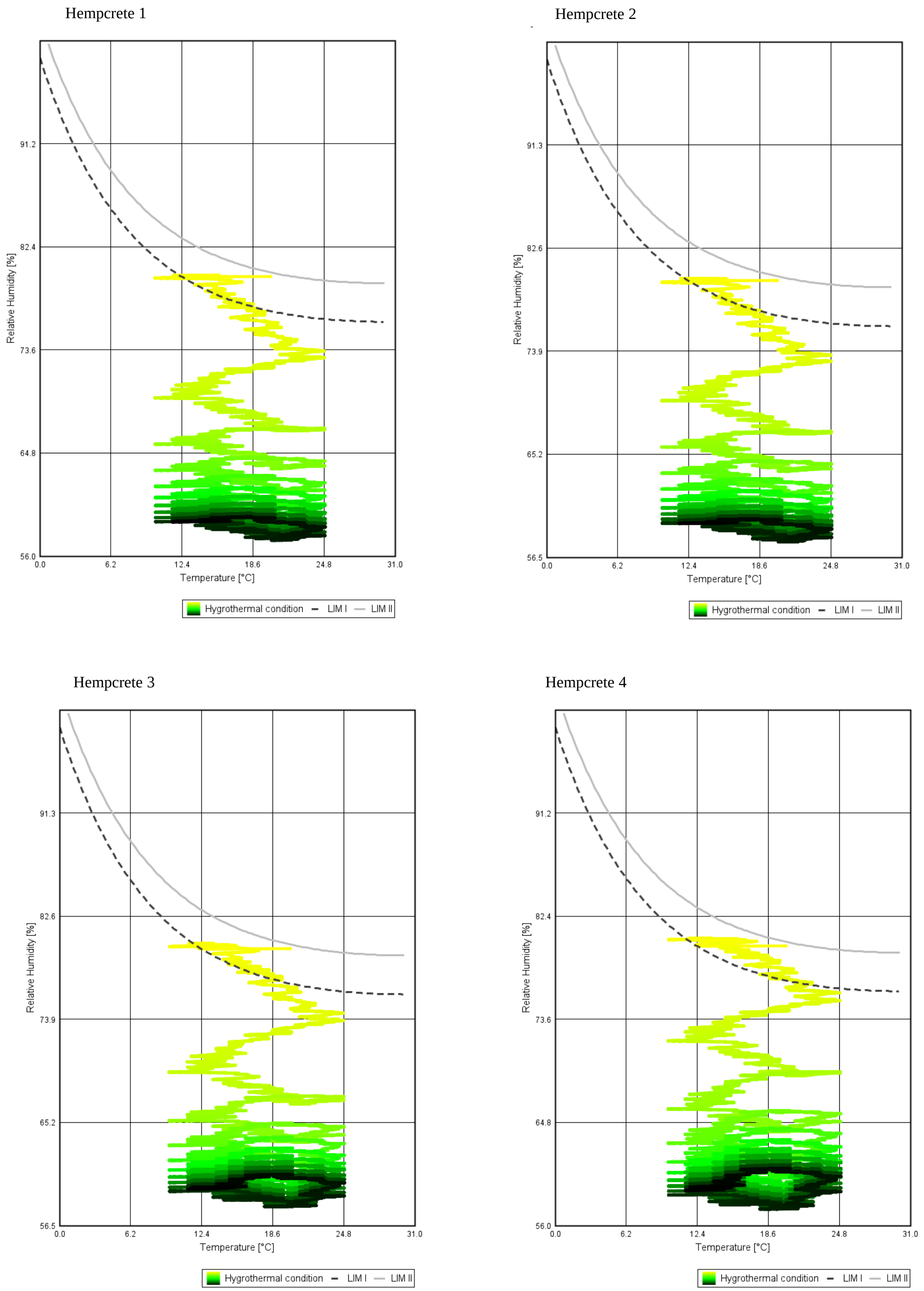


Figure A.18: Isopleths on the inner side of the spruce column - Detail 2.

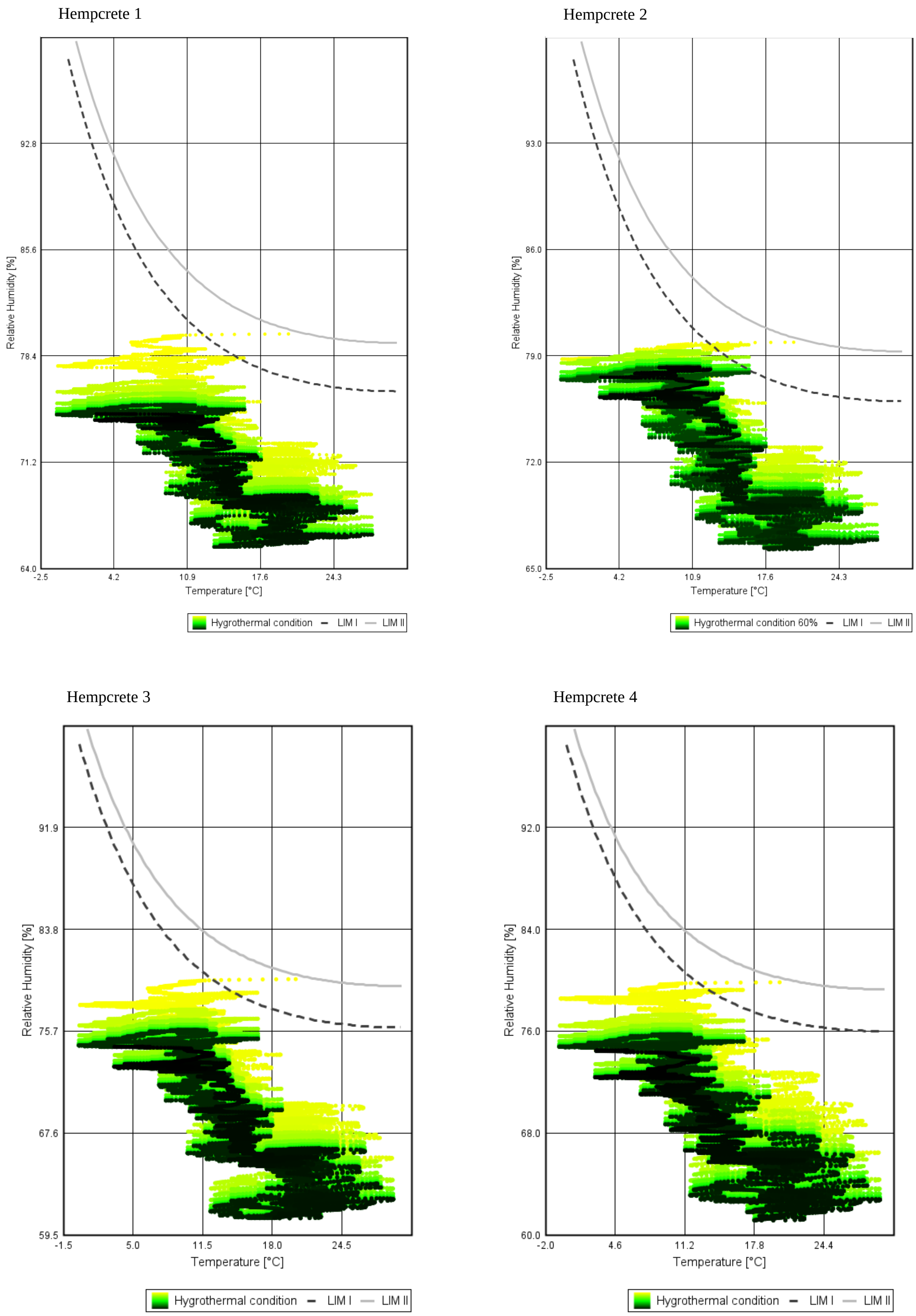


Figure A.19: Isopleths on the side of the spruce supporting frame towards the exterior. - Detail 1

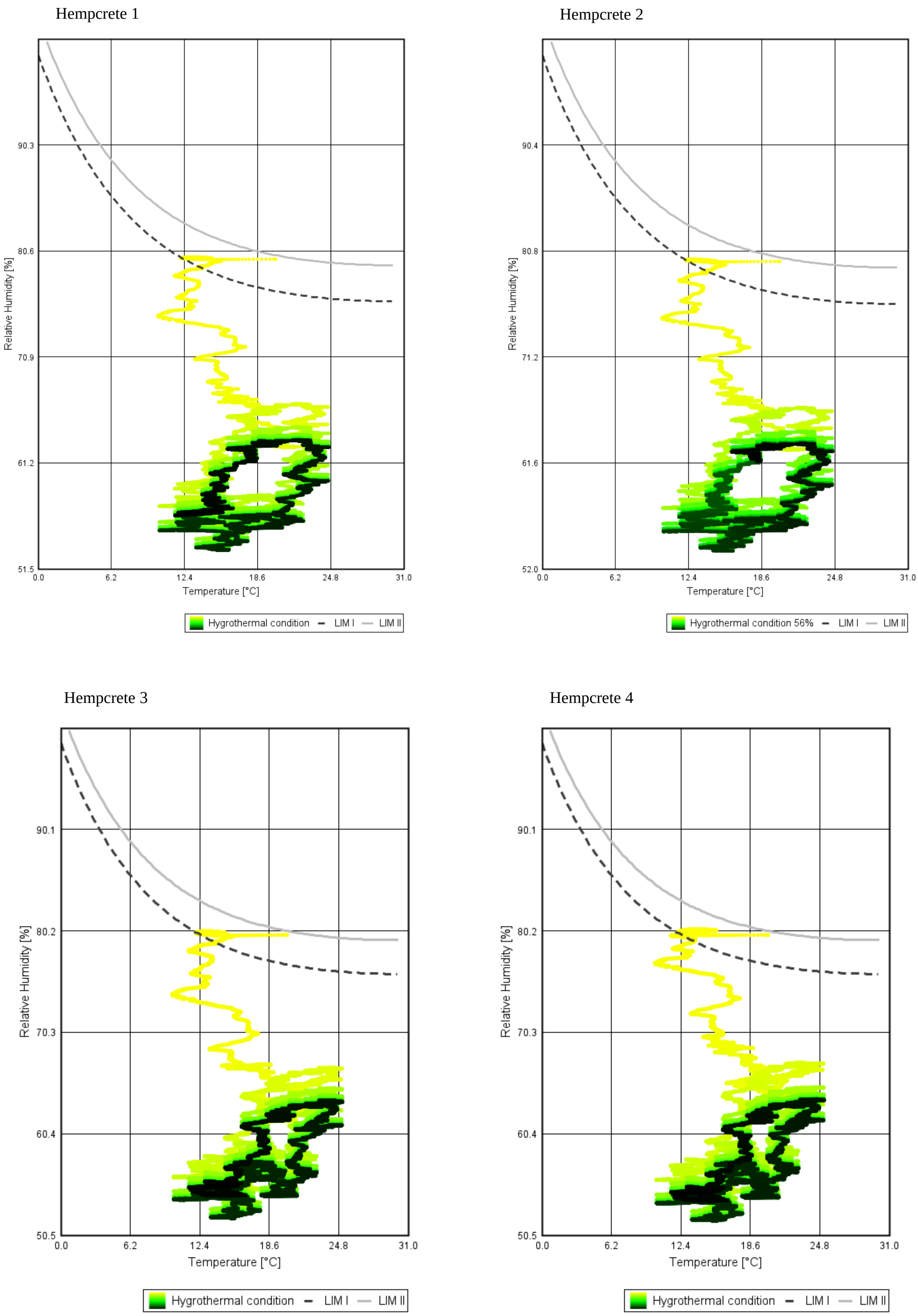
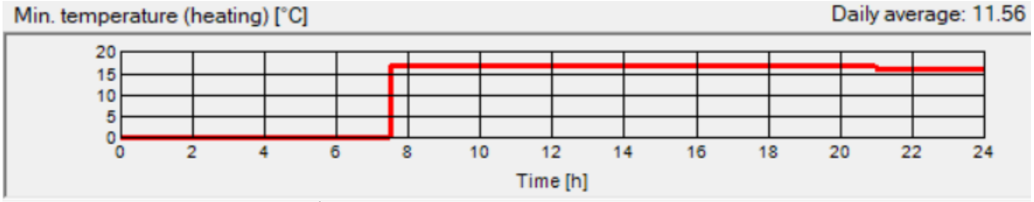
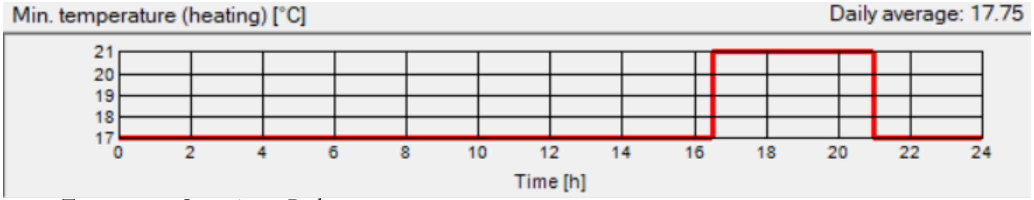


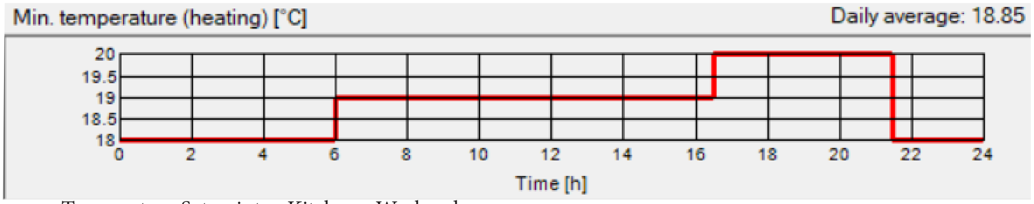
Figure A.20: Isopleths on the inner side of the spruce supporting frame. - Detail 1



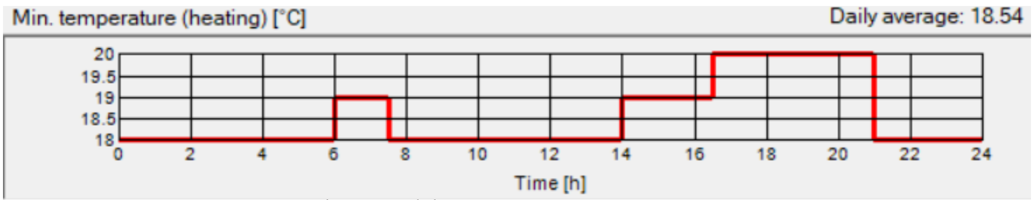
Temperature Set points - Bedrooms



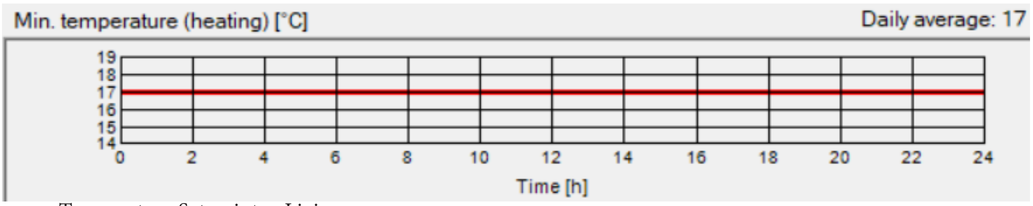
Temperature Set points - Bathroom



Temperature Set points - Kitchen - Weekends



Temperature Set points - Kitchen - Weekdays



Temperature Set points - Living room

Figure A.21: Heating set points - WUFI Plus analysis

Hempcrete Façade - Total impact		PRODUCTION			CONSTRUCTION PHASE		USE PHASE							END OF LIFE				BENEFITS
		A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
GWP-Total	kg CO2eq/UF	-1.98E+03	8.08E+02	-4.00E+03	0.00E+00	9.55E+02	-1.63E+03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.14E+01	2.02E+02	2.89E+03	6.64E+03	-4.74E+02
GWP-Fossil	kg CO2eq/UF	7.32E+03	8.08E+02	-2.30E+03	0.00E+00	5.88E+02	-1.63E+03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.14E+01	2.02E+02	8.06E+01	1.55E+02	-1.80E+03
GWP-Biogeneic	kg CO2eq/UF	-9.30E+03	4.43E-01	-1.70E+03	0.00E+00	3.68E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.60E-02	1.59E-01	2.82E+03	6.49E+03	1.32E+03
GWP-Luluc	kg CO2eq/UF	5.60E+00	2.46E-01	1.10E-01	0.00E+00	2.37E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	8.71E-03	1.67E-01	2.20E-02	2.55E-02	-1.15E+00
ODP	kg CFC 11 eq/UF	3.95E-04	1.79E-04	1.90E-05	0.00E+00	5.21E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.35E-05	4.11E-05	7.64E-06	1.02E-05	-1.15E-04
AP	mol H+eq/UF	3.65E+01	2.79E+00	6.79E-01	0.00E+00	2.49E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.56E-01	6.94E-01	7.71E-01	4.99E+00	-3.44E+00
EP-Freshwater	kg P eq/UF	5.66E-01	5.85E-04	3.99E-03	0.00E+00	2.83E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.13E-05	1.93E-04	1.67E-04	2.36E-03	-1.89E-02
Ep-Seawater	kg N eq/UF	1.82E+01	9.13E-01	1.67E-01	0.00E+00	1.08E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.94E-01	2.32E-01	2.85E-01	3.65E-01	-1.04E+00
EP-land	mol N eq/UF	1.27E+02	1.01E+01	2.11E+00	0.00E+00	8.58E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.23E+00	2.57E+00	3.68E+00	2.05E+01	-1.05E+01
POCP	kg NMVOC eq/UF	1.19E+01	2.68E+00	6.17E-01	0.00E+00	1.10E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	8.82E-01	6.63E-01	8.07E-01	1.49E+00	-2.86E+00
ADP-Elements	kg Sb eq/UF	8.04E-04	4.90E-05	2.26E-04	0.00E+00	9.87E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.70E-05	1.29E-05	2.02E-05	3.71E-05	-4.31E-04
ADP -Comb.& f.f.	MJ/UF	4.09E+04	1.14E+04	3.20E+03	0.00E+00	4.49E+03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	8.49E+02	2.84E+03	1.38E+03	1.03E+03	-3.48E+04
WDP	Prev. water in m3/UF	5.88E+02	-1.98E+00	3.25E+01	0.00E+00	4.52E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.74E-01	-2.79E-01	3.52E+02	2.81E+00	-1.41E+02

UF Hempcrete Façade		PRODUCTION			CONSTRUCTION PHASE		USE PHASE							END OF LIFE				BENEFITS
		A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
GWP-Total	kg CO2eq/UF	-1.50E+01	5.81E+00	-2.87E+01	0.00E+00	6.86E+00	-1.17E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.41E-01	1.46E+00	2.16E+01	4.77E+01	-3.72E+00
GWP-Fossil	kg CO2eq/UF	5.26E+01	5.81E+00	-1.65E+01	0.00E+00	4.22E+00	-1.17E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.41E-01	1.46E+00	5.93E-01	1.11E+00	-1.32E+01
GWP-Biogeneic	kg CO2eq/UF	-6.76E+01	3.22E-03	-1.22E+01	0.00E+00	2.64E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.88E-04	1.16E-03	2.11E+01	4.66E+01	9.48E+00
GWP-Luluc	kg CO2eq/UF	4.07E-02	1.84E-03	7.91E-04	0.00E+00	1.70E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.48E-05	1.25E-03	1.60E-04	1.83E-04	-8.29E-03
ODP	kg CFC 11 eq/UF	2.84E-06	1.28E-06	1.36E-07	0.00E+00	3.74E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	9.70E-08	2.95E-07	5.49E-08	7.32E-08	-8.23E-07
AP	mol H+eq/UF	2.62E-01	2.01E-02	4.89E-03	0.00E+00	1.79E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.71E-03	5.01E-03	5.68E-03	3.58E-02	-2.51E-02
EP-Freshwater	kg P eq/UF	4.07E-03	4.24E-06	2.89E-05	0.00E+00	2.03E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.70E-07	1.41E-06	1.22E-06	1.70E-05	-1.36E-04
Ep-Seawater	kg N eq/UF	1.31E-01	6.57E-03	1.21E-03	0.00E+00	7.77E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.11E-03	1.68E-03	2.09E-03	2.62E-03	-7.60E-03
EP-land	mol N eq/UF	9.09E-01	7.24E-02	1.52E-02	0.00E+00	6.16E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.32E-02	1.86E-02	2.71E-02	1.47E-01	-7.69E-02
POCP	kg NMVOC eq/UF	8.55E-02	1.93E-02	4.45E-03	0.00E+00	7.91E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.33E-03	4.78E-03	5.92E-03	1.07E-02	-2.08E-02
ADP-Elements	kg Sb eq/UF	5.82E-06	3.53E-07	1.62E-06	0.00E+00	7.09E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.94E-07	9.34E-08	1.47E-07	2.67E-07	-3.14E-06
ADP -Comb.& f.f.	MJ/UF	2.94E+02	8.20E+01	2.30E+01	0.00E+00	3.22E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.10E+00	2.05E+01	1.01E+01	7.41E+00	-2.55E+02
WDP	Prev. water in m3/UF	4.22E+00	-1.41E-02	2.34E-01	0.00E+00	3.25E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.26E-03	-1.92E-03	2.63E+00	2.02E-02	-1.02E+00

UF Hempcrete Façade - Hempcrete related impact		PRODUCTION			CONSTRUCTION PHASE		USE PHASE							END OF LIFE				BENEFITS
		A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
GWP-Total	kg CO2eq/UF	5.49E+00	5.53E+00	-2.88E+01	0.00E+00	6.82E+00	-1.17E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.32E-01	1.28E+00	2.34E-01	4.77E+01	4.27E+00
GWP-Fossil	kg CO2eq/UF	5.21E+01	5.53E+00	-1.66E+01	0.00E+00	4.18E+00	-1.17E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.32E-01	1.28E+00	2.32E-01	1.11E+00	-5.25E+00
GWP-Biogeneic	kg CO2eq/UF	-4.66E+01	2.27E-03	-1.22E+01	0.00E+00	2.64E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.57E-04	5.22E-04	2.74E-03	4.66E+01	9.52E+00
GWP-Luluc	kg CO2eq/UF	2.84E-02	4.38E-05	7.52E-04	0.00E+00	1.70E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.26E-06	1.01E-05	1.12E-04	1.83E-04	-7.43E-03
ODP	kg CFC 11 eq/UF	2.74E-06	1.28E-06	1.36E-07	0.00E+00	3.74E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	9.70E-08	2.95E-07	5.49E-08	7.32E-08	-8.23E-07
AP	mol H+eq/UF	2.59E-01	1.91E-02	4.44E-03	0.00E+00	1.79E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.67E-03	4.41E-03	2.12E-03	3.58E-02	-1.48E-02
EP-Freshwater	kg P eq/UF	3.95E-03	3.29E-06	2.16E-05	0.00E+00	2.03E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.39E-07	7.57E-07	7.63E-07	1.70E-05	-1.26E-04
Ep-Seawater	kg N eq/UF	1.29E-01	6.14E-03	1.02E-03	0.00E+00	7.77E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.09E-03	1.41E-03	9.25E-04	2.62E-03	-4.79E-03
EP-land	mol N eq/UF	8.93E-01	6.76E-02	1.32E-02	0.00E+00	6.16E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.30E-02	1.55E-02	1.01E-02	1.47E-01	-4.67E-02
POCP	kg NMVOC eq/UF	7.68E-02	1.84E-02	3.91E-03	0.00E+00	7.90E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.28E-03	4.25E-03	2.77E-03	1.07E-02	-1.29E-02
ADP-Elements	kg Sb eq/UF	4.54E-06	3.26E-07	1.59E-06	0.00E+00	7.08E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.93E-07	7.50E-08	1.01E-07	2.67E-07	-1.96E-06
ADP -Comb.& f.f.	MJ/UF	2.86E+02	7.83E+01	2.07E+01	0.00E+00	3.22E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.99E+00	1.80E+01	4.88E+00	7.41E+00	-1.20E+02
WDP	Prev. water in m3/UF	4.14E+00	-1.72E-02	2.19E-01	0.00E+00	3.21E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.16E-03	-3.97E-03	2.19E-02	2.02E-02	-9.34E-01

UF Hempcrete Façade - Timber related impact		PRODUCTION			CONSTRUCTION PHASE		USE PHASE							END OF LIFE				BENEFITS
		A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
GWP-Total	kg CO2eq/UF	-2.05E+01	2.81E-01	1.21E-01	0.00E+00	4.55E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	9.12E-03	1.85E-01	2.14E+01	0.00E+00	-8.00E+00
GWP-Fossil	kg CO2eq/UF	5.14E-01	2.78E-01	1.21E-01	0.00E+00	4.55E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	9.01E-03	1.83E-01	3.61E-01	0.00E+00	-7.97E+00
GWP-Biogeneic	kg CO2eq/UF	-2.10E+01	9.47E-04	2.78E-04	0.00E+00	2.59E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.05E-05	6.42E-04	2.10E+01	0.00E+00	-4.25E-02
GWP-Luluc	kg CO2eq/UF	1.23E-02	1.79E-03	3.93E-05	0.00E+00	1.43E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.86E-05	1.24E-03	4.76E-05	0.00E+00	-8.64E-04
ODP	kg CFC 11 eq/UF	1.03E-07	2.63E-14	6.18E-10	0.00E+00	2.33E-15	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	8.53E-16	1.80E-14	1.89E-12	0.00E+00	-5.27E-11
AP	mol H+eq/UF	3.58E-03	9.76E-04	4.49E-04	0.00E+00	5.16E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.36E-05	5.96E-04	3.56E-03	0.00E+00	-1.03E-02
EP-Freshwater	kg P eq/UF	1.21E-04	9.52E-07	7.38E-06	0.00E+00	1.26E-09	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.10E-08	6.55E-07	4.52E-07	0.00E+00	-1.08E-05
Ep-Seawater	kg N eq/UF	1.49E-03	4.31E-04	1.86E-04	0.00E+00	1.30E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.04E-05	2.70E-04	1.17E-03	0.00E+00	-2.81E-03
EP-land	mol N eq/UF	1.56E-02	4.81E-03	2.01E-03	0.00E+00	2.44E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.27E-04	3.05E-03	1.69E-02	0.00E+00	-3.02E-02
POCP	kg NMVOC eq/UF	8.75E-03	8.83E-04	5.48E-04	0.00E+00	3.53E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.72E-05	5.35E-04	3.16E-03	0.00E+00	-7.89E-03
ADP-Elements	kg Sb eq/UF	1.28E-06	2.73E-08	3.26E-08	0.00E+00	7.65E-11	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	8.75E-10	1.85E-08	4.60E-08	0.00E+00	-1.18E-06
ADP -Comb.& f.f.	MJ/UF	7.65E+00	3.74E+00	2.40E+00	0.00E+00	8.48E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.14E-01	2.40E+00	5.22E+00	0.00E+00	-1.35E+02
WDP	Prev. water in m3/UF	8.53E-02	3.13E-03	1.52E-02	0.00E+00	4.15E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	9.71E-05	2.05E-03	2.61E+00	0.00E+00	-8.18E-02

UF Hempcrete - Load bearing internal walls		PRODUCTION			CONSTRUCTION PHASE		USE PHASE							END OF LIFE				BENEFITS
		A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
GWP-Total	kg CO2eq/UF	-1.65E+01	1.13E+00	-4.57E+00	0.00E+00	1.14E+00	-1.89E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.99E-02	2.06E-01	3.80E-02	7.72E+00	6.92E-01
GWP-Fossil	kg CO2eq/UF	8.87E+00	1.13E+00	-2.59E+00	0.00E+00	7.15E-01	-1.89E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.99E-02	2.06E-01	3.75E-02	1.80E-01	-8.51E-01
GWP-Biogeneic	kg CO2eq/UF	-2.54E+01	1.17E-03	-1.98E+00	0.00E+00	4.28E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.54E-05	8.45E-05	4.43E-04	7.55E+00	1.54E+00
GWP-Luluc	kg CO2eq/UF	1.50E-02	1.53E-03	1.55E-04	0.00E+00	2.76E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.01E-06	1.63E-06	1.82E-05	2.97E-05	-1.20E-03
ODP	kg CFC 11 eq/UF	5.30E-07	2.08E-07	2.25E-08	0.00E+00	6.06E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.57E-08	4.78E-08	8.88E-09	1.19E-08	-1.33E-07
AP	mol H+eq/UF	4.49E-02	3.92E-03	1.10E-03	0.00E+00	2.90E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	7.56E-04	7.14E-04	3.43E-04	5.80E-03	-2.40E-03
EP-Freshwater	kg P eq/UF	7.43E-04	1.34E-06	9.74E-06	0.00E+00	3.29E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.48E-08	1.23E-07	1.24E-07	2.75E-06	-2.04E-05
Ep-Seawater	kg N eq/UF	2.22E-02	1.36E-03	3.23E-04	0.00E+00	1.26E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.39E-04	2.28E-04	1.50E-04	4.25E-04	-7.76E-04
EP-land	mol N eq/UF	1.58E-01	1.50E-02	3.84E-03	0.00E+00	1.00E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.72E-03	2.52E-03	1.64E-03	2.38E-02	-7.56E-03
POCP	kg NMVOC eq/UF	1.98E-02	3.73E-03	1.10E-03	0.00E+00	1.28E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.02E-03	6.88E-04	4.48E-04	1.73E-03	-2.09E-03
ADP-Elements	kg Sb eq/UF	1.82E-06	7.59E-08	2.85E-07	0.00E+00	1.15E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.13E-08	1.21E-08	1.63E-08	4.32E-08	-3.17E-07
ADP -Comb.& f.f.	MJ/UF	5.29E+01	1.59E+01	5.37E+00	0.00E+00	5.23E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	9.70E-01	2.92E+00	7.91E-01	1.20E+00	-1.95E+01
WDP	Prev. water in m3/UF	7.43E-01	-1.42E-04	4.83E-02	0.00E+00	5.54E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.88E-04	-6.43E-04	3.55E-03	3.27E-03	-1.51E-01

UF Hempcrete - Separation walls		PRODUCTION			CONSTRUCTION PHASE		USE PHASE							END OF LIFE				BENEFITS
		A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
GWP-Total	kg CO2eq/UF	-3.75E+00	1.24E+00	-6.09E+00	0.00E+00	1.46E+00	-2.48E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	9.16E-02	2.71E-01	4.97E-02	1.01E+01	9.07E-01
GWP-Fossil	kg CO2eq/UF	1.12E+01	1.24E+00	-3.50E+00	0.00E+00	8.97E-01	-2.48E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	9.16E-02	2.71E-01	4.92E-02	2.36E-01	-1.11E+00
GWP-Biogeneic	kg CO2eq/UF	-1.49E+01	7.09E-04	-2.59E+00	0.00E+00	5.60E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.33E-05	1.11E-04	5.81E-04	9.89E+00	2.02E+00
GWP-Luluc	kg CO2eq/UF	8.97E-03	4.39E-04	1.69E-04	0.00E+00	3.60E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.33E-06	2.13E-06	2.38E-05	3.89E-05	-1.58E-03
ODP	kg CFC 11 eq/UF	6.06E-07	2.72E-07	2.89E-08	0.00E+00	7.95E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.06E-08	6.27E-08	1.16E-08	1.55E-08	-1.75E-07
AP	mol H+eq/UF	5.57E-02	4.29E-03	1.05E-03	0.00E+00	3.79E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	9.91E-04	9.36E-04	4.50E-04	7.60E-03	-3.14E-03
EP-Freshwater	kg P eq/UF	8.67E-04	9.25E-07	6.34E-06	0.00E+00	4.31E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	7.18E-08	1.61E-07	1.62E-07	3.60E-06	-2.67E-05
Ep-Seawater	kg N eq/UF	2.78E-02	1.41E-03	2.62E-04	0.00E+00	1.65E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.44E-04	2.99E-04	1.96E-04	5.56E-04	-1.02E-03
EP-land	mol N eq/UF	1.93E-01	1.55E-02	3.28E-03	0.00E+00	1.31E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.88E-03	3.30E-03	2.15E-03	3.12E-02	-9.91E-03
POCP	kg NMVOC eq/UF	1.84E-02	4.12E-03	9.60E-04	0.00E+00	1.68E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.33E-03	9.01E-04	5.87E-04	2.27E-03	-2.74E-03
ADP-Elements	kg Sb eq/UF	1.27E-06	7.57E-08	3.45E-07	0.00E+00	1.50E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.10E-08	1.59E-08	2.13E-08	5.66E-08	-4.15E-07
ADP -Comb.& f.f.	MJ/UF	6.26E+01	1.75E+01	4.96E+00	0.00E+00	6.84E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.27E+00	3.83E+00	1.04E+00	1.57E+00	-2.55E+01
WDP	Prev. water in m3/UF	8.99E-01	-2.91E-03	5.01E-02	0.00E+00	6.90E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.46E-04	-8.42E-04	4.65E-03	4.29E-03	-1.98E-01

Figure A.22: Environmental impact - Hempcrete walls

AAC Façade - Total impact		PRODUCTION	CONSTRUCTION PHASE		USE PHASE							END OF LIFE				BENEFITS
		A1-A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
GWP-Total	kg CO2eq/UF	1.24E+04	0.00E+00	1.39E+03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	9.72E+01	1.35E+02	1.09E+02	1.25E+01	-2.27E+02
GWP-Fossil	kg CO2eq/UF	1.25E+04	0.00E+00	8.49E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	9.72E+01	1.34E+02	1.09E+02	1.25E+01	-2.27E+02
GWP-Biogeneic	kg CO2eq/UF	-8.33E+01	0.00E+00	5.37E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.71E-02	9.79E-02	3.03E-02	2.47E-02	-4.08E-01
GWP-Luluc	kg CO2eq/UF	4.41E+01	0.00E+00	3.45E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	8.21E-03	4.04E-02	9.20E-03	3.70E-03	-8.47E-02
ODP	kg CFC 11 eq/UF	8.49E-04	0.00E+00	7.61E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.10E-05	3.16E-05	2.35E-05	5.13E-06	-7.69E-05
AP	mol H+eq/UF	2.99E+01	0.00E+00	3.63E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.02E+00	5.64E-01	1.14E+00	1.18E-01	-1.87E+00
EP-Freshwater	kg P eq/UF	1.18E+00	0.00E+00	4.12E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.94E-04	1.09E-03	4.40E-04	1.50E-04	-2.95E-03
Ep-Seawater	kg N eq/UF	6.28E+00	0.00E+00	1.58E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.50E-01	1.70E-01	5.03E-01	4.07E-02	-6.52E-01
EP-land	mol N eq/UF	8.54E+01	0.00E+00	1.25E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.94E+00	1.88E+00	5.51E+00	4.48E-01	-7.16E+00
POCP	kg NMVOC eq/UF	2.37E+01	0.00E+00	1.61E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.36E+00	6.04E-01	1.52E+00	1.30E-01	-2.07E+00
ADP-Elements	kg Sb eq/UF	1.13E-01	0.00E+00	1.44E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.49E-04	2.29E-03	1.66E-04	1.14E-04	-3.21E-03
ADP -Comb.& f.f.	MJ/UF	8.40E+04	0.00E+00	6.55E+03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.34E+03	2.09E+03	1.50E+03	3.48E+02	-5.28E+03
WDP	Prev. water in m3/UF	1.63E+03	0.00E+00	6.51E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.50E+00	7.75E+00	2.79E+00	1.61E+01	-1.91E+02

UF AAC Façade		PRODUCTION	CONSTRUCTION PHASE		USE PHASE							END OF LIFE				BENEFITS
		A1-A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
GWP-Total	kg CO2eq/UF	8.88E+01	0.00E+00	9.93E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.97E-01	9.65E-01	7.82E-01	8.95E-02	-1.63E+00
GWP-Fossil	kg CO2eq/UF	8.93E+01	0.00E+00	6.08E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.97E-01	9.61E-01	7.82E-01	8.95E-02	-1.62E+00
GWP-Biogeneic	kg CO2eq/UF	-5.97E-01	0.00E+00	3.85E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.95E-04	7.02E-04	2.17E-04	1.77E-04	-2.92E-03
GWP-Luluc	kg CO2eq/UF	3.16E-01	0.00E+00	2.47E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.89E-05	2.90E-04	6.59E-05	2.65E-05	-6.08E-04
ODP	kg CFC 11 eq/UF	6.09E-06	0.00E+00	5.46E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.51E-07	2.27E-07	1.69E-07	3.68E-08	-5.51E-07
AP	mol H+eq/UF	2.15E-01	0.00E+00	2.60E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	7.30E-03	4.05E-03	8.15E-03	8.48E-04	-1.34E-02
EP-Freshwater	kg P eq/UF	8.44E-03	0.00E+00	2.96E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.83E-06	7.82E-06	3.16E-06	1.08E-06	-2.11E-05
Ep-Seawater	kg N eq/UF	4.51E-02	0.00E+00	1.13E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.23E-03	1.22E-03	3.60E-03	2.92E-04	-4.67E-03
EP-land	mol N eq/UF	6.12E-01	0.00E+00	8.97E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.54E-02	1.35E-02	3.95E-02	3.21E-03	-5.13E-02
POCP	kg NMVOC eq/UF	1.70E-01	0.00E+00	1.15E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	9.75E-03	4.33E-03	1.09E-02	9.33E-04	-1.48E-02
ADP-Elements	kg Sb eq/UF	8.13E-04	0.00E+00	1.03E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.07E-06	1.64E-05	1.19E-06	8.15E-07	-2.30E-05
ADP -Comb.& f.f.	MJ/UF	6.02E+02	0.00E+00	4.70E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	9.61E+00	1.50E+01	1.07E+01	2.50E+00	-3.78E+01
WDP	Prev. water in m3/UF	1.17E+01	0.00E+00	4.67E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.79E-02	5.56E-02	2.00E-02	1.15E-01	-1.37E+00

UF AAC Façade -AAC related impact		PRODUCTION	CONSTRUCTION PHASE		USE PHASE							END OF LIFE				BENEFITS
		A1-A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
GWP-Total	kg CO2eq/UF	7.16E+01	0.00E+00	9.93E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.97E-01	9.65E-01	7.82E-01	8.95E-02	-1.63E+00
GWP-Fossil	kg CO2eq/UF	7.21E+01	0.00E+00	6.08E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.97E-01	9.61E-01	7.82E-01	8.95E-02	-1.62E+00
GWP-Biogeneic	kg CO2eq/UF	-6.12E-01	0.00E+00	3.85E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.95E-04	7.02E-04	2.17E-04	1.77E-04	-2.92E-03
GWP-Luluc	kg CO2eq/UF	2.72E-01	0.00E+00	2.47E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.89E-05	2.90E-04	6.59E-05	2.65E-05	-6.08E-04
ODP	kg CFC 11 eq/UF	4.16E-06	0.00E+00	5.46E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.51E-07	2.27E-07	1.69E-07	3.68E-08	-5.51E-07
AP	mol H+eq/UF	1.65E-01	0.00E+00	2.60E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	7.30E-03	4.05E-03	8.15E-03	8.48E-04	-1.34E-02
EP-Freshwater	kg P eq/UF	7.54E-04	0.00E+00	2.96E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.83E-06	7.82E-06	3.16E-06	1.08E-06	-2.11E-05
Ep-Seawater	kg N eq/UF	4.48E-02	0.00E+00	1.13E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.23E-03	1.22E-03	3.60E-03	2.92E-04	-4.67E-03
EP-land	mol N eq/UF	5.23E-01	0.00E+00	8.97E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.54E-02	1.35E-02	3.95E-02	3.21E-03	-5.13E-02
POCP	kg NMVOC eq/UF	1.37E-01	0.00E+00	1.15E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	9.75E-03	4.33E-03	1.09E-02	9.33E-04	-1.48E-02
ADP-Elements	kg Sb eq/UF	6.41E-04	0.00E+00	1.03E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.07E-06	1.64E-05	1.19E-06	8.15E-07	-2.30E-05
ADP -Comb.& f.f.	MJ/UF	4.85E+02	0.00E+00	4.70E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	9.61E+00	1.50E+01	1.07E+01	2.50E+00	-3.78E+01
WDP	Prev. water in m3/UF	9.37E+00	0.00E+00	4.67E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.79E-02	5.56E-02	2.00E-02	1.15E-01	-1.37E+00

UF AAC Façade - Mortar related impact		PRODUCTION	CONSTRUCTION PHASE		USE PHASE							END OF LIFE				BENEFITS
		A1-A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
GWP-Total	kg CO2eq/UF	1.72E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
GWP-Fossil	kg CO2eq/UF	1.72E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
GWP-Biogeneic	kg CO2eq/UF	1.53E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
GWP-Luluc	kg CO2eq/UF	4.40E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ODP	kg CFC 11 eq/UF	1.93E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
AP	mol H+eq/UF	4.97E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
EP-Freshwater	kg P eq/UF	7.69E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ep-Seawater	kg N eq/UF	2.66E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
EP-land	mol N eq/UF	8.92E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
POCP	kg NMVOC eq/UF	3.29E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ADP-Elements	kg Sb eq/UF	1.72E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ADP -Comb.& f.f.	MJ/UF	1.17E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
WDP	Prev. water in m3/UF	2.35E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

UF AAC - Load bearing internal walls		PRODUCTION	CONSTRUCTION PHASE		USE PHASE							END OF LIFE				BENEFITS
		A1-A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
GWP-Total	kg CO2eq/UF	3.05E+01	0.00E+00	3.41E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.40E-01	3.32E-01	2.69E-01	3.08E-02	-5.60E-01
GWP-Fossil	kg CO2eq/UF	3.07E+01	0.00E+00	2.09E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.40E-01	3.30E-01	2.69E-01	3.08E-02	-5.58E-01
GWP-Biogeneic	kg CO2eq/UF	-2.05E-01	0.00E+00	1.32E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.69E-05	2.41E-04	7.46E-05	6.09E-05	-1.01E-03
GWP-Luluc	kg CO2eq/UF	1.09E-01	0.00E+00	8.50E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.02E-05	9.96E-05	2.27E-05	9.11E-06	-2.09E-04
ODP	kg CFC 11 eq/UF	2.09E-06	0.00E+00	1.88E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.18E-08	7.79E-08	5.80E-08	1.26E-08	-1.89E-07
AP	mol H+eq/UF	7.37E-02	0.00E+00	8.95E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.51E-03	1.39E-03	2.80E-03	2.91E-04	-4.61E-03
EP-Freshwater	kg P eq/UF	2.90E-03	0.00E+00	1.02E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	9.71E-07	2.69E-06	1.08E-06	3.71E-07	-7.27E-06
Ep-Seawater	kg N eq/UF	1.55E-02	0.00E+00	3.89E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.11E-03	4.19E-04	1.24E-03	1.00E-04	-1.61E-03
EP-land	mol N eq/UF	2.10E-01	0.00E+00	3.08E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.22E-02	4.63E-03	1.36E-02	1.10E-03	-1.76E-02
POCP	kg NMVOC eq/UF	5.84E-02	0.00E+00	3.96E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.35E-03	1.49E-03	3.74E-03	3.21E-04	-5.10E-03
ADP-Elements	kg Sb eq/UF	2.79E-04	0.00E+00	3.55E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.67E-07	5.65E-06	4.10E-07	2.80E-07	-7.92E-06
ADP -Comb.& f.f.	MJ/UF	2.07E+02	0.00E+00	1.61E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.30E+00	5.15E+00	3.69E+00	8.58E-01	-1.30E+01
WDP	Prev. water in m3/UF	4.03E+00	0.00E+00	1.61E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.17E-03	1.91E-02	6.88E-03	3.97E-02	-4.71E-01

UF AAC - Separation walls		PRODUCTION	CONSTRUCTION PHASE		USE PHASE							END OF LIFE				BENEFITS
		A1-A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
GWP-Total	kg CO2eq/UF	1.85E+01	0.00E+00	2.07E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.45E-01	2.01E-01	1.63E-01	1.86E-02	-3.39E-01
GWP-Fossil	kg CO2eq/UF	1.86E+01	0.00E+00	1.27E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.45E-01	2.00E-01	1.63E-01	1.86E-02	-3.39E-01
GWP-Biogeneic	kg CO2eq/UF	-1.24E-01	0.00E+00	8.01E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.05E-05	1.46E-04	4.52E-05	3.69E-05	-6.09E-04
GWP-Luluc	kg CO2eq/UF	6.59E-02	0.00E+00	5.15E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.23E-05	6.03E-05	1.37E-05	5.52E-06	-1.27E-04
ODP	kg CFC 11 eq/UF	1.27E-06	0.00E+00	1.14E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.14E-08	4.72E-08	3.51E-08	7.66E-09	-1.15E-07
AP	mol H+eq/UF	4.47E-02	0.00E+00	5.42E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.52E-03	8.43E-04	1.70E-03	1.77E-04	-2.80E-03
EP-Freshwater	kg P eq/UF	1.76E-03	0.00E+00	6.16E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.89E-07	1.63E-06	6.57E-07	2.25E-07	-4.41E-06
Ep-Seawater	kg N eq/UF	9.39E-03	0.00E+00	2.36E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.72E-04	2.54E-04	7.51E-04	6.08E-05	-9.73E-04
EP-land	mol N eq/UF	1.27E-01	0.00E+00	1.87E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	7.38E-03	2.81E-03	8.23E-03	6.69E-04	-1.07E-02
POCP	kg NMVOC eq/UF	3.54E-02	0.00E+00	2.40E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.03E-03	9.02E-04	2.27E-03	1.94E-04	-3.09E-03
ADP-Elements	kg Sb eq/UF	1.69E-04	0.00E+00	2.15E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.23E-07	3.42E-06	2.48E-07	1.70E-07	-4.80E-06
ADP -Comb.& f.f.	MJ/UF	1.25E+02	0.00E+00	9.78E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.00E+00	3.12E+00	2.24E+00	5.20E-01	-7.88E+00
WDP	Prev. water in m3/UF	2.44E+00	0.00E+00	9.73E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.74E-03	1.16E-02	4.17E-03	2.40E-02	-2.86E-01

Figure A.23: Environmental impact - AAC walls

SL Façade - Total impact		PRODUCTION	CONSTRUCTION PHASE		USE PHASE							END OF LIFE				BENEFITS
		A1-A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
GWP-Total	kg CO2eq/UF	7.03E+03	0.00E+00	6.26E+02	-1.85E+03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.39E+01	6.63E+01	0.00E+00	5.54E+02	-9.58E+01
GWP-Fossil	kg CO2eq/UF	7.18E+03	0.00E+00	3.13E+02	-1.85E+03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.48E+01	6.59E+01	0.00E+00	6.01E+02	-9.56E+01
GWP-Biogeneic	kg CO2eq/UF	-1.55E+02	0.00E+00	3.13E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	-1.05E+00	2.49E-02	0.00E+00	-4.68E+01	-1.89E-01
GWP-Luluc	kg CO2eq/UF	6.60E+00	0.00E+00	1.92E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	9.95E-02	2.67E-01	0.00E+00	1.71E+00	-9.08E-02
ODP	kg CFC 11 eq/UF	2.00E-04	0.00E+00	3.62E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.85E-15	1.17E-07	0.00E+00	8.88E-07	-9.43E-06
AP	mol H+eq/UF	1.72E+01	0.00E+00	7.10E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.17E-01	7.53E-02	0.00E+00	4.32E+00	-1.51E-01
EP-Freshwater	kg P eq/UF	3.39E-01	0.00E+00	9.60E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.19E-05	1.38E-04	0.00E+00	1.02E-13	-7.37E-05
EP-Freshwater	kg P04 eq/UF	4.53E-02	0.00E+00	1.19E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.12E-05	0.00E+00	6.91E-05	-9.43E-04
Ep-Seawater	kg N eq/UF	2.56E+00	0.00E+00	1.13E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.54E-02	2.54E-02	0.00E+00	1.12E+00	-3.12E-02
EP-land	mol N eq/UF	6.24E+01	0.00E+00	1.85E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.12E-01	3.00E-01	0.00E+00	1.23E+01	-3.41E-01
POCP	kg NMVOC eq/UF	9.92E+00	0.00E+00	3.53E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.55E-01	7.06E-02	0.00E+00	3.39E+00	-1.03E-01
ADP-Elements	kg Sb eq/UF	1.06E-02	0.00E+00	1.59E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.98E-06	1.07E-05	0.00E+00	6.10E-05	-2.94E-04
ADP -Comb.& f.f.	MJ/UF	6.53E+04	0.00E+00	1.64E+03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.16E+02	8.83E+02	0.00E+00	7.97E+03	-2.14E+03
WDP	Prev. water in m3/UF	1.28E+06	0.00E+00	1.53E+04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.03E-01	1.10E+02	0.00E+00	4.63E+02	-4.39E+04

UF SL Façade - SL related impact		PRODUCTION	CONSTRUCTION PHASE		USE PHASE							END OF LIFE				BENEFITS
		A1-A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
GWP-Total	kg CO2eq/UF	3.52E+01	0.00E+00	8.50E-01	-1.33E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.71E-01	4.59E-01	0.00E+00	3.91E+00	-2.61E-01
GWP-Fossil	kg CO2eq/UF	3.52E+01	0.00E+00	8.50E-01	-1.33E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.78E-01	4.56E-01	0.00E+00	4.25E+00	-2.60E-01
GWP-Biogeneic	kg CO2eq/UF	1.86E-03	0.00E+00	-2.18E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	-7.55E-03	1.83E-04	0.00E+00	-3.36E-01	-9.28E-04
GWP-Luluc	kg CO2eq/UF	2.41E-02	0.00E+00	1.26E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	7.13E-04	1.91E-03	0.00E+00	1.22E-02	-3.30E-04
ODP	kg CFC 11 eq/UF	1.14E-13	0.00E+00	3.47E-16	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.19E-17	1.12E-16	0.00E+00	1.59E-14	-3.69E-15
AP	mol H+eq/UF	2.91E-02	0.00E+00	2.96E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	8.42E-04	4.22E-04	0.00E+00	3.05E-02	-5.43E-04
EP-Freshwater	kg P eq/UF	3.47E-05	0.00E+00	6.88E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.72E-07	9.93E-07	0.00E+00	7.30E-16	-5.29E-07
Ep-Seawater	kg N eq/UF	1.10E-02	0.00E+00	4.25E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.97E-04	1.32E-04	0.00E+00	7.83E-03	-1.10E-04
EP-land	mol N eq/UF	1.21E-01	0.00E+00	4.78E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.39E-03	1.60E-03	0.00E+00	8.61E-02	-1.19E-03
POCP	kg NMVOC eq/UF	3.05E-02	0.00E+00	1.29E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.11E-03	3.50E-04	0.00E+00	2.37E-02	-3.08E-04
ADP-Elements	kg Sb eq/UF	2.94E-06	0.00E+00	6.94E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.42E-08	3.80E-08	0.00E+00	3.83E-07	-1.98E-06
ADP -Comb.& f.f.	MJ/UF	2.61E+02	0.00E+00	5.82E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.27E+00	6.07E+00	0.00E+00	5.56E+01	-3.64E+00
WDP	Prev. water in m3/UF	2.30E+00	0.00E+00	2.27E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	7.35E-04	1.97E-03	0.00E+00	4.42E-01	-1.07E-02

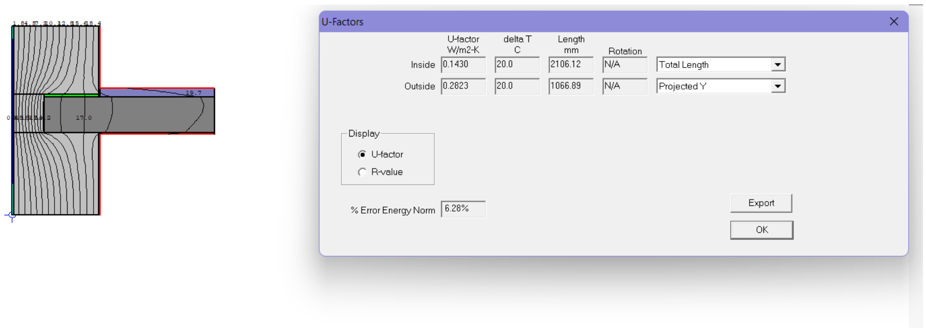
UF SL Façade - FG related impact		PRODUCTION	CONSTRUCTION PHASE		USE PHASE							END OF LIFE				BENEFITS
		A1-A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
GWP-Total	kg CO2eq/UF	9.76E+00	0.00E+00	3.64E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.66E-02	0.00E+00	5.82E-02	-4.26E-01
GWP-Fossil	kg CO2eq/UF	1.09E+01	0.00E+00	1.39E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.66E-02	0.00E+00	5.82E-02	-4.26E-01
GWP-Biogeneic	kg CO2eq/UF	-1.12E+00	0.00E+00	2.25E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	-4.63E-06	0.00E+00	1.67E-06	-4.27E-04
GWP-Luluc	kg CO2eq/UF	9.44E-03	0.00E+00	1.18E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.06E-06	0.00E+00	3.60E-06	-3.21E-04
ODP	kg CFC 11 eq/UF	8.32E-07	0.00E+00	2.59E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	8.40E-10	0.00E+00	6.37E-09	-6.76E-08
AP	mol H+eq/UF	7.87E-02	0.00E+00	2.13E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.18E-04	0.00E+00	4.58E-04	-5.43E-04
EP-Freshwater	kg P04 eq/UF	3.25E-04	0.00E+00	8.56E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.24E-07	0.00E+00	4.95E-07	-6.76E-06
Ep-Seawater	kg N eq/UF	7.31E-03	0.00E+00	3.82E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.04E-05	0.00E+00	1.90E-04	-1.14E-04
EP-land	mol N eq/UF	2.98E-01	0.00E+00	8.48E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.54E-04	0.00E+00	2.10E-03	-1.26E-03
POCP	kg NMVOC eq/UF	3.04E-02	0.00E+00	1.24E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.57E-04	0.00E+00	6.23E-04	-4.29E-04
ADP-Elements	kg Sb eq/UF	1.96E-05	0.00E+00	4.50E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.85E-08	0.00E+00	5.42E-08	-1.30E-07
ADP -Comb.& f.f.	MJ/UF	1.70E+02	0.00E+00	5.95E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.61E-01	0.00E+00	1.47E+00	-1.17E+01
WDP	Prev. water in m3/UF	9.20E+03	0.00E+00	1.10E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	7.86E-01	0.00E+00	2.88E+00	-3.14E+02

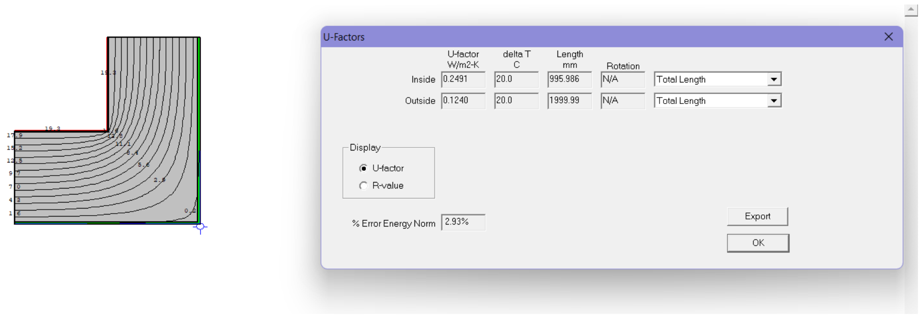
UF SL Façade - Mortar related impact		PRODUCTION	CONSTRUCTION PHASE		USE PHASE							END OF LIFE				BENEFITS
		A1-A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
GWP-Total	kg CO2eq/UF	5.38E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
GWP-Fossil	kg CO2eq/UF	5.38E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
GWP-Biogeneic	kg CO2eq/UF	4.76E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
GWP-Luluc	kg CO2eq/UF	1.37E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ODP	kg CFC 11 eq/UF	6.02E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
AP	mol H+eq/UF	1.55E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
EP-Freshwater	kg P eq/UF	2.40E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ep-Seawater	kg N eq/UF	8.30E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
EP-land	mol N eq/UF	2.78E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
POCP	kg NMVOC eq/UF	1.03E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ADP-Elements	kg Sb eq/UF	5.37E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ADP -Comb.& f.f.	MJ/UF	3.66E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
WDP	Prev. water in m3/UF	7.32E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

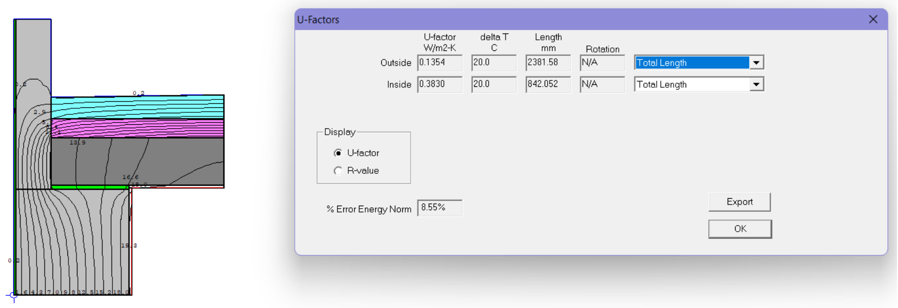
UF SL - Load bearing walls		PRODUCTION	CONSTRUCTION PHASE		USE PHASE							END OF LIFE				BENEFITS
		A1-A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
GWP-Total	kg CO2eq/UF	4.28E+01	0.00E+00	8.97E-01	-1.40E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.81E-01	4.84E-01	0.00E+00	-2.75E-01	-7.99E-01
GWP-Fossil	kg CO2eq/UF	4.28E+01	0.00E+00	8.97E-01	-1.40E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.88E-01	4.81E-01	0.00E+00	-2.74E-01	-8.02E-01
GWP-Biogeneic	kg CO2eq/UF	6.98E-03	0.00E+00	-2.30E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	-7.96E-03	1.94E-04	0.00E+00	-9.79E-04	4.99E-03
GWP-Luluc	kg CO2eq/UF	4.00E-02	0.00E+00	1.33E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	7.52E-04	2.01E-03	0.00E+00	-3.48E-04	-2.65E-03
ODP	kg CFC 11 eq/UF	6.35E-07	0.00E+00	3.66E-16	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.42E-17	1.18E-16	0.00E+00	-3.89E-15	-1.14E-14
AP	mol H+eq/UF	4.70E-02	0.00E+00	3.13E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	8.88E-04	4.45E-04	0.00E+00	-5.72E-04	-2.52E-03
EP-Freshwater	kg P eq/UF	2.57E-03	0.00E+00	7.26E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.92E-07	1.05E-06	0.00E+00	-5.58E-07	-2.41E-06
Ep-Seawater	kg N eq/UF	1.17E-02	0.00E+00	4.48E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.19E-04	1.39E-04	0.00E+00	-1.16E-04	-9.56E-04
EP-land	mol N eq/UF	1.57E-01	0.00E+00	5.04E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.63E-03	1.68E-03	0.00E+00	-1.25E-03	-1.05E-02
POCP	kg NMVOC eq/UF	4.30E-02	0.00E+00	1.36E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.17E-03	3.69E-04	0.00E+00	-3.24E-04	-2.26E-03
ADP-Elements	kg Sb eq/UF	5.98E-05	0.00E+00	7.32E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.50E-08	4.01E-08	0.00E+00	-2.09E-06	-1.72E-07
ADP -Comb.& f.f.	MJ/UF	3.14E+02	0.00E+00	6.14E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.39E+00	6.40E+00	0.00E+00	-3.83E+00	-1.04E+01
WDP	Prev. water in m3/UF	3.20E+00	0.00E+00	2.40E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	7.76E-04	2.07E-03	0.00E+00	-1.12E-02	-1.94E-02

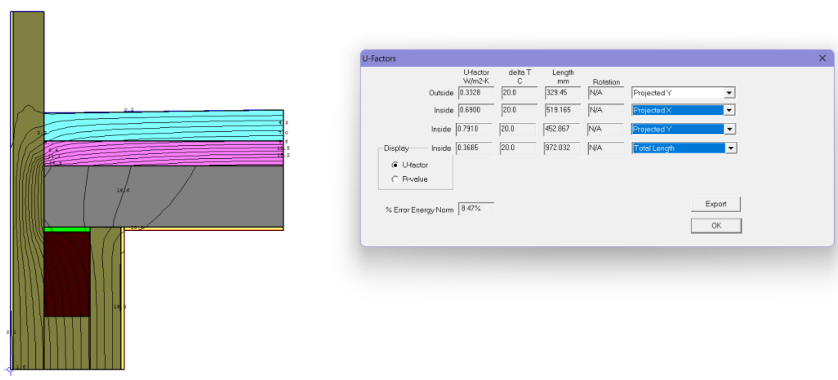
UF SL -Separation walls		PRODUCTION	CONSTRUCTION PHASE		USE PHASE							END OF LIFE				BENEFITS
		A1-A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
GWP-Total	kg CO2eq/UF	1.90E+01	0.00E+00	3.97E-01	-6.20E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	7.99E-02	2.14E-01	0.00E+00	-1.22E-01	-3.54E-01
GWP-Fossil	kg CO2eq/UF	1.90E+01	0.00E+00	3.97E-01	-6.20E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	8.30E-02	2.13E-01	0.00E+00	-1.21E-01	-3.55E-01
GWP-Biogeneic	kg CO2eq/UF	3.09E-03	0.00E+00	-1.02E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	-3.52E-03	8.56E-05	0.00E+00	-4.33E-04	2.21E-03
GWP-Luluc	kg CO2eq/UF	1.77E-02	0.00E+00	5.89E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.33E-04	8.91E-04	0.00E+00	-1.54E-04	-1.17E-03
ODP	kg CFC 11 eq/UF	2.81E-07	0.00E+00	1.62E-16	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.96E-17	5.22E-17	0.00E+00	-1.72E-15	-5.02E-15
AP	mol H+eq/UF	2.08E-02	0.00E+00	1.38E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.93E-04	1.97E-04	0.00E+00	-2.53E-04	-1.11E-03
EP-Freshwater	kg P eq/UF	1.14E-03	0.00E+00	3.21E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.74E-07	4.63E-07	0.00E+00	-2.47E-07	-1.07E-06
Ep-Seawater	kg N eq/UF	5.15E-03	0.00E+00	1.98E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.85E-04	6.15E-05	0.00E+00	-5.14E-05	-4.23E-04
EP-land	mol N eq/UF	6.94E-02	0.00E+00	2.23E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.05E-03	7.45E-04	0.00E+00	-5.53E-04	-4.65E-03
POCP	kg NMVOC eq/UF	1.90E-02	0.00E+00	6.02E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.18E-04	1.63E-04	0.00E+00	-1.44E-04	-1.00E-03
ADP-Elements	kg Sb eq/UF	2.64E-05	0.00E+00	3.24E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.62E-09	1.77E-08	0.00E+00	-9.23E-07	-7.60E-08
ADP -Comb.& f.f.	MJ/UF	1.39E+02	0.00E+00	2.71E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.06E+00	2.83E+00	0.00E+00	-1.70E+00	-4.62E+00
WDP	Prev. water in m3/UF	1.41E+00	0.00E+00	1.06E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.43E-04	9.17E-04	0.00E+00	-4.97E-03	-8.60E-03

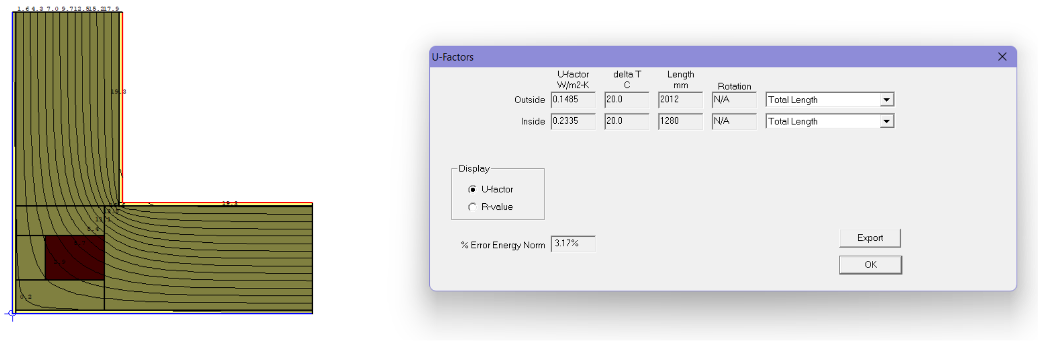
Figure A.24: Environmental impact - SL walls

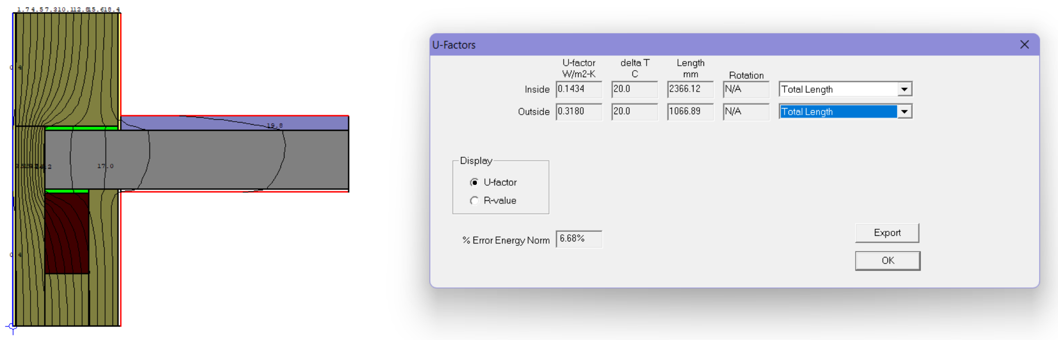

U-Factors
U-factor W/m2-K
delta T C
Length mm
Rotation
Inside 0.1430 20.0 2106.12 N/A Total Length
Outside 0.2823 20.0 1066.89 N/A Projected Y
Display
U-factor
R-value
% Error Energy Norm 6.28%
Export
OK


U-Factors
U-factor W/m2-K
delta T C
Length mm
Rotation
Inside 0.2491 20.0 995.986 N/A Total Length
Outside 0.1240 20.0 1999.99 N/A Total Length
Display
U-factor
R-value
% Error Energy Norm 2.93%
Export
OK


U-Factors
U-factor W/m2-K
delta T C
Length mm
Rotation
Outside 0.1354 20.0 2381.58 N/A Total Length
Inside 0.3830 20.0 842.052 N/A Total Length
Display
U-factor
R-value
% Error Energy Norm 8.55%
Export
OK


U-Factors
U-factor W/m2-K
delta T C
Length mm
Rotation
Outside 0.3328 20.0 329.45 N/A Projected Y
Inside 0.6900 20.0 519.165 N/A Projected X
Inside 0.7910 20.0 452.867 N/A Projected Y
Inside 0.3685 20.0 972.032 N/A Total Length
Display
U-factor
R-value
% Error Energy Norm 8.47%
Export
OK

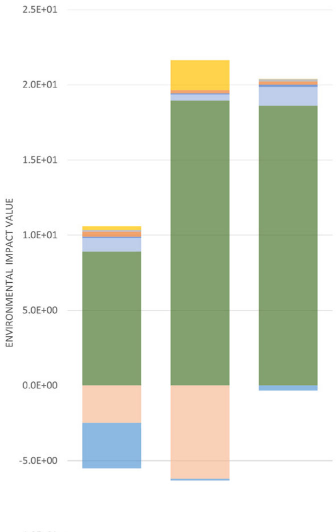




			AAC			
	U Factor	Length (m)	LD	U ideal	AC Ideal (m2)	ψ
Corner	0.249	1.00	0.248	0.208	1.00	0.041
Middle floor	0.282	1.07	0.301	0.208	1.07	0.079
Flat roof	0.383	0.84	0.323	0.208	0.45	0.165
				0.163	0.39	
			SL			
						ψ
Corner	ISO Reference 205.2.7.01					0.075
Middle floor	External insulation					0.000
Flat roof	ISO Reference 205.2.7.01					0.188
			Hempcrete			
	U Factor	Length (m)	LD	U ideal	AC Ideal (m2)	ψ
Corner	0.234	1.28	0.30	0.21	1.28	0.032
Middle floor	0.318	1.07	0.34	0.21	1.07	0.117
Flat roof	0.369	0.97	0.36	0.21	0.45	0.179
				0.16	0.52	

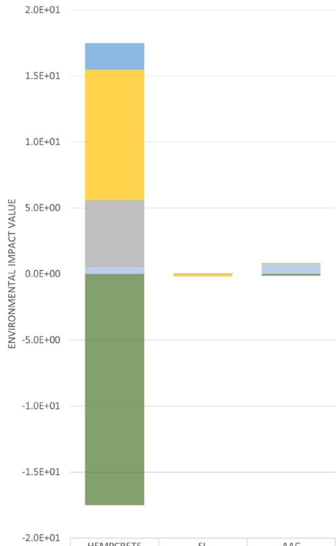
Figure A.25: Calculation thermal bridges

GWP - FOSSIL
COMPARISON OF THE ENVIRONMENTAL IMPACT OF 1 UF OF SEPARATION WALLS (KG CO2EQ/UF)



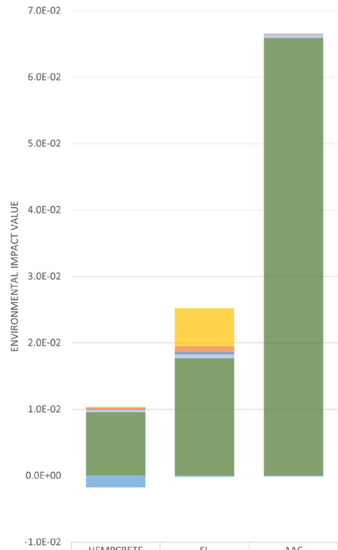
	HEMPCRETE	SL	AAC
D	-3.0E+00	-1.2E-01	-3.4E-01
C4	2.4E-01	2.0E+00	1.9E-02
C3	1.4E-01	0.0E+00	1.6E-01
C2	3.1E-01	2.1E-01	2.0E-01
C1	9.4E-02	8.3E-02	1.5E-01
B1	-2.5E+00	-6.2E+00	0.0E+00
A5	9.0E-01	4.0E-01	1.3E+00
A1-A3	8.9E+00	1.9E+01	1.9E+01

GWP - BIOGENIC
COMPARISON OF THE ENVIRONMENTAL IMPACT OF 1 UF OF SEPARATION WALLS (KG CO2EQ/UF)



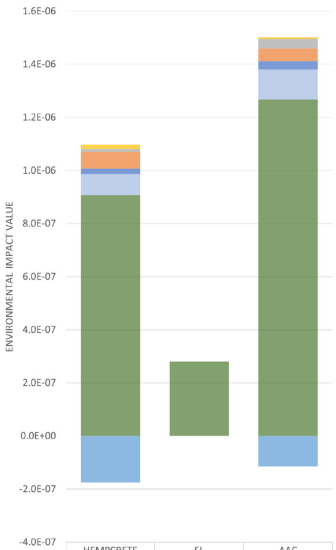
	HEMPCRETE	SL	AAC
D	2.0E+00	-4.3E-04	-6.1E-04
C4	9.9E+00	-1.6E-01	3.7E-05
C3	5.0E+00	0.0E+00	4.5E-05
C2	2.6E-04	8.6E-05	1.5E-04
C1	4.1E-05	-3.5E-03	4.1E-05
B1	0.0E+00	0.0E+00	0.0E+00
A5	5.6E-01	-1.0E-03	8.0E-01
A1-A3	-1.8E+01	3.1E-03	-1.2E-01

GWP - LULUC
COMPARISON OF THE ENVIRONMENTAL IMPACT OF 1 UF OF SEPARATION WALLS (KG CO2EQ/UF)



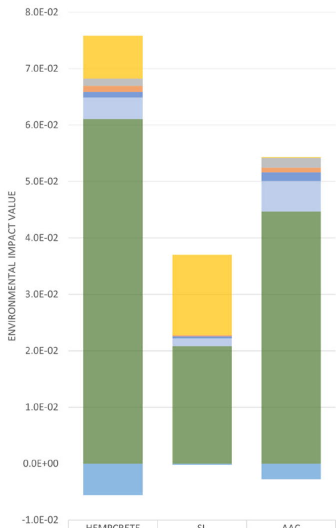
	HEMPCRETE	SL	AAC
D	-1.8E-03	-1.5E-04	-1.3E-04
C4	3.9E-05	5.7E-03	5.5E-06
C3	3.5E-05	0.0E+00	1.4E-05
C2	3.0E-04	8.9E-04	6.0E-05
C1	1.5E-05	3.3E-04	1.2E-05
B1	0.0E+00	0.0E+00	0.0E+00
A5	3.6E-04	5.9E-04	5.2E-04
A1-A3	9.6E-03	1.8E-02	6.6E-02

ODP
COMPARISON OF THE ENVIRONMENTAL IMPACT OF 1 UF OF SEPARATION WALLS (KG CFC 11 EQ/UF)



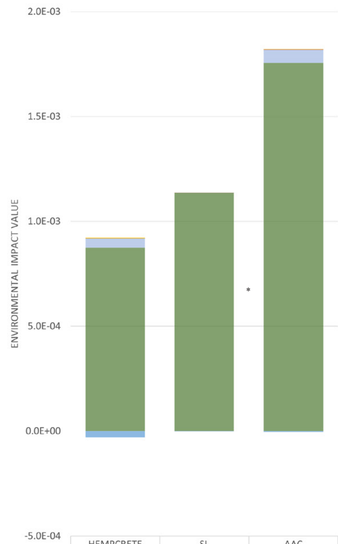
	HEMPCRETE	SL	AAC
D	-1.7E-07	-1.7E-15	-1.1E-07
C4	1.6E-08	7.4E-15	7.7E-09
C3	1.2E-08	0.0E+00	3.5E-08
C2	6.3E-08	5.2E-17	4.7E-08
C1	2.1E-08	2.0E-17	3.1E-08
B1	0.0E+00	0.0E+00	0.0E+00
A5	7.9E-08	1.6E-16	1.1E-07
A1-A3	9.1E-07	2.8E-07	1.3E-06

AP
COMPARISON OF THE ENVIRONMENTAL IMPACT OF 1 UF OF SEPARATION WALLS (MOL H+EQ/UF)



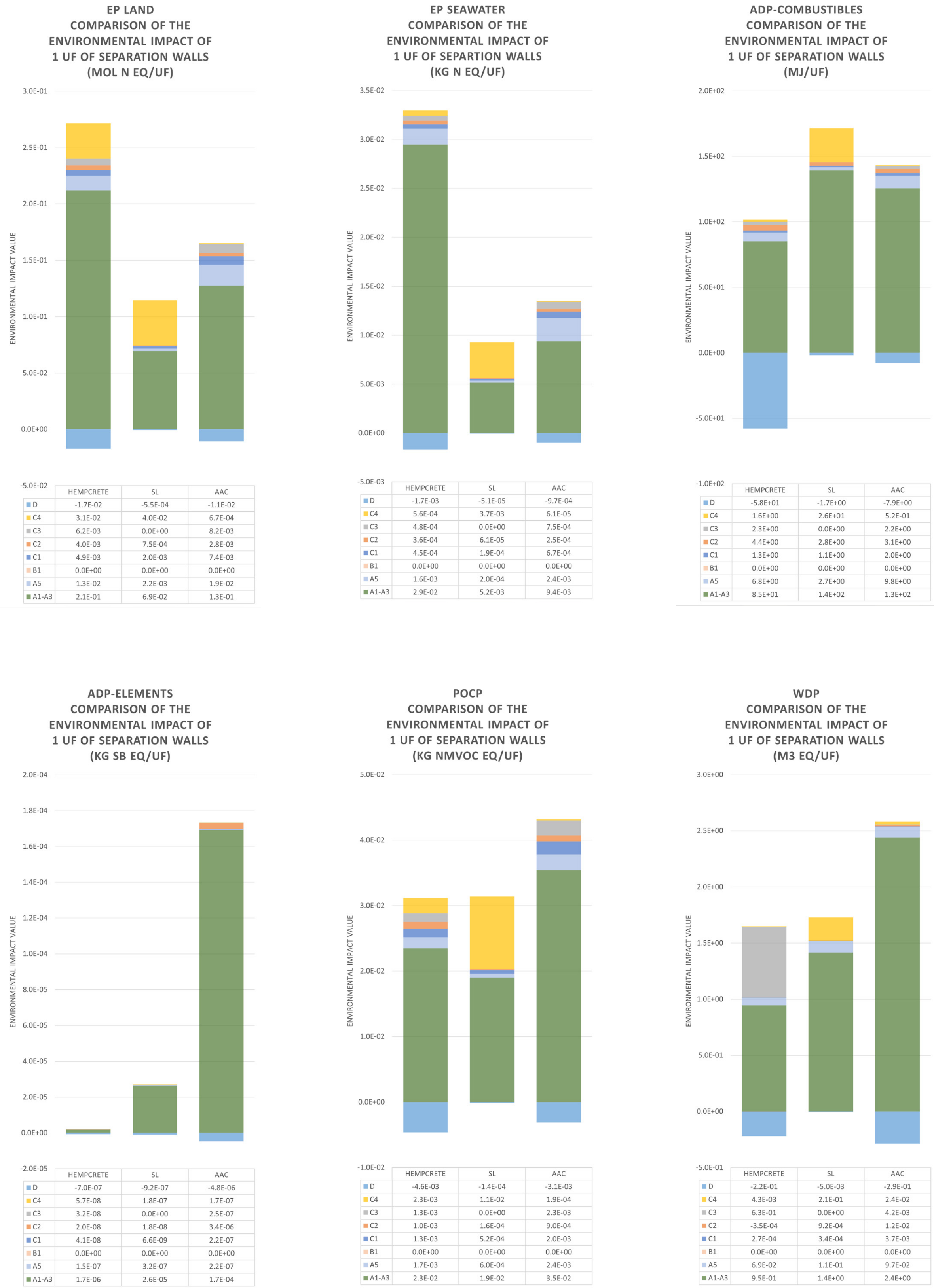
	HEMPCRETE	SL	AAC
D	-5.6E-03	-2.5E-04	-2.8E-03
C4	7.6E-03	1.4E-02	1.8E-04
C3	1.3E-03	0.0E+00	1.7E-03
C2	1.1E-03	2.0E-04	8.4E-04
C1	1.0E-03	3.9E-04	1.5E-03
B1	0.0E+00	0.0E+00	0.0E+00
A5	3.8E-03	1.4E-03	5.4E-03
A1-A3	6.1E-02	2.1E-02	4.5E-02

EP FRESHWATER
COMPARISON OF THE ENVIRONMENTAL IMPACT OF 1 UF OF SEPARATION WALLS (KG P EQ/UF)



	HEMPCRETE	SL	AAC
D	-2.9E-05	-2.5E-07	-4.4E-06
C4	3.6E-06	3.4E-16	2.2E-07
C3	2.7E-07	0.0E+00	6.6E-07
C2	3.2E-07	4.6E-07	1.6E-06
C1	7.9E-08	1.7E-07	5.9E-07
B1	0.0E+00	0.0E+00	0.0E+00
A5	4.3E-05	3.2E-07	6.2E-05
A1-A3	8.7E-04	1.1E-03	1.8E-03

Figure A.26: The environmental impact of 1 UF of separation wall - Comparison between the assemblies under scrutiny.



EP LAND (MOL N EQ/UF)

	HEMPCRETE	SL	AAC
D	-1.7E-02	-5.5E-04	-1.1E-02
C4	3.1E-02	4.0E-02	6.7E-04
C3	6.2E-03	0.0E+00	8.2E-03
C2	4.0E-03	7.5E-04	2.8E-03
C1	4.9E-03	2.0E-03	7.4E-03
B1	0.0E+00	0.0E+00	0.0E+00
A5	1.3E-02	2.2E-03	1.9E-02
A1-A3	2.1E-01	6.9E-02	1.3E-01

EP SEAWATER (KG N EQ/UF)

	HEMPCRETE	SL	AAC
D	-1.7E-03	-5.1E-05	-9.7E-04
C4	5.6E-04	3.7E-03	6.1E-05
C3	4.8E-04	0.0E+00	7.5E-04
C2	3.6E-04	6.1E-05	2.5E-04
C1	4.5E-04	1.9E-04	6.7E-04
B1	0.0E+00	0.0E+00	0.0E+00
A5	1.6E-03	2.0E-04	2.4E-03
A1-A3	2.9E-02	5.2E-03	9.4E-03

ADP-COMBUSTIBLES (MJ/UF)

	HEMPCRETE	SL	AAC
D	-5.8E+01	-1.7E+00	-7.9E+00
C4	1.6E+00	2.6E+01	5.2E-01
C3	2.3E+00	0.0E+00	2.2E+00
C2	4.4E+00	2.8E+00	3.1E+00
C1	1.3E+00	1.1E+00	2.0E+00
B1	0.0E+00	0.0E+00	0.0E+00
A5	6.8E+00	2.7E+00	9.8E+00
A1-A3	8.5E+01	1.4E+02	1.3E+02

ADP-ELEMENTS (KG SB EQ/UF)

	HEMPCRETE	SL	AAC
D	-7.0E-07	-9.2E-07	-4.8E-06
C4	5.7E-08	1.8E-07	1.7E-07
C3	3.2E-08	0.0E+00	2.5E-07
C2	2.0E-08	1.8E-08	3.4E-06
C1	4.1E-08	6.6E-09	2.2E-07
B1	0.0E+00	0.0E+00	0.0E+00
A5	1.5E-07	3.2E-07	2.2E-07
A1-A3	1.7E-06	2.6E-05	1.7E-04

POCP (KG NMVOC EQ/UF)

	HEMPCRETE	SL	AAC
D	-4.6E-03	-1.4E-04	-3.1E-03
C4	2.3E-03	1.1E-02	1.9E-04
C3	1.3E-03	0.0E+00	2.3E-03
C2	1.0E-03	1.6E-04	9.0E-04
C1	1.3E-03	5.2E-04	2.0E-03
B1	0.0E+00	0.0E+00	0.0E+00
A5	1.7E-03	6.0E-04	2.4E-03
A1-A3	2.3E-02	1.9E-02	3.5E-02

WDP (M3 EQ/UF)

	HEMPCRETE	SL	AAC
D	-2.2E-01	-5.0E-03	-2.9E-01
C4	4.3E-03	2.1E-01	2.4E-02
C3	6.3E-01	0.0E+00	4.2E-03
C2	-3.5E-04	9.2E-04	1.2E-02
C1	2.7E-04	3.4E-04	3.7E-03
B1	0.0E+00	0.0E+00	0.0E+00
A5	6.9E-02	1.1E-01	9.7E-02
A1-A3	9.5E-01	1.4E+00	2.4E+00

Figure A.27: The environmental impact of 1 UF of separation wall - Comparison between the assemblies under scrutiny.

Impact category		cost per eq. (€)	Hempcrete	SL	AAC	
GWP Fossil	(kg CO2 eq/UF)	0.05	2.55 E-01	7.66 E-01	1.00 E+00	
GWP Bio-genic	(kg CO2 eq/UF)	0.05	-6.77 E-04	-7.92E-03	3.38 E-02	
GWP luluc	(kg CO2 eq/UF)	0.05	4.27 E-04	1.25 E-03	3.32E-03	
ODP	(kg CFC11 eq/UF)	30.0	2.77 E-05	8.42 E-06	4.16 E-05	
AP	(mol H+eq/UF)	4.0	3.79 E-01	1.98 E-01	2.78 E-01	
EP Fresh water	(kg P eq/UF)	1.90	1.70 E-03	2.16 E-03	3.45 E-03	
EP Sea water	(kg N eq/UF)	3.11	9.72 E-02	2.86 E-02	3.89 E-02	
EP Land	(mol N eq/UF)	0.04	1.11 E-02	4.97 E-03	6.73 E-03	
POCP	(kg NMVOC eq/UF)	2.0	5.56 E-02	6.56 E-02	8.42 E-02	
ADP Ele-ments	(kg Sb eq/UF)	0.16	2.07 E-07	4.17 E-06	2.70 E-05	
ADP Fossils	(MJ/UF)	7.70E-05	3.36 E-03	1.32 E-02	1.04 E-02	
WDP	(m3 water/UF)	1 E-04	1.43 E-04	1.72 E-04	2.30 E-04	
Total		(€)	8.03 E-01	1.07 E+00	1.46 E+00	(incl. WDP)

*conversion: 1 mol N =0.014 kg N

** conversion: MJ/UF x 4.81E-04 = kg Sb-eq

Table A.2: The final environmental costs per UF of separation walls

Hempcrete		Envir. Impact per type of walls and category			Sum
		Façade	Separation	Load bearing	
GWP-Fossil	kg CO2eq/UF	3.50E+03	1.57E+02	-2.96E+01	3.62E+03
GWP-Biogeneic	kg CO2eq/UF	-8.57E+00	-4.18E-01	-1.44E+00	-1.04E+01
GWP-Luluc	kg CO2eq/UF	5.27E+00	2.63E-01	1.20E+00	6.73E+00
ODP	kg CFC 11 eq/UF	6.03E-04	2.84E-05	5.70E-05	6.88E-04
AP	mol H+eq/UF	4.61E+01	2.16E+00	3.90E+00	5.22E+01
EP-Freshwater	kg P eq/UF	5.83E-01	2.75E-02	5.62E-02	6.67E-01
Ep-Seawater	kg N eq/UF	2.05E+01	9.64E-01	1.80E+00	2.33E+01
EP-land	mol N eq/UF	1.67E+02	7.84E+00	1.49E+01	1.89E+02
POCP	kg NMVOC eq/UF	1.72E+01	8.17E-01	1.79E+00	1.99E+01
ADP-Elements	kg Sb eq/UF	8.43E-04	3.98E-05	8.35E-05	9.67E-04
ADP -Comb.& f.f.	MJ/UF	3.13E+04	1.34E+03	-3.11E+03	2.95E+04
WDP	Prev. water in m3/UF	8.77E+02	4.41E+01	2.10E+02	1.13E+03

Hempcrete		Cost (€)	Total (€)	
GWP-Fossil	kg CO2eq/UF	0.05	1.81E+02	
GWP-Biogeneic	kg CO2eq/UF	0.05	-5.21E-01	
GWP-Luluc	kg CO2eq/UF	0.05	3.36E-01	
ODP	kg CFC 11 eq/UF	30.00	2.06E-02	
AP	mol H+eq/UF	4.00	2.09E+02	
EP-Freshwater	kg P eq/UF	1.90	1.27E+00	5.14E+02
Ep-Seawater	kg N eq/UF	3.11	7.23E+01	
EP-land	mol N eq/UF	0.04	8.25E+00	
POCP	kg NMVOC eq/UF	2.00	3.97E+01	
ADP-Elements	kg Sb eq/UF	0.16	1.55E-04	
ADP -Comb.& f.f.	MJ/UF	7.70E-05	2.27E+00	
WDP	Prev. water in m3/UF	1.00E-04	1.13E-01	

AAC		Envir. Impact per type of walls and category			Sum
		Façade	Separation	Load bearing	
GWP-Fossil	kg CO2eq/UF	1.34E+04	5.95E+02	1.28E+03	1.53E+04
GWP-Biogeneic	kg CO2eq/UF	4.53E+02	2.01E+01	4.32E+01	5.16E+02
GWP-Luluc	kg CO2eq/UF	4.44E+01	1.97E+00	4.24E+00	5.06E+01
ODP	kg CFC 11 eq/UF	9.30E-04	4.12E-05	8.86E-05	1.06E-03
AP	mol H+eq/UF	3.45E+01	1.53E+00	3.29E+00	3.93E+01
EP-Freshwater	kg P eq/UF	1.22E+00	5.40E-02	1.16E-01	1.39E+00
Ep-Seawater	kg N eq/UF	8.37E+00	3.71E-01	7.98E-01	9.54E+00
EP-land	mol N eq/UF	1.03E+02	4.59E+00	9.87E+00	1.18E+02
POCP	kg NMVOC eq/UF	2.68E+01	1.19E+00	2.56E+00	3.06E+01
ADP-Elements	kg Sb eq/UF	1.13E-01	5.01E-03	1.08E-02	1.29E-01
ADP -Comb.& f.f.	MJ/UF	9.06E+04	4.01E+03	8.63E+03	1.03E+05
WDP	Prev. water in m3/UF	1.54E+03	6.81E+01	1.47E+02	1.75E+03

AAC		Cost (€)	Total (€)	
GWP-Fossil	kg CO2eq/UF	0.05	7.65E+02	
GWP-Biogeneic	kg CO2eq/UF	0.05	2.58E+01	
GWP-Luluc	kg CO2eq/UF	0.05	2.53E+00	
ODP	kg CFC 11 eq/UF	30.00	3.18E-02	
AP	mol H+eq/UF	4.00	1.57E+02	
EP-Freshwater	kg P eq/UF	1.90	2.64E+00	1.06E+03
Ep-Seawater	kg N eq/UF	3.11	2.97E+01	
EP-land	mol N eq/UF	0.04	5.14E+00	
POCP	kg NMVOC eq/UF	2.00	6.12E+01	
ADP-Elements	kg Sb eq/UF	0.16	2.06E-02	
ADP -Comb.& f.f.	MJ/UF	7.70E-05	7.94E+00	
WDP	Prev. water in m3/UF	1.00E-04	1.75E-01	

SL		Envir. Impact per type of walls and category			Sum
		Façade	Separation	Load bearing	
GWP-Fossil	kg CO2eq/UF	6.24E+03	4.99E+02	1.42E+03	8.16E+03
GWP-Biogeneic	kg CO2eq/UF	1.10E+02	-5.16E+00	-1.47E+01	9.00E+01
GWP-Luluc	kg CO2eq/UF	8.77E+00	8.16E-01	2.33E+00	1.19E+01
ODP	kg CFC 11 eq/UF	1.95E-04	9.15E-06	2.61E-05	2.30E-04
AP	mol H+eq/UF	2.23E+01	1.20E+00	3.42E+00	2.69E+01
EP-Freshwater	kg P eq/UF	3.40E-01	3.70E-02	1.06E-01	4.82E-01
EP-Freshwater	kg P04 eq/UF	4.57E-02	0.00E+00	0.00E+00	4.57E-02
Ep-Seawater	kg N eq/UF	3.84E+00	3.00E-01	8.56E-01	5.00E+00
EP-land	mol N eq/UF	7.71E+01	3.72E+00	1.06E+01	9.14E+01
POCP	kg NMVOC eq/UF	1.38E+01	1.02E+00	2.90E+00	1.77E+01
ADP-Elements	kg Sb eq/UF	1.06E-02	8.49E-04	2.42E-03	1.38E-02
ADP -Comb.& f.f.	MJ/UF	7.40E+04	5.54E+03	1.58E+04	9.54E+04
WDP	Prev. water in m3/UF	1.26E+06	5.62E+01	1.60E+02	1.26E+06

SL		Cost (€)	Total (€)	
GWP-Fossil	kg CO2eq/UF	0.05	4.08E+02	
GWP-Biogeneic	kg CO2eq/UF	0.05	4.50E+00	
GWP-Luluc	kg CO2eq/UF	0.05	5.96E-01	
ODP	kg CFC 11 eq/UF	30.00	6.91E-03	
AP	mol H+eq/UF	4.00	1.08E+02	
EP-Freshwater	kg P eq/UF	1.90	9.17E-01	
EP-Freshwater	kg P04 eq/UF	9.00	4.11E-01	7.10E+02
Ep-Seawater	kg N eq/UF	3.11	1.55E+01	
EP-land	mol N eq/UF	0.04	3.98E+00	
POCP	kg NMVOC eq/UF	2.00	3.54E+01	
ADP-Elements	kg Sb eq/UF	0.16	2.22E-03	
ADP -Comb.& f.f.	MJ/UF	7.70E-05	7.34E+00	
WDP	Prev. water in m3/UF	1.00E-04	1.26E+02	

Figure A.28: Total environmental costs per design

In order to have a broader image on what influences the differences in the emissions between the three design options, the main aspects of the life cycle stages which were taken into account for each material are presented below.

The EPD of the hempcrete blocks.

The EPD of the hempcrete blocks which was used, accounts for a hempcrete wall section with a service life of 60 years, made of hempcrete blocks -30cm (height) * 60 cm (lenght) and adhesive mortar -3mm thickness- capable to provide a thermal resistance of around 5 m^2*K/W. Hempcrete blocks with the same width and length (30 * 60 cm) but a different thickness are assumed to be used for the case study, as a result the change in the environmental emissions is regarded as proportional to the change in the thickness of the block.

- *A1 + A2 + A3 (Raw material supply, Transport and Manufacturing) :*
  These stages include the emissions related to the production, extraction, transformation and transportation of the raw materials to the manufacturing site and those related to the manufacturing of the blocks. Blocks with defects are re-used either by re-incorporating them in the mixture or by storing to be used as a different product. Then the blocks are stored to dry naturally and acquire the required strength, at this

stage carbonisation happens. Packaging is also accounted in this stage.

- *A5 - Construction installation:*
  This stage accounts for the installation of the blocks at the construction site. It includes the processes needed for the mixing of the dry adhesive mortar with water at the construction site. A percentage of material losses is also taken into account in this stage as well as the environmental influence of the products' packaging related to the blocks and the mortar that are unpacked to the site. The calculation also includes the direct emissions related to the decomposition of the hemp shives that are spread to the site. The waste treatment which is required after the construction, is divided into landfilling, incineration, re-use and recycling according to the waste type. The emissions related to these procedure and to the transportation distances from the site to the waste treatment center are included in the calculation.

- *B - Use stage:*
  This stage takes into account the emissions that take place during the use life of the hempcrete wall. No maintenance, water use or energy is required during the lifetime of the wall. The carbonisation of the lime which is present in the blocks and the adhesive mortar is taken into account in stage B1.

- *C1 - Deconstruction - Demolition:*
  The demolition of the blocks is considered to co-occur with the demolition of the building. The emissions of fine particles and the amount of the diesel consumption by the demolition machines are considered in this stage.

- *C2 - Transport:*
  This stage accounts for the emissions related to the transportation of the waste from the construction site to the waste treatment center.

- *C3 - Waste processing:*
  The products are considered to be sorted and crushed.

- *C4 - Disposal:*
  After their life time the materials are considered to be 100% land-filled with inert materials. A partial degradation 15% of the shiv is considered to take place, so 15% of mass content is emitted into the air, half in the form of CO_2 and half in the form of methane. The decomposition of the organic waste is captured in the co-generation unit and burned there, in this process 30% of methane is assumed to escape towards the atmosphere and the rest 70% to be converted to electricity and heat.

- *D - Reuse -Recovery -Recycling-potential:*
  At this stage the benefits beyond the systems boundaries are taken into account. This benefits are related to the re-use, recycling, and energy recovering of the packaging

during A1 and the combustion of methane from the hemp from the installation waste (A5) or the disposal (C4).

The EPD of the sawn spruce timber

For the calculation of the environmental emissions related to the timber usage, an EPD of sawn timber products spruce and pine wood was used. The declared unit of the relevant EPD is 1 m^3 of sawn dried timber (17% moisture content).

The EPD includes the modules A1-A3, C, D and the additional modules. Module B has been excluded from the system because due to the numerous applications of the sawn timber in the building construction, a default scenario for end-use is not possible to be declared.

- *A1 - Raw material supply:*
  This stage accounts for the environmental impact of the timber product during the wood supply. It takes into account the processes of seedling nursery, site preparation, foresting and harvesting. The production of energy that is used for the manufacturing of the product (A3) is also included in this module.

- *A2 - Transport:*
  This stage accounts for the transportation of the timber logs to the sawmills.

- *A3 - Manufacturing:*
  This stage accounts for the debarking and sawing of logs. During this stage multiple co-products are produced. Heat and electricity is used for the treatment of the timber, however these resources have already been included in stage A1. The impact of packaging that does not leave the sawmills is included in this stage.

- *A5 - Construction installation:*
  This stage accounts for the installation of the material. In this stage only the environmental effects of the packaging of the material are taken into account. Due to the various uses of the product not a specific end use scenario could be defined. Plastic packaging waste is led to energy recovery and steel to material waste recovery.

- *C1 - Deconstruction - Demolition:*
  In this stage, the environmental impacts related to the production and combustion of diesel fuel by an construction excavator for the deconstruction and demolition are considered.

- *C2 - Transport:*
  In this stage, the environmental impacts related to the transport of the timber after its demolition to the treatment plant are considered.

- *C3 - Waste processing:*
  Incineration with energy recovery is considered in this stage. Due to the multiple ways of use of the material, material re-use was considered quite uncertain to be assumed. Due to the EU ban related to the landfill of organic waste, landfill disposal was not considered.

- *C4 - Disposal:*
  Due to aforementioned, no environmental emissions were assumed in this stage.

- *D - Reuse -Recovery -Recycling-potential:*
  The benefits for energy (related to packaging and incineration of timber) and material recovery (packaging) for the processes done in stages A3, A5 and C3.

The EPD of the autoclaved aerated blocks

This EPD accounts for different aerated autoclaved block products. A5 was an optional stage and was not taken into account in the EPD. Their environmental emissions are taken into account by estimating the mean values of emissions in products with a similar density. The products that can cover the required needs for the current case study (external loadbearing bricks with a thermal conductivity of 0.10 W/mK and internal blocks with an acoustic insulation of 37 dB) belong to the same density group and therefore have similar emissions.

- *A1 + A2 + A3 (Raw material supply, Transport and Manufacturing) :*
  This stage accounts for the environmental impact of the blocks during the supply, the transport to the manufacturing place and the manufacturing. It takes into account the electricity use during the manufacturing too. The packaging includes plastic sheets and wooden pallets.

- *B - Use stage:*
  This stage is not taken into account in the EPD. The carbonisation of concrete during its use stage is not taken into account in the calculations.

- *C1 - Deconstruction - Demolition:*
  In this stage an average consumption for demolition was considered.

- *C2, C3,C4 (Transport, Waste processing and disposal):*
  No mass loss is assumed in this stage. The total amount of the product mass which was used is assumed to be transported to the closest waste management facilities (recycling and land-filling). It is assumed that the vast majority (higher than 90%) of the product is recycled into raw materials. The rest material that has not be recycled is sent for disposal in local facilities.

- *D - Reuse -Recovery -Recycling-potential:*
  It considers the recycled raw materials.

The EPD of the Sand-lime bricks

The EPD used accounted for a sand lime brick product with a density of 1800 kg/m^3. The thermal resistance range which was stated in the EPD included the value of the thermal resistance of the product which was used in the WUFI simulations. The unit factor of the EPD was in mass terms. Therefore, multiplying by the density was required to deliver the unit factor in terms of volume. Sand lime bricks can be fully recyclable however to date hardly any walls made of sand-lime bricks have been recycled. Two different scenarios have been considered in the EPD. However, due to the absence of recycling of SL in practice, the scenario with the deposition will be considered.

- *A1 + A2 + A3 (Raw material supply, Transport and Manufacturing) :*
  In this stage all the required processes for the supply, transportation to the manufacturing site and the manufacturing of the material were included. As packaging material, wooden pallets, plastic and still straps and recycled polyethylene film was considered. The waste management processes were considered as land filling.

- *A5 (Construction installation):*
  This stage includes the installation to the construction site. The waste treatment of the packaging materials with incineration was considered.

- *B - Use stage:*
  The carbonisation of the lime is considered in this stage. No other processes are required during the use phase of the bricks.

- *C1 - Deconstruction - Demolition:*
  An excavator is considered in this stage.

- *C2, C3,C4 (Transport, Waste processing and disposal):*
  This thesis will cope with the scenario of disposal.

- *D - Reuse -Recovery -Recycling-potential:*
  The credits for the recycling of the packaging are considered in this stage.

The EPD of the FG Insulation

The EPD used accounted for glass wool insulation board with a thermal conductivity range that includes the values of the insulation used in the current research (between 0.033-0.041 W/(mK).

- *A1 + A2 + A3 (Raw material supply, Transport and Manufacturing) :*

  In this stage the materials and energy that are required for the production of the FG boards are taken into account.

- *A5 (Construction installation):*
  The waste treatment of the packaging materials with incineration is considered. The FG boards are installed manually without requiring further effort.

- *B - Use stage:*
  Zero impacts are considered in this stage.

- *C1 - Deconstruction - Demolition:*
  The material is deconstructed without further effort and energy. Only particle emissions are considered in this stage.

- *C2, C3,C4 (Transport, Waste processing and disposal):*
  The impact of transportation. waste processing and disposal is taken into account in this stage. 100% of the material is assumed to be disposed in an inert fill land.

- *D - Reuse -Recovery -Recycling-potential:*
  The credits for the recycling of the packaging and of the energy mix are considered in this stage.

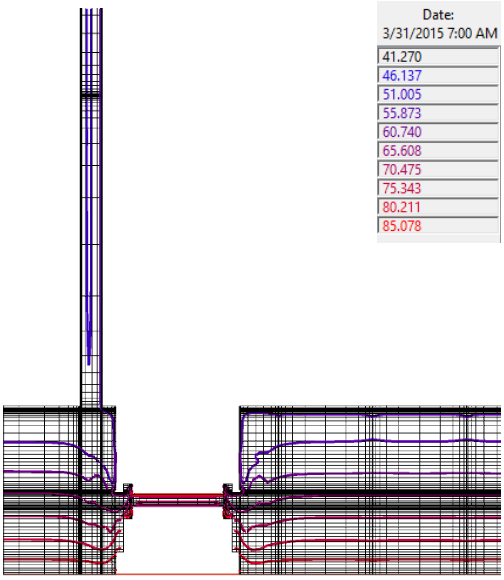
The EPD of the bedding mortar

The EPD of the hempcrete blocks included also the emissions which are related to the bed lime mortar of the wall. Therefore, to make a fair comparison between the wall assemblies, the emissions related to the thin bed mortar of the loadbearing masonry construction are also considered. For the brick connections in both sand-lime and AAC assemblies 3mm bonding joints are created. The mortar considered was of type M10. The influence of the mortar in the environmental emissions of the conventionally designed walls was estimated by creating a 3D representation of a wall assembly made of SL and AAC blocks with the same length and height as those of the hempcrete blocks, and a thin 3mm bonding mortar.

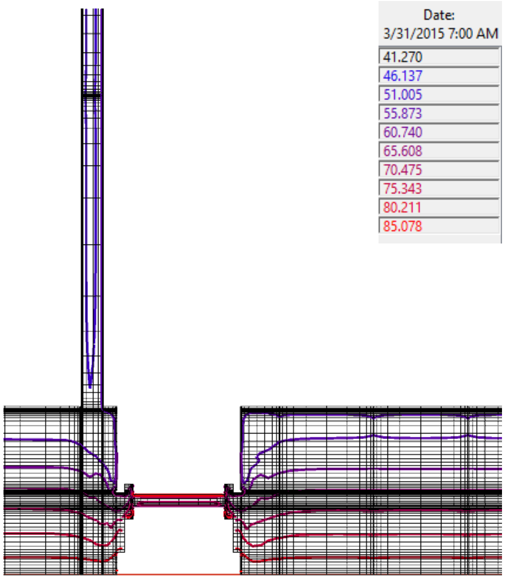
The EPD is of type D (Cradle to gate approach) so the influence of the mortar in the environmental impact of the wall assembly was only considered during the stages A1-A3. For the rest of the stages the impact is expected to be fractional and thus it was considered acceptable to not include it in the comparison.

- *A1 + A2 + A3 (Raw material supply, Transport and Manufacturing) :*
  The majority of the raw materials arrive without packaging, a small proportion arrives in paper packages. The impact of the packaging (manufacturing and transportation) which is intended for the final products storage and transportation has also been included. The latter includes wooden pallets, paper and Polyethylene films. No recycled materials are used as sources. The declared unit in the EPD is 1 kg of the mortar.

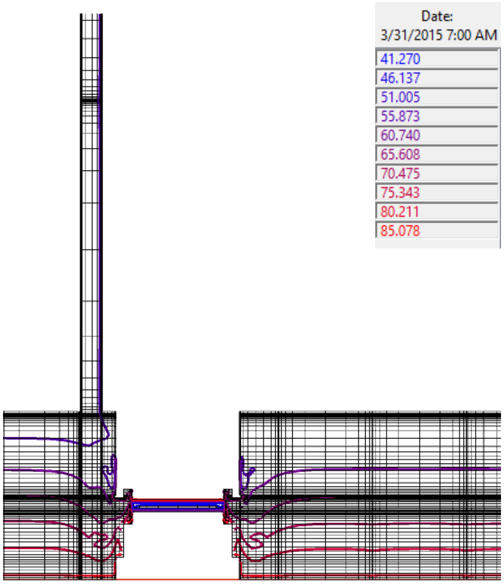
The four hempcrete options - 31/3/2015



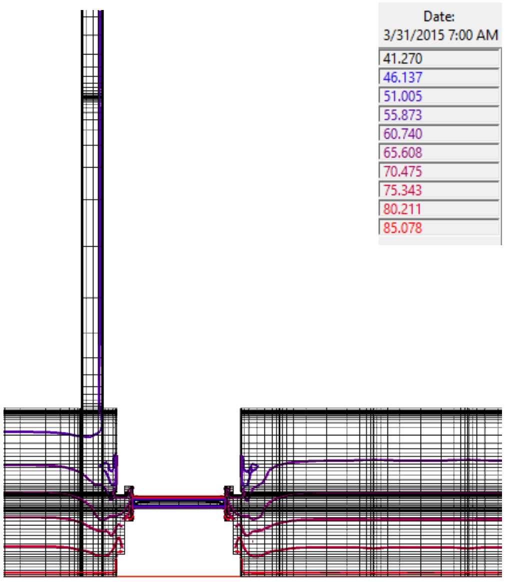
(a) Hempcrete 1



(b) Hempcrete 2

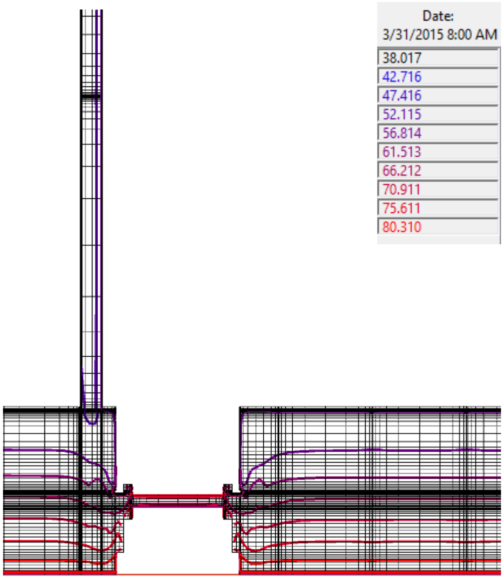


(c) Hempcrete 3

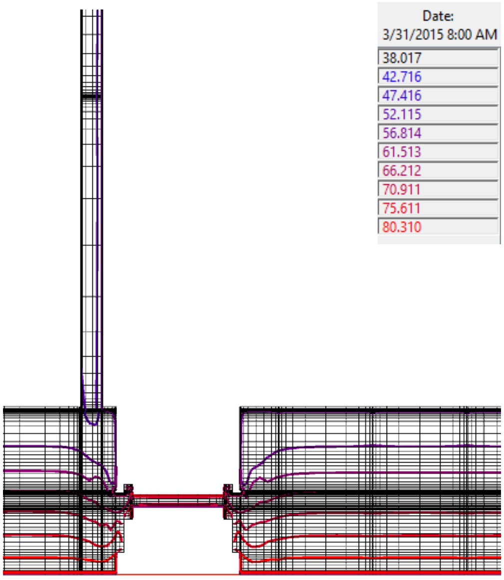


(d) Hempcrete 4

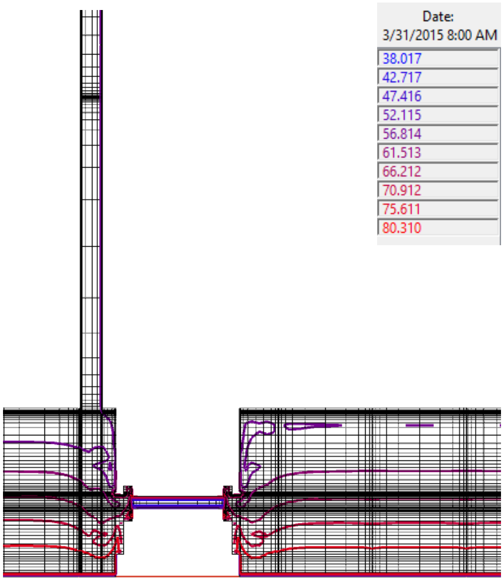
Figure A.29: Hempcrete behaviour - Date 31/3/2015 at 7:00.



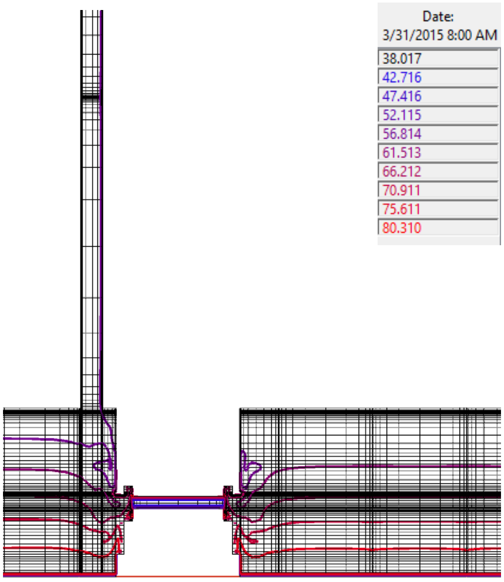
(a) Hempcrete 1



(b) Hempcrete 2

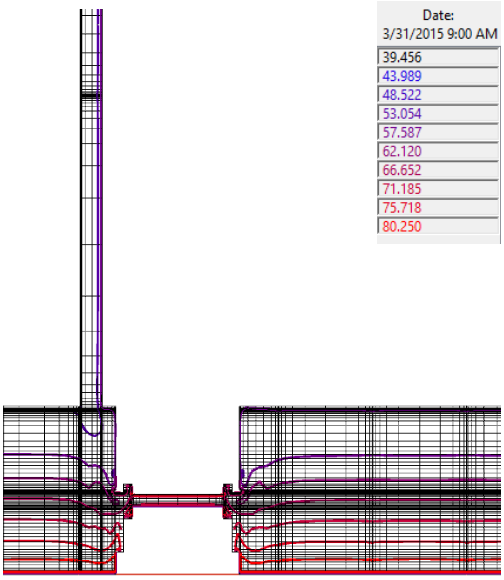


(c) Hempcrete 3

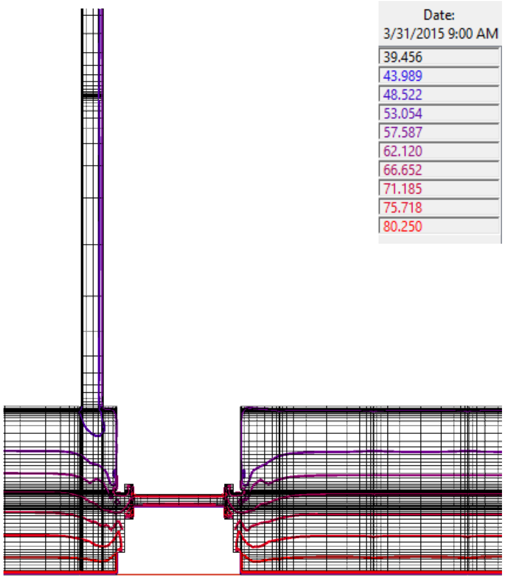


(d) Hempcrete 4

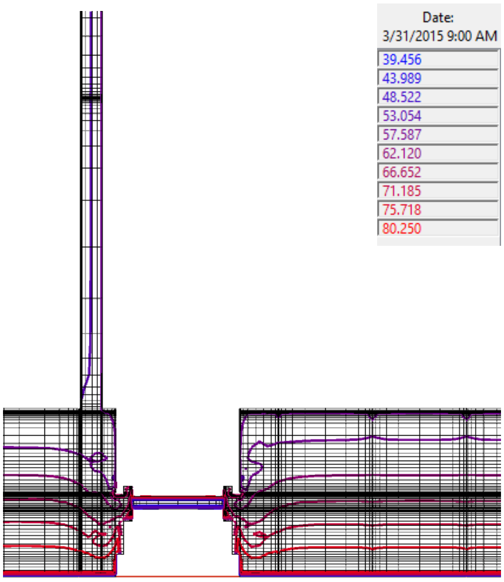
Figure A.30: Hempcrete behaviour - Date 31/3/2015 at 8:00.



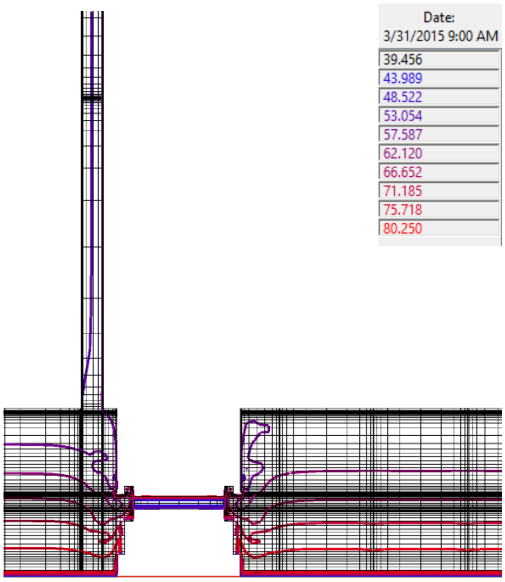
(a) Hempcrete 1



(b) Hempcrete 2

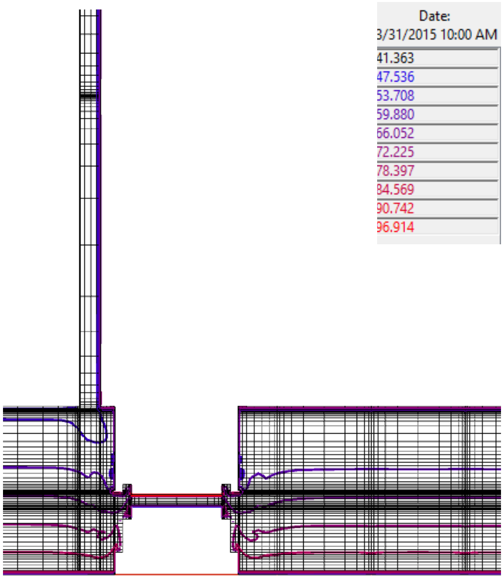


(c) Hempcrete 3

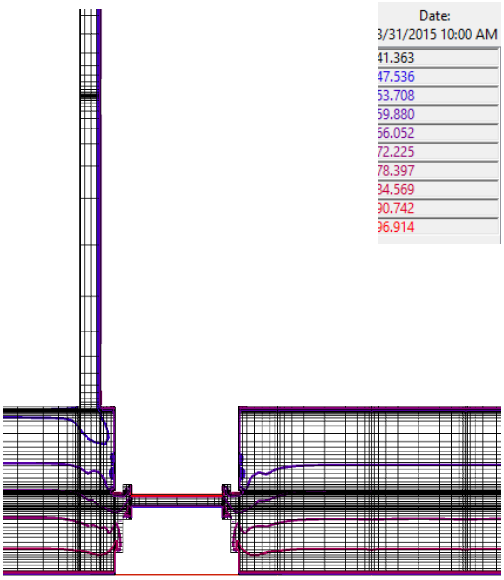


(d) Hempcrete 4

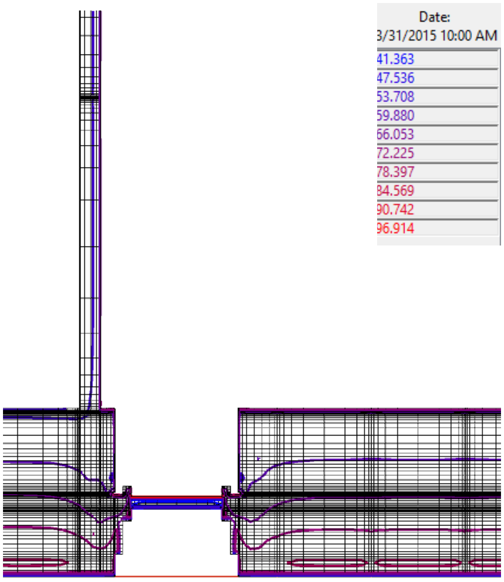
Figure A.31: Hempcrete behaviour - Date 31/3/2015 at 9:00.



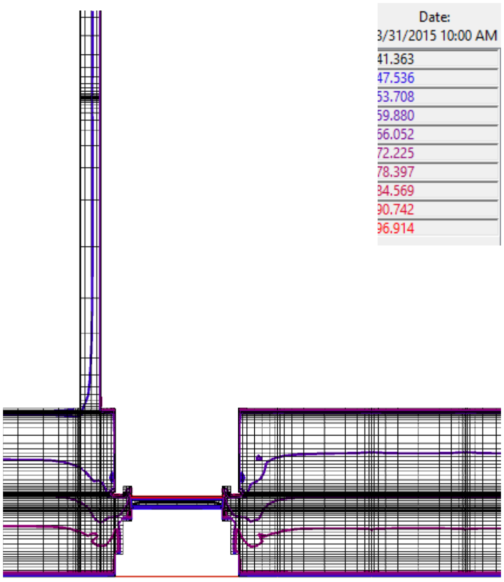
(a) Hempcrete 1



(b) Hempcrete 2

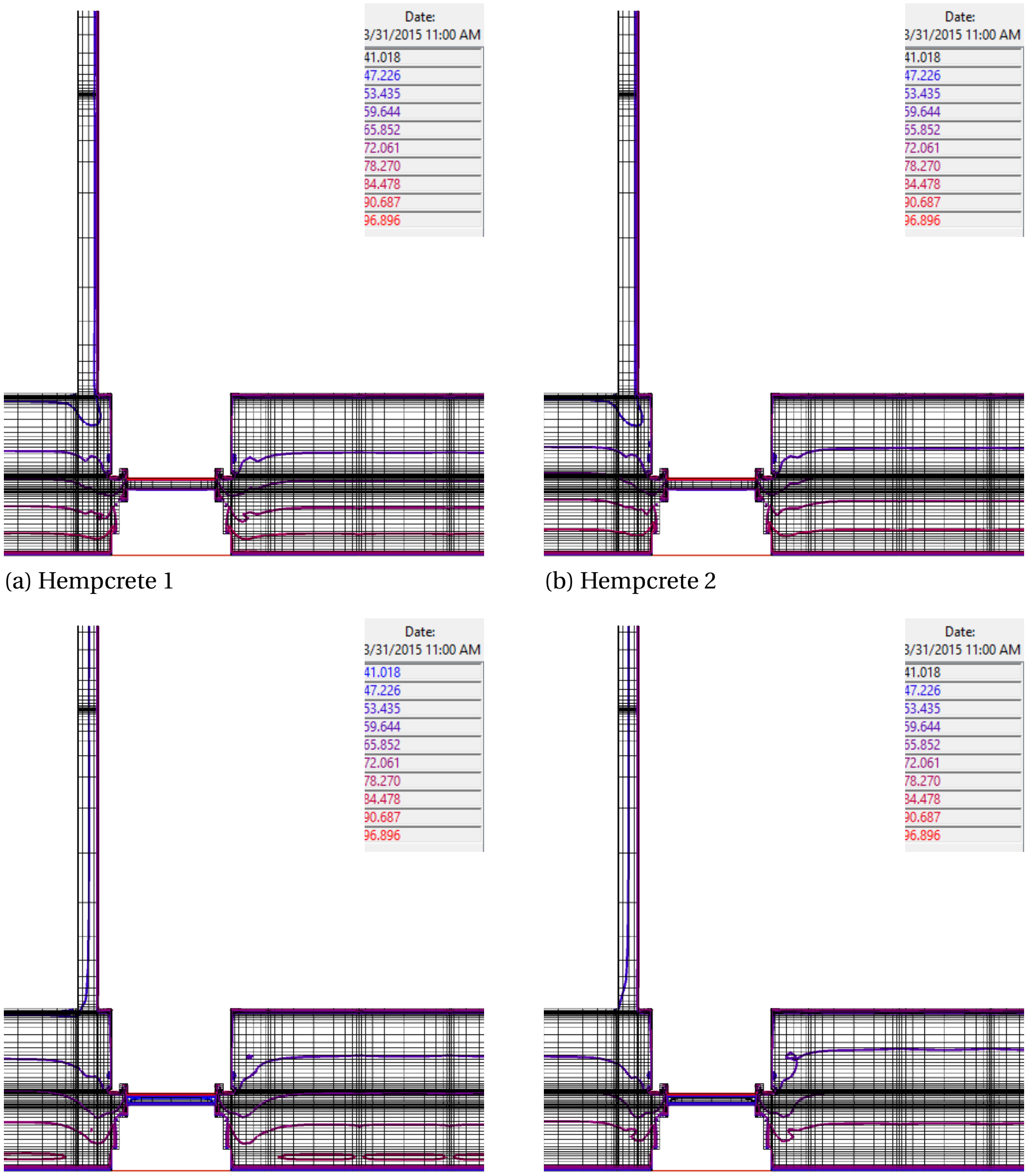


(c) Hempcrete 3



(d) Hempcrete 4

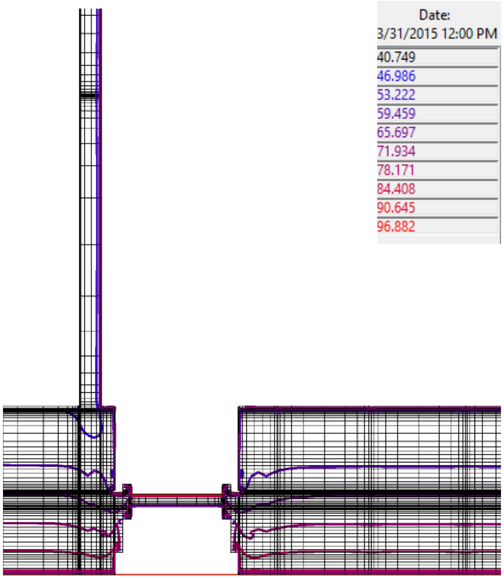
Figure A.32: Hempcrete behaviour - Date 31/3/2015 at 10:00.



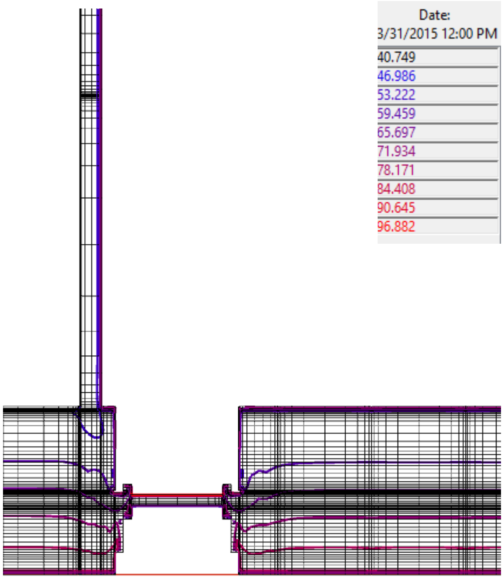
(a) Hempcrete 1 (b) Hempcrete 2

(c) Hempcrete 3 (d) Hempcrete 4

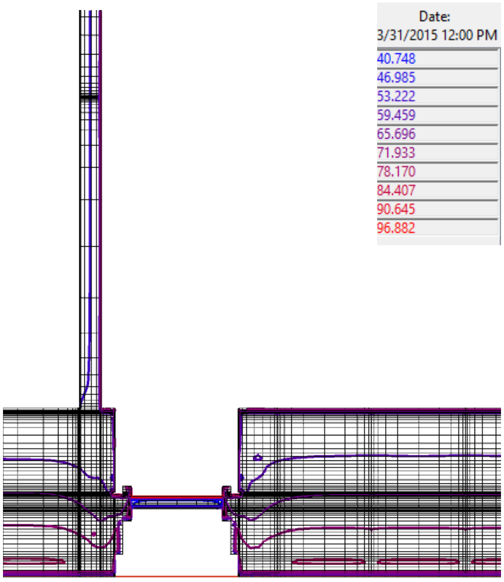
Figure A.33: Hempcrete behaviour - Date 31/3/2015 at 11:00.



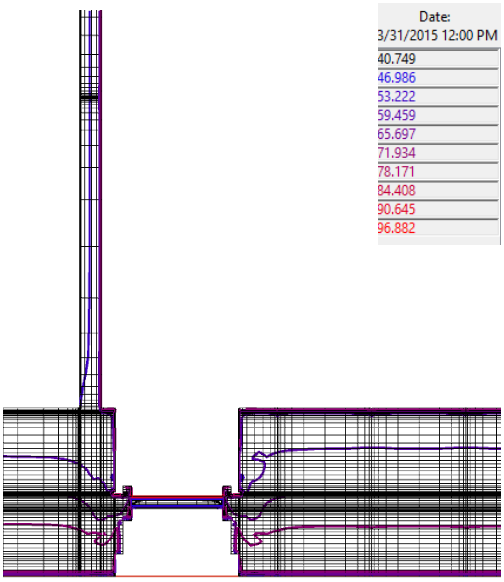
(a) Hempcrete 1



(b) Hempcrete 2



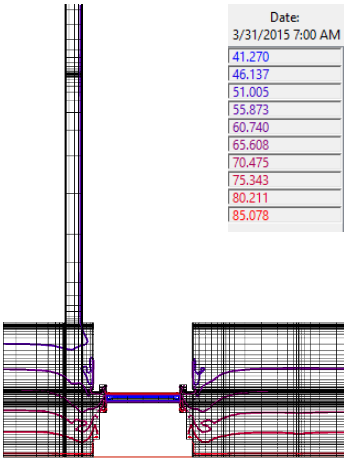
(c) Hempcrete 3



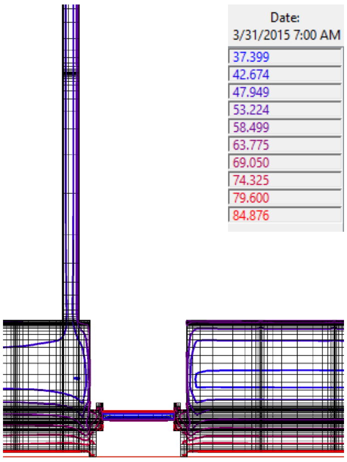
(d) Hempcrete 4

Figure A.34: Hempcrete behaviour - Date 31/3/2015 at 12:00.

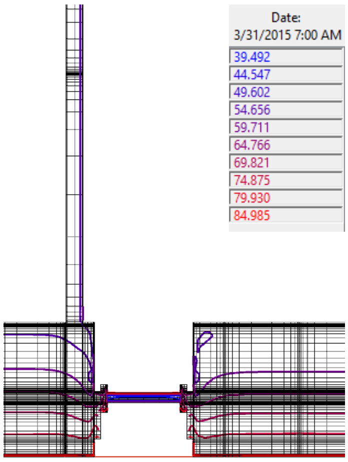
The different materials same thickness - 31/3/2015



(a) Hempcrete 3

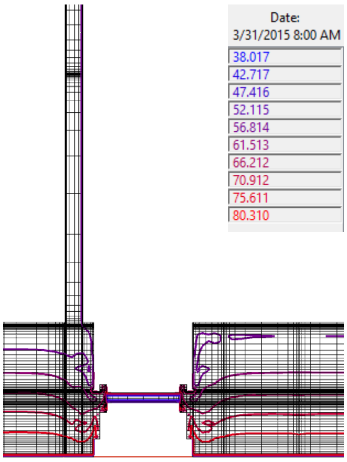


(b) Sand Lime Bricks

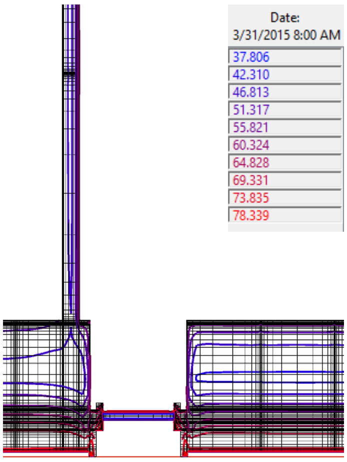


(c) AAC

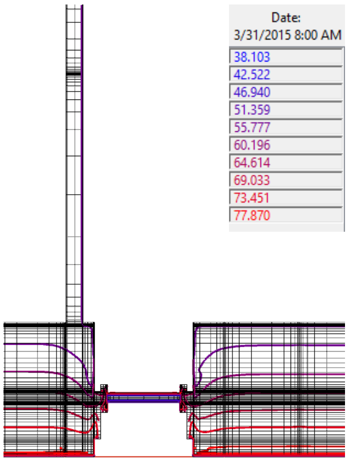
Figure A.35: Comparison between materials (Same thickness) - Date 31/3/2015 at 7:00.



(a) Hempcrete 3

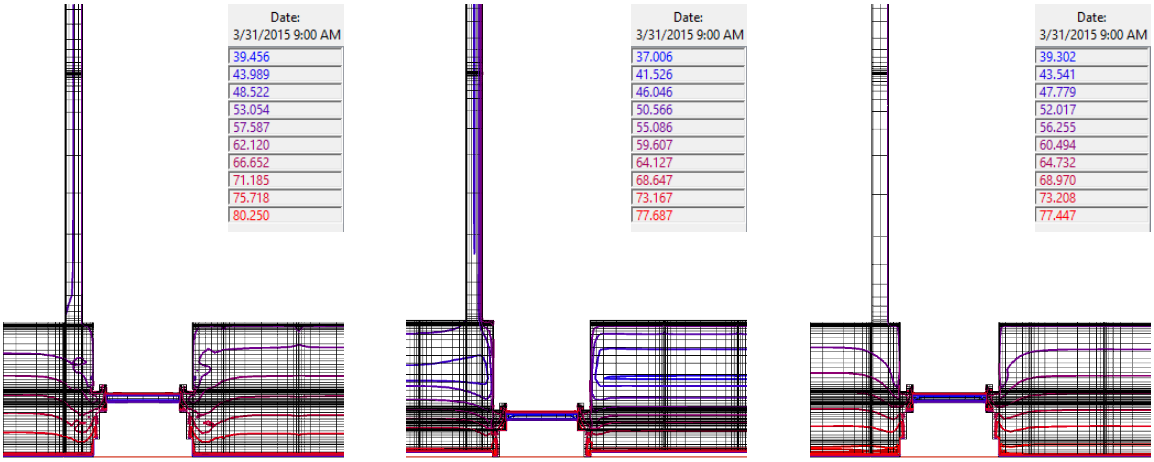


(b) Sand Lime Bricks



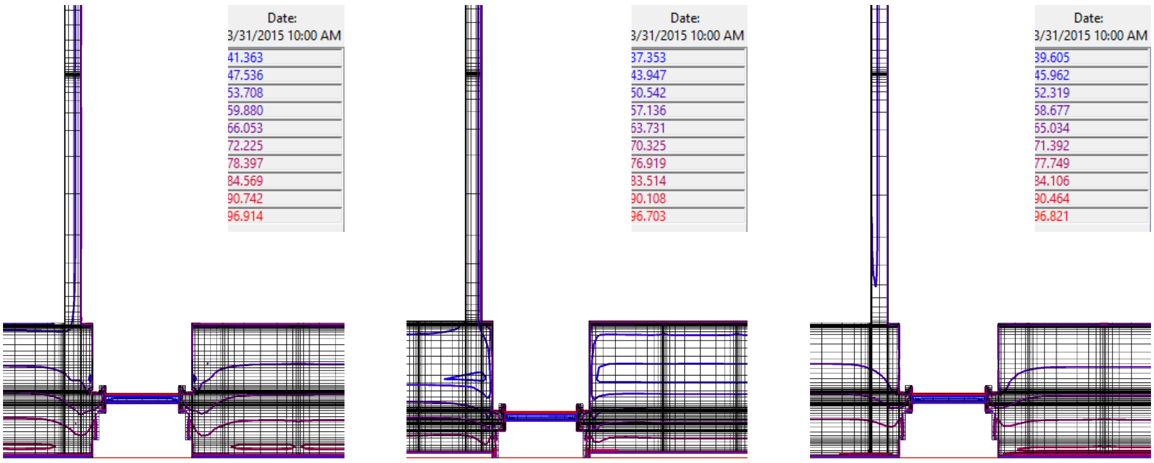
(c) AAC

Figure A.36: Comparison between materials (Same thickness) - Date 31/3/2015 at 8:00.



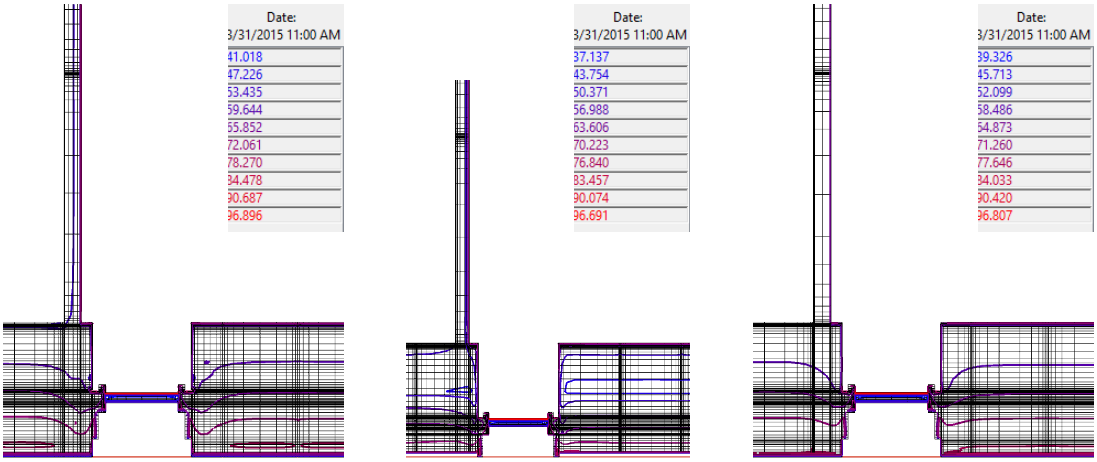
(a) Hempcrete 3 (b) Sand Lime Bricks (c) AAC

Figure A.37: Comparison between materials (Same thickness) - Date 31/3/2015 at 9:00.



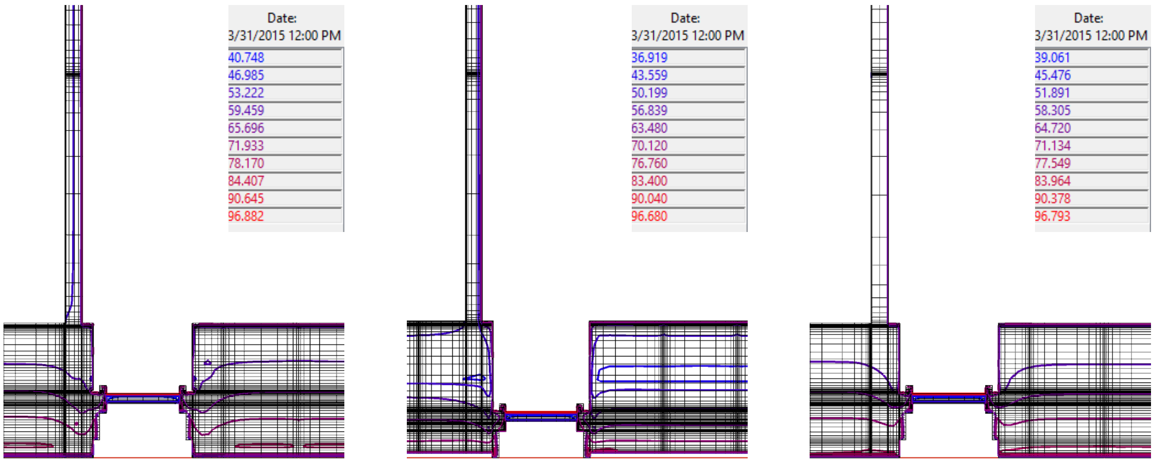
(a) Hempcrete 3 (b) Sand Lime Bricks (c) AAC

Figure A.38: Comparison between materials (Same thickness) - Date 31/3/2015 at 10:00.



(a) Hempcrete 3 (b) Sand Lime Bricks (c) AAC

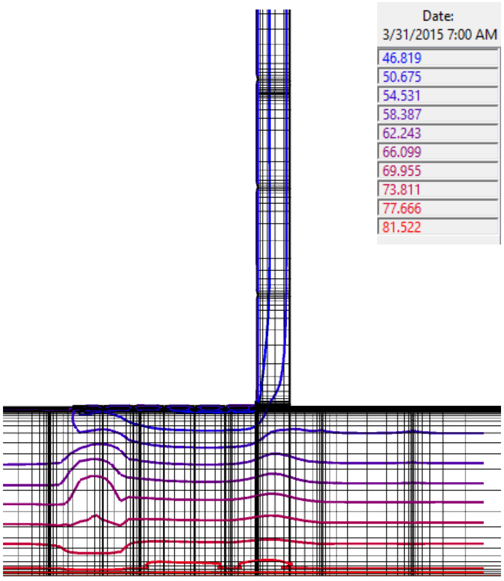
Figure A.39: Comparison between materials (Same thickness) - Date 31/3/2015 at 11:00.



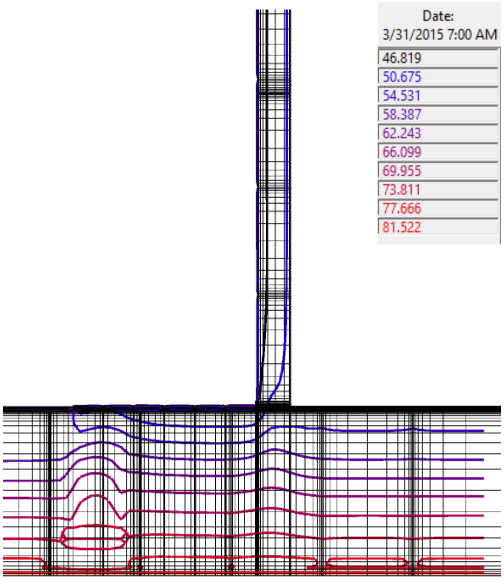
(a) Hempcrete 3 (b) Sand Lime Bricks (c) AAC

Figure A.40: Comparison between materials (Same thickness) - Date 31/3/2015 at 12:00.

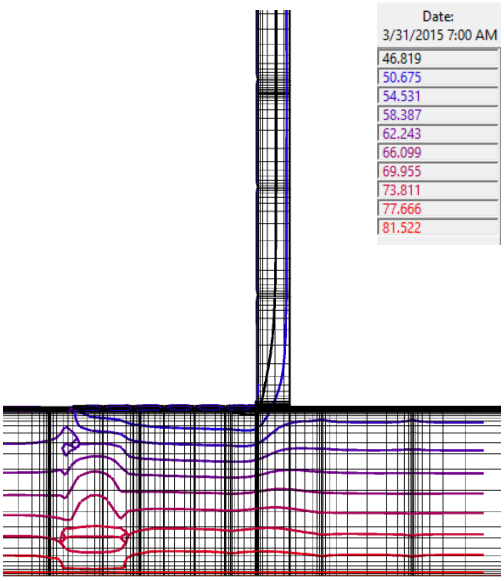
The four hempcrete options - 31/3/2015



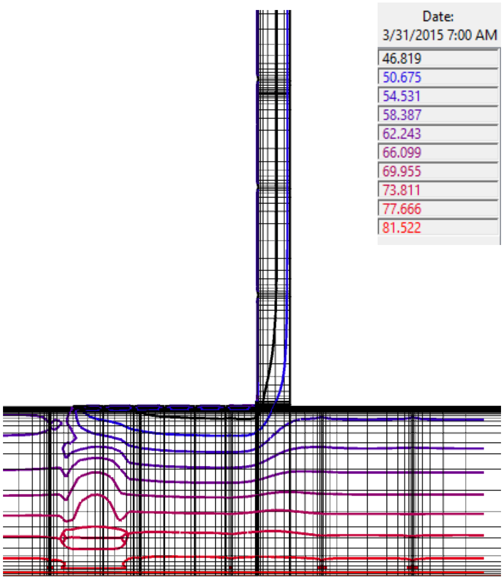
(a) Hempcrete 1



(b) Hempcrete 2

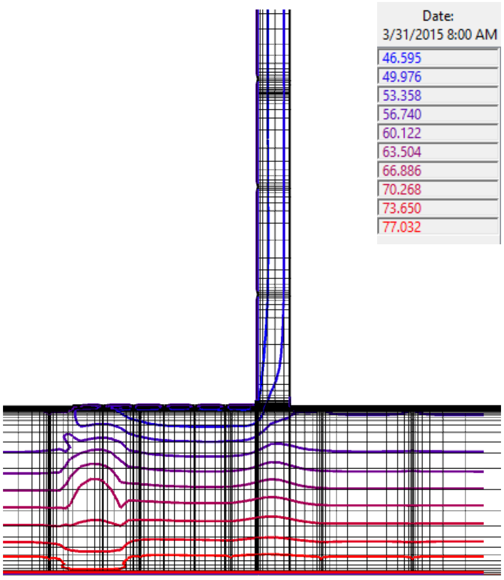


(c) Hempcrete 3

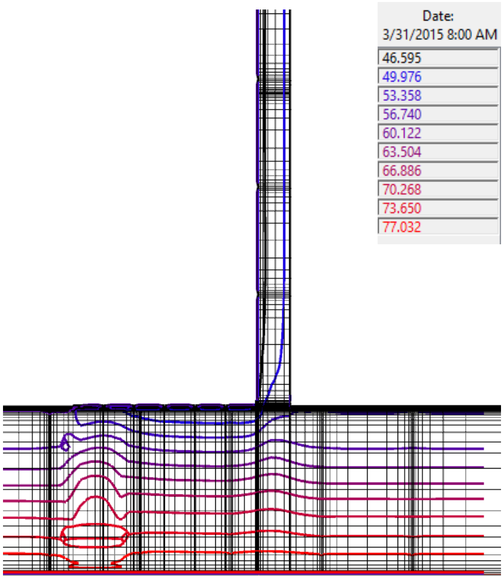


(d) Hempcrete 4

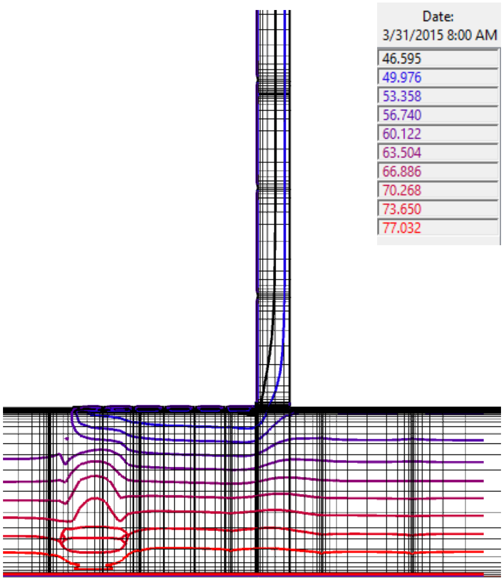
Figure A.41: Hempcrete behaviour - Date 31/3/2015 at 7:00.



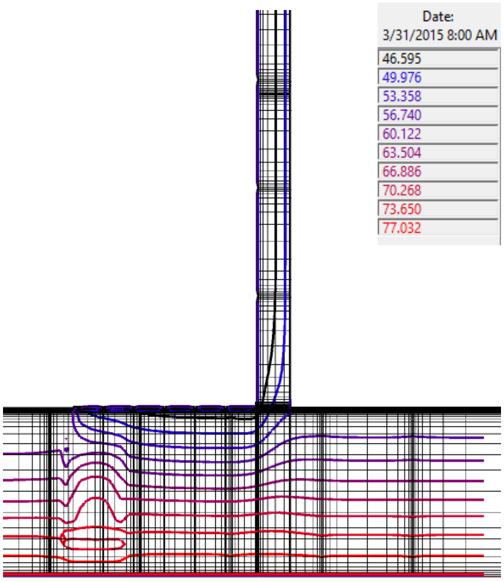
(a) Hempcrete 1



(b) Hempcrete 2

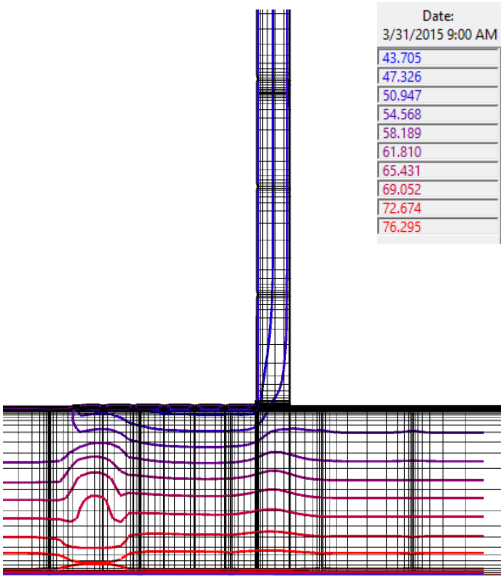


(c) Hempcrete 3

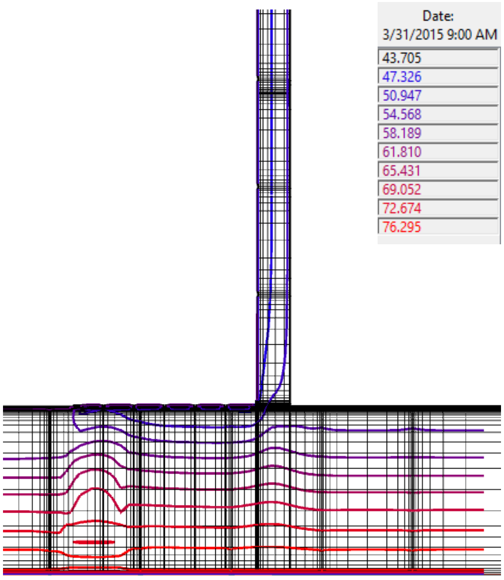


(d) Hempcrete 4

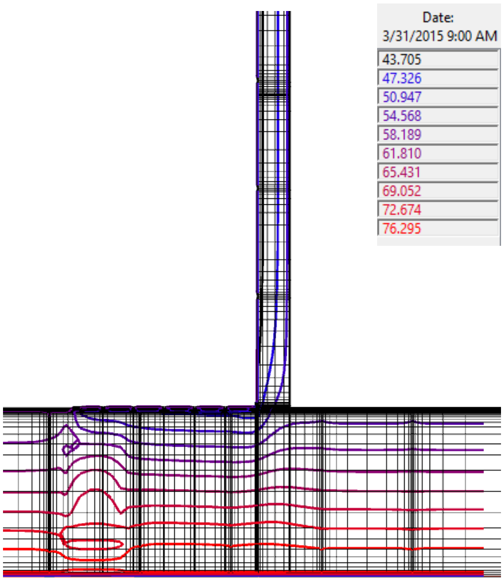
Figure A.42: Hempcrete behaviour - Date 31/3/2015 at 8:00.



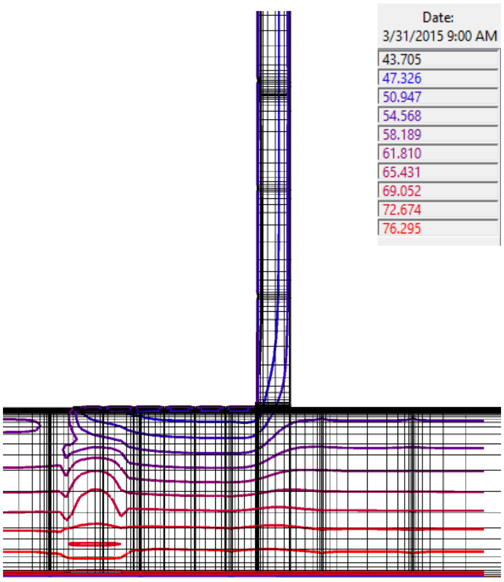
(a) Hempcrete 1



(b) Hempcrete 2

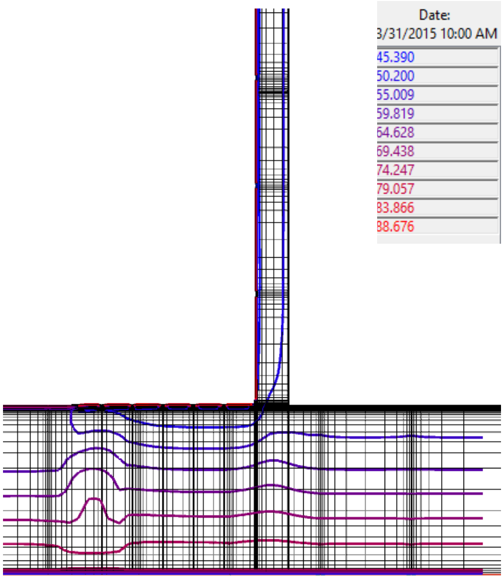


(c) Hempcrete 3

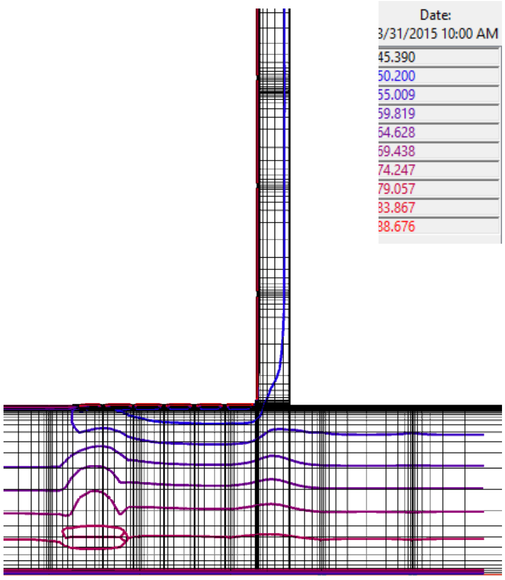


(d) Hempcrete 4

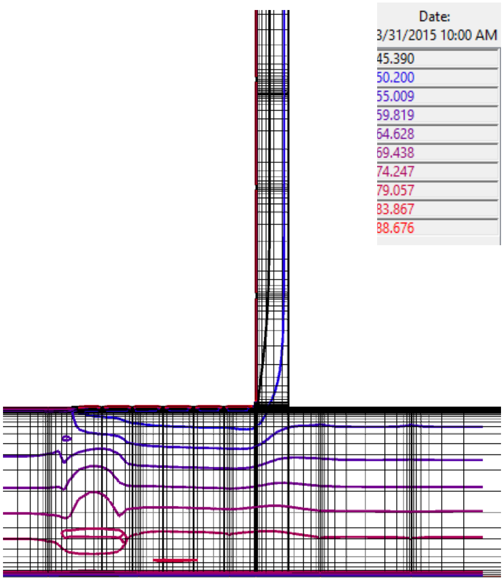
Figure A.43: Hempcrete behaviour - Date 31/3/2015 at 9:00.



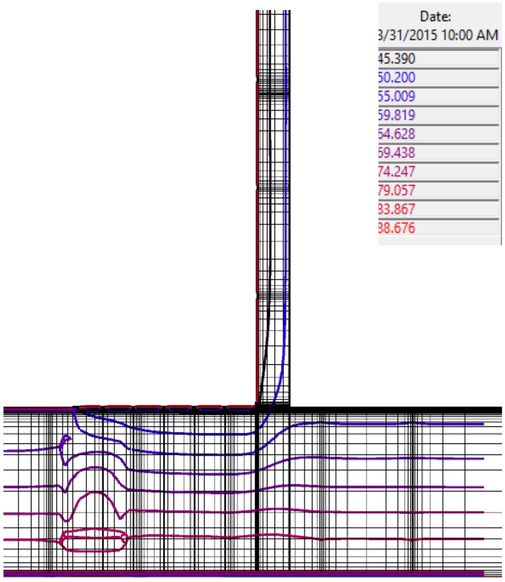
(a) Hempcrete 1



(b) Hempcrete 2

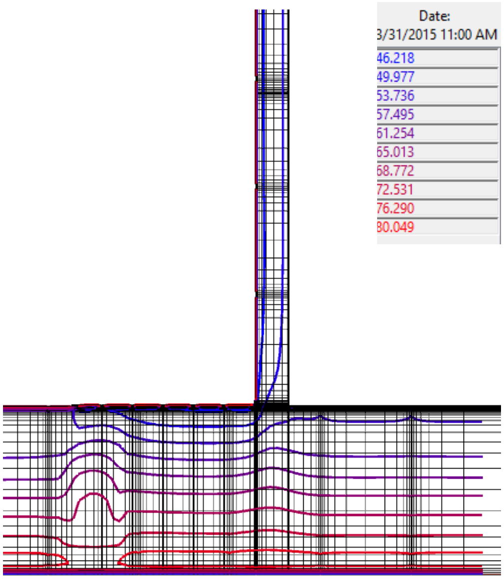


(c) Hempcrete 3

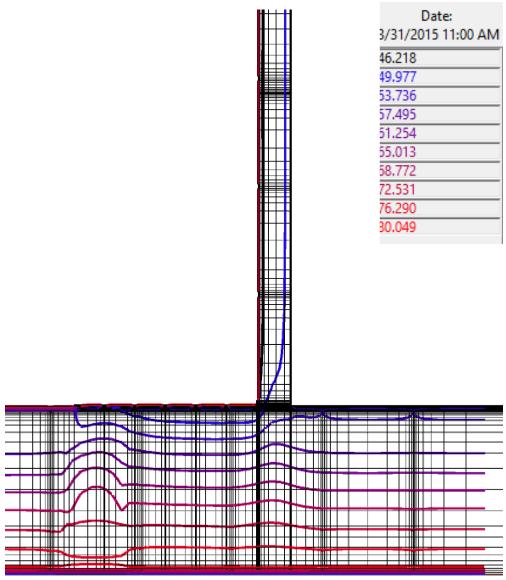


(d) Hempcrete 4

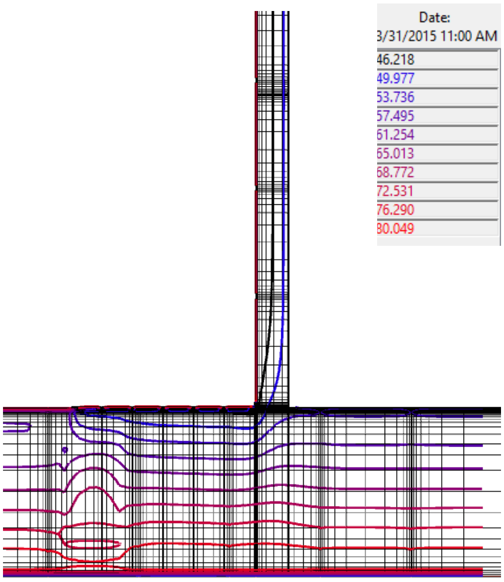
Figure A.44: Hempcrete behaviour - Date 31/3/2015 at 10:00.



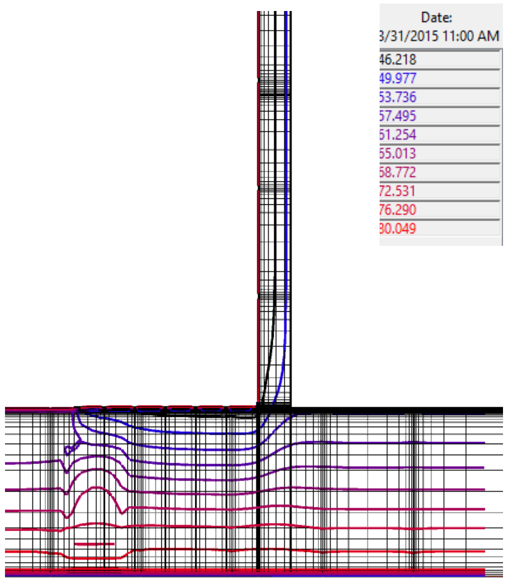
(a) Hempcrete 1



(b) Hempcrete 2

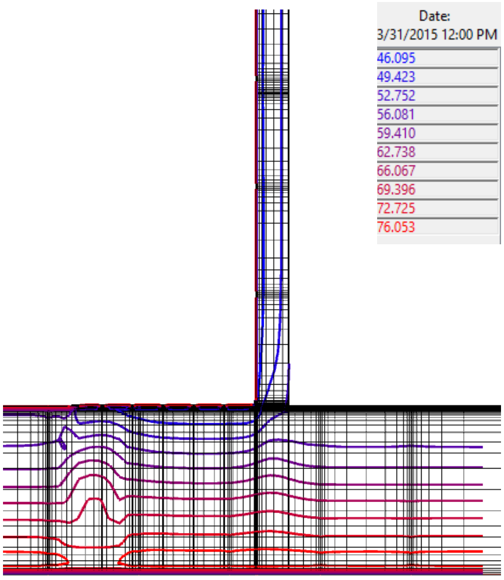


(c) Hempcrete 3

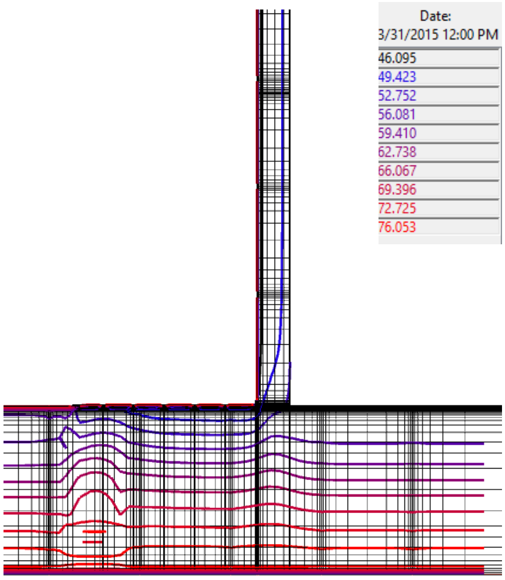


(d) Hempcrete 4

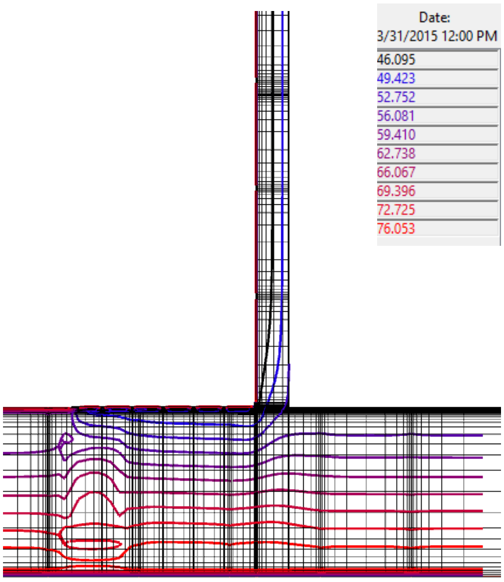
Figure A.45: Hempcrete behaviour - Date 31/3/2015 at 11:00.



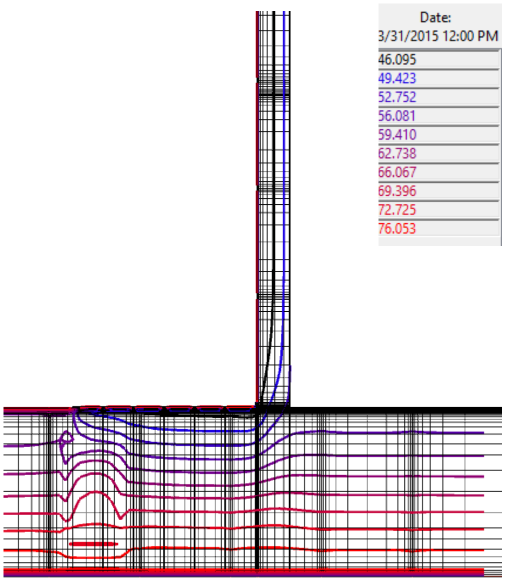
(a) Hempcrete 1



(b) Hempcrete 2



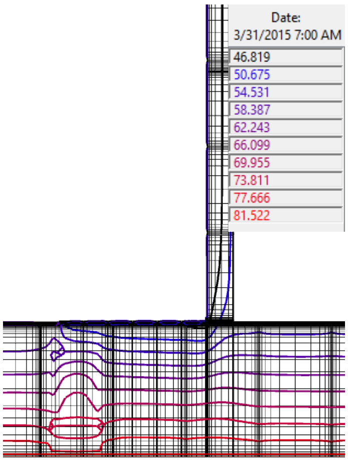
(c) Hempcrete 3



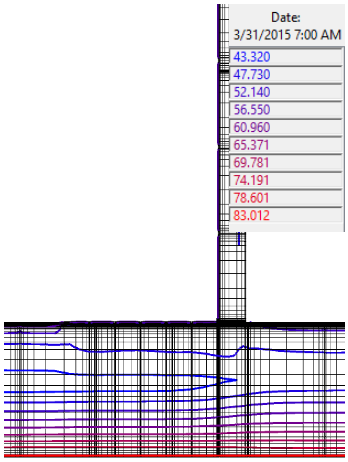
(d) Hempcrete 4

Figure A.46: Hempcrete behaviour - Date 31/3/2015 at 12:00.

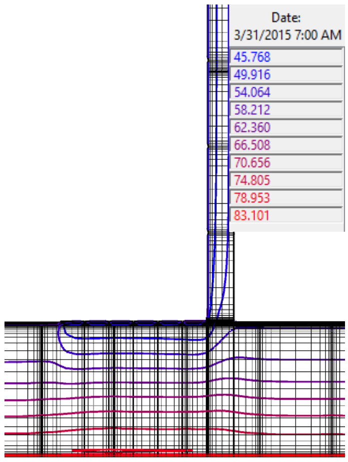
The different materials same thickness - 31/3/2015



(a) Hempcrete 3

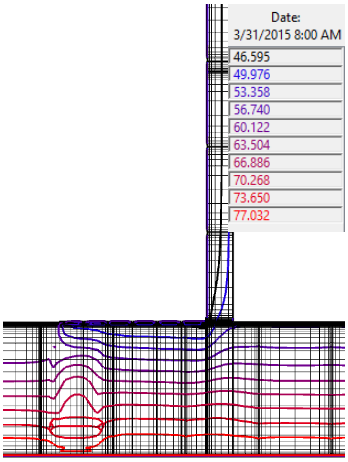


(b) Sand Lime Bricks

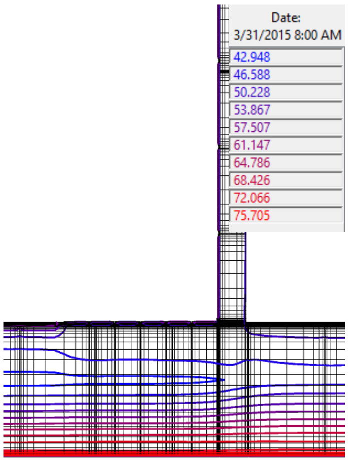


(c) AAC

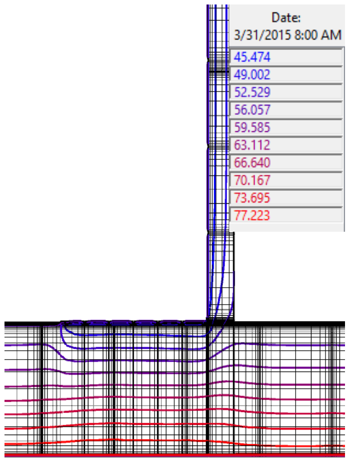
Figure A.47: Comparison between materials (Same thickness) - Date 31/3/2015 at 7:00.



(a) Hempcrete 3

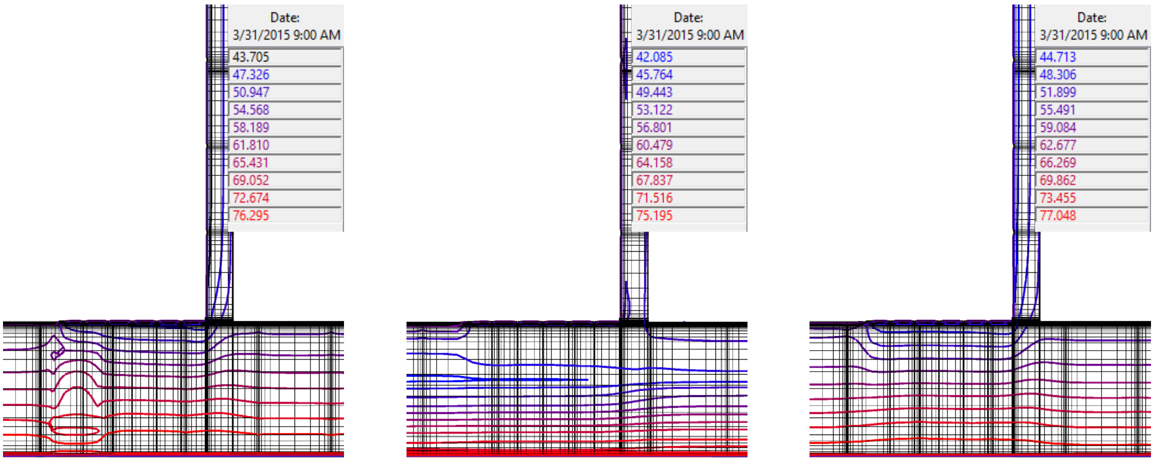


(b) Sand Lime Bricks



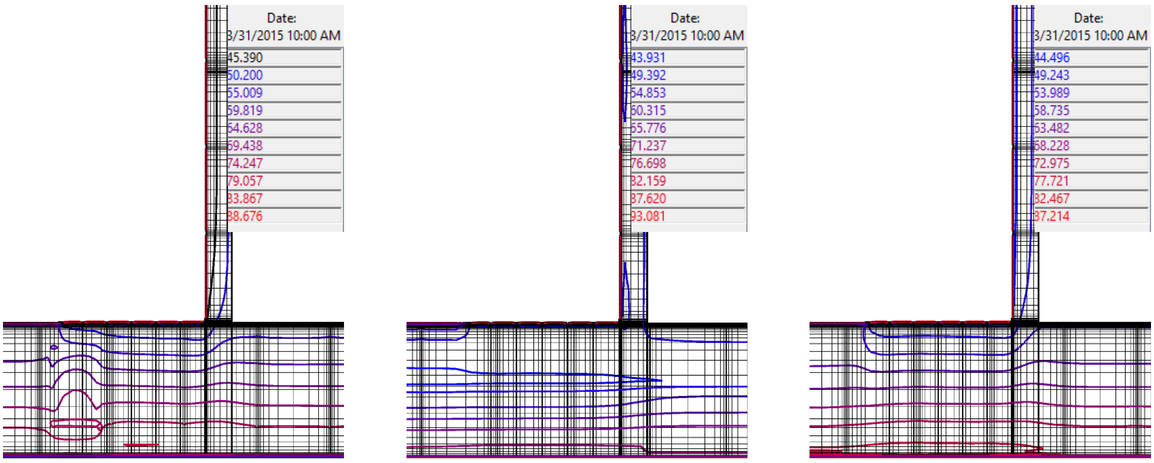
(c) AAC

Figure A.48: Comparison between materials (Same thickness) - Date 31/3/2015 at 8:00.



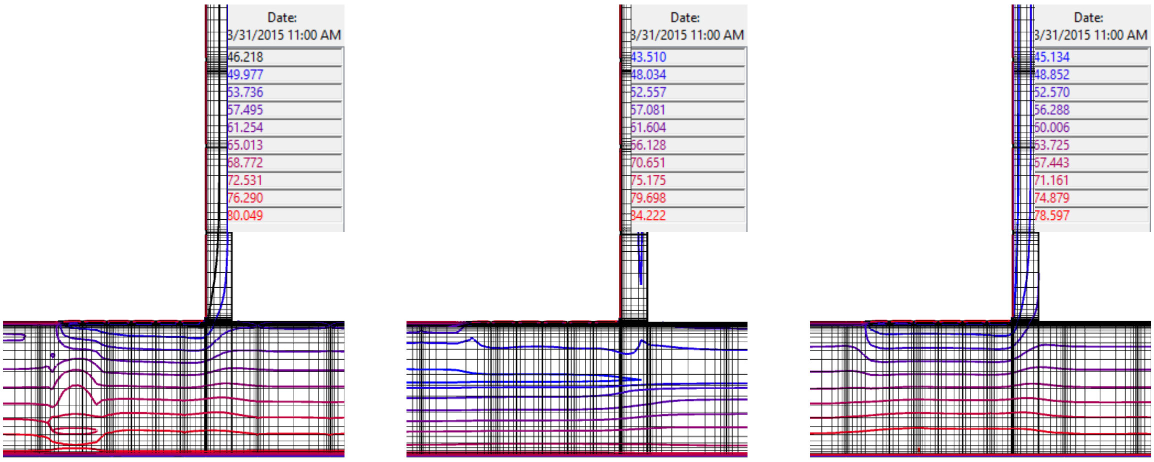
(a) Hempcrete 3 (b) Sand Lime Bricks (c) AAC

Figure A.49: Comparison between materials (Same thickness) - Date 31/3/2015 at 9:00.



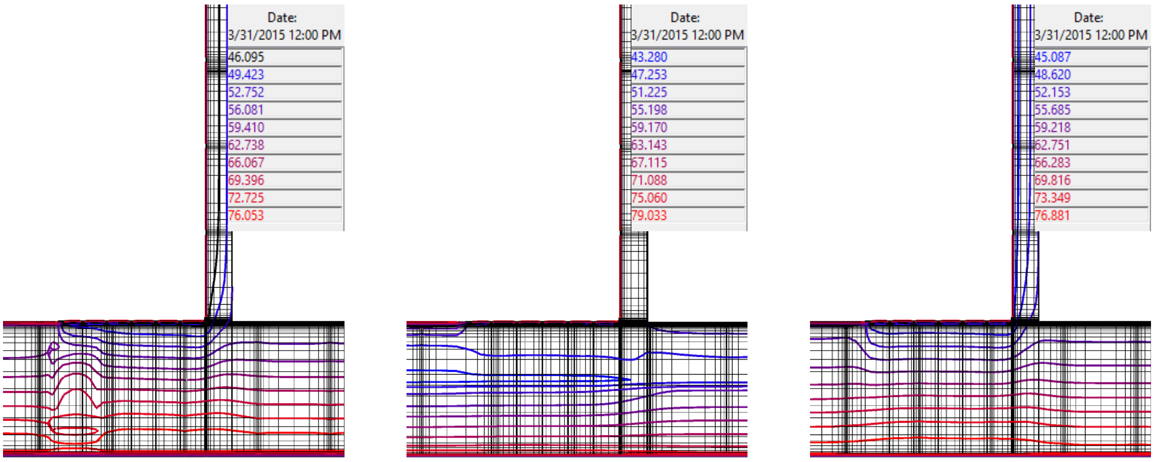
(a) Hempcrete 3 (b) Sand Lime Bricks (c) AAC

Figure A.50: Comparison between materials (Same thickness) - Date 31/3/2015 at 10:00.



(a) Hempcrete 3 (b) Sand Lime Bricks (c) AAC

Figure A.51: Comparison between materials (Same thickness) - Date 31/3/2015 at 11:00.



(a) Hempcrete 3 (b) Sand Lime Bricks (c) AAC

Figure A.52: Comparison between materials (Same thickness) - Date 31/3/2015 at 12:00.

Beam number	b(mm)	h(mm)	L (mm)	N left (KN)	N Middle (KN)	N rigth (KN)	N (max) (KN)	Q support A (KN)	Q support B (KN)	M middle (KNm)
1a	150	180	3400	-11.50	-7.63	-3.53	-11.50	3.75	-3.75	3.28
1b	150	180	3400	-3.53	-7.63	-11.50	-11.50	3.75	-3.75	3.28
2a	150	250	3400	-22.10	-14.43	-6.75	-22.10	7.18	-7.18	6.28
2b	150	250	3400	-6.75	-14.43	-22.10	-22.10	7.18	-7.18	6.28
3a	150	180	3400	-10.51	-6.87	-3.23	-10.51	3.43	-3.43	3.00
3b	150	180	3400	-3.23	-6.87	-10.51	-10.51	3.43	-3.43	3.00
11	150	250	4800	8.88	8.88	8.88	8.88	10.90	-10.90	15.40
				5.97	5.97	5.97	5.97	11.80	-11.80	16.82
10	150	300	4800	16.55	16.55	16.55	16.55	21.60	-21.60	33.80
				10.20	10.20	10.20	10.20	26.30	-26.30	41.20
4	150	350	4800	8.18	8.18	8.18	8.18	28.34	-28.34	43.32
				5.04	5.04	5.04	5.04	33.00	-33.00	50.73
20	150	180	4000	0	0	0	0	1.3	-1.3	1.3
18	150	300	4300	0.00	0.00	0.00	0.00	27.10	-27.10	29.12
17	150	300	4950	0.00	0.00	0.00	0.00	31.20	-31.20	38.90
19	150	180	4000	0	0	0	0	1.30	-1.30	1.30
12	150	300	4950	0.00	0.00	0.00	0.00	29.70	-29.70	36.80
3	150	250	4300	0.00	0.00	0.00	0.00	25.80	-25.80	27.75
15	150	180	4950	0.00	0.00	0.00	0.00	1.63	-1.63	2.02
16	150	250	4300	0.00	0.00	0.00	0.00	19.32	-19.32	27.15
9	150	180	1600	0	0	0	0	0.52	-0.52	0.21
7	150	250	4800	0	0	0	0	12.27	-12.27	14.73
8	150	180	1600	0	0	0	0	0.52	-0.52	0.21
5	150	250	4300	0	0	0	0	-25.3	32.3	30.34
6	150	250	4950	0	0	0	0	-14.8	10.2	16.7

Figure A.53: The loading and dimensions of the beams.

Column	b(mm)	h(mm)	H buck	N (max) (KN)	Q support ground (KN)	Q middle (KN)	Q support B (KN)	M left (KNm)	M middle (KNm)	M right (KNm)
:1	150	150	4900	-12.75	0	0	0	0	0	0
:2	150	150	4900	-12.75	0	0	0	0	0	0
:3	150	200	4900	-31.7	3.77	3.77	3.77	2.86	-1.77	-6.4
:4	150	300	4900	-92.7	6.8	6.8	6.8	5.22	-3.065	-11.35
C5	150	200	4900	-57.6	3.51	3.51	3.51	2.67	-1.62	-5.91
	150	200	4900	-58.9	2.16	2.16	2.16	1.65	-0.995	-3.64
:6	150	200	4900	-54.23	4.05	4.05	4.05	-3.46	1.5	6.46
:7	150	300	4900	-115.3	-6.7	-6.7	-6.7	-5.63	2.57	10.77
:8	150	250	4900	-80.9	-3.78	-3.78	-3.78	-3.21	1.42	6.05
	150	250	4900	-82.28	-2.33	-2.33	-2.33	-1.98	0.875	3.73
:9	150	200	6100	-32.4	0	0	0	0	0	0
10	150	200	6100	-58.3	0	0	0	0	0	0
11	150	200	6100	-28.3	0	0	0	0	0	0

Figure A.54: The loading and dimensions of the columns.

								Compression	(N/mm^2)
	σNd	σNd/kc1	σNd/kc2	Strength Class	fc0d	fck	E0,0,5	Verification	fmd
1	0.57	0.37	0.37	C14	7.38	16.00	4700.00	0.37	6.46
2	0.57	0.37	0.37	C14	7.38	16.00	4700.00	0.37	6.46
3	1.06	0.21	0.35	C40	12.00	26.00	9400.00	0.35	18.46
4	2.06	0.21	0.61	C50	13.38	29.00	10700.00	0.61	23.08
C5	1.92	0.34	0.57	C50	13.38	29.00	10700.00	0.57	23.08
	1.96	0.35	0.58	C50	13.38	29.00	10700.00	0.58	23.08
6	1.81	0.36	0.60	C40	12.00	26.00	9400.00	0.60	18.46
7	2.56	0.26	0.75	C50	13.38	29.00	10700.00	0.75	23.08
8	2.16	0.31	0.72	C40	12.00	26.00	9400.00	0.72	18.46
	2.19	0.31	0.73	C40	12.00	26.00	9400.00	0.73	18.46
9	1.08	0.32	0.54	C40	12.00	26.00	9400.00	0.54	18.46
.0	1.94	0.50	0.86	C50	13.38	29.00	10700.00	0.86	23.08
.1	0.94	0.28	0.48	C40	12.00	26.00	9400.00	0.48	18.46

(N/mm^2)

Figure A.55: Strength verification for columns.

			Flexural Buckling				
	Fyd Max	fyd (min)	[a]	[b]	Compression verification+[a]	Compression verification+[b]	Verification
			fmd/fyd max	fmd/fyd min			
1	0.0	0.00					
2	0.0	0.00					
3	-2.9	6.40	-0.15	0.3467	0.20	0.70	0.70
4	-2.3	5.04	-0.10	0.2186	0.51	0.82	0.82
C5	-2.7	5.91	-0.12	0.2561	0.45	0.82	0.82
	-1.7	3.64	-0.07	0.1577	0.51	0.74	0.74
6	3.5	-6.46	0.19	-0.3499	0.79	0.25	0.79
7	2.5	-4.79	0.11	-0.2074	0.86	0.55	0.86
8	2.1	-3.87	0.11	-0.2097	0.83	0.51	0.83
	1.3	-2.39	0.07	-0.1293	0.80	0.60	0.80
9	0.0	0.00					
.0	0.0	0.00					
.1	0.0	0.00					

Figure A.56: Strength verification for columns.

Strength verification for combined bending and axial tension stresses:

Beam number	σt,0,d	ft,0,d	σm,y,d	fm,y,d	Verification	Strength class
11	0.2	7.38	9.86	12.46	0.82	C27
	0.2	7.38	10.76	12.46	0.89	
10	0.4	12.46	15.02	20.77	0.75	C45
	0.2	12.46	18.31	20.77	0.90	
4	0.2	12.46	14.15	20.77	0.69	C45
	0.1	12.46	16.56	20.77	0.81	

Strength verification for combined bending and axial tension stresses:

$$\frac{\sigma_{t,0,d}}{f_{t,0,d}} + \frac{\sigma_{m,y,d}}{f_{m,y,d}} + k_m \frac{\sigma_{m,z,d}}{f_{m,z,d}} \leq 1$$

$$\frac{\sigma_{t,0,d}}{f_{t,0,d}} + k_m \frac{\sigma_{m,y,d}}{f_{m,y,d}} + \frac{\sigma_{m,z,d}}{f_{m,z,d}} \leq 1$$

Figure A.57: Strength verification for combined bending and axial tension stresses.

Beam number	σc,0,d	fc,0,d		σm,y,d	fm,y,d	Verification	Strength class	t	fv
1a	-0.28	7.38		4.05	6.46	0.63	C14	0.14	1.38
1b	-0.28	7.38		4.05	6.46	0.63	C14	0.14	1.38
2a	-0.38	7.38		4.02	6.46	0.62	C14	0.19	1.38
2b	-0.38	7.38		4.02	6.46	0.62	C14	0.19	1.38
3a	-0.25	7.38		3.70	6.46	0.57	C14	0.13	1.38
3b	-0.25	7.38		3.70	6.46	0.57	C14	0.13	1.38
	$\left(\frac{\sigma_{c,0,d}}{f_{c,0,d}}\right)^2 + \frac{\sigma_{m,y,d}}{f_{m,y,d}} + k_m \frac{\sigma_{m,z,d}}{f_{m,z,d}} \leq 1$							0.29	1.85
								0.48	1.85
								0.54	1.85
	Verification for bending								
20				1.60	6.46	0.25	C14	0.05	1.38
18				12.94	16.15	0.80	C35	0.60	1.85
17				17.29	20.77	0.83	C45	0.69	1.85
19				1.60	6.46	0.25	C14	0.05	1.38
12				16.36	18.46	0.89	C40	0.66	1.85
3				17.76	20.77	0.86	C45	0.69	1.85
15				2.49	6.46	0.39	C14	0.06	1.38
16				17.38	20.77	0.84	C45	0.52	1.85
9				0.26	6.46	0.04	C14	0.02	1.38
7				9.43	11.08	0.85	C24	0.33	1.38
8				0.26	6.46	0.04	C14	0.02	1.38
5				19.42	23.08	0.84	C50	-0.67	1.85
6				10.69	12.46	0.86	C27	-0.39	1.85

Figure A.58: Strength verification for combined bending and compression tension stresses.

ULS	people	y0	0.4	floors
	people and furniture	y0	0.4	floors
	snow	y0	0	roof
	Wind	y0	0	façade
SLS	people	y1	0.5	floors
	people and furniture	y1	0.5	floors
	snow	y1	0.2	roof
	Wind	y1	0.2	façade
	people	y2	0.3	floors
	people and furniture	y2	0.3	floors
	snow	y2	0	roof
	Wind	y2	0	façade

ULS:

$$6.10(a):\ 1.2\,G_k + 1.35 y_{0,1} Q_{k1} + 1.35 \sum_{i=2}^{n} y_{0,i} Q_{ki}$$

$$6.10(b):\ 1.1\,G_k + 1.35 Q_{k1} + 1.35 \sum_{i=2}^{n} y_{0,i} Q_{ki}$$

SLS:

$$6.14(b):\ G_k + y_1 Q_{k1} + 1.35 \sum_{i=2}^{n} y_{2,i} Q_{ki}$$

Figure A.59: Tested combinations and factors.

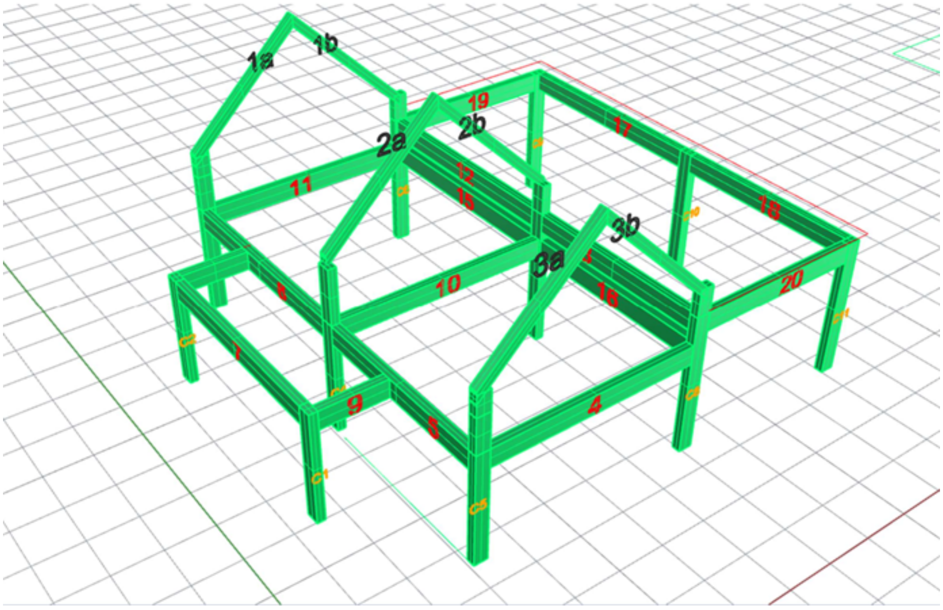


Figure A.60: The structural system.

Beam number	d (m)	h (m)	l (m)	l'(m)	V (m3)	Location	Location code	Partly factors	Total V
1a	0.15	0.18	3.40	3.40	0.09	Facade			
1b	0.15	0.18	3.40	3.40	0.09	Facade			
2a	0.15	0.25	3.40	3.40	0.13	Indoors			
2b	0.15	0.25	3.40	3.40	0.13	Indoors			
3a	0.15	0.18	3.4	3.40	0.09	Facade			
3b	0.15	0.18	3.40	3.40	0.09	Facade			
3	0.15	0.25	4.30	4.15	0.16	Indoors			
4	0.15	0.35	4.80	4.575	0.24	Facade			
5	0.15	0.25	4.30	4.075	0.09	Partly facade		0.56	0.15
					0.07			0.44	
6	0.15	0.25	4.95	4.70	0.07	Partly facade		0.38	0.18
					0.11			0.62	
7	0.15	0.25	4.80	4.65	0.17	Facade			
8	0.15	0.18	1.60	1.45	0.04	Facade			
9	0.15	0.18	1.60	1.45	0.04	Facade			
10	0.15	0.30	4.80	4.65	0.21	Indoors			
11	0.15	0.25	4.80	4.6	0.17	Facade			
12	0.15	0.30	4.95	4.725	0.21	Indoors			
15	0.15	0.18	4.95	4.725	0.13	Indoors			
16	0.15	0.25	4.30	4.15	0.16	Indoors			
17	0.15	0.30	4.95	4.775	0.21	Facade			
18	0.15	0.30	4.30	4.125	0.19	Facade			
19	0.15	0.18	4.00	3.8	0.10	Facade			
20	0.15	0.18	4.00	3.8	0.10	Facade			

Figure A.61: Volumes beams.

Columns	d (m)	h (m)	l (m)	V (m3)	Location	Location code	Total element V	Factor
C1	0.15	0.15	2.45	0.1	Facade	W2		
C2	0.15	0.15	2.45	0.1	Facade	W2		
C3	0.15	0.20	3.65	0.1	Facade	W2	0.11	0.50
				0.1		W3		0.50
C4	0.15	0.30	3.65	0.1	Partly facade	W2	0.16	0.33
				0.1		Indoors - Load Bearing		0.67
C5	0.15	0.20	3.65	0.1	Facade	W1	0.11	0.50
				0.1		W2		0.50
C6	0.15	0.20	3.65	0.1	Facade	W3		
C7	0.15	0.30	3.65	0.03	Partly facade	W5	0.16	0.16
				0.14		Indoors - Load Bearing		0.84
C8	0.15	0.25	3.65	0.1	Facade	W1		
C9	0.15	0.20	3.05	0.05	Facade	W3	0.1	0.5
				0.05		W4		0.5
C10	0.15	0.20	3.05	0.1	Facade	W4		
C11	0.15	0.20	3.05	0.05	Facade	W1	0.1	0.5
				0.05		W4		0.5

Figure A.62: Volumes columns.

Facade			
Wall	Area (m2)	Thickness (m)	V facade(m3)
W1	40.55	0.35	14.2
W2	46.70	0.35	16.3
W3	40.55	0.35	14.2
W4	36.00	0.35	12.6
W5	5.75	0.35	2.0
Total	169.55		59.3

Wall	Thickness (m)	V (m3)
Load Bearing	0.075	5.0
Separation	0.075	3.1

Wall	Wall Volume (m3)	Timber Beams V (m3)	Timber Columns V (m3)	Timber studs Volumes	Window - openings	Timber sum	Hempcrete
W1	12.46	0.53	0.24	0.24	1.73	1.00	11.46
W2	12.54	0.41	0.27	0.35	3.81	1.03	11.51
W3	10.41	0.46	0.21	0.19	3.79	0.86	9.55
W4	11.40	0.40	0.18	0.11	1.20	0.69	10.71
W5	2.01	0.00	0.03	0.00	0.00	0.03	1.99
Load Bearing	5.53	1.29	0.25	0.13	0.97	1.67	3.86
Separation	2.31	0.00	0.00	0.20	0.81	0.20	2.11
Total	56.67	3.08	1.18	1.21	12.30	5.47	51.19

Figure A.63: Hempcrete design.

Studs on façade			
External openings		Total Volum studs Facade	
w1	1	0.044	
	2	0.044	
	3	0.055	
	4	0.047	
	5	0.047	0.238
w4	6	0.053	
	7	0.055	0.108
w3	8	0.071	
	9	0.060	
	10	0.057	0.188
W2	11	0.039	
	12	0.240	
	13	0.034	
	14	0.036	0.348
Indoors		0.000	0.00

Figure A.64: Studs.

Windows			
External openings		Total Area windows Facade	Sum
w1	1	0.720	
	2	0.720	
	3	1.900	
	4	0.800	
	5	0.800	4.940
w4	6	1.520	
	7	1.900	3.420
w3	8	5.760	
	9	3.520	
	10	1.540	10.820
W2	11	4.800	
	12	2.000	
	13	1.440	
	14	2.640	10.880

Figure A.65: Windows.

array

List of Figures

List of Tables